

**TOWARDS AN UNDERSTANDING OF WATER STRUCTURE  
AND WATER MOVEMENT THROUGH DENSE CLAYS**

**by**

**DAVID A. DIXON**

**A Thesis  
Submitted to the Faculty of Graduate Studies  
in Partial Fulfilment of the Requirements for the Degree of**

**DOCTOR OF PHILOSOPHY**

**Department of Civil and Geological Engineering  
University of Manitoba  
Winnipeg, Manitoba**

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## ABSTRACT

The Canadian Nuclear Fuel Waste Management Program is proposing the use of a dense, bentonite clay-based material as one of the engineered barriers in its deep geological disposal concept. This barrier material, known as the buffer, is expected to limit water movement to and contaminant migration away from the disposal vault. The density of the buffer is such that there is little free pore space available for water or contaminant movement. Under conditions of low regional hydraulic gradient the mass transport in the buffer is largely a diffusion-driven process and the validity of the Darcian flow model for flow through a porous medium is in question.

Thermal expansion testing was conducted to determine the nature of the water associated with quartz sand, illitic clay, bentonitic clays and sand clay mixtures. These tests found little evidence for the presence of a structured water component in sand and illitic systems. However, bentonite clay exhibited considerable evidence of a structured water component, especially in low density systems.

The influence of initial degree of saturation, back pressuring, permeant salinity, flow direction, bacterial activity, and hydraulic gradient changes on the flux measured were all examined and found to be insignificant in densely compacted bentonites. Evidence of changes in the hydraulic character of illitic clays and low density ( $<1.0 \text{ Mg/m}^3$ ) bentonites were found. These gradient-dependent changes may be associated with the presence of weakly bonded water layers which can be sheared by elevated hydraulic gradients. Dense bentonite, and sand-bentonite specimens showed no evidence of changes in their hydraulic character as a result of changes in any of the above conditions. The hydraulic conductivity of dense bentonite-based materials was found to be approximately that predicted using the Poiseuille equation for flow through capillaries.

These data provide confidence in the efficacy of using contaminant transfer models which assume the buffer barrier to be a porous medium having very small and uniform pores. Only low density bentonitic barriers are likely to be affected by the presence of structured water components and changes in the ground water environment.

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## GLOSSARY OF SYMBOLS AND ABBREVIATIONS

|                  |                                                                                                |
|------------------|------------------------------------------------------------------------------------------------|
| a                | cross-sectional area of tubular-shaped pore                                                    |
| A                | cross-sectional area                                                                           |
| $C_s$            | shape coefficient                                                                              |
| CEC              | cation exchange capacity                                                                       |
| CFU              | colony forming units of bacteria                                                               |
| d                | half distance between clay particles                                                           |
| d'               | effective half distance between parallel particles                                             |
| $d_i$            | distance occupied by immobilized water                                                         |
| D                | dielectric constant of fluid                                                                   |
| DDL              | Diffuse Double Layer model for water structure in clay-water systems                           |
| DLVO             | model describing particle interactions as a sum of attractive and repulsive forces (Ch. 2.3.6) |
| e                | void ratio                                                                                     |
| $E_i(r)^*$       | the electric field strength at a distance r from the nucleus of the ion specified.             |
| F                | force applied                                                                                  |
| F                | flux (quantity/unit time)                                                                      |
| g                | gravitational constant ( $9.81 \text{ m/s}^2$ )                                                |
| $G_s$            | specific weight of soil particles, varying subscript denotes specific soil components          |
| $G_{\text{mix}}$ | specific weight of soil particles in a specific sand-clay mixture                              |
| i                | gradient                                                                                       |
| $i_h$            | applied hydraulic gradient                                                                     |
| $i_o$            | threshold gradient for flow initiation                                                         |
| $i_{os}$         | osmotic/chemical gradient                                                                      |
| $i_c$            | critical gradient for flow                                                                     |
| $i_{ch}$         | hydraulic gradient at which a change in hydraulic conductivity occurs                          |
| j                | number of monolayers present on a clay surface                                                 |
| k                | Boltzman constant ( $1.38 \times 10^{-16} \text{ erg/}^\circ\text{K}$ )                        |
| k, $k_h$         | hydraulic conductivity                                                                         |
| K                | permeability coefficient                                                                       |
| m                | pore shape factor                                                                              |
| $m_c$            | mass of clay                                                                                   |

|                 |                                                                       |
|-----------------|-----------------------------------------------------------------------|
| $m_s$           | mass of sand                                                          |
| $m_w$           | mass of water present in a specimen                                   |
| $n$             | porosity                                                              |
| $n_o$           | electrolyte concentration in bulk solution                            |
| $n_s$           | fractional volume occupied by solids                                  |
| $n_g$           | fractional volume occupied by gas                                     |
| $n_w$           | fractional volume occupied by liquids                                 |
| $n_w', n_{eff}$ | porosity available for flow (effective porosity)                      |
| $N$             | flow index                                                            |
| NMR             | nuclear magnetic resonance                                            |
| $P$             | dry mass ratio of clay to sand in a mixture                           |
| $q, q_h$        | flow rate (volume/unit time)                                          |
| $Q$             | flow volume                                                           |
| $R$             | radius of a tubular flow channel                                      |
| $r_p$           | average pore radius of a soil                                         |
| $R_h$           | hydraulic radius of a pore channel                                    |
| $S$             | degree of saturation                                                  |
| $S_o$           | specific surface area of clay ( $m^2/g$ )                             |
| $S_{eff}$       | effective specific surface area of mineral particles                  |
| $S_b$           | exposed specific basal surface area per gram of clay                  |
| SHM             | Surface Hydration Model for mineral-water interaction (Section 2.3.5) |
| SRB             | sulphate reducing bacteria                                            |
| $t$             | time                                                                  |
| $T$             | pore tortuosity                                                       |
| $T$             | temperature                                                           |
| $u_T$           | total of attractive and repulsive forces in DLVO model                |
| $u_A$           | attractive (van der Waals) force used in DLVO model                   |
| $u_R$           | repulsive forces generated by overlapping double layers in DLVO model |
| $u_B$           | Born repulsive energy, used in DLVO model                             |
| $v$             | valence of ions in solution, flow velocity                            |
| $v_{ave}$       | average fluid velocity                                                |
| $v_h$           | mean effective flow velocity of fluid                                 |
| $v'$            | effective fluid velocity                                              |



|               |                                                                  |
|---------------|------------------------------------------------------------------|
| $V$           | volume                                                           |
| $V_s$         | volume of solids                                                 |
| $V_T$         | specific volume of water                                         |
| $V_T'$        | normalized specific volume of water (Chapter 5)                  |
| $w_c$         | gravimetric moisture content at saturation of clay portion (%)   |
| $\beta_b$     | coefficient of thermal expansion of bulk water                   |
| $\beta_w$     | coefficient of thermal expansion of free water                   |
| $\beta_w'$    | normalized coefficient of thermal expansion of free water        |
| $\beta_s$     | coefficient of thermal expansion of structured water             |
| $\beta_c$     | coefficient of thermal expansion of crystalline (ice-like) water |
| $\beta_m$     | coefficient of thermal expansion for mineral(s)                  |
| $\gamma_d$    | dry bulk density of a soil                                       |
| $\gamma_c$    | effective clay dry density                                       |
| $\varepsilon$ | unit electron charge ( $4.8 \times 10^{-10}$ esu)                |
| $\eta$        | fluid viscosity                                                  |
| $\eta'$       | flow index (a shear-rate dependent variable)                     |
| $\rho_w$      | density of liquid water                                          |
| $\rho_c$      | density of clay particles                                        |
| $\xi$         | slip (shear) plane of water                                      |
| $\psi$        | potential                                                        |
| $\Omega$      | rate at which fluid is sheared                                   |
| $\Omega_c$    | critical shear rate for flow behaviour                           |
| $\sigma$      | shear stress                                                     |
| $\sigma_o$    | initial yield stress in a fluid                                  |
| $\sigma_B$    | Bingham yield stress                                             |
| $1/\kappa$    | thickness of the double layer                                    |
| $\alpha$      | inner Helmholtz plane                                            |
| $\rho$        | unit weight                                                      |

## 1.0 INTRODUCTION

Clay-based barriers to the movement of water and contaminants have seen increasing use during the past decade. They are required to perform reliably and predictably for decades, and in some proposed applications for centuries or millennia. Such barriers are expected to limit advective flow in such a way that contaminant movement is controlled by diffusion. In designing a diffusion-controlled barrier system the engineer is required to understand mineralogy, chemistry, physics and hydraulics. When dealing with the very low rates of mass transport that are involved, it is necessary to re-examine many of the long-accepted models for flow and mass transport in earthen materials. Where simple models for flow through porous media are often adequate for coarse grained natural soils, they may be inadequate for use in engineered materials under the low hydraulic gradients that exist in most applications. The thesis examines the applicability of the most commonly accepted models for flow through porous media to results obtained in an extensive program of laboratory testing.

The need for "impermeable" barriers to water and contaminant movement are particularly crucial in the conceptual designs being developed for high level nuclear fuel waste disposal. The concept being examined by the Canadian Nuclear Fuel Waste Management Program (CNFWMP) includes the use of clay-based materials to act as barriers to contaminant migration. These barriers are needed to prevent or delay any escape of radioactive materials or decay products from a disposal vault. A sufficiently long isolation time to allow the natural decay of the radioactive waste materials is central to this disposal concept.

The Canadian reference concept for nuclear fuel waste disposal involves emplacement of waste containers in boreholes drilled in the floor of rooms constructed at depths of 500m to 1000m in the crystalline rocks of the Canadian Shield. It includes the use of a compacted clay-based "buffer" material to fill the annulus between the waste container and the surrounding granitic rock mass. The buffer must support the waste container, conduct heat away from the heat-generating waste container, and provide an ability for the system to self-seal while maintaining a low hydraulic conductivity and diffusion coefficient to limit the movement of radionuclides.

A range of candidate clays has been examined to establish their potential for use in the buffer material. The montmorillonitic clays of the smectite family of layer silicates have shown the greatest potential for successful application. Much work has been done over the past 40 years on the behaviour of these clays. However most of this work has been on slurried or low density material and so has been more theoretical than of practical use in the nuclear waste isolation application. One of the primary reasons for the lack of data on the hydraulic behaviour of dense smectites has been the technical difficulty in actually measuring flow through them. These materials commonly exhibit hydraulic conductivities (k) in the order of  $10^{-10}$  m/s to  $10^{-14}$  m/s, and typically, the hydraulic gradients used to test such materials have to be much higher than encountered in practice.

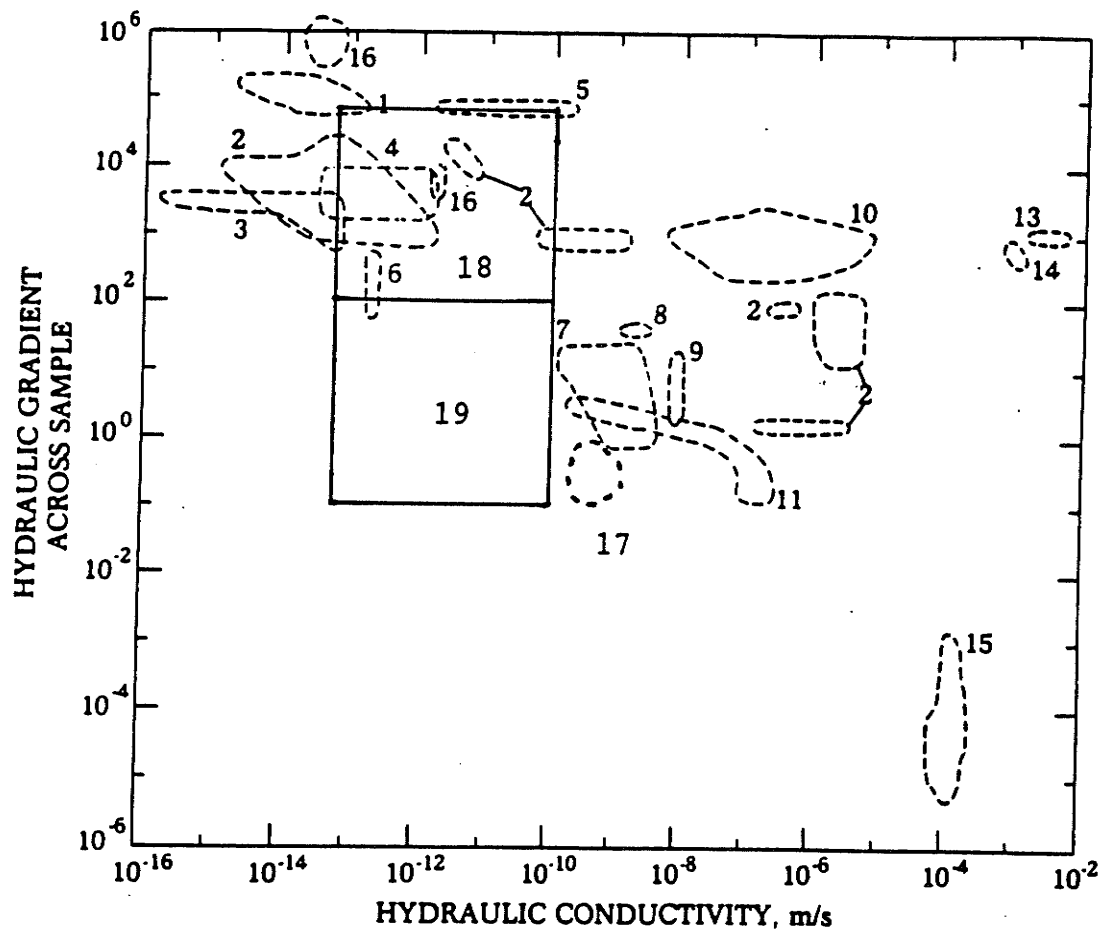
Bentonite is the name used both as a generic label for montmorillonite-type smectitic clays sold commercially as sealants and binders, and for a specific variety of swelling clay mineral first identified at Fort Benton Texas. For the purposes of simplicity, unless required for purposes of specific reference, the generic term bentonite will be used throughout this thesis when discussing montmorillonite-type clay minerals.

Although the actual data base on the generic behaviour of bentonitic clays is limited, it is accompanied by an extensive literature that encompasses a range of opinions regarding the physics and chemistry of bentonite-water systems. Literature abounds with theories and models for fluid movement through clays and bentonite-water mixtures. Many of the models and theories represent contradictory explanations for the same observed behaviour, or are based on extensions of behaviours observed in low density slurries.

Much of the literature describes attempts to apply classical models for fluid flow in granular media to fluid flow through dense, saturated clays. Little data is available on water movement or ionic diffusion through dense, bentonite clay-based materials exposed to very low regional ground water gradients. A paper by Neuzil (1986) provides an excellent review of the testing that has been conducted to obtain hydraulic conductivity values. This summary shows clearly the lack of data available for materials of hydraulic conductivity less than  $10^{-10}$  m/s using applied hydraulic gradients of less than 100 (Figure 1.1). This low hydraulic gradient condition is of particular interest in the Canadian nuclear fuel waste management program. The lack of data is the result of technological limitations, and the demanding time requirements for such tests. For most researchers, one to two years duration for each test is an impractical application of laboratory resources and too expensive to undertake. Due to the particular sensitivity of the high level nuclear waste management research program, the resources needed to conduct such tests have been made available for this doctoral program.

This thesis presents results of a study of the hydraulic conduction behaviour of clays tested under a range of densities, hydraulic gradients and back pressure conditions. The physical nature of the water associated with densely packed clay particles and the

movement of this water through saturated clay soils is also investigated. The results obtained are compared to a number of flow models, including the Darcian, Poiseuille, Kozeny-Carman and Buckingham-Reiner models. The potential for non-proportional flux-gradient relationships, critical gradients, and threshold gradients below which flow will not occur must be known if selection and development of water movement models are to be achieved.



- 17 Sri Ranjan & Gilham (1991)
- 18 Dixon et al. (1987,1992b)
- 19 Dixon PhD. (1990-1994)

Figure 1.1 Range of Hydraulic Conductivity Measurements and Applied Hydraulic Gradients Reported in Literature (after Neuzil, 1986)

## **2.0 CLAY MINERALOGY, WATER STRUCTURE AND CLAY-WATER BEHAVIOUR**

### **2.1 Structure and Sources of Surface Charge in Clay Minerals**

The minerals present in a soil are arguably the most important parameter in determining the ultimate hydraulic performance of a barrier material. Their size, shape, orientation, and electro-chemical properties all combine to determine the manner in which water, other permeant, or solvated ions will be transported through the soil.

The mineral composition of the materials investigated as part of this thesis include quartz, illite, and montmorillonite. Feldspar, chlorite and kaolinite clay minerals as well as gypsum have been identified as minor components in some of the mineralogical analyses. A detailed presentation of the results of mineralogical analysis of the materials tested is presented in Chapter 4.2.

Quartz is a silicon dioxide ( $\text{SiO}_2$ ) which is linked in a framework of  $\text{SiO}_4$  tetrahedra (Mason and Berry 1968). The feldspar group of minerals are continuous three-dimensional networks of  $\text{SiO}_4$  and  $\text{AlO}_4$  tetrahedra with positively charged sodium, potassium, calcium, or barium in the interstices of the negatively charged tetrahedra (Mason and Berry 1968). As these minerals are generally electrically neutral internally they carry only weak surface charges which are readily satisfied by water molecules. Quartz and feldspar are primary minerals and so they are typically larger in dimension than the secondary clay minerals such as illite, kaolinite or smectite. As a result they have a much lower specific surface  $S$  ( $\text{m}^2/\text{g}$ ) than clay minerals and hence a proportionally lower potential effect on pore fluid structure and behaviour.

Carbonates and sulphates can be present either as individual particles or as coatings on other particles (Yong et al. 1992). Carbonates such as calcite ( $\text{CaCO}_3$ ), magnesite ( $\text{MgCO}_3$ ), or dolomite ( $\text{Ca,Mg}(\text{CO}_3)_2$ ), and sulphates (gypsum ( $\text{CaSO}_4 \cdot 2\text{H}_2\text{O}$ )) have been identified as minor components in the bentonite deposits of Canada and the United States (Quigley 1984; Dixon and Woodcock 1986; Oscarson and Dixon 1989). Gypsic, and carbonate minerals are most commonly found in arid or semi-arid regions as they are relatively soluble in water or acidic environments. They are therefore much more susceptible to dissolution when placed in an environment where there is a considerable volume of fluid which is not calcium or magnesium saturated. This means that hydraulic conductivity testing of calcareous or sulphate-containing soils must have either very little pore fluid exchange or must involve so much flow that all the readily soluble material is removed.

Clay minerals are weathering or alteration products of primary minerals such as, feldspar, mica, pyroxenes or amphiboles (Yong et al. 1992). As primary minerals weather, the weathering products can recrystallize to produce small particles composed of alternating sheets of silica tetrahedra (Figure 2.1), aluminum or magnesium octahedra (Figure 2.2) and in some cases oxides of iron or potassium.

Figure 2.1 shows an idealized structure for tetrahedra that will bond to form a sheet structure. This idealized sheet is  $4.93\text{\AA}$  ( $0.493\text{nm}$ ) thick in clay minerals. The volume in the centre of the tetrahedron is  $0.55\text{\AA}$  ( $0.055\text{nm}$ ) in radius, permitting a  $0.05\text{nm}$  radius silicon atom to fit without causing structural distortion (Yong and Warkentin 1975). The silicon ion has a valence of +4 and the oxygen has a valence of -2. As each silicon has one bonded oxygen, and shares three others to form the  $\text{SiO}_2$  chain, the unit cells have

a net negative charge of -1. When the top oxygen is allowed to take on a hydrogen atom (valence +1), a neutral hydroxyl unit is formed and the unit cell becomes net neutral in charge (Yong and Warkentin 1975).

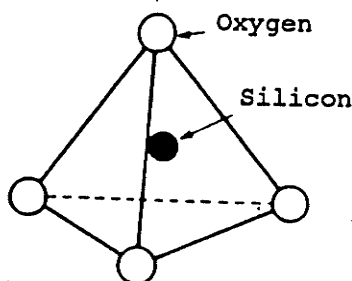


Figure 2.1  
Schematic of silica tetrahedral Unit

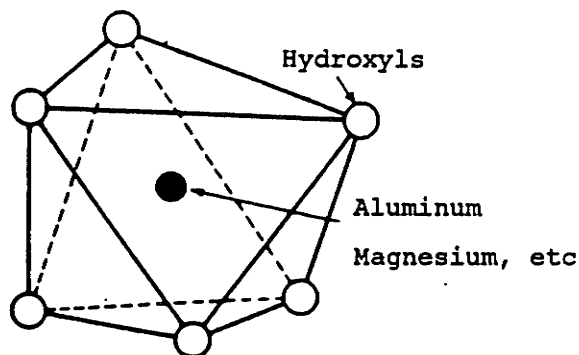


Figure 2.2  
Schematic of Octahedral Unit

Under ideal conditions, the octahedral sheet in clay minerals is composed of joined units where an aluminum atom is placed equidistantly from six hydroxyls in an octahedral shape (Figure 2.2, Yong and Warkentin 1975). The hydroxyls are shared by two aluminum atoms to form 0.505nm thick sheets of hydroxyl in a closely packed structure. In reality only about two thirds of the aluminum locations are occupied by aluminum. Other sites are commonly occupied by magnesium, iron or other atoms which can fit into the 0.061nm radius octahedral space without completely disrupting the layer structure. These spaces can also be left unfilled, resulting in the generation of a strong net negative charge within the octahedral sheet. Clay minerals with two thirds of the octahedral sites filled are known as dioctahedral clays and when all or nearly all are filled they are trioctahedral clays (Yong and Warkentin 1975)



The manner in which octahedral sheets are arranged and bonded controls the specific clay mineral formed (Figure 2.3). As a result of isomorphous substitution within the octahedral layer, a charge imbalance is generated. The resulting negative charge expresses itself on the surface of the clay particle as a negative face charge (Yong and Warkentin 1975). The layer silicates (phyllosilicates) are among the most highly charged mineral particles present in a soil. The magnitude of the charge depends on the structure of the layer silicates, the specific cations in the crystal lattice and the size of the particles.

The building blocks for the creation of clay minerals, namely the tetrahedral silica sheets, and the octahedral aluminum sheets are found in three basic layer combinations. The clay types are defined by the number of each layer type present in the basic unit of the clay. The specific clay mineral families are presented in Figure 2.3 and in Table 2.1.

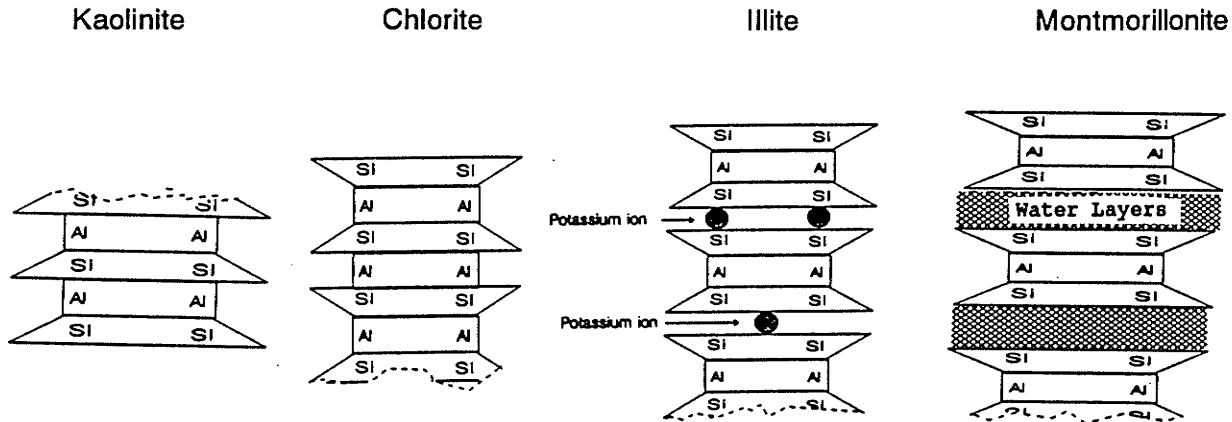


Figure 2.3 General Structural Arrangement For Clay Minerals  
(After Yong et al. 1992)

Kaolinite is composed of alternating silica and alumina sheets, each sheet sharing a plane of oxygen atoms, making this a 1:1 layer clay, between these layers the tetrahedral and octahedral sheets in adjoining layers are strongly hydrogen bonded (Yong and Warkentin 1975). The strong hydrogen bonds prevent the kaolinite crystal from hydrating and expanding under most conditions. Multiple layers tend to accumulate, leading to formation of relatively large particles (70 to 100 layers thick) (Yong and Warkentin 1975). Kaolinite particles have low specific surfaces and cation exchange capacities relative to most other clay minerals (Table 2.1). The kaolinite unit layer is 0.713nm in thickness. As it is relatively stable, it will not show changes in unit cell dimension as the result of hydration or glycolation. This produces a strong and permanent x-ray diffraction pattern of peaks at 7.13Å (0.713nm), 3.56Å (0.356nm) and 2.37Å (0.237nm) (Yong and Warkentin 1975). A typical x-ray diffraction pattern generated by kaolinite is presented in Figure 2.4.

Illite is composed of an octahedral alumina sheet sandwiched between two silica sheets. The octahedral and tetrahedral sheets share oxygen atoms, resulting in the formation of a four oxygen thick layer between these sheets. The unit cells are 9.98Å (10Å) thick and are bonded together by potassium ions. Potassium ions fit into the ditrigonal spaces present in the silica sheet neutralizing the negative charges caused by aluminum substitution or empty sites within the octahedral layer (Yong and Warkentin 1975). Under ideal conditions these potassium ions co-ordinate with 12 oxygen atoms, six from each unit layer of illite. This is a relatively stable bond and hence illite does not readily expand when it is chemically pure.

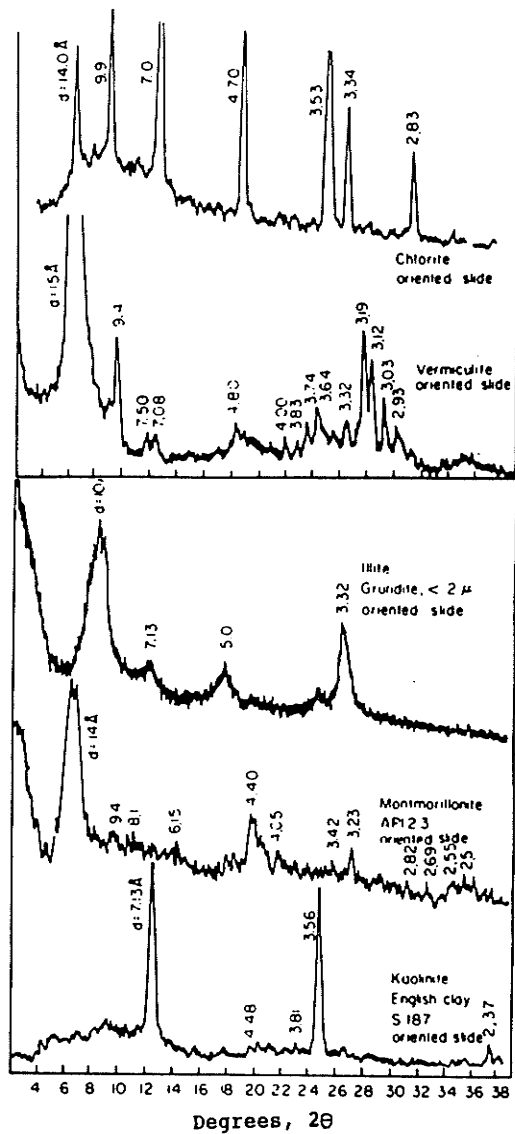


Figure 2.4 Typical X-Ray Diffraction Patterns For Clay Minerals  
(From Yong et al. 1992)

Illites found in soil tend to be less strongly ordered or structured, and have fewer potassium ions present in the interlayers than their structural equivalent in rock (muscovite or biotite). This leads to weaker bonding between the layers and the presence of other ions such as calcium, magnesium or sodium to balance the surface charge requirements. The result is a mineral which can expand to some degree given the right environmental

circumstances. Illite therefore shows properties such as specific surface, and cation exchange capacity (CEC) which are intermediate between low activity kaolinite and high activity bentonite clays (Table 2.1). Illites, being relatively stable, tend to exhibit a stable x-ray diffraction pattern and are little affected by hydration or glycolation. A typical x-ray diffraction pattern presented in Figure 2.4 shows strong peaks at 10Å (1.0nm), 5Å (0.5nm), 3.3Å (0.33nm) and 2.5Å (0.25nm).

Table 2.1

Mineral Groups, Chemical Compositions and Physico-chemical Properties  
(After Yong et al. 1992)

| Clay Mineral    | Lattice Description  | Isomorphous Substitution             | Cation Exchange Capacity (cmol/kg) | Specific Surface (m <sup>2</sup> /g) | Source of Charge                       | Charge Type                  |
|-----------------|----------------------|--------------------------------------|------------------------------------|--------------------------------------|----------------------------------------|------------------------------|
| Kaolinite       | 1:1 Strong H - Bonds | 1/3 of Dioctahedral Sites are not Al | 5 - 15                             | 10-20                                | edges broken bonds                     | Variable & permanent charges |
| Illites         | 2:1 Strong K - Bonds | Al for Si<br>Al for Mg               | 25                                 | 70-150                               | isomorphous substitution<br>edge bonds | mostly permanent charges     |
| Chlorites       | 2:2 Strong Bonds     | Al for Si                            | 10 - 40                            | 80                                   | isomorphous substitution               | mostly permanent charges     |
| Montmorillonite | 2:1 Very Weak Bonds  | Mg for Al<br>Al for Si<br>Fe for Al  | 80 - 100                           | 600-800                              | isomorphous substitution<br>edge bonds | mostly permanent charges     |
| Vermiculite     | 2:1 Weak Mg - Bonds  | Al for Si                            | 100 - 150                          | 700                                  | isomorphous substitution               | mostly permanent charges     |

Montmorillonitic clays are similar in general composition to illite, having an alumina sheet located between two tetrahedral silica sheets. In montmorillonites, isomorphous

substitution, typically magnesium for iron within the octahedral layer, leads to high surface charges. The specific ions substituted dictate the exact mineral type generated, the intensity of surface charge and associated cation exchange capacity, and specific surface. The main difference between illite and montmorillonites is the lack of potassium ions to bond the unit cells together. Water can easily enter between the layers, leading to disaggregation and expansion of the clay in an attempt to decrease the intensity of the repulsive forces between the adjacent negatively charged clay faces. This tendency to dissociate provides a simple means for identifying the montmorillonite family of clays. Oven-dried clay will show a first-order diffraction peak at 1.0nm, an air-dry clay will have a first-order diffraction peak at approximately 1.4nm, representing 1.0nm of mineral and 0.4nm of surface-bound water. By replacing this surface water with various organic liquids the amount by which the clay platelets will expand can be controlled. Glycerol is among the most commonly used fluids. It results in 1.77nm spacing, 1.0nm of clay and 0.77nm of glycerol, (Yong and Warkentin 1975). In general, as is shown in Table 2.1, smectitic clays such as montmorillonite and vermiculite have the ability to dissociate, exchange cations, and change volume, and so are classified as high activity clays. They have a correspondingly higher CEC and specific surface than illite or kaolinite.

## **2.2 Mineralogical Characterization of Clay Materials**

### **2.2.1 X-Ray Diffraction Analysis**

Figures 2.5, 2.6 and 2.7 present the x-ray diffraction traces obtained for the clays examined in this thesis and they can be compared to those for reference clays presented in Figure 2.4. Table 2.2 presents a summary of the most important x-ray diffraction peaks observed for minerals believed to be present in the soil materials examined. Mineral

identification was accomplished by matching the strong peaks listed in Table 2.2 for each mineral. This is particularly important as a number of the minerals examined have some peaks which occur at or near the same angle. No attempt is made to quantify the various minerals present in the specimens, such a task would not be particularly useful as the best that could be hoped for from such an exercise would be a semi-quantitative evaluation. The purpose of these tests was simply to identify the minerals present in order to confirm that the materials are what they were supposed to be: an illitic clay, and bentonite (montmorillonite). The strongest of the peaks detected by the x-ray analysis were identified and labelled, minor peaks can be identified using the data provided in Table 2.2.

X-ray diffraction analyses were conducted on both untreated random powder and glycolated specimens using a Rigaku Rotoflex x-ray diffractometer equipped with a 12 kW rotating anode Cu-K $\alpha$  x-ray source with a diffracted beam graphite monochromator.

Comparison of the patterns obtained (Figures 2.5, 2.6, 2.7) for x-ray diffraction analyses to the reference traces (Figure 2.4, and Table 2.2), shows that the materials examined are not mineralogically pure clays. The materials examined in this thesis are commercial products such as would be encountered in an actual application and so the presence of minor components are to be expected.

Table 2.2 X-Ray, DTA and TGA Values for Soil Minerals  
(Adapted from Yong et al. 1975)

| Mineral                  | Strongest X-Ray Peaks<br>(Cu-K $\alpha$ Radiation)<br>(Degrees 2 $\theta$ ) | Strongest DTA Peaks              |                      |
|--------------------------|-----------------------------------------------------------------------------|----------------------------------|----------------------|
|                          |                                                                             | endothermic<br>T (°C)            | exothermic<br>T (°C) |
| Kaolinite                | 12.4, 20, 24.5, 34, 38.4                                                    | 80*<br>550-600                   | 950-980              |
| Chlorite                 | 6.2, 12.5, 18.4, 34, 35.3                                                   | 600-650                          | 840-900              |
| Clay Mica<br>(Illite)    | 8.8, 17.7, 19.6, 26.8, 29.4                                                 | 100*<br>570-580<br>870-880       | approx. 900          |
| Bentonite<br>(air dried) | 4.5-9.2 (Broad peak)<br>7.1, 10, 19.2, 28.7, 34.4                           | 185*, 235*<br>690-700<br>860-880 | 940-1000             |
| Glycolated               | 5.2, 15.5, 19.7, 26.1, 31.9                                                 |                                  |                      |
| Vermiculite              | 6, 12.3, 19.3, 24.7                                                         | 150-200                          | ----                 |
| Gypsum                   | 11.6, 20.6, 28.8, 30.8, 47.3                                                | 160-190<br>180-210               | 370-380              |
| Calcite                  | 29.4, 39.5, 47.3                                                            | 900-930                          |                      |
| Dolomite                 | 39.6, 41.1, 50.7                                                            |                                  |                      |
| Quartz                   | 20.4, 21.1, 26.6, 50.2                                                      | 573                              | ----                 |
| Feldspar                 | 13.4-14, 27.8                                                               | ----                             | ----                 |

\* Peaks resulting from loss of adsorbed water layers

#### Definition of Symbols used in x-Ray Diffraction Traces

Q = Quartz

F = Feldspar

C = Carbonate

I = Illite

Chl = Chlorite

S = Smectite (Montmorillonite)

I\Chl = Mixed layer clay Illite/Chlorite

S\I = Mixed layer clay Smectite/Illite

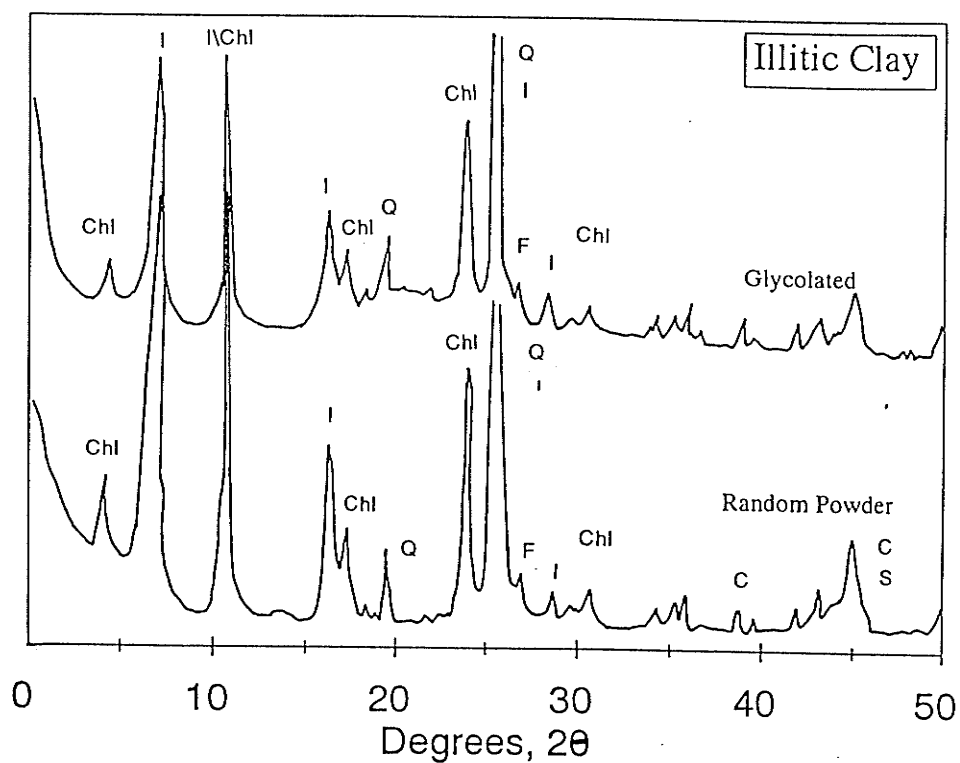


Figure 2.5 X-Ray Trace Obtained For Illitic Clay Material

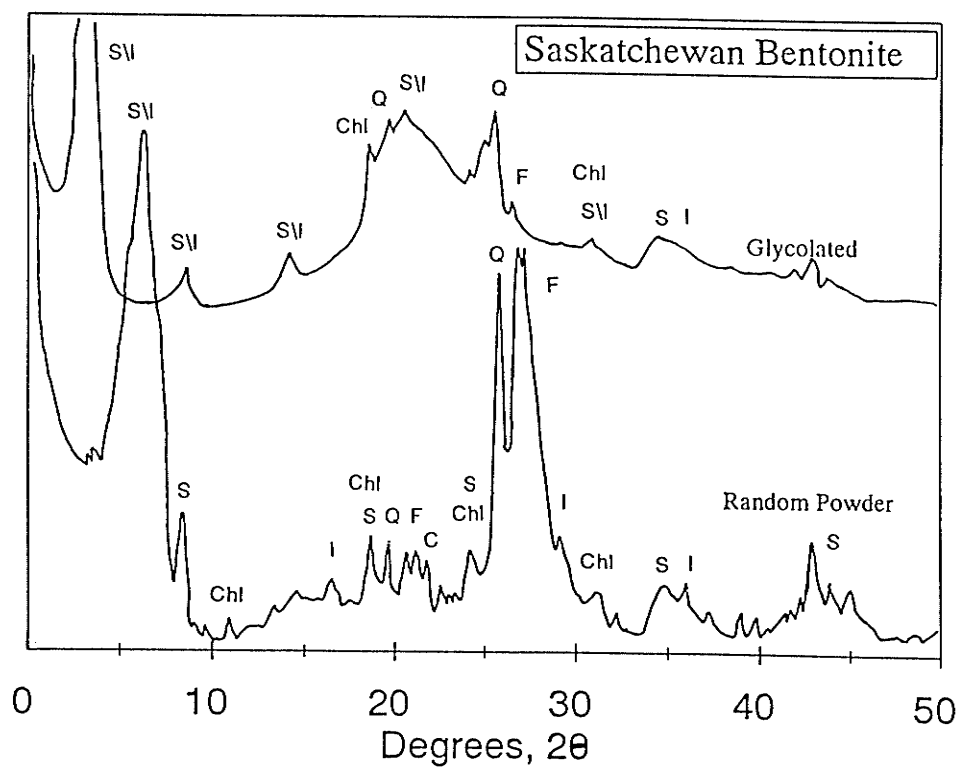


Figure 2.6 X-Ray Trace Obtained For Saskatchewan Bentonite Clay Material



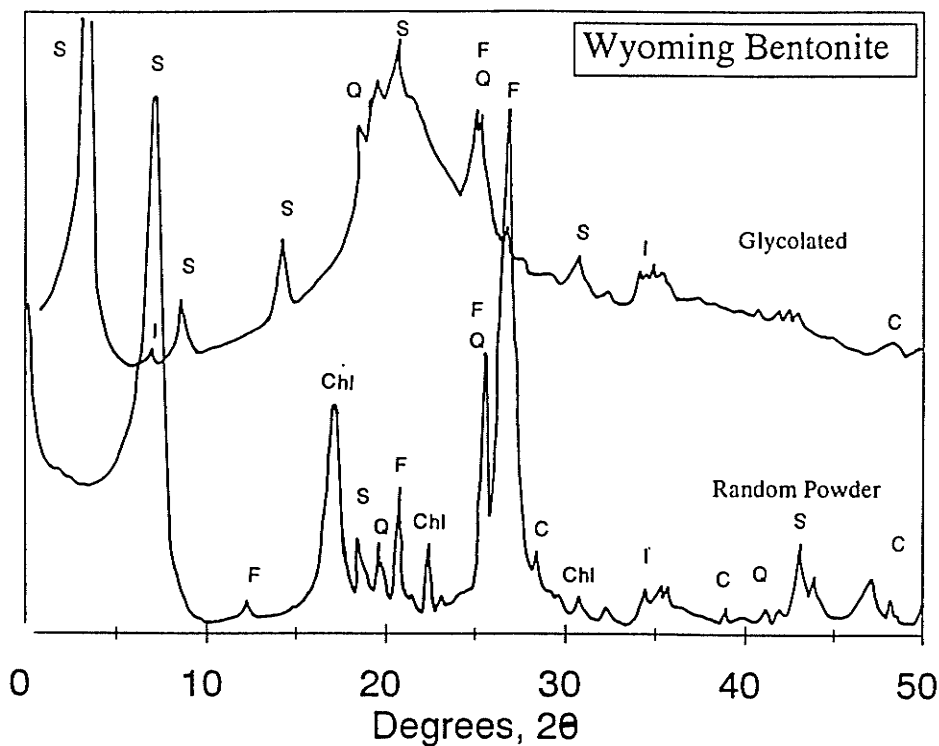


Figure 2.7 X-Ray Trace Obtained For Wyoming Bentonite Clay Material

The untreated illitic clay specimen showed clear illite, chlorite, quartz and feldspar peaks, with traces of kaolinite, dolomite and calcite (Figure 2.5). To better define the mineralogy of the specimen, a glycolated specimen was also analyzed. Glycolation is a commonly conducted treatment to assist in determining the type of clay minerals present in a specimen. The presence of ethylene glycol causes the spacing between the individual platelets of swelling clays (d-spacing), to change, the amount of change will depend on the specific clay mineral present. These changes in the d-spacing result in a shift in the x-ray diffraction patterns obtained. In non-swelling clays, such as illite and kaolinite, glycolation will not change the platelet spacings. As none of the x-ray peaks shifted or changed significantly, on glycolation of the illitic clay specimen, it can be concluded that there is little or no swelling clay material present. Hence, the general classification of this material as an illitic clay is appropriate.

The Saskatchewan bentonite (Figure 2.6) shows a pattern associated with a lower purity montmorillonitic clay, likely an interstratified montmorillonite-illite, montmorillonite-chlorite type, or perhaps a Calcium-rich clay material (the presence of Ca in the exchange sites on the particle surfaces can affect the d-spacing of the clay platelets). The presence of these features is evidenced by the slightly shifted peaks at approximately  $8^{\circ}$  and  $5^{\circ}$  in the powder and glycolated specimens respectively, when compared to the traces obtained for the Wyoming bentonite. The Saskatchewan bentonite also shows the presence of illite, quartz, feldspar, chlorite and calcite.

The Wyoming bentonite specimen (Figure 2.7), exhibited a pattern which is quite typical of a high quality commercial bentonite (Dixon and Miller 1995) (Quality generally being defined as the swelling volume change of the clay). The montmorillonite clay peaks dominate the pattern but are also accompanied with traces of quartz, feldspar, illite, and chlorite. Once glycolated the peaks observed (Figure 2.6) show a clear shift as the d-spacing of the clay has been altered by the glycol replacement of water.

Based on these x-ray diffraction tests it might be expected that the Wyoming bentonite will behave much as a "pure" montmorillonite clay and exhibit the physical and chemical properties appropriate to such a material. The Saskatchewan bentonite is of lower "purity" and so its physical characteristics are likely to be intermediate between those of the Wyoming bentonite and the illitic clay. The physical and chemical properties of these materials are presented and discussed in Chapter 4 of this thesis.

### **2.2.2 Differential Thermal Analysis and Thermo-Gravimetric Analysis of Clay Materials**

A second technique often used to determine the minerals present in a soil is Differential Thermal Analysis (DTA). It is conducted in conjunction with Thermal Gravimetric Analysis (TGA) and is normally known as Differential Thermal Gravimetric Analysis (DTGA). A specimen of clay or soil is heated and the specimen is monitored for the heat energy required to raise the temperature of the specimen and the change in mass of the specimen with increasing temperature. When a temperature is achieved where the mineral loses water or undergoes a phase change, the change in phase for the liquid or solid will either generate or require heat and the mass of the specimen will change. A heat adsorption, such as is required to vaporize water, is an endothermic reaction which is recorded on a strip recorder. Likewise, an exothermic reaction which occurs at higher temperature, (such as when a phase change occurs in the mineral) is recorded as an exothermic peak on the same strip chart. Table 2.2 tabulates the index peaks for reference minerals. The procedures required for this analysis are described by Yong and Warkentin (1975), Bish and Duffy (1990), and van Groos and Guggenheim (1990). These techniques will provide a rough measure of the amount of various minerals which are present. However, when a highly mixed system is tested, the presence of overlapping peaks makes the results more difficult to interpret.

Figure 2.8 presents typical DTA traces produced by "reference" minerals, and Figure 2.9 presents the traces obtained for the materials actually used in this thesis. The DTA results shown in Figure 2.9 support the interpretation previously provided for the x-ray diffraction analyses (Figures 2.5 through 2.7). Comparison of the DTA traces measured to "reference" traces and the peak locations identified in Table 4.2 indicates that the

Wyoming bentonite used in this project contains only minor quantities of other minerals. The Saskatchewan material is clearly bentonitic but contains quantities of other minerals (indicated by endotherm valleys at 450° C and 750°C). Figure 2.9 shows that the illitic clay is a mixture of illite, chlorite, or mixed layer illite-chlorite (low temperature endotherms in the 90° - 105°C with a hump at 100°C). The endotherm around 500°C is caused by the dehydroxylation of the interlayer hydroxide sheet of chlorite or illite-chlorite. The high temperature endotherm near 690°C is caused by a high degree of Mg substituting for Al in the octahedral sheet of the Wyoming bentonite, and to a lesser extent the Saskatchewan bentonite and the illitic materials.

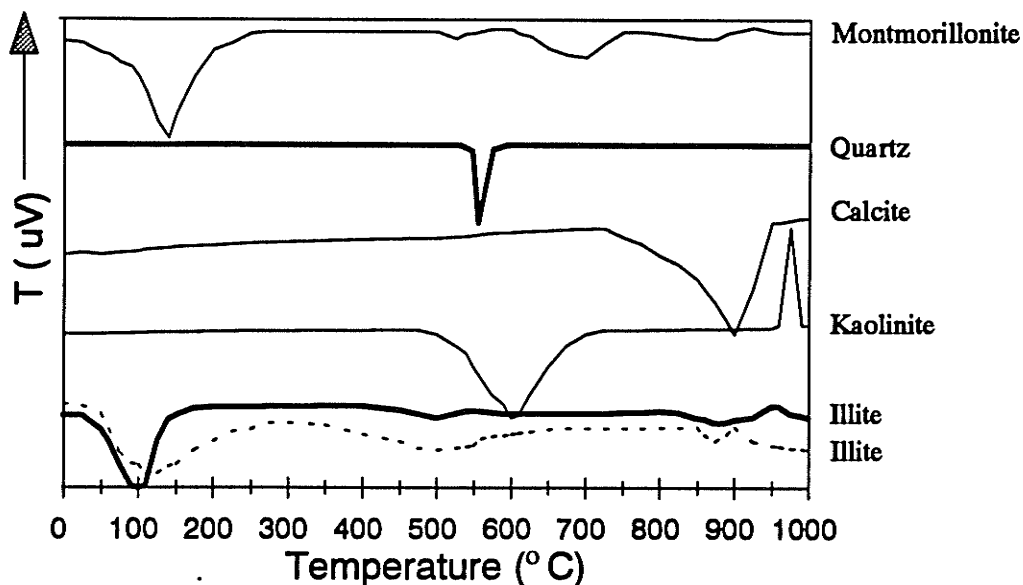


Figure 2.8 Typical DTA Plots For Clay Minerals  
(from Wilson 1987; van Olphen & Fripiat 1974)

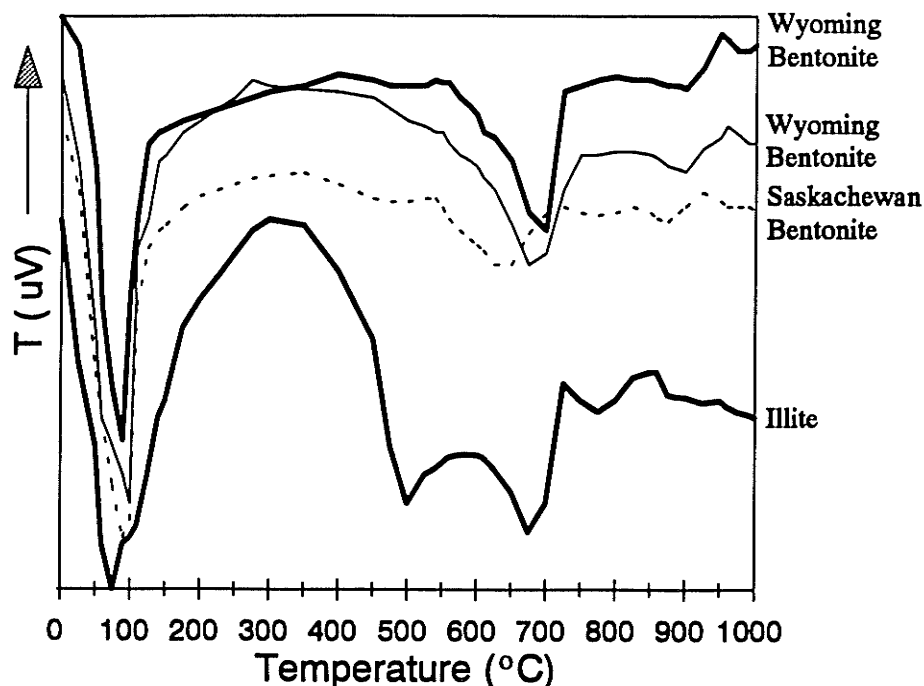


Figure 2.9 DTA Plots Obtained For Clays Studied

Figures 2.10 and 2.11 respectively present TGA traces for reference minerals (excepting illite) and the actual materials examined in this thesis. The trace that records change in mass with increasing temperature presented in Figure 2.11 shows that the illitic and bentonitic clays experienced weight changes at approximately the same temperature as the reference minerals. However, the slope of the illitic clay trace indicates there may be more than just illite present in this material. Beyond that general conclusion, not much information is generated by this trace. The bentonitic materials show the general pattern of a montmorillonite clay but, as with the illitic clay, they show differences in the shape and length of their slopes. Once again this indicates that there are materials present other than montmorillonite. In particular, the Saskatchewan bentonite shows a larger than typical weight loss at low temperature and a lower than expected loss at elevated

temperature. This perhaps indicates a lower content of montmorillonite, or the presence of mixed layer clays.

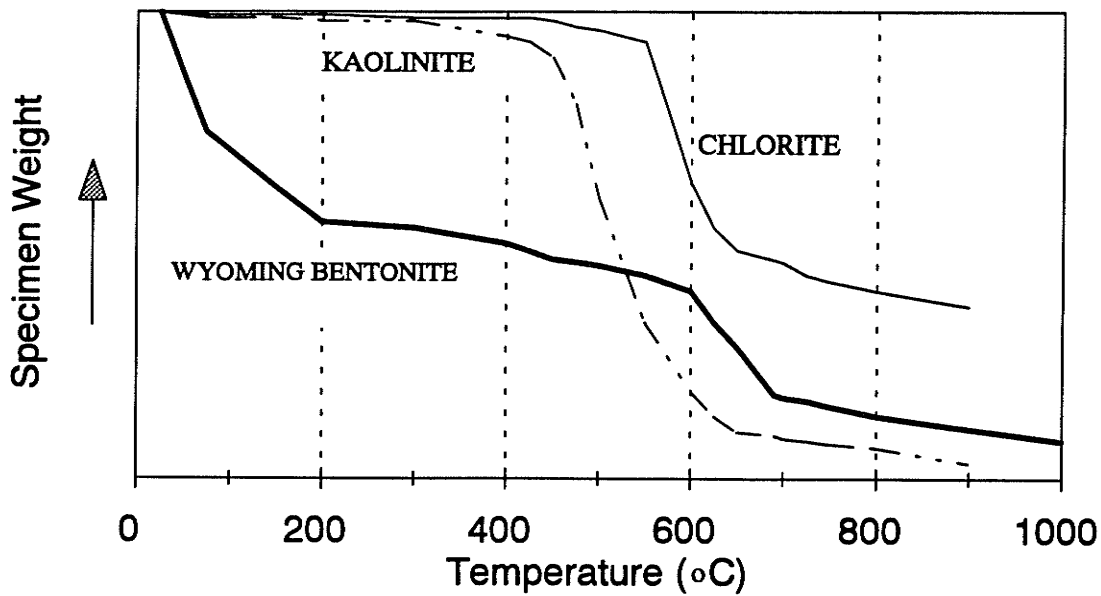


Figure 2.10 Typical TGA Traces Obtained For Reference Clays  
(from Bish and Duffy, 1992)

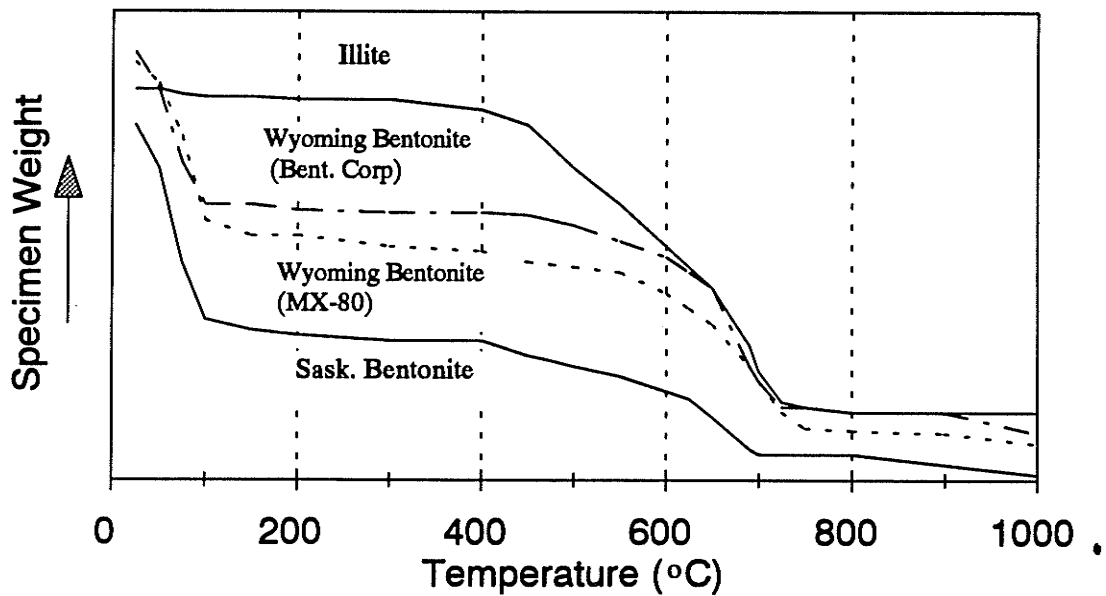


Figure 2.11 TGA Results Obtained For Clays Studied

### 2.2.3 Summary of Mineralogical Analyses

Mineralogical analyses have established that the materials used in this research project represent examples of two very different clay minerals. Table 2.3 presents a summary of the results obtained for x-ray diffraction, DTA and TGA tests conducted as part of the material characterization process.

The illitic clay examined in this thesis and whose mineralogy is summarized in Table 2.3 is composed of low surface charge illitic clay minerals and contains some low surface charge impurities which are unlikely to affect the chemical or hydraulic behaviour of the clay.

Table 2.3 Summary of Mineralogical Studies

| MATERIAL          | X-RAY DIFFRACTION ANALYSES |                                                        |                                 | DTA and TGA ANALYSES     |                               |                         |
|-------------------|----------------------------|--------------------------------------------------------|---------------------------------|--------------------------|-------------------------------|-------------------------|
|                   | Dominant Mineral Present   | Notable Quantity Present                               | Traces Present                  | DTA Shows To Be Dominant | DTA Shows To Be Present       | TGA Shows To Be Present |
| Illitic Clay      | Illite                     | Chlorite<br>Illite<br>Quartz<br>Feldspar               | Dolomite<br>Olivine             | Illite                   | Quartz<br>Chlorite<br>Calcite | Illite                  |
| Sask. Bentonite   | Smectite                   | Mixed Clay<br>Quartz<br>Feldspar<br>Chlorite<br>Illite | Calcite<br>Dolomite<br>Olivine  | Bentonite                | Illite<br>Chlorite<br>Gypsum  | Bentonite<br>Illite?    |
| Wyoming Bentonite | Smectite                   | Chlorite<br>Illite<br>Quartz<br>Feldspar               | Kaolinite<br>Olivine<br>Calcite | Bentonite                | Illite<br>Chlorite            | Bentonite               |

The bentonite materials are notably different from one another. The Wyoming bentonite is a high-quality commercial clay, composed of montmorillonite and only small quantities of other minerals. It is expected that this clay behaves as closely to a "pure" bentonite as is possible when using natural materials. Such a clay with its high surface area (Section 4.2.4 presents data on surface area), and high surface charge could potentially influence the structure of the associated pore fluid. The high negative surface charge could induce water (a dipole) to reorient to try and satisfy the charge present on the clay surfaces. The influence of surface charge on water structure is discussed in Section 2.3. The Saskatchewan bentonite is a lower "purity" smectite clay, likely consisting of a mixed system of interlayered montmorillonite and other clay minerals. This material, while still exhibiting a high surface area and a significant swelling capacity (Section 4.2.4), may have a lower overall influence on the pore water than the higher surface area Wyoming material (Section 2.3).

When considering the use of clays with high surface charge as barriers to contaminant movement it is important to establish what role this surface charge and resultant water structuring will have on mass transport through the clay. Following sections of this chapter discuss the nature of water, its structure, and the likely interaction between the mineral and fluid components.



## **2.3 Water and Clay - Water Interactions**

### **2.3.1 Models for Water Structure**

Before deviations from normal water behaviour can be assessed, it is necessary to understand what normal water is. As the result of its molecular structure, each water molecule has four places available for bonding with other molecules. There are therefore five possible states of molecular structure possible for each water molecule, ranging from no bonds, to all four possible bond sites occupied (Grjotheim & Krogh-Moe 1954 and Frank 1972). From this structural basis, a variety of models have been developed to describe the physical, chemical and thermal behaviour of water.

Frank (1972) presented a review of the behaviour of pure water, based on the bond-state (also known as significant structure) model. Water seemed to contain no significantly different density or specific volume domains larger than could be associated with short-range ordering of the water structure. He postulated that mutual stabilization of adjacent bonds which were favourably oriented could occur. This could produce associations between bond formation and bond breaking which, interacting with thermal fluctuations, would result in the existence in liquid water of "flickering clusters" of structure (Figure 2.12).

Using the Flickering Cluster model for structure, Frank (1972) proposed that conditions of thermal fluctuation could permit local formation of a group of mutually reinforcing hydrogen bonds. The detailed geometry of each water cluster this produces would be different depending on the momentary locations of the molecules within that region. Under the most favourable condition (the lowest energy state achievable), there would be the

formation of the largest possible number of bonds, and the production of an open, tetrahedrally bonded region of low (ice-like) density.

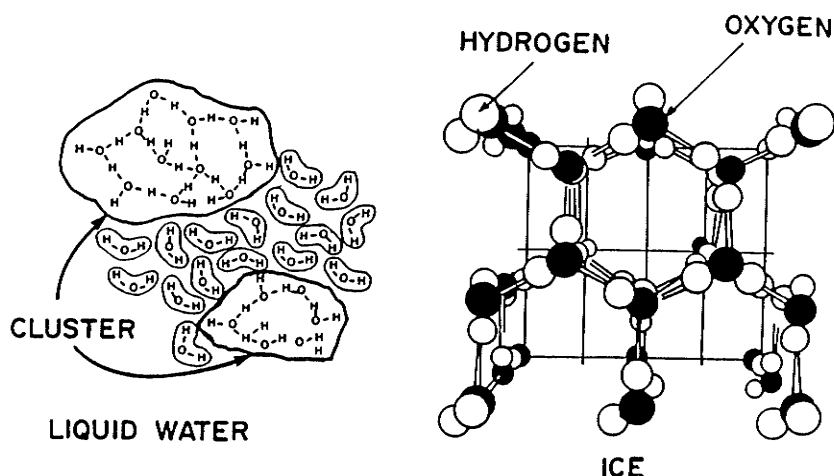


Figure 2.12 Models for Water Structure (from Gray et al. 1990)

From the Significant Structure model comes the mixture model for water structure. This model pictures water as a mixture, not of two kinds of species (bonded and unbonded), but rather of 5 kinds based on the number of potential bonding positions actually utilized. Frank (1972) employed this concept to account for the dielectric dispersion properties of water. A 3- or 4-bonded molecule could not rotate, a 0-bonded one could rotate about all three axes, and intermediately bonded molecules could rotate about one or two axes, depending on what state of bonding existed.

Grjotheim and Krogh-Moe (1954) employed the mixture model to simplify water structure into three basic structures. The first type of structured water occurs at low temperatures. A dense quartz-like structure where all potential bond sites are occupied is used to account for the high density of water near the freezing point, as compared to the density

of ice. At temperatures somewhat higher than the freezing point, an ice-like structure is predominant. At even higher temperatures the usual close packing of normal liquids was seen as being prevalent. These authors concluded that the total volume of a fixed mass of water ( $V$ ) at a given temperature will be altered if bonds are formed or broken, the effect being proportional to the number of bonds. From their tests and others reviewed by them in their paper, Grjotheim and Krogh-Moe (1954) concluded that water in the temperature interval from 25°C to 90°C appears to have an average coordination number of slightly more than two. This would mean that about half the possible number of intermolecular bonds were broken. This partially structured fluid will be called "free water" in this thesis.

Another commonly referenced conceptual model for water structure is the continuum model. This model conceptualizes water as a continuous medium where all water molecules are bonded together. The existing bonds do not break and reform, they simply lengthen, shorten or bend in response to changes in thermal environment (Kell 1972). This model predicts a near-linear thermal expansion response to changes in the thermal conditions, and that a direct relationship exists between temperature and structure. In many ways this model is similar to the ice-like structure for water at low temperature described by Grjotheim and Krogh-Moe (1954) and presented in Figure 2.12. As it is based on a linear thermal response model, rather than changing the basic structure, this model is potentially useful in describing the behaviour of water close to the surface of charged minerals.

Based on these studies of water structure, it is important to consider models for water behaviour which are intermediate to those of ice-like and free water behaviour reported

in literature. This is particularly relevant when considering the structural and behavioral changes resulting from the charged surfaces of clay platelets.

### 2.3.2 Clay-Water Interaction

The progression from describing and modelling a water-only system to mixed clay-water systems containing electrolytes, makes the development of models to describe behaviour difficult. Accounting for the influence of a surface charge on the mineral faces is just the first step in understanding the very complex interactions in a clay-water system. Added to the surface charge effect is the need to account for the influence of ions in solution and sorbed to particle surfaces. There are also many potentials which may exist across a specimen, all of which may affect water structure and movement.

A number of models have been proposed to describe the interaction between the water and mineral components in clay-water systems. It is generally accepted that some quantity of water is actually structurally bonded to the surface of highly charged clay platelets (Guvén 1992a). The role of mineral charge and structure on the water associated with smectite minerals has been discussed in considerable detail by Guvén (1992a). In fine-grained materials such as smectites, a general relationship was developed to provide an approximation of the number of layers of adsorbed water and the density of the water present on the surface of smectite minerals (Guvén 1992a). The relationships developed in Equations 2.1 through 2.5 take into account possible variations in the number of individual crystals present in each quasicrystal (package of unseparated basic mineral platelets), as well as the number of layers of water present:

$$m_w = S_b \, dt \, \rho_w \quad (2.1)$$

$$m_c = S_b d_{001} \rho_c / 2 \quad (2.2)$$

where  $d_{001}$  is the unit layer thickness of the individual crystals (0.96 nm),  $S_b$  is the exposed specific basal surface area per gram of clay,  $d_t$  is the thickness of a monolayer of water (assuming normal density of liquid water a single water layer is approximately 0.25nm thick),  $\rho_w$  is the density of liquid water,  $\rho_c$  is the density of the mineral,  $m_w$  is the mass of the water component and  $m_c$  is the mass of the clay component (Guvén 1992a).

For a single (mono) layer of water on the surface of a specimen consisting of fully dispersed clay, Equations 2.1 and 2.2 can be simplified.

$$m_w/m_c \approx 0.2j \quad (2.3)$$

where  $j$  is the number of monolayers of water present on the surface of the particle. Under conditions where the clay is not entirely dispersed, Equation 2.3 can be altered to give a more general solution where the number of silicate layers ( $n$ ) in the quasicrystal is taken into account.

$$m_w/m_c \approx 0.1((n+1)/n))j\rho_w \quad (2.4)$$

In a system where the number of silicate layers are significant ( $>10$ ), then the relationship in Equation 2.4 can be simplified to provide a general equation for estimating the quantity of water which will be present.

$$m_w/m_c \approx 0.1j \quad (2.5)$$

All the models try to account for changes in molecular diffusion, hydraulic flow through mineral-water systems, and swelling behaviour in terms of water structure or lack thereof. The nature and extent of water structuring in mixed systems has been inferred from a variety of studies on mineral-water systems. These include, thermal expansion, water density analyses, rheological testing, isothermal compressibility, and changes in diffusion with specimen density.

The literature indicates that water associated with charged surfaces of clay particles is more highly structured and perhaps of a different density than that of free water (Miller and Low 1963; Yong and Warkentin 1975). Anderson and Low (1958) reported that the density of water associated with bentonitic clays is much less than that of free water. However, a number of other researchers including Mitchell (1976) have suggested that the density of water associated with bentonites is higher than that of free water. The density decrease reported by Anderson and Low (1958) was reported to extend as far as 6 nm from the particle surface. Although no mention of water density changes was reported, Lutz and Kemper (1959) reported structured water to exist to more than 10 nm from the mineral surface in sodium bentonite, whereas structured water seemed to exist only to 1 nm in calcium bentonite. The density of this water was reported to decrease as the surface of the clay particle was approached. A decrease of 2% to 3% in the density was reported at a distance of approximately 1 nm from the clay surface. Lutz and Kemper (1958) described the water in clay-water systems as having a "broken down ice structure" in which there is a tendency for each water molecule to bond itself tetrahedrally to four neighbouring water molecules. The bonds are continually breaking and reforming so that, on the average, each molecule is bonded to less than four neighbours and has other

neighbours at longer distances. This is equivalent to the mixture model for water previously discussed by Grjotheim and Krogh-Moe (1954).

### **2.3.3 Clay-Water-Ion Interaction and Resultant Water Structure**

The presence of surface charges on clay particles, especially clays such as bentonite, can have a significant effect on the structure of the pore water and the distribution of ions within the solution. As discussed previously, bentonites are negatively charged as the result of isomorphous substitution within their mineral lattices (Mitchell 1976; van Olphen 1977, Yong et al. 1992, Guven 1992a). This results in repulsion of solution anions and attraction of the cations, leading to a double layer of cations associated with the clay, an inner positively charged cation layer and an outer negatively charged region. As the result of the extremely small pore sizes in clays and the presence of high surface charges, clays can exhibit behaviour similar to that of a semi-permeable membrane (Mitchell 1991). Such a membrane may mean that certain ions, depending on their size, may be excluded from pore spaces smaller than a certain size. This will result in the generation of high osmotic potentials and the through flow of water may be initiated by mechanisms other than pore pressure differences across the soil. This is discussed in greater detail in Section 3.4 of this thesis.

When ions are added to the water, it's loosely co-ordinated structure is disrupted and a closer packing (increase in density) of the water molecules results. Anderson and Low (1958) proposed that a "broken down ice structure" is stabilized by the polarizing influence of the negatively charged clay surface, or by hydrogen bonding to this surface (known as Epitaxy). This stabilized structure is not rigid but is a more regular ordering of the water molecules. This represents an apparent combination of both the continuum and mixture

models for water. It permits both a stabilized continuum-type structure and the making and breaking of bonds between water molecules which is the basis of the mixture model. As this new model permits the making and breaking of bonds (not allowed in the continuum model), it is most properly classified as a modified mixture model for water. This type of structure should result in changes in both the mass transport properties of the system, and the thermal expansion for clay-water systems as bonds are formed or broken. Using this modified mixture model for water, structural types can be separated into three forms, free, structured and crystalline. The importance of these structural types is discussed in subsequent sections in this chapter and then the role of water structure in determining the rheological properties of water in mixed clay-water systems is discussed in Chapter 3. The structure of water will also have a major impact on the thermal expansion characteristics of mixed mineral-water systems (Chapter 5).

#### **2.3.4 Diffuse Double Layer Models for Ion Distribution in Clay-Water-Electrolyte Systems**

A number of models are commonly used to try and explain the nature of the mineral-fluid-ion interaction and ionic distribution in clay-water systems. The best known of the models developed to predict ionic concentration at various distances from the surface of a charged surface are the Diffuse-Double-Layer (DDL) models. The best known of these models, known as the Gouy-Chapman model provides a means of accounting for ionic mobility in solution (Mitchell, 1976). Equation 2.6 presents the basic formulation of this model.

$$1/\kappa = (DkT/8\pi n_0 \epsilon^2 v^2)^{1/2} \quad (2.6)$$



where,  $1/\kappa$  is the thickness of the double layer (actually the centre of gravity of the diffuse charge is located at a distance  $x=1/\kappa$  from the particle surface),  $D$  is the dielectric constant of the medium,  $k$  is the Boltzman Constant ( $1.38 \times 10^{-16}$  erg/°K),  $T$  is the temperature in °Kelvin,  $\pi$  is the value pi (3.141569),  $n_o$  is electrolyte concentration in the bulk solution,  $e$  is the unit electron charge ( $16 \times 10^{-20}$  coulomb or  $4.8 \times 10^{-10}$  esu) and  $v$  is the valence of the ions in solution. The  $1/\kappa$  parameter is based on the assumption that the electrical potential associated with a particle surface decreases exponentially with distance.

It is recognized that the Gouy-Chapman equation does not truly represent the conditions actually present in a clay-water system. The equation does provide a means of estimating the thickness of the diffuse layer and the influences of surface potential, pore solution and temperature on the diffuse double layer thickness (Mitchell 1976).

As there is only a limited quantity of water percolated through the tests conducted as part of this research project the variables in Equation 2.6 should not change, and so the double layer thickness should remain constant. Percolation of excessive amounts of low ionic strength water through the high salt content bentonite specimens (details of the pore fluid composition are provided in Section 4.3 of this thesis) would result in changing the parameters  $D$ ,  $n_o$  and ultimately  $v$  as the more mobile monovalent ions are flushed from the system. Changes such as these have the potential to alter the porosity available for advective flow.

The Gouy-Chapman model has been found to be inadequate to allow accurate prediction of ion distributions in most systems. Because it assumes a number of severely limiting parameters (Table 2.4) a number of modifications have been made to the originally

developed relationships (Guvén 1992a). Modification of the original model includes incorporation of factors to limit the shortcomings between the theory and experimental results identified in Table 2.4. The most important of the modifications made was accounting for the real size of the ions which are surface bonded and the adsorption of ions at the particle/solution interface (Guvén 1992a). This adsorbed (Stern) layer then allowed a modified Gouy-Chapman formula to be used to predict ionic distributions within the diffuse region of the double layer.

Table 2.4      Limitations of the Diffuse-Double-Layer Model

1.    Ion size is ignored. Ions are assumed to be point charges which are indifferent to the particle surface.
2.    The structure and electrical properties of water molecules were not considered at all. The solvent has a fixed dielectric constant.
3.    The surface charge was assumed to be uniform, a smeared charge was coupled with a uniformly decreasing magnitude with distance from the surface.
4.    Hydration of ions and clay surfaces were ignored
5.    The statistical basis used to determine ion distribution was unrealistic and resulted in much too high concentrations being calculated for the surface ions.

Extensive discussions on the surface charge sources, magnitudes and locations in clay-water-ion systems have been presented by Yong et al. (1992) and Guvén (1992a). These authors both present modified diffuse double layer models which include a rigidly bonded Stern water layer and attempt to account for ionic complexes in solution. The counterions (ions which balance the surface charges of the clay minerals), were visualized as forming three types of complexes with the reactive sites on particle surfaces (Figures 2.13 and 2.14). These complexes were as follows:

- "a) Inner-sphere complexes in which the counter ions are directly bound to the surface without a solvent molecule linking them," (Figure 2.13A),

- "b) Outer-sphere complexes which contain at least one solvent molecule between the counterion and the surface" (Figure 2.13B), and
- "c) The diffuse ion swarms consisting of hydrated ion clusters that move (diffuse) parallel to the surface." (Figure 2.14)

(Guvén, 1992a)

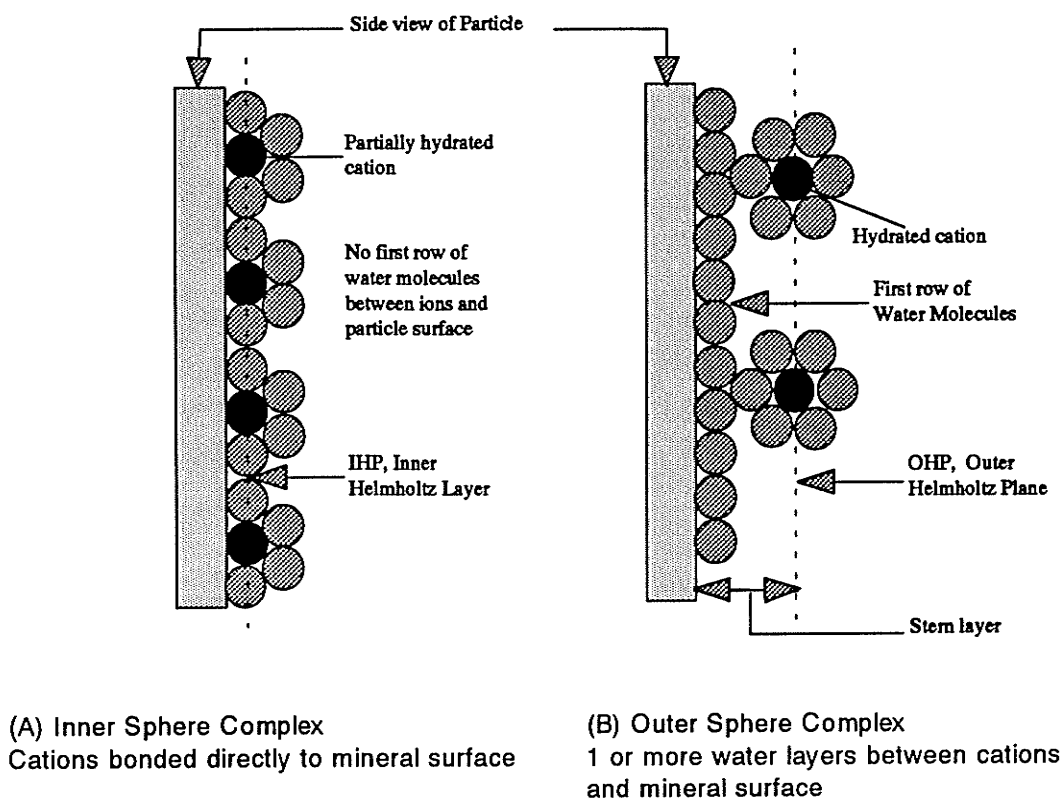


Figure 2.13 Potential Ion Arrangements at the Particle-Water Interface  
(Yong et al. 1992)

A detailed derivation of a modified Gouy-Chapman model for the electrical double layer has been presented by Sposito (1992). In his discussion of the Gouy-Chapman theory he presents evidence of, and arguments for, the presence of quasicrystals which are generally perceived to form in solutions where divalent cations are present. These quasicrystals are composed of stacks of cations four to seven layers in thickness which have been solvated

by six water molecules in an outer-sphere surface complex structure. These hydrated cations (also referred to as counterions) provide an electrostatic binding mechanism to hold the clay layers together.

The quasicrystal concept also provides a means by which a portion of the total porosity of the clay can be defined as being unable to conduct water in a normal Newtonian manner. Newtonian flow is the condition where a constant, linear relationship exists between rate-of fluid-shear (velocity) and the shear stress (pressure difference across fluid). Rheological models are discussed in greater detail in Section 3.1 of this thesis.

It has been noted in the literature that quasicrystals can form using monovalent cations as the bonding ion (Sposito 1992). The monovalent cation mechanism for quasicrystal formation is believed to be active only in relatively dense (non-slurry) clays (Sposito 1992). It is dense clays which are examined in this thesis and so this monovalent mechanism may be of significance in affecting water structure and movement.

The model for a multilayer clay-water interface presented in Figure 2.14 consists of several regions (Yong et al. 1992; Guven 1992a), and these include;

1. The  $\alpha$ -, (inner Helmholtz) plane is mainly oriented water dipoles on the clay surfaces. De-hydrated counterions may also exist between this plane and the surface. These molecules and ions represent the inner-sphere or bonded layer of the clay particle. This is also known as the Stern water layer.
2. The  $\beta$ -plane represents the first layer of hydrated ions.
3. The D-plane is the beginning of the diffuse double layer, and may coincide with the outer-Helmholtz plane.

4. The  $(1/\kappa)$  plane is located somewhere in the diffuse region, where the potential  $(\psi)$  drops to a value of  $(\psi_0/e)$ .  $1/\kappa$  is the thickness of the double layer and  $e$  is the electron charge ( $1.602 \times 10^{-19}$  C).
5. The  $\xi$ -plane is the slip (shear) plane which separates the section of the double layer that moves with the clay particle, or alternatively the portion of the double layer which does not take part in normal flow. This plane is located somewhere in the diffuse layer, probably close to the  $(1/\kappa)$ -plane

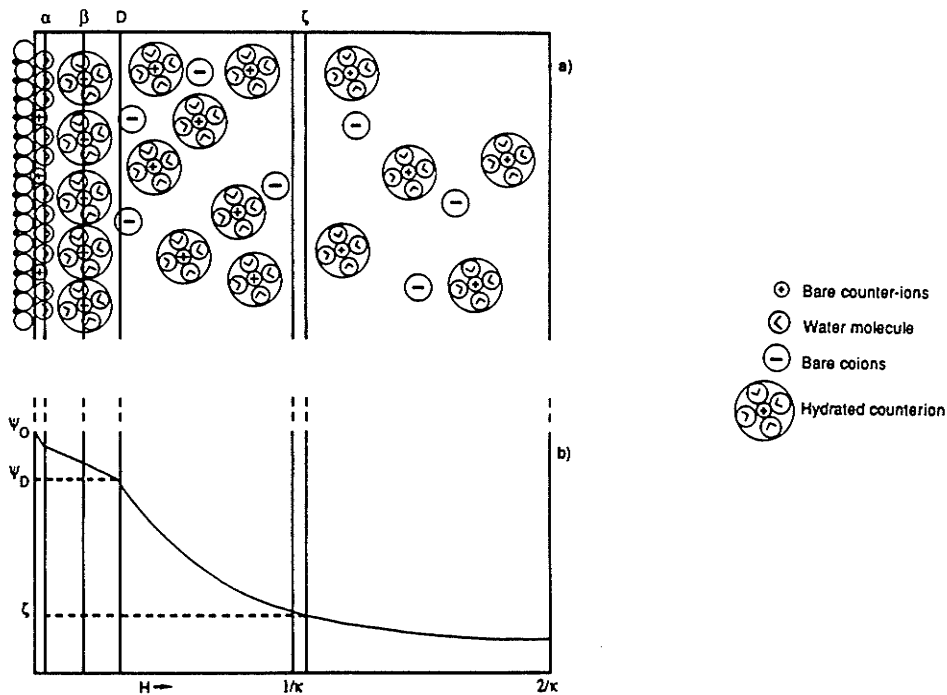


Figure 2.14 Theoretical Distribution of Ions at a Charged Surface  
(Guen 1992a) a) Model for multilayer configuration at clay-water interface  
b) Decay of surface potential  $(\psi_0)$  in interface region

The diffuse double layer model presented in Figure 2.14 calls for the counterions of the inner-sphere to be immobile and located on the  $\alpha$ -, (inner Helmholtz) plane. The distance

they extend outwards is determined by the radii of the dehydrated ions. This model provides for the existence of an ordered layer between the particle surface and the diffuse double layer (Guvén 1992a). Figure 2.14 presents a conceptual diagram of the nature of the DDL distribution of pore fluid ions. The fluid-solid interface consists of an electrical double layer (EDL), composed of a row of negative charges on the particle and the first row of positive charged ions (cations) in solution. Neighbouring particles possess similar charges and therefore net unit repulsive forces are developed between them. These forces are related to particle spacings, pore fluid chemistry, temperature and external loading. Any change in these parameters can result in changes in the EDL and any structured water associated with it.

The highly structured region of the double layer is normally defined as including the  $\alpha$ - and  $\beta$ -planes and is believed to extend approximately 0.5 nm (2 water layers thickness), (Guvén 1992a). Other researchers have found evidence that the hydration forces can have effects on the pore fluid at distances as great as 2.5 nm (10 water layers thickness), from the surface (Pashley and Israelachvili 1984a, 1984b). This would quantify the diffuse layer as existing between 0.5 nm and 2.5 nm (some 2 to 10 water layers out from the mineral surface).

An extensive region of structured water can have a significant impact on the behaviour of dense clay materials. In dense systems where the clay platelets or quasicrystals are present in a homogeneous structure there may only be a limited amount of water in the system which is other than Stern or  $\beta$ -plane water. In addition to the influence of the space available between clay platelets, there is a significant influence from the type of hydrated cations present in solution. As shown in Table 2.5, a hydrated cation can occupy

a very significant portion of the pore space available, and may exhibit a range of field strengths. Likewise, changing the pore fluid chemistry can increase the ease of water movement if a small size hydrated cation is available to replace a larger complex that was previously associated with the particle surfaces. An example of such a ionic replacement would be potassium ( $K^+$ ) replacing sodium ( $Na^+$ ).

Table 2.5 The size of solvated ions and their charge strength

| Ion       | Ion-Solvent Distance ( $r$ ) <sup>*</sup><br>(nm) | Hydrated Radius <sup>**</sup><br>(nm) | Field Strength<br>$E_i(r)$ <sup>*</sup><br>( $10^{10}Vm^{-1}$ ) |
|-----------|---------------------------------------------------|---------------------------------------|-----------------------------------------------------------------|
| $Li^+$    | 0.208                                             | (.73-1.0)                             | 3.33                                                            |
| $Na^+$    | 0.235                                             | (.56-.79)                             | 2.61                                                            |
| $K^+$     | 0.273                                             | (.38-.53)                             | 1.93                                                            |
| $Cs^+$    | 0.309                                             |                                       | 1.51                                                            |
| $Mg^{+2}$ | 0.205                                             | (1.08)                                | 6.85                                                            |
| $Ca^{+2}$ | 0.239                                             | (0.96)                                | 5.04                                                            |
| $Sr^{+2}$ | 0.253                                             | (0.96)                                | 4.50                                                            |
| $Al^{+3}$ | 0.190                                             |                                       | 11.97                                                           |
| $Cl^-$    | 0.321                                             |                                       | 1.40                                                            |
| $I^-$     | 0.356                                             |                                       | 1.14                                                            |

where  $r = r_i + r_w$  with  $r_w = 0.14$  nm for the radius of water molecule,  $r_i$  = ion radius, and field strength  $E_i(r)$ <sup>\*</sup> is the electric field strength at a distance  $r$  from the nucleus of the ion specified.

<sup>\*</sup>(From Guven 1992a) <sup>\*\*</sup> (From Mitchell 1976)

### 2.3.5 Surface Hydration Model for Mineral-Water-Ion Interaction

A model known as the Surface Hydration (SH) Model which also models distribution of ions and water molecules in the vicinity of charged clay surfaces has been presented by Low (1987, 1992), Viani et al. (1987) and others. The SHM for bentonite-water-ion systems does not credit the double-layer forces present in these systems for the repulsive forces developed. Instead the repulsive forces are attributed to an epitaxial structure developed

outwards from the clay surface. Epitaxy is the development of an aligned molecular structure which fits the template provided by the point charges on the mineral surface. A series of oriented layers of water develop outwards from the mineral surface. The polar nature of these molecules result in repulsive forces that extend much farther from the mineral surface than predicted by the traditional double-layer model.

Using data from pressure-moisture content experiments Low (1992), concluded that the hydration shells around clay particles are difficult to displace when they are as much as 2nm in thickness. Such a distance equates to 8 water layers, or approximately 3 hydrated cation layers (Based on hydration ion sizes given in Table 2.5). This was interpreted as being inconsistent with the double layer theory but could be explained by the repulsive forces generated by the formation of hydration envelopes surrounding the clay platelets. These envelopes possess greater integrity as the particle surface is approached. This results in step-like energy barriers when particles are separated by less than approximately 1.5 nm spacing, not the smoother relationship predicted by the double layer theory (Low 1992). This type of model was supported by results obtained by Israelachvili and Pashley (1983). They observed alternating minima and maxima in the energy - spacing relationship as the spacing changed by approximately 0.25 nm (the diameter of a water molecule).

The DDL and more specifically the SH model for the sorption of water molecules by clays, particularly bentonite has been described as proceeding in two types of active centres (Erish and Tret'Yakova 1970),

- i) through co-ordination around sorbed cations and,
- ii) as result of interaction with oxygen ions of the silicate layers with formation of hydrogen bonds.



When there are only a few molecular layers of water on the particle surfaces, most of this water is in intimate association with the pore water ions. Under some conditions the structure of the pore fluid may be more significantly affected by these mobile cations than it is by the presence of the charged mineral surfaces (Oster and Low, 1963). When there is more water present (lower densities) the ions can dissociate further from the clay surfaces. With the movement of the ions into solution, it is possible for the surface charges to exert a greater influence on the structure of the pore water. The water structure close to the mineral surfaces of such low density systems may therefore be more structured and rigid. As a result low clay content (low density) systems may exhibit much different behaviour than is observed for bulk, unstructured water (Oster and Low 1963). At higher densities the cations will be forced into closer association with the clay surfaces and so may act to prevent the development of a structured water component between parallel clay platelets. In such cases, the pore water may behave in a manner similar to that of bulk, unstructured water.

### 2.3.6 The DLVO Theory for Water Structure

The DLVO theory is based on the work of Derjaguin-Landau-Verwey-Overbeek (DLVO). It is presented in detail in papers by Derjaguin and Churaev (1974) and Guven (1992a). This model describes particle interactions in a dispersion as the sum of contributions from repulsive forces generated by overlapping double layers of adjacent particles ( $u_R$ ), attractive (van der Waals) forces ( $u_A$ ) and the Born repulsive energy ( $u_B$ ) (Equation 2.7).

$$u_T = u_A + u_R + u_B \quad (2.7)$$

The van der Waals forces are an attraction between particles resulting from attractive interaction between atoms and molecules. It is inversely proportional to the second power of the interparticle distance. This means in practice that van der Waals attractive forces can only be effective over a distance of up to 1.0 nm (Guvén 1992b). Born repulsive energy is the result of interaction of the electron clouds of the surface atoms and the ions. This force is inversely proportional to the twelfth power of the interparticle separation (Guvén 1992b). The purpose of this model is to provide a predictive tool to determine at what interparticle distances a suspension will be stable. The ranges of the minimum energy condition will permit a slurry to be tailored to require the minimum energy input to induce movement or stability. The DLVO theory is based on the Gouy-Chapman equation for the diffuse double layer and so has the same limitations as the original DDL model (Table 2.4). This is especially important in terms of the forces relating to the hydration of ions and clay surfaces, as well as the molecular structure of the double layer (Pashley 1981a,b; Guvén 1992a). The swelling pressure (net repulsive force generated between parallel clay platelets), developed by bentonite clays based on the DLVO theory has been found to significantly under-estimate the values actually measured (Low 1987, 1992).

The DLVO model, the Double-Layer, and Surface Hydration models are of limited use in predicting the rheological properties of the adsorbed, structured or double layer water in denser systems. They do however provide an indication of the likely magnitude and rigidity of these regions of somewhat "altered" water. Table 2.6 provides a brief summary of the reported extent of structured fluid in high surface activity clays such as bentonite.

Table 2.6 Distance Over-Which Hydration Effects are Evident and, Number of Hydrated Cation Layers Required to Occupy This Space.

| Data Source             | Hydrated Layer Thickness (nm) | # Layers Water | # Layers $\text{Na}^+_{\text{H}}$ | # Layers $\text{K}^+_{\text{H}}$ | # Layers $\text{Ca}^{+2}_{\text{H}}$ |
|-------------------------|-------------------------------|----------------|-----------------------------------|----------------------------------|--------------------------------------|
| Anderson & Low (1958)   | 6                             | 21             | 4                                 | 6                                | 3                                    |
| Lutz & Kemper (1958)    | 10                            | 35             | 7                                 | 11                               | 3                                    |
| Pashley & Quirk (1989)* | 2.5                           | 9-10           | <2                                | <3                               | 1                                    |
| Guyen (1992a)**         | 0.5                           | 2              | .5                                | .5                               | .25                                  |
| Low (1992)*             | 2                             | 7-8            | <2                                | 2                                | 1                                    |

Note: The thickness of a water molecule is between 0.25nm and 0.28nm

H subscript stands for Hydrated Ionic Complex

\* Refers to the very tightly bonded layers

\*\* Refers to water rigidly adsorbed to clay surface (Stern Layer)

## 2.4 Water Structure and Thermal Expansion of Clay-Water Systems

Based on the modified mixture theory for water structure described in the preceding sections, it can be postulated that the measured thermally-induced expansion of an entire clay-water system should be lower than the sum of the theoretical expansion of its components. The lower volumetric expansion is expected because the water is at least partially structured and its thermal expansion would be proportionally lower than that of free water.

The coefficient of thermal expansion ( $\beta_f$ ) of the fluid portion of such a composite system can be described by the relationship presented in Equation 2.8.

$$\beta_b = f(\beta_w, \beta_s, \beta_c) \quad (2.8)$$

where  $\beta_b$  is the bulk thermal expansion coefficient of the fluid and,  $\beta_w$ ,  $\beta_s$  and  $\beta_c$  are the thermal expansion coefficients of free water, structured water, and crystalline (ice-like) water respectively. This bulk fluid coefficient is not a constant but will change with the changing proportions of the various forms of system water. It is therefore possible to infer water structure from observations of volume change in clay-water systems.

Clementz and Low (1976) and Ruiz and Low (1976) tested very low density bentonite-water systems to determine their thermal expansion behaviour at temperatures ranging from 0°C to 25°C. They found that the thermal expansion behaviour of the systems was measurably lower than that of a water-only system. The findings were interpreted as evidence of epitaxial water structure associated with the clay particles. In addition to the issue of the nature of water structure itself, there is the question of water structure changes occurring as a result of changes in temperature. As with the models for water structure, the role of temperature changes on the thermal expansion coefficient is still uncertain. Mitchell (1976) used the Gouy-Chapman equation previously presented as equation 2.6 (and reproduced below), to show that the double layer should not be affected to any appreciable extent by temperature.

$$1/\kappa = (DkT/8\pi n_0 e^2 v^2)^{-1/2} \quad (2.6)$$

Equation 2.6 predicts that increasing temperature will result in increased double-layer thickness and decreased surface potential if the surface charge is constant. However, this is not an entirely representative condition (Mitchell 1976). Increasing temperature also results in a decrease in the dielectric constant (D) of the water. This decreases the product DT in Equation 2.6 by less than 10 % over a temperature increase from 0° C to 60° C (Mitchell 1976). A slight change in DT should not greatly alter the double layer of the clay

and soil water properties should be relatively constant throughout this range of temperature. Hence, the thermal expansion coefficient of clay-water systems should be predictable using a sum-of-components model, regardless of ambient temperature. In contrast, Morin and Silva (1984) found that for high porosity clays, increasing temperature affects the thermal expansion of the system. They found that increasing the temperature compressed the thickness of the diffused double layer, decreased the ionic concentration and led to the eventual breakdown of the adsorbed water. This would result in a change in the thermal expansion behaviour from a lower-expansion composite system, to a free higher-expansion water, and likely a more mobile fluid. This aspect of water structure and behaviour is particularly important where the barrier will ultimately experience elevated temperature.

Baldi et al. (1988) conducted high temperature and pressure tests to determine the thermal expansion properties of low porosity smectite-water and illite-water systems. They observed a reduction in the thermal expansion coefficient of water for the temperature range of 40°C to 100°C, which averaged 40% of the free water value. This observed behaviour supported earlier work of Derjaguin et al. (1986) who reported that reduced thermal expansion occurs. Derjaguin et al. (1986) reported that the deviation in the thermal expansion behaviour of water from that of free water seemed to disappear at approximately 90°C. Their tests were performed using a fine mixture of silica gel and titanium oxide. In a later paper, Derjaguin et al. (1987), reported a gradual disintegration of the structure of adsorbed water beginning at approximately 70°C.

The modified mixture, epitaxial and DLVO water structure models described above all assume that water will be influenced by charged mineral surfaces. The presence of an

imposed structure to the water component suggests that a finite stress may be required to disrupt the structure or shear the water in close association with the particle surface. In such a situation, water in such a clay-water system should behave as a Bingham fluid. A Bingham fluid is one in which a measurable stress must be applied before Newtonian flow is initiated (see Section 3.1 for a detailed discussion of rheology). This type of fluid flow would result in a threshold gradient and perhaps a critical gradient for flow through the soil as water is gradually sheared away from the particle surfaces.

### **3.0 RHEOLOGY, POROSITY AND FLUID FLOW: A REVIEW OF LITERATURE**

This chapter provides a review of basic rheological principles and relates them to the movement of water through soil materials, particularly through soils containing clay particles with high surface charges. For the purposes of this thesis rheology is defined as the flow behaviour of the water component of clay-water systems. Any investigation of the rheological properties of water or other fluid as they move through soil materials requires an understanding of the fluids involved as well as the amount of and structure of the pore spaces available for through-flow. Understanding of both of these aspects is particularly important when considering clay soils where the properties of the percolating fluid and pore space available for flow may be affected by the electro-chemical properties of the soil. Once a basic understanding of the rheological properties of the water phase is achieved, and porosity available for flow is determined, it should be possible to identify deviations from the water flow behaviour predicted using conventional models. Chapter 3 presents a review of rheology (Section 3.1), porosity (Section 3.2), commonly used flow models (Section 3.3), influences of soil structure (Section 3.4) and a brief review of the opinions found in the literature regarding water flow through clay soils (Section 3.5)

#### **3.1 RHEOLOGY AND FLUID FLOW IN POROUS MEDIA**

The movement of fluid through a porous medium requires that the fluid in the pore spaces be sheared. In an aqueous system the shearing of the fluid is normally described in terms of the laminar flow model. Laminar flow describes the movement of an infinite number of layers of water of infinitesimal thickness. These layers move by gliding past each other along the same plane (Figure 3.1), but no mixing occurs between neighbouring layers.

Water can also move by turbulent flow. Turbulent flow occurs predominantly in very coarse granular soils where the particle diameter exceeds approximately 1mm (Hough 1969). In most soils this type of flow is unlikely to exist and in the materials examined in this research project the particle size is certainly less than 1mm. Hence, laminar flow behaviour is assumed to be occurring in all the specimens examined in this thesis.

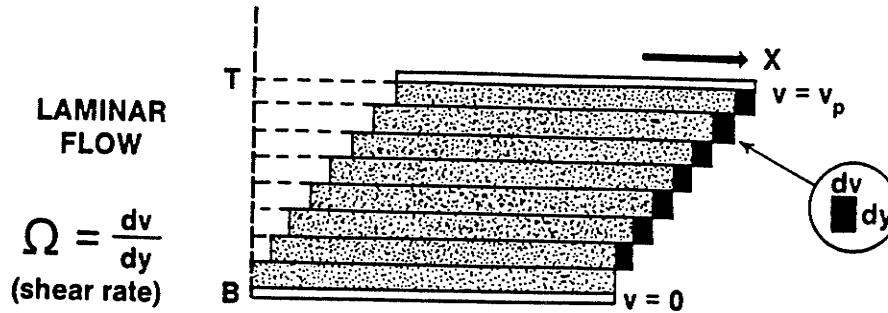


Figure 3.1 Conceptual Model For Laminar Flow (Guven 1992b).

The laminar flow model can be used to describe two types of fluid movement, Newtonian and non-Newtonian. The Newtonian flow model is used to describe fluids where a linear relationship (defined by the shear viscosity (internal friction),  $\eta$ ), exists between shear rate ( $\Omega$ ) and shear stress ( $\sigma$ ), (Equation 3.1a).

$$\sigma = \eta \Omega \quad (3.1a) \quad (\text{Guven 1992b})$$

This relationship plots as a straight line which passes through the origin of a shear stress - shear rate diagram (Figure 3.2). This equation can also be modified using an exponential relationship to empirically account for the flow behaviour of non-Newtonian fluids (Eq. 3.1b)

$$\sigma = \sigma_0 + \eta' \Omega^N \quad (3.1b) \quad (\text{Guven 1992b})$$



Where  $\sigma_0$  is the initial yield stress,  $\eta'$  is a variable viscosity term which will depend on the system studied and,  $N$  (flow index) is a variable which describes the character of the fluid,  $N=1$  for a Newtonian fluid,  $N>1$  for a shear thickening fluid and  $N<1$  for a shear thinning fluid, as described in Table 3.1 below.

The viscosity ( $\eta$ ) of a Newtonian fluid is a constant for a given temperature and pressure, and is not affected by shear rate or shearing time. Bulk water is classified as a Newtonian fluid which makes flow modelling fairly simple. Non-Newtonian flow describes any fluid whose movement cannot be described using the definition (3.1 a), provided for Newtonian fluids. Table 3.1 presents the shear rate - shear stress relationships exhibited by the various types of non-Newtonian fluid flows and their unique characteristics (Guen 1992b). Flow in these non-Newtonian fluids has been classified into four basic flow patterns, Bingham, Plastic, Shear Thinning and Shear Thickening (Figure 3.2). In these flow characterizations a number of parameters ( $N$  (flow index),  $\eta'$  (plastic viscosity),  $\sigma_0$  (initial yield stress)) are used to account for the differences in the properties of these fluids.

Table 3.1 Types of Non-Newtonian Flow Behaviour

1. Bingham Flow (Ideal Plastic Flow): requires a finite shear stress to be applied to initiate flow. Once this stress is exceeded the fluid exhibits a linear  $\sigma/\Omega$  relationship and a constant viscosity  $\eta_{pl}$ 

$$\sigma = \sigma_B + \eta_{pl} \Omega \quad (3.2)$$
2. Plastic Flow: Similar to Bingham flow excepting that it displays a non-linear initial portion, characterized by an initial calculated yield stress ( $\sigma_0$ ) and a critical shear rate  $\Omega_c$  above which linear  $\sigma/\Omega$  exists.
3. Shear-thinning flow: Exhibits a nonlinear  $\sigma/\Omega$  relationship. It may have an initial yield stress ( $\sigma_0$ ), and exhibits a flow behaviour index ( $N$ ) of less than 1.0. This type of behaviour has been observed in high clay content smectite suspensions or at high shear rates (Guen 1992b).

4. Shear-thickening flow: These materials exhibit a nonlinear  $\sigma/\Omega$  relationship with a flow index  $N > 1$ . This type of flow is often called dilatant flow. Fluid viscosity increases with increasing shear rate and/or time.

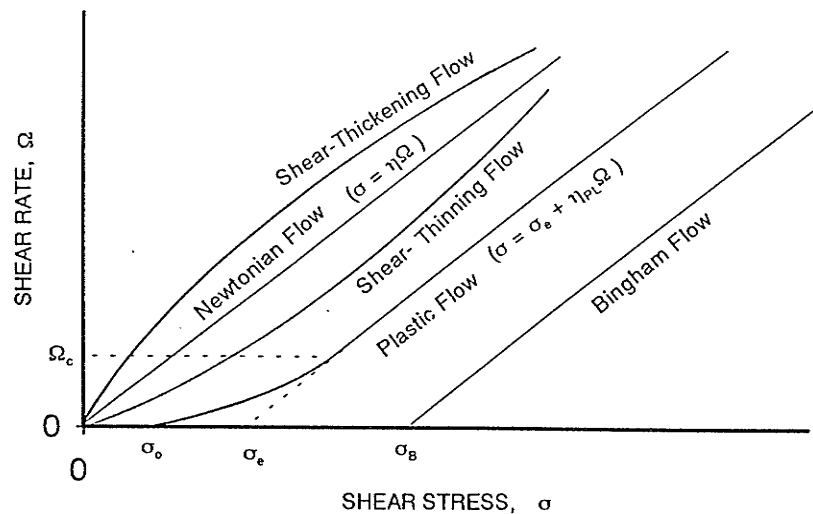


Figure 3.2 Shear Rate - Shear Stress Relationships For Fluids (after Guven 1992a)

Swartzendruber (1961) observed that there was "no qualitative change in the type of curve as one passes from the shear rate - shear stress graph ... to the flow-velocity - hydraulic-gradient graph" (Figures 3.2 and 3.3 respectively). The measurement of fluid flow through porous materials is typically expressed in terms of flux (volume per unit time per unit cross-sectional area of soil), or flow velocity as a function of the hydraulic gradient applied across the specimen. This means that the flux-gradient relationship for a Newtonian fluid is a straight line which passes through the origin. Non-Newtonian fluids will also exhibit the same shape for a flux-hydraulic gradient graph as they exhibited for plots of shear-rate vs shear stress (Swartzendruber 1962a). Other types of flux-gradient relationships can

therefore be related to a change in the structure of the pore fluid, as is permitted by the modified mixture model for water structure presented in Section 2.3.3.

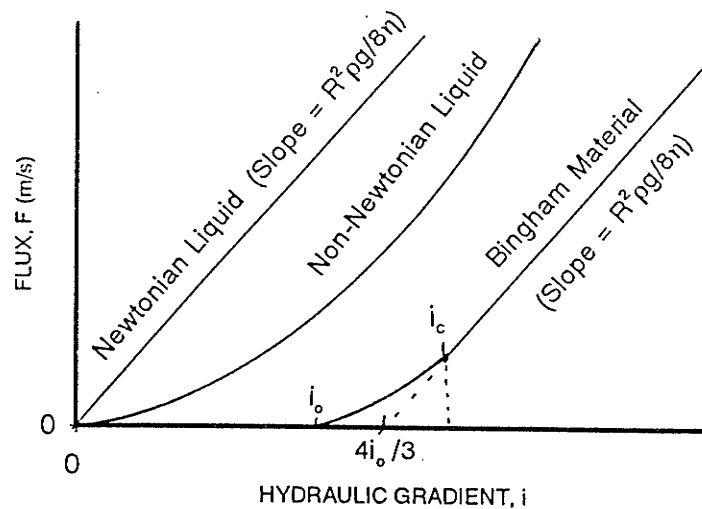


Figure 3.3 Flux - Gradient Relationships Possible For Fluid Flow Through Clays (after Swartzendruber 1962a)

Swartzendruber's (1961) correlation of the shear stress - shear rate and the hydraulic gradient - Flux relationships assumed that the shear rate of the water ( $\Omega$ ) is proportional to the flow rate through the specimen (Flux,  $F$ ). Additionally, the shear stress ( $\sigma$ ) applied to the pore fluid is assumed to be proportional to the hydraulic gradient ( $i$ ) (Figure 3.3). The rheological parameters of initial yield stress ( $\sigma_0$ ), extrapolated yield stress ( $\sigma_e$ ) and Bingham yield stress ( $\sigma_B$ ) presented in Figure 3.2 are therefore equivalent to the threshold gradient ( $i_0$ ) in a Flux-Gradient plot (Figure 3.3). Likewise the critical shear rate ( $\Omega_c$ ) would be related to the critical gradient ( $i_c$ ).

The relationships established between flux and shear rate, and shear stress and hydraulic gradient provide a good basis for examining the behaviour of a fluid which is known to be Newtonian (water) in the presence of clay particles containing high surface charge. Any

deviations from Newtonian flow behaviour would mean that there are mechanism(s) present which have altered the structure and behaviour of the pore fluid. With this in mind it is possible to compare of the shape of flux-gradient plots for soils of various compositions and densities. If the straight-line relationship is not observed to pass through the origin then it is possible there has been a change in the structure of the percolating fluid.

A number of attempts have been made to develop numerical relationships for modelling and predicting fluid behaviour in non-Newtonian materials. Guven (1992b) proposed a series of equations for use in modelling non-Newtonian flow. A transfer of energy is assumed to occur in these fluids and so Equation 3.1 is modified by replacing shear stress ( $\sigma$ ) with a Force per unit Area term ( $F/A$ ), and shear rate ( $\Omega$ ) with a change in velocity with change in fluid layer thickness ( $dv/dy$ ). This produces a general equation for non-Newtonian flow (Equation 3.3) (Guven 1992b).

$$(F/A) dv/dy = \eta(dv/dy)^2 \quad (3.3)$$

Since  $dv=dx/dt$  and  $\Omega =dv/dy$

$$(F dx/dt)/A dy = \eta\Omega^2 \quad (3.4)$$

Since  $(F dx)$  is equal to change in energy ( $\Delta E$ ) and  $(A dy)$  equals change in volume ( $\Delta V$ ) as described in Figure 3.1, Equation 3.4 can be rewritten as an energy-volume relationship.

$$(\Delta E/dt)/\Delta V = \eta\Omega^2 \quad (3.5)$$

Equation 3.5 can be further developed to account for energy losses and non-Newtonian flow. This was described by Guven (1992b);

"The left side of the equation" (Equation 3.5) "represents the rate of energy dissipation per unit volume of the fluid; it is the energy needed to sustain the flow at a rate  $dv/dy$ . The rate of energy dissipation is directly proportional to the product of the square of shear rate and the viscosity coefficient. The total dissipated energy can also be expressed as the product ( $\sigma\Omega$ ) by replacing  $\eta$  with  $\sigma/\Omega$ . As long as the flow is the only mechanism of energy dissipation, the ratio  $\sigma/\Omega$  will remain constant, with the proportionality constant being  $\eta$ . However, energy may be also dissipated by other processes during the flow; for example, additional energy may be needed for breaking up clay flocs or stretching the links between them. Under these conditions, the linear relationship between  $\sigma$  and  $\Omega$  is lost. The flow then does not display a constant shear stress/shear rate ratio ( $\sigma/\Omega$ ) and its viscosity may change with the prevailing shear rate and/or shear time. Newton's flow Eq. 1" (Equation 3.1) "has been modified by an exponential  $\sigma/\Omega^N$  relationship (power law) to empirically account for the flow behaviour of such dispersions:"

$$\sigma = \sigma_o + \eta' \Omega^N \quad (3.6)$$

where  $N$  is the flow behaviour index,  $\sigma_o$  is the initial yield stress and  $\eta'$  is a shear rate dependent variable often called the consistency or plastic viscosity. While this equation can be useful in describing the flow through ideal systems where all the parameters affecting flow are known, it is of limited use in explaining the flow through dense clays where unknown sources of resistance to flow are present.

The inability to deal with the unknowns present in a real system containing many unknown influences on the structure and behaviour of the permeant can be seen in the types of systems chosen by many researchers for study. Much of the literature related to the rheological characterization of water-clay mixtures deals with the flow of clay suspensions rather than the movement of water through dense clays. While this literature does not provide data on the nature of movement through dense clays it provides valuable information on nature of pore fluid in a loose system. Guven (1992b) reported that suspensions containing high concentrations of bentonite clay often exhibit shear-thinning. These materials have a flow index ( $n$ ) in the range of 0.5 to 0.9 (see Equation 3.6), which decreases with increasing degrees of flocculation (Guven 1992b). This implies there is

some change in the structure of the suspension which persists over a wide range of shear rates. This means that changes are occurring in the structure of the suspension with changing shear rate. Such changes can be the result of changing clay particle arrangement, or changes in the amount of free water available to act as a lubricant in the shearing process. While these results are interesting and may have application in more dense clay-water systems, care should be exercised in applying the behaviour of fluids in a clay suspension to the behaviour of fluids in a dense soil. The reasons for taking such care in the application of information provided by clay suspensions become evident in Section 3.2 and Chapter 5 of this thesis. In these sections the potential impacts of relatively minor changes in system chemistry and interparticle spacing on the structure of the pore fluid are discussed.

### 3.2 Porosity and Pore Volume Available For Flow

The porosity of a soil is the single most important parameter influencing the ability of a soil to conduct water. Porosity ( $n$ ) is a measure of proportion of the soil not occupied by solid particles and is commonly derived by calculation of the fractional volumes occupied by solids ( $n_s$ ), liquids ( $n_w$ ) and gas ( $n_g$ ). In a fully saturated system the parameter  $n_g$  becomes zero and the calculation of the remaining fractional volumes can be accomplished using Equations 3.7 and 3.8.

$$n_s = \gamma_d / G_s \quad (3.7)$$

$$n_w = 1 - n_s = 1 - (\gamma_d / G_s) \quad (3.8)$$

where  $\gamma_d$  is the dry bulk density ( $\text{Mg/m}^3$ ) of the soil and  $G_s$  is the specific weight ( $\text{Mg/m}^3$ ) of the soil particles. The porosity parameter has been used in the Kozeny-Carman equation for prediction of water flow through soil. The Kozeny-Carman model is presented in Section 3.4.3.

In clays with high specific surface areas, the potential for at least a portion of the pore volume to be occupied by structured water has led to the development of a parameter defined as the effective porosity ( $n_{\text{eff}}$ ), (Gray et al. 1984) or the porosity available for flow ( $n_w$ ), (Yong and Warkentin 1975). This parameter reduces the porosity by an amount proportional to the volume occupied by structured water. For specimens composed of clay only, the effective porosity can be described by determining the space between parallel clay platelets ( $2d$ ) and reducing this distance by the amount occupied by strongly bound water. The remaining space is the effective distance available for flow ( $2d'$ ). Equation 3.9a is the simplified equation for calculating the d-spacing present between parallel platelets.

$$d = V_w / S \quad (3.9a)$$

Where,  $V_w$  is the volume of water ( $\text{m}^3$ ), present in a saturated specimen having a total volume of  $1 \text{ m}^3$ . For sand-clay specimens, the volume occupied by non-clay components is not included in the calculation of total specimen volume. The parameter  $S$  is the surface area of the solids portion of the specimen ( $\text{m}^2$ ) in the  $1 \text{ m}^3$  specimen.

and, 
$$d = [(1/\gamma_c) - (1/G_c)] [10^3/S_o] \quad (3.9b)$$

The d-spacing defined in Equation 3.9b is measured in nanometres ( $10^{-9}\text{m}$ ),  $\gamma_c$  is the effective clay dry density ( $\text{g/m}^3$ ) and  $G_c$  is the specific weight of the clay mineral particles

(g/m<sup>3</sup>),  $S_o$  is the specific surface area of the clay (m<sup>2</sup>/g). The effective clay dry density was defined by Gray et al. (1984) as the mass of the clay portion of a specimen divided by the volume occupied by the clay and voids. The mass and volume occupied by the non-clay solids are considered to act as inert components of the system and so are not included in calculating the density of the specimen.

To determine the effective half distance available for flow ( $d'$ ) between parallel particles, the distance occupied by immobilized water ( $d_i$ ) is subtracted from the total  $d$ -spacing.

$$d' = d - d_i \quad (3.10)$$

The portion of the pore water which is completely immobilized is commonly assumed to be the Stern water layer (see Figures 2.13 and 2.14). The thickness of this layer is believed to be between 0.1nm and 0.4nm (Yong and Warkentin 1975; Cheung et al. 1987).

With the determination of a range of values for  $d'$ , the effective porosity of a specimen can be estimated. For a pure clay specimen, the effective porosity is defined as,

$$n_{eff} = \gamma_c S_o d' \quad (3.11)$$

where,  $\gamma_c$  is given in units of g/m<sup>3</sup>,  $S_o$  in m<sup>2</sup>/g, and  $d'$  in m.

Cheung et al. (1987) discussed the importance of the particle spacing and observed that if  $2d' < 0.25\text{nm}$  (size of one water molecule), water cannot flow between the platelets. If this reduction in water available for flow occurs, then the distance between the parallel plates can be reduced to a distance of  $2d'$ . This will cause a reduction in the size of the internal porosity (porosity within a group of parallel clay platelets) and may force all flow



to go through the larger pores located between the micro peds in the clay rather than through the soil as a whole. The reduction in the surface area available for flow means that the effective surface area ( $S_o'$ ) of the clay will be reduced. If the micro peds are composed of an assemblage of individual clay platelets (say 5 platelets/assemblage), the effective surface area of the specimen is only about 1/10 of the sum of the areas of the individual particles since the internal porosity is not available for flow (Cheung et al. 1987). This possibility means that effective porosity may not completely describe the nature of the pore space available for flow since water movement does not occur through any pores where the spacing  $2d'$  is less than the size of a water molecule. Flow is channelled through the few remaining pores where sufficient space remains for advective movement.

If the pore space available for flow is determined by the average d-spacing (actually  $d'$ ), then there may be a number of clay densities where changes in the nature of fluid flow occurs. In an ideal system the average interparticle spacings need to remain some multiple of 0.25nm. If the density is such that this requirement is met, then the pore space available for unaffected flow will be minimized as most of the water is associated (bonded), with the particle surfaces. If the density state is not such that a whole number of water layers can be present between the platelets, the clays will form a system where the maximum number of water layers will be formed. The excess porosity may be present as either unattracted water on the outer surfaces of the particle or a few more highly spaced plates within the specimen. In either of these cases, this un-bonded or more weakly associated water will be more easily sheared than the water present between the rest of the clay platelets. A further examination of the role of porosity and the effective porosity

parameter in the prediction of the rate of water movement through clays and clay-sand materials is presented in Chapter 8.

### **3.3 Theories and Models Used to Describe Fluid Flow in Soils**

One of the commonly accepted relationships used in predicting advective groundwater flow is Darcy's Law. Other models for predicting water flow through porous media include the Poiseuille, the Kozeny-Carman, and Buckingham-Reiner equations. Despite the common usage of these models they all have practical limitations which limit their applicability to natural systems and materials. Much of the difficulty in using these relationships has been attributed to natural soil anisotropy (Section 3.5), and the presence of non-hydraulic (chemical, thermal, electrical or other) gradients in soils. Such gradients have been repeatedly reported in the literature (Low 1961; Miller and Low 1963; Li 1963; Bolt and Groenevelt 1969; Law and Lee 1981; Desaulniers and Cherry 1989; Sri Ranjan and Gillham 1991; Sri Ranjan and Karthigesu 1992; Karthigesu 1994). Sections 3.3.1 through 3.3.5 present the basic models for flow thorough a porous medium and discusses the strengths and weakness of these models, particularly when they are applied to clay soils.

#### **3.3.1 The Darcy Equation**

The Darcy Equation, or "Law" was developed in the 19th Century by D'arcy (1856). The name Darcy is commonly used in literature when referring to this work and this is the label given to this relationship in the remainder of this thesis excepting when making direct reference to the originator of this relationship. This equation is based on an empirical relationship found for the flow of water through sand and gravel. D'arcy (1856) found that the mean effective flow velocity of water ( $v_n$ ) is directly proportional to the flow rate ( $q_p$ ) and

the applied hydraulic gradient ( $i_h$ ) (Equations 3.12 and 3.13). Hydraulic gradient ( $i_h$ ) is defined as  $\Delta h/\Delta l$  (change in hydraulic head divided by the flow distance through specimen). Hydraulic head is the difference (in metres) between the water potential on the inflow and the outflow surfaces of the soil column. While Darcy's law is suitable for predicting flow through sands and gravels, it is recognized as inadequate to describe the flow of fluids through low permeability clays under low applied hydraulic conditions. The basic relationship developed by D'arcy is well known and is the basis for most of the models for predicting water flow (Yong and Warkentin 1975; Olsen 1965; Mitchell 1976, 1991; Olsen and Daniel 1981; Lambe and Whitman 1979). While the symbols used by these authors vary, the relationships presented are the same. For the purposes of consistency, the symbols used by either Yong and Warkentin (1975) or Mitchell (1976) have been adopted for use, where appropriate, in this thesis. The basic equations which are used to describe Darcian flow are presented in Equations 3.12 through 3.15 (Yong and Warkentin 1975).

$$v_h = Q/At = k_h i_h = k_h \Delta h/\Delta l \quad (3.12)$$

$$\text{and} \quad q_h = k_h i_h A \quad (3.13)$$

where  $A$  is the cross-sectional area of the specimen normal to the direction of flow and  $Q$  is the quantity of flow measured over time increment  $t$ . The hydraulic conductivity,  $k_h$  (or  $k$  as it is normally expressed for fully saturated specimens), is the flow velocity term normalized to a flux at a hydraulic gradient of 1.0.

Equations 3.12 and 3.13 can be more clearly expressed if the properties of the fluid flowing through the soil can be defined, leading to equations 3.14 and 3.15.

$$v_h = K\rho g i / \eta \quad (3.14)$$

or  $K = k\eta / \rho \quad (3.15)$

where  $\rho$  is fluid specific weight,  $\eta$  is fluid viscosity,  $K$  is permeability,  $g$  is the gravitational constant. The permeability  $K$ , is a coefficient (expressed in units of  $\text{length}^2$ ) which excludes the effect of permeant viscosity ( $\eta$ ) and the fluid unit weight ( $\gamma$ ) on the flow velocity. It is commonly thought of as a measure of the geometry (area and tortuosity) of the channels available for flow by any permeant, including water.

Table 3.2 presents the basic assumptions for the application of the Darcy equation and compares these with the conditions believed to exist in three different soil materials. The table provides a good indication of the potential short-comings of using the Darcy equation to estimate flow through clays, and in particular through soils containing clays with a high surface charge.

Table 3.2 Basic Assumptions For Application of Darcy's Law

| Requirement For Darcy's Law                                | Validity of Darcian Assumptions in: |        |           |
|------------------------------------------------------------|-------------------------------------|--------|-----------|
|                                                            | SAND                                | ILLITE | BENTONITE |
| 1) Isotropic Soil Structure Exists                         | Yes                                 | No     | No        |
| 2) Fluid Viscosity is Constant                             | Yes                                 | Yes ?  | No ?      |
| 3) Fluid Density is Constant                               | Yes                                 | Yes ?  | No ?      |
| 4) Soil Fabric does not Change                             | Yes                                 | ?      | ?         |
| 5) Laminar Flow Occurs                                     | Yes                                 | ?      | ?         |
| 6) Absence of Non-Pressure Gradients and Counter-gradients | Yes ?                               | ?      | No ?      |

While Darcy's equation for flow through a porous medium was found to be adequate for the measurement of water flow through most granular soils it was soon determined that this "law" had some serious limitations (King 1898). King (1898) was one of the first to report deviations from Darcian flow behaviour. He observed that for clayey materials there was a tendency for hydraulic conductivity to increase with increasing hydraulic gradient. A large number of researchers have also observed deviations from the Darcy equation for flow in soils other than sands and gravels. The apparent limitations of the Darcy equation has led to the development of a large number of flow models, including the Poiseuille and Buckingham-Reiner equations presented in Sections 3.3.2 and 3.3.3.

### 3.3.2 Poiseuille Equation

The Poiseuille equation provides the starting point for most attempts to describe water flow through soils (Lambe and Whitman 1979; Mitchell 1976, 1991; Yong and Warkentin 1975). This equation was developed to predict the average fluid flow through a tubular capillary with circular cross-section. In its simplest form it can be expressed by Equation 3.16.

$$v_{ave} = \rho_w R^2 i_h / 8\eta \quad (3.16)$$

where  $v_{ave}$  is the average fluid velocity,  $R$  is the tube radius,  $\rho_w$  is the mass density of the permeating water,  $i_h$  is the hydraulic gradient and  $\eta$  is the water viscosity. Modification of this basic equation begins with recognition that the size of the pores may vary, and so an average size must be used. The average pore size is accounted for using the hydraulic radius ( $R_h$ ), which for a circular tube flowing full is defined in Equation 3.17 (Mitchell 1976).

$$R_h = \pi R^2 / 2\pi R = R/2 \quad (3.17)$$

From this, the Poiseuille equation can be used to estimate flow rate (q) through a tube.

$$q = \rho_w R_h^2 i_h a / 2\eta \quad (3.18)$$

where "a" is the cross-sectional area of the tube. However since the pores in a soil are not ideal tubular capillaries, a shape coefficient ( $C_s$ ) is used to modify the flow rate prediction (Equation 3.19).

$$q = C_s \rho_w R_h^2 i_h a / \eta \quad (3.19) \text{ (Mitchell 1976)}$$

Equation 3.19 can be further developed to account for parameters such as degree of saturation (S), specific surface of the soil particles ( $S_o$ ), void ratio (e), total cross-sectional area (A) of the specimen and Volume of particles ( $V_s$ ). On completion of these substitutions Equation 3.19 can be expressed as,

$$q = C_s V_s^2 \rho_w e^3 S_o^2 i_h A / (\eta S_o^2 (1+e)) \quad (3.20) \text{ (Mitchell 1976)}$$

Parameters such as degree of saturation (S), and Shape Factor ( $C_s$ ), for fully saturated materials have established values (Mitchell 1976). Saturation is 1.0 in a fully saturated specimen, and  $C_s = 1/mT^2$  (Mitchell 1976). The "m" is the pore shape factor (approximately 2.5) and the tortuosity factor T is used to account for the fact that the pore paths are not straight. The tortuosity factor is defined as being the ratio of the effective flow path and the thickness of the test sample and is generally defined as being  $\sqrt{2}$ .

The Poiseuille equation is normally only taken as a starting point in the development of predictive equations. It is often combined with an assumption that the Darcy equation for flow is correct and then developed into relationships such as the Kozeny-Carman equation presented in section 3.3.3, (Kozeny 1927; Carman 1941).

### 3.3.3 The Kozeny-Carman Equation

The Kozeny-Carman Equation for water flow is a relationship which combines Darcy's law (Equation 3.13) and the Poiseuille equation (Equation 3.20).

$$\text{Darcy's Law} \quad q = k_h i A \quad (3.13)$$

$$\text{Poiseuille Equation} \quad q = C_s V_s^2 \rho_p e^3 S_o^2 i_h A / (\eta S_o^2 (1+e)) \quad (3.20)$$

For a fully saturated system,  $k_h = k$ ,  $\rho_p = 1$ ,  $V_s = 1$ ,  $S = 1$ , tortuosity  $T = \sqrt{2}$ , and with a pore shape factor  $m$  ( $m=2.5$ ), the Poiseuille equation can be expressed as equation 3.21 (Lambe and Whitman 1979).

$$k = \rho e^3 / (m T^2 \eta S_o^2 (1+e)) = C_s \rho e^3 / (\eta S_o^2 (1+e)) \quad (3.21) \quad (\text{Mitchell 1976})$$

or in terms of porosity ( $n$ ),

$$k = C_s \rho n^3 / m T^2 S_o^2 (1-n)^2 \quad (3.22) \quad (\text{Yong \& Warkentin 1975})$$

In terms of permeability ( $K$ );

$$K = k \eta / \rho = e^3 / (m T^2 S_o^2 (1+e)) \quad (3.23) \quad (\text{Mitchell 1976})$$

The coefficients  $T$  and  $m$  used in Equations 3.22 and 3.23 assume a porous medium of approximately uniform pore sizes.

Equations 3.21 through 3.23 have shown that the Kozeny-Carman equation can be expressed in terms of either porosity ( $n$ ) or void ratio ( $e$ ). The shape factor ( $C_s$ ) has a relatively narrow range of commonly accepted values (0.5 for circle, 0.33 for a strip, 0.56 for a square shaped pore structure). Yong and Warkentin (1975) recommended the use of an average  $C_s$  value of 0.4. This provides a calculated  $k$  which should be within 25 % of the values produced using the extreme values of  $C_s$  and so is assumed to be more representative of the variability of natural materials.

Even though the Kozeny-Carman equation for flow is commonly recognized as one of the best models available for predicting the hydraulic conductivity of soils, its applicability is severely limited (Scheidegger 1960; Yong and Warkentin 1975; Mitchell 1976; Cheung et al. 1987; Yong et al. 1992). Equations 3.21 through 3.23 are recognized as being generally valid only for materials where there is,

- a) relatively uniform particle size,
- b) no soil structure or fissuring,
- c) laminar flow of liquid through pores,
- d) Darcian flow behaviour,
- e) an absence of long and short-range forces of interaction

These limitations to the application of this equation mean that it can only be applied for materials such as gravels, sands and perhaps coarse silts. The structure and anisotropic fabric of most clays violate the basic requirements for the application of the Darcian, Poiseuille or Kozeny-Carman equations.

### 3.3.4 Buckingham-Reiner Equation

A number of relationships have been developed which attempt to account for some of the limitations of the Darcian and Kozeny-Carman equations. Of these relationships, one of the best known is the Buckingham-Reiner equation for flow. Swartzendruber (1962a) presented a model which attempted to account for non-Newtonian behaviour of water in clay soils. The water in clay-water systems was assumed to be Bingham in nature (Figure 3.3). An assumption of Bingham behaviour means that there is a critical hydraulic gradient which must be exceeded before water flow will occur (Swartzendruber 1962a). This relationship between applied gradient, critical gradient and the resultant water flow velocity through a clay soil (Buckingham-Reiner equation) is presented in Equation 3.24.

$$v = (R^2 \rho g i / 8 \eta) (1 - 4 i_0 / 3 i + 1/3 (i_0 / i)^4) \quad (3.24)$$



where  $\rho$  is the fluid density,  $g$  is gravitational acceleration and the value determined for the threshold gradient ( $i_o$ ) uses a capillary tube model where the yield stress of the fluid is directly related to the capillary radius (Equation 3.25).

$$i_o = 2\sigma_o/\rho gR \quad (3.25)$$

where  $R$  is the capillary radius and  $\sigma_o$  is the yield stress of the fluid.

The characteristic behaviour described by Equation 3.24 is presented in Figure 3.3 as the Bingham material. This equation reduces to the Poiseuille equation (Equation 3.16), when  $T=0$  and  $i_o=0$ . This model does not reject the Darcian model for flow but considers Darcy's law to be a special case. Swartzendruber (1962a) also described the flow behaviour of clays as becoming more Newtonian as the salt concentration of the pore fluid increases. This supports the model for the structure of clay-water systems presented in Chapter 2 which predicts that cations can act as water structure-breakers in clay soils at high density or high cation concentration. The Buckingham-Reiner equation represents an attempt to use rheological models to develop a numerical model for use in predicting water flow through active clay soil. The applicability of this relationship to flow of water through dense, high-activity clays is examined in Chapter 8.1.

### 3.3.5 Comparison of Four Models For Prediction of Water Movement

Sections 3.3.1 through 3.3.4 have presented four techniques which have been developed to try and provide a quantitative tool for use in predicting the advective transportation of water through a porous medium. Each of these models has attempted to account for

different parameters present in a porous medium in order to generate a workable "predictive" tool.

The Darcy equation is the simplest of these four equations. It attempts only to account for potential changes in the viscosity of the permeant and applies an empirical equation to a set of physical measurements in order to generate a relationship to predict advective flow under a different set of environmental conditions (T,  $\mu$ , fluid density/viscosity).

The Poiseuille equation is the basis for most fluid mechanics. It works with water flow through a circular, water-filled tube. The material parameters are all known before the solution is generated and it provides an estimate of the tube's (in this case a capillary in a porous medium) ability to conduct the permeant. In this type of solution a number of material parameters must be known or assumed, the most important of which are the hydraulic radius (Equation 3.17), and the specific surface area of the soil particles. From these measured (or estimated) properties it is possible to estimate the advective transport through a porous medium without conducting any physical measurements. Unfortunately, as discussed in Section 3.3.1 it has some severe limitations, especially when it comes to the effects of pore size variability and particle specific surface on the results obtained. The presence of only a few larger than estimated capillaries can have a considerable influence on the measured advective flow versus that predicted. Appendix C provides a number of numerical solutions made using the Poiseuille equation and compares them to the measurements actually made for sand, illitic clay and bentonitic clay specimens. A detailed comparison of predicted advective flow and that measured is provided in Chapter 8.

The Kozeny-Carman equation for advective flow is an attempt to build on the Poiseuille equation and account for a few more of the physical parameters which are present in a soil material, namely pore shape and the recognition that pores in soil materials are not straight circular tubes and that some degree of tortuosity exists in the flow path. Appendix C also contains solutions for the Kozeny-Carman equation for materials that were well characterized and whose advective transport characteristics were actually measured. Detailed comparison of measured and predicted advective transportation of water is provided in Chapter 8 of this thesis.

The Buckingham-Reiner equation is an effort to further develop the Poiseuille and Kozeny-Carman equations. This equation provides a means of accounting for potentially non-newtonian flow in the pores of a soil. Section 3.3.4 presents the solution of the equation developed to predict non-newtonian flow through a porous medium.

The chief limitation of applying the Poiseuille, Kozeny-Carman or Buckingham-Reiner equations can be summarized as being the result of two limiting assumptions.

- 1) Uniform Pore Sizes of very accurately known dimension
- 2) Uniform particle size of the porous medium and hence an accurately known surface area for these particles.

Despite these limitations these relationships remain the best techniques available for providing a prediction of the ability of a porous medium to transmit a fluid. A major component of this research project is to determine whether it is possible to use any of these techniques to provide an estimate of the rate at which a fluid can pass through dense clays. The influence of soil structure and other parameters on the movement of water through soils will be discussed in greater detail in subsequent sections of this chapter.

### 3.4 Influence of Soil Structure on Water Flow

Lambe (1958) provided a good general review of potential effects on the structure of soil and the movement of water through these soils. In Lambe's (1958a,b) papers, soil structure was defined as resulting from the physical arrangement of soil particles and the electrical forces acting between particles. This section focusses on the influences of soil-structure on mass transport through dense clays, particularly how it may affect the identification of non-Darcian flow behaviour.

The ways in which soil structure affects mass transport through soils are numerous and include the following.

1. Presence and stability of soil colloids. These materials can be transported through the soil and may block, or be removed from narrow pore passages in soils. This can be a significant influence on fluid movement. These colloids can result in changes in the soil pore size distribution, or flow path tortuosity.

2. Soil particle orientation. Preferential or anisotropic flow may be induced if the soil particle arrangement results in an anisotropic soil fabric. The flow rate will be greatest along the direction of lowest tortuosity. This can result in an inaccurate estimation of flow velocity when materials are tested at inappropriate orientations. This is particularly relevant in natural soils which may have significant structural orientation.

3. Particle size and shape. As with particle orientation, this will effect the type of flow path available to conduct the pore fluid. The smaller the size of the soil particles, the smaller are the passages available for flow (Mesri and Olson 1971; Witt and Brauns 1983). Both these papers discussed the role of the size of clay particles on the pore size, and the resulting value of  $k$  that will be measured. The smallest particles, smectites, were

observed to have the lowest  $k$ . Illite and kaolinite clays, composed of particles which are progressively larger than smectites, exhibited hydraulic conductivities some 200 and 200,000 times higher than smectite, for the same clay density (Mesri and Olson 1971). Differences in the measured  $k$  were attributed to the particle size. Decreasing particle size results in an increase in the effective length of the passage through which water must move (Witt and Brauns, 1983). This is in essence the tortuosity factor in flow measurement used in the Kozeny-Carman Equation presented in Section 3.2.3.

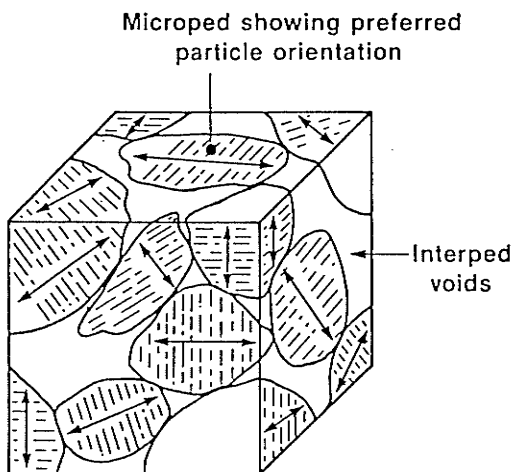
Secondary soil structures have also been recognized as influencing fluid flow. Soils may be composed of several levels of organization and structure. The finer particles in the soil may actually be micro-peds of differing particle-size orientation than the overall soil. This type of micro-ped structure has been described by Gray et al. (1985), (Figure 3.4a) and Yong et al. (1992), (Figure 3.4b). Such a soil structure will result in three potential levels of fluid flow:

- 1) Flow occurring through the soil macro-pores,
- 2) Flow through the pores within the micro-peds and,
- 3) Flow between the clay platelets within the micro-ped.

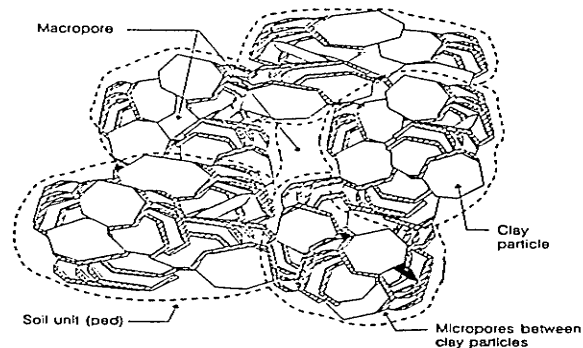
The fluid flow through each of these pore types represents increasing levels of tortuosity. As a result, the flow velocity through each of these components will differ. This variation of the flow velocity through various sub-structures within the soil is particularly important when considering the influences of changing clay density or increasing compactive effort.

With increasing compactive effort and increasing soil density comes a decrease in the number of, or the size of the macropores available to conduct flow (Garcia-Bengochea and Lovell 1981). The micropores within the individual micro-peds will remain relatively

constant until the macropores have been collapsed by soil compaction. On elimination of macropores, the flow through the soil unit will be controlled by flow through the micropores within the individual micro-peds and between the individual clay platelets. A study by Oliphant and Tice (1985) found that flow in silty material is highly channelled, indicating that the macropores are the dominating factor in determining flow through low activity materials. In their study, Oliphant and Tice (1985) also reported that the pathways taken to conduct the water through bentonitic clays did not appear to change with density. These findings support a structural model for bentonite which predicts that there will be a few macropores available in dense, saturated and volumetrically stable bentonite soils.



Gray et al. (1985)



Yong et al. (1992)

Figure 3.4 Pore Structure Within A Clay Soil

4. The type of consolidation or compaction used to densify a soil has also been reported to influence  $k$ . There is a considerable body of data available which shows that the soil structure in compacted soils will be affected by initial (moulding) moisture content

and the compactive effort applied to the soil (Figure 3.5). Soils densified using a low moulding moisture content and/or a low compactive effort will generally exhibit a more isotropic (random) soil particle arrangement (Lambe 1958a; Harrop-Williams 1985). Such soils will be more likely to contain larger pores and exhibit a wide range of pore sizes. In contrast, a higher moulding moisture content and/or high compactive effort will generally result in a more parallel particle arrangement (anisotropic soil structure). These soils will contain a smaller average pore size and exhibit a narrower range of pore sizes. Such differences in soil structure will affect the manner in which water flows through soils (Lambe 1954, 1958a,b; Mitchell et al. 1965; Boynton and Daniel 1985). This does not necessarily mean that Darcy's law is invalid. It does mean that the Darcian flow velocity, will be different with different flow path orientations.

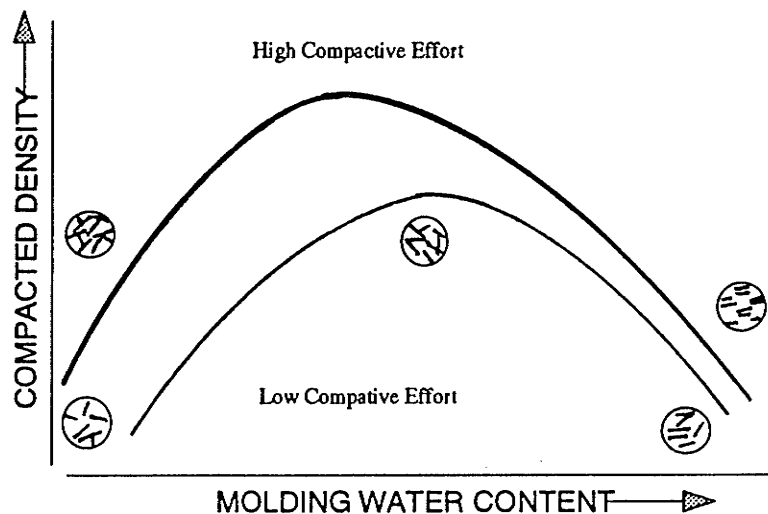


Figure 3.5 Effects of Compaction and Moisture Content on Soil Structure (after Lambe 1958)

With all these potential physical influences on the hydraulic conductivity of soils it is particularly important to limit potential sources of physical variation in the preparation of

specimens for laboratory testing. While many of the described influences can be extremely important in controlling the flow rate through natural clay soils, they are less critical in an engineered barrier where the material effects and structural variability commonly found in nature can be eliminated or at least controlled. For the purposes of this research project, standard techniques for the preparation and testing of the clays were developed to limit these structural influences (Chapter 7.2).

### **3.5 Coupled and Non-Hydraulic Causes of, and Influences on Fluid Flow**

#### **3.5.1 Introduction**

Over the past 30 years considerable controversy has existed regarding the validity of Darcy's Law in clay soils. Much attention has been on non-mechanical influences on flow, and the structure of water in low density non-swelling and swelling clays (see papers by Low 1976a,b, 1979; Olsen 1965, 1985; Barbour and Fredlund 1989; and Mitchell 1991). A number of possible explanations for Non-Darcian flow in clays have been identified. These include, thermal, chemico-osmotic and electrical gradients.

The preceding sections of Chapter 3 have presented basic relationships and physical mechanisms that can affect fluid flow in materials such as sand and silt. These relationships are not necessarily valid for finer grained clay-based materials. Mass transport can also be the result of gradients other than hydraulic gradients across specimens. Non-linear flow, either as a direct or coupled process has been well documented in the literature (Barbour and Fredlund 1989; Mitchell 1991; Quigley et al. 1987; Brandon and Mitchell 1989; Sri Ranjan and Gillham 1991).



Table 3.3 presents the range of parameters affecting mass transport through soils, particularly highly charged clay soils. Of the 16 sources of direct or coupled flow identified in this Table several are not relevant to most laboratory testing conditions. Isothermal laboratory tests will eliminate the temperature gradient, or thermally induced mass transport. This eliminates cells 2, 5, 6, 7, 8, 10 and 14 from Table 3.3. In a cell constructed of an electrically conductive material such as steel (as were the permeameters used in this research), it is not possible to maintain an electrical gradient across the specimen. Any current or electrical gradient would be grounded through or neutralized by flow through the cell walls. This grounding or short circuiting through the cell wall eliminates cells 3, 7, 10, 11, 12, 13, 14 and 15 in Table 3.3 from the list of potential sources of direct or coupled flow in this project.

Table 3.3 Sources and Types of Direct and Coupled Flow Phenomena  
(Adapted From Mitchell 1991)

| Flow (J) | Gradient                        |                                                           |                                           |                                            |
|----------|---------------------------------|-----------------------------------------------------------|-------------------------------------------|--------------------------------------------|
|          | Hydraulic Head                  | Temperature                                               | Electrical                                | Chemical Concentration                     |
| Fluid    | Hydraulic:<br>Darcy's Law (1)   | Thermo-osmosis<br>(2)                                     | Electro-osmosis (3)                       | Chemical Osmosis<br>(4)                    |
| Heat     | Isothermal<br>Heat Transfer (5) | Thermal Conduction:<br>Fouriers Law (6)                   | Peltier Effect<br>(7)                     | Dufour Effect<br>(8)                       |
| Current  | Streaming Potential<br>(9)      | Thermo-electricity:<br>Seebeck Effect<br>(10)             | Electric Conduction:<br>Ohm's Law<br>(11) | Diffusion &<br>Membrane<br>Potentials (12) |
| Ion      | Streaming Current<br>(13)       | Thermal Diffusion of<br>Electrolyte:<br>Soret Effect (14) | Electrophoresis<br>(15)                   | Diffusion:<br>Fick's Law<br>(16)           |

On elimination of the potential effects of electrically and thermally induced flow, three potential mechanisms are left in Table 3.3 which influence mass transport and hence the fluid displacements measured in this project. These influences are; Cell 1 - Hydraulic Conduction (Darcy's Law), Cell 4 -Chemical Osmosis and Cell 16 - Diffusion (Fick's Law). Darcy's Law and its associated equations has already been discussed in Chapter 3.1 and is the principal focus of this thesis. Chemical Osmosis and Diffusion are briefly discussed in Section 3.5.2.

### **3.5.2 Chemical Diffusion and Osmosis**

Diffusion is the movement of ions or molecules through a soil as the result of differences in the concentration of these molecules. Diffusion in clay soils can, if the concentration differences of charged ions are great enough, result in chemical osmosis across the specimen (Mitchell 1991). These mechanisms for flow can be significant in systems such as clays where there is a low hydraulically-induced transportation rate. Osmosis is a mechanism whereby molecules will try to move from areas of high concentration to areas of low concentration in an effort to reach a concentration balance. In a system composed of highly charged clay particles, there can be an exclusion (full or partial), of certain sizes or types of ions and molecules from the interparticle regions of the soil. This results in the generation of an osmotic potential, which means that the soil will exhibit semi-permeable membrane behaviour. Water may move with or against hydraulic pressure gradients in its effort to establish an osmotic balance.

The osmotic and diffusive mechanisms for inducing mass transport are particularly important when a region containing a high concentration of an ion, for example in a landfill or other waste isolation facility is hydraulically connected to a region of low concentration.

Considerable work has been done on this mechanism for mass transport by researchers such as Kemper and Rollins (1966), Bolt and Groenevelt (1969), Elrick et al. (1976), Marine and Fritz (1981), Barbour (1987) and, Barbour and Fredlund (1989). These authors all agree that chemical osmosis can be an important mechanism in soil consolidation (Barbour and Fredlund 1989), water flow through clay soils (Kemper and Rollins 1966) and the generation of anomalous hydraulic heads (Marine and Fritz 1981).

There is evidence in the literature which indicates that the hydraulic pressure-head generated by osmotic forces can be significant. This pressure-head is a measure of the effectiveness of the clay as a semi-permeable membrane. The term commonly used to quantify the effectiveness of the clay as a semi-permeable membrane in preventing ion movement while allowing water to pass through it is Osmotic Efficiency (Mitchell 1991). A membrane of 100% efficiency would prevent any ionic transfer across the membrane and as a result the full osmotic pressure difference would be generated between the regions of high and low ionic concentration. The ability of an actual membrane to prevent ion transfer is normally somewhat less than perfect, hence osmotic efficiency is typically expressed as some % of full efficiency. As the efficiency of the membrane decreases so does its ability of the maintain the pressure difference between the two fluids. When the pressure difference exceeds the efficiency of the membrane it will allow some ionic leakage between the reservoirs.

Olsen (1969) reported osmotic pressures of 40 cm of water for kaolin (a 5% osmotic efficiency) while Kemper and Rollins (1966) and Groenevelt and Elrick (1976) reported osmotic efficiencies of up to 90 % for bentonite - saline solution systems. This means that very high osmotic pressure heads are possible in bentonite clay systems, as has been

estimated by Mitchell (1991), (Figure 3.6). This type of osmotic pressure model has been used to explain anomalous hydraulic pressure heads (790kPa to 1300 kPa), for natural clay shale deposits (Marine and Fritz 1981).

In situations such as those present under waste isolation conditions, the ionic concentrations inside the repository would be greater than on the outside. In such a situation the osmotically driven flow would be from the outside to the inside (Mitchell, 1991). This can have a number of potential influences. Firstly, the rate of contaminant release may be reduced and secondly, there may be anomalous pressures generated in the water within the soil unit.

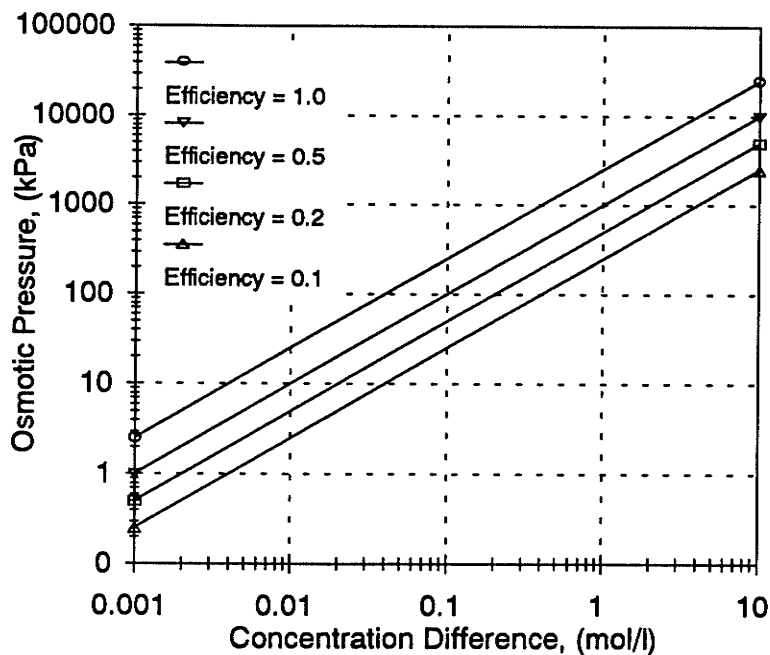


Figure 3.6 Theoretical Values of Osmotic Pressure as a Function of Concentration Difference Across a Clay Liner For Different Values of Osmotic Efficiency (from Mitchell, 1991)

Recent work by Oswell (1991) reported the presence of locked in pore water pressures in compacted bentonite-sand specimens. These pressures were evident when triaxial

specimens had their externally applied pore water pressure shut off, and the internal pore pressure was subsequently monitored. These locked in pressures are believed to be the result of osmotic potential differences present in the specimens. Due to installation and test procedures, the salt concentration in the pore fluid at the centre of the specimens was higher than in the fluids at either end of the specimen, so the osmotically driven pressure gradient would have been inwards. As the applied pore water pressure was decreased the internal pore water pressure would only have decreased to the point at which the osmotic efficiency of the specimen became the controlling feature in pore pressure. The result of this was a total stress which exceeded the sum of the swelling pressure and applied pore water pressure. In another series of tests Oswell (1991) prepared specimens where a pore water pressure gradient was maintained across the specimens despite a cessation of the shearing. These specimens, which originally had a 200 kPa pressure difference between their top and base had their top and bottom drains closed and were allowed to sit and equilibrate. A difference of approximately 50 kPa was observed in the pore pressure monitored at the top and base of the specimens examined. It should be noted that the pore pressures recorded in Oswell's (1991) research were monitored immediately above and below the top and bottom filterstones respectively. The pore pressures within the specimens were assumed to be proportional to these externally measured values. These data show that the mechanism causing this pore pressure difference acted through both the micro and macro pores which are present. The low pressure difference which was maintained across these specimens was somewhat lower than might be expected in a bentonitic material. In a buffer material, the sand matrix is partially interconnected and may provide a pathway which allows much of the osmotic pressure potential of the bentonite clay to be eliminated by water flow along sand particle contacts.

Chapter 4 will show that Saskatchewan or Wyoming bentonite clays with a density of 1.25 Mg/m<sup>3</sup> will have an initial internal pore fluid ionic concentration, expressed as [Na<sup>+</sup>] of approximately 4 mol/l. If a specimen is initially percolated with deionized water starting at one end, this will mean that large concentration differences will exist in the pore fluid. Based on theoretical osmotic pressures within a clay soil (Figure 3.6) and assuming an osmotic efficiency of 90% for bentonite (Kemper and Rollins, 1966; and Groenevelt and Elrick, 1976) it should be possible to estimate the maximum osmotic pressure generated. The potential osmotic pressure generated in such a system appears to be in the order of 5000 kPa (Table 3.6). This means that it is theoretically possible for a locked in pore water pressure of 5000 kPa to be present if the pore water pressure exceeded this value at some point in the history of the specimen. As the salinity of the pore fluid gradually decreases through diffusional movement, there would likely be corresponding reduction in the osmotic pressure within the specimen. The time required for diffusional driven reduction of the pore fluid salinity to equal that of the surrounding fluids is unknown, but is likely to be long.

The influence of these "locked-in" pressures is potentially significant. If a specimen has experienced a high pore water pressure at some point in its history, the pore spaces where such pressures existed may not be available for flow at lower pore pressures. These pressurized pores are basically occluded or "dead" porosity which do not take part in the hydraulic conduction process. If this occluded pore space is available only for flow at higher pore pressures and hydraulic gradients, then the porosity available for flow at lower pore pressures and gradients should be smaller. This change in available porosity should be reflected in a decrease in the hydraulic conductivity of the specimen. This situation should be maintained until the osmotic pressure is once again exceeded by the hydraulic pressure, at which point the effective porosity should increase. For a specimen having an

initial pore fluid salinity of approximately 4 mol/l, an osmotic pressure of 5000 kPa (510m water head) could be expected. If this specimen were 20mm in length, a gradient exceeding 25,000 would be necessary before the entire porosity became available for flow.

It is also possible for the influence of chemical osmosis and diffusion to be masked or increased by chemically-induced changes in soil structure. The diffusional flow of ions into or out of a high activity clay such as bentonite, can result in changes in the soil's microstructure. The micro structure may alter towards dispersion (a breakdown of the micro peds or particle aggregations), or flocculation (the formation of new and stronger interparticle connections). As the soil structure changes, so does its osmotic efficiency and hence the magnitude of the effects of chemical osmosis and diffusion. This situation should only be significant in systems where the soil structure is loose enough (has sufficiently low density), to permit particle reorientation. In densely compacted systems this reorientation should not be possible so the osmotic efficiency of the soil should remain relatively constant provided significant chemical concentration changes have not occurred.

In testing for mass transport through clays, there are two commonly accepted means of limiting the effects of chemical changes on the flow of water through clay soils. The first is to limit the volume of fluid displaced through the specimen and thereby limit the effects of chemical changes on osmotic processes. That is, the osmotic and chemical gradients are kept constant. Alternatively, enough fluid must be percolated through the specimen to eliminate the effects of changing chemical gradients.

The need to minimize effects of changing chemistry on the measured flow rate is difficult to rationalize, and numerous attempts have been made to specify the minimum number of

pore volumes that must be percolated through a specimen before steady-state flow conditions can be defined. Authors such as Peirce and Whitter (1986) for example have recommended that a significant volume of permeant be percolated through clay soils to ensure that steady-state flow has been achieved.

The very low hydraulic conductivity of compacted bentonite clays ( $<10^{-10}$  m/s), and the potential influences of applied hydraulic gradient on soil structure and porosity available for flow make a minimum pore volume specification impractical in the present study. A detailed discussion and description of the testing procedures used in this thesis is presented in Section 6.2, but it is useful here to outline how the foregoing discussion has influenced the test program. Hydraulic testing was conducted in a manner which limited the total displacement through the specimens to less than 0.5 pore volumes. The testing was done in such a manner that the applied hydraulic gradient was increased and decreased on a number of occasions in the course of testing. This meant that any significant changes in the osmotic gradients present with percolation would be identifiable as inconsistent flux-gradient data and considerable scatter in the plot of this data.

Limiting total displacement through the specimens also limits the ability of the permeant to flush ions from the specimen and thereby generate a chemical gradient. Large volume fluid reservoirs were used for both inflow and outflow to ensure that the composition of the fluid was the same on both sides of the specimen. Each of the tests that have been conducted took approximately 9 months to complete, and in some cases, the test duration exceeded 18 months. At the end of several tests, the specimen was sectioned to determine the quantity of soluble material still present and if there was any discernable chemical gradient across the specimen. Chapter 4.3 presents the results of these tests.



### **3.5.3 Non-Osmotic Counter-Gradients Resulting From Mineralogical Alteration and Changing Thermal Conditions**

A paper by Graf (1982) discusses a combination of mineralogical, osmotic and chemical processes which can be particularly important in fine-grained hydrated clays, such as bentonites. In his paper Graf (1982) reviews the data of a number of researchers and presents a case for the generation of hydraulic overpressures, that is, the development of pore water pressures in excess of those which would be developed simply by the hydrostatic or thermal history of the material. The most commonly attributed mechanisms causing the presence of, or eventual generation of excess pore water pressures are;

1. rapid sedimentation of fine-grained materials
2. lateral tectonic compression
3. aquathermal pressurizing (Barker 1972)
4. dehydration of gypsum and/or clay minerals.
5. locked in hydraulic pressures (Graf 1982, Oswell 1991)

The first mechanism is not applicable in an engineered material. The other four mechanisms have the potential to be active in engineered barriers, particularly for deep geological disposal sites where bentonite-based clay barriers and heat generating wastes are present.

Lateral tectonic compression could occur during a tectonic episode or could occur as the result of glacial loading of an overlying geological medium of low porosity and permeability. This loading could result in the compression of the stratum in question and the pore water pressure can increase as this loading occurs. Subsequent unloading of the stratum may not be accompanied with a relaxation of the compressed material and the pore water pressure may remain locked-in at levels higher than can be attributed to current lithostatic or hydrostatic stresses. This is a process which occurs over the geological time-scale and so is not a factor which will effect laboratory measurements of flow through clays.

The concept of aquathermal pressurization was introduced by Barker (1972) and describes the increase of pore pressure in an isolated volume of fluid as it moves downwards in the geothermal column. With increasing temperature comes rapid increases in the pore water pressure which would be generated by the thermal expansion of the rock and the water components. In an open hydraulic system, pressures generated by thermal expansion are dissipated by draining of the excess pore water volume. If however, the surrounding or confining geological units are of very low permeability, the drainage of excess pore water volume will be delayed or prevented. Hence, the pore water pressure present in such a material will be much higher than can be accounted for with knowledge of the current and past lithostatic or hydrostatic conditions. As with lateral tectonic compression, this mechanism occurs over geological time and will not influence laboratory testing.

Graf (1982) identifies dehydration of smectites and gypsum as being the most important mechanism for creating excess pore pressures. Dehydration of gypsum will result in a 10% increase in the molar volume of the system and in a closed system will generate considerable pore pressures. The effect of dehydration of smectites (including bentonitic clays) is more difficult to determine. It is uncertain whether smectite-water volume increases or decreases on dehydration, Anderson and Low (1958) and Martin (1962) reached opposite conclusions. Also significant is the role of mineralogical alteration of smectite to mixed-layer and ultimately to illitic clay. It has been predicted that the conversion of interlayered illite:smectite (80:20 overall) would release approximately 15.5 volume % of water (Perry and Hower 1972). The conversion of smectite to illite is a very slow process unless there is a significant supply of potassium ( $K^+$ ) (Hower et al. 1976 and Boles and Franks 1979) and so the excess pore pressure generation may occur over a very long period. If the surrounding medium is capable of dissipating the excess pressure

then the clay unit may not exhibit a significant change in pore pressure. Once again the gradual nature of mineralogical dehydration and diagenesis means that these processes will not affect the measurement of hydraulic conductivity in laboratory experiments.

The densification of clay-based hydraulic barriers involves compression or compaction. During compaction, clay is exposed to stresses which may be higher than will be present in the environment into which the barrier is placed. As a result the clay can in principle have initially higher pore water pressures than the surrounding geological medium. In a high density material of very low hydraulic conductivity, this locked in pore pressure may not be able to dissipate. An inability to dissipate excess pore pressures may be caused by the presence of a critical hydraulic gradient for flow. Until the pressure difference between the points in the medium exceeds this gradient, flow will not occur. Alternatively the pressurized pore fluid may be located in hydraulically occluded pores. This can happen when the clay packets or particles surrounding these pores are so tightly packed that flow of water between the occluded pores and the hydraulically active pores is not possible. Such pores could only become depressurized when the pressure in the hydraulically active porosity exceeds the locked-in pressures. This could cause the clay particles to strain enough to connect the occluded pores to the rest of the soil porosity. The magnitude and likelihood of this effect is unclear, and in any case would be unique since each soil has a unique compaction history and microstructure. This process is one which might occur in laboratory testing but there is no effective way to predict or account for its presence.

Accounting for such mechanisms in hydraulic conductivity modelling is unlikely to be successful, since these processes violate one of the basic assumptions of most models, that the hydraulically active porosity remains constant.

#### **3.5.4 Influence of Bacterial Activity on Water Movement**

The presence of bacteria in natural soil materials is an unavoidable situation. The role of these organisms in the movement of water or other permeants in soils is both complex and controversial. Quigley et al. (1987) observed a pore-size reduction near the interface of a bentonitic liner and domestic landfill, as well as elevated bacterial activity at this interface relative to that observed in the liner itself. Bacteria require void spaces sufficiently large to permit their growth, water, a food supply, suitable pH, oxygen (aerobic bacteria), or lack of oxygen (anaerobic bacteria), suitable temperature and other less clearly defined conditions. Under a given set of environmental conditions there is almost always one or more species of bacteria which are able to survive if not thrive, it is therefore important to establish the impact of biological activity on the movement of water and contaminants through clays.

Different bacteria have the ability to preferentially sorb a large variety of elements or compounds and can move these materials considerable distances if there is a pathway available for the organism to move. Bacterial activity can also have a positive role in limiting contaminant migration by retarding the movement of contaminants through a soil. As a result of their relatively large size ( $0.2\mu\text{m}$  to  $10\mu\text{m}$ , ( $1\mu\text{m} = 1000\text{nm}$ )), these organisms tend to grow along interfaces (for example of cracks and fissures), where there is sufficient space for them to grow and thrive. This can result in the formation of bio-films that can coat the interface surface and plug the larger passages through which contaminants can

travel, thereby reducing the rate of contaminant dispersion. Contaminant sorption by micro-organisms also results in an increase in the effective size of the contaminant, since not only the contaminant but the entire organism must move for transport to occur. If the dimensions of the available pore passages are smaller than the contaminant-containing organism, then the movement of the contaminant through the soil will be greatly retarded or perhaps even prevented.

The clays and clay-sand mixtures examined in this project are all relatively dense to very dense. Table 3.4 shows the relationship between average clay platelet spacing, density and the approximate size of soil bacteria. Since the size of healthy and stressed bacteria are often significantly different, and the range of sizes possible for such organisms is considerable, only an estimate of the size range can be made. The bacteria observed in the clay systems tested as part of this thesis ranged from  $0.1\mu\text{m}$  to  $10\mu\text{m}$  in smallest dimension (100nm to 10,000nm). A more detailed presentation of actual counts and types of bacteria observed in clay specimens are presented in Section 4.3.2. The comparison of pore size to organism size presented in Table 3.4 assumes the presence of uniform pore-sizes, an unlikely condition, but it does provide an approximate measure of the sizes involved and the likelihood of bacterial movement occurring.

Table 3.4 Clay-Density, Pore-Size and Biological Organism Size Comparisons

| Clay Density<br>( $\gamma_d$ )<br>( $\text{Mg/m}^3$ ) | Porosity<br>(n) | d-Spacing<br>(nm) | Total Distance<br>Size (diameter)<br>(nm) | Organism<br>Diameter<br>(nm) |
|-------------------------------------------------------|-----------------|-------------------|-------------------------------------------|------------------------------|
| 0.5                                                   | 0.824           | 2.20              | 4.40                                      | >1000                        |
| 0.75                                                  | 0.736           | 1.31              | 2.62                                      | >1000                        |
| 1.00                                                  | 0.648           | 0.86              | 1.72                                      | >1000                        |
| 1.25                                                  | 0.560           | 0.60              | 1.20                                      | >1000                        |
| 1.50                                                  | 0.472           | 0.42              | 0.84                                      | >1000                        |
| 1.75                                                  | 0.384           | 0.22              | 0.44                                      | >1000                        |

It is clear from Table 3.4 that there is little chance of an active biological organism being able to passively move through the pore spaces available in a system having an effective clay dry density exceeding  $0.5 \text{ Mg/m}^3$ . It is still possible that these organisms could grow along the interfaces between the specimens and their confinement or to displace particles to cause openings greater than were initially present. In both cases they could generate a bio-film which would further limit or prevent pore fluid movement through the clay. A biofilm would be expected to take some time to develop and would vary with the health of the general biological population. A biofilm might then be detected by a time dependent change in the flux passing through the specimen under a given gradient. The pore size distribution in a clay or clay-sand mixture will have considerable influence on the ultimate ability of the soil to conduct water. The pore-size distribution of clay and clay sand mixtures, and the possible influences on biological movement and water movement are presented in Chapter 4. Section 7.5 discusses the likely influence of bacterial activity on the results of this thesis.

### 3.5.5 Composite Relationship For Calculating Water Flow

Based on the influence of osmotic and pressure gradients in clays, the movement of water through a specimen can be represented by an equation that sums the active influences on mass transport (Mitchell 1991). As the key parameters likely to affect flow through dense clay soils are hydraulic head, chemical osmosis and diffusion, the flow of water through fine-grained soils can be expressed as Equation 3.27.

$$\text{Flow Rate, } q = (k_h(i_{os} + i_h))A \quad (3.27)$$

where  $k_h$  is the darcian hydraulic conductivity,  $i_{os}$  is osmotic/chemical gradient,  $i_h$  is the pressure induced gradient, and  $A$  is the cross-sectional area of the specimen.

In order to study the structure of water associated with clay particles and establish how this affects through-flow, it is important to keep the  $i_{os}$  parameter low or at least constant throughout the testing process. To accomplish this, it is important to limit the volume of fluid percolated through the specimen. Small flow volumes will minimize changes in pore fluid and reservoir chemistry and so the osmotic/chemical gradients across the specimens should be almost constant.

If non-hydraulic gradients across a soil are acting in the same direction as the hydraulic gradient ( $i_H + i_{os} > i_H$ ), the  $F$  vs  $i$  relationship predicted using the Darcian flow model should underpredict the measured flux. This would plot as a line with a gradually increasing slope which would cut the  $y$ -axis at some positive value (Figure 3.7). As the applied hydraulic gradient becomes large relative to the non-hydraulic gradient, the flux-gradient plot should approach the straight-line relationship expected of a Newtonian fluid (Figure 3.7). If the non-hydraulic gradient(s) act against the hydraulic gradient, ( $i_H + i_{os} < i_H$ ), a gradually increasing  $f$  vs  $i$  slope will be observed as  $i$  increases. This line would cut the  $x$ -axis (Flux-axis), at some positive value when the applied hydraulic gradient is zero. Ultimately as non-hydraulic forces become second-order influences, a straight line relationship which approaches that of the Darcian flow model should be observed (Figure 3.7).

These flux-applied hydraulic gradient relationships are based on a number of identical assumptions regarding the soil. Principal of these assumptions is that the porosity available for flow must be a constant. This does not allow for unconnected porosity changes or changes in the quantity of water available for flow with changing applied hydraulic gradient. As a result, most models used to predict fluid flow are inherently prone to inaccurately predict the flow through soils where changes in fluid structure, flow path or

porosity available for flow occur. The ability of these models to predict flow through a number of different soils is tested in Section 7.1 of this thesis.

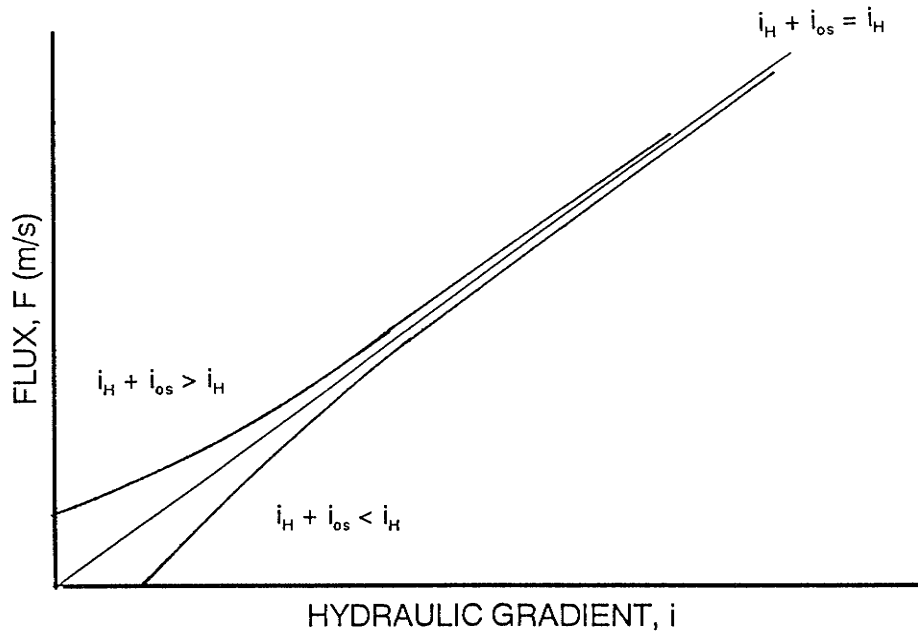


Figure 3.7 Influences on the Shape of Flux-Gradient Relationship

### 3.6 Water Flow in Soils: A Summary of Current Views

#### 3.6.1 Plotting of Flux - Hydraulic Gradient Data

The ultimate test of the validity of the Darcy or any other model for fluid movement is the ability of the model to predict the hydraulic gradient versus the flux relationship for a specimen. Two widely used plotting methods to evaluate deviations from the Darcian flow model are;

- 1) Flux or flow velocity versus hydraulic gradient.
- 2) Log flux versus log hydraulic gradient



A plot of measured flux (or flow velocity) versus hydraulic gradient such as was presented by Yong and Warkentin (1975) should provide a measure of any threshold or critical gradients. Changes in hydraulic conductivity are detected as changes in the slope of these plots (Figure 3.8). While significant changes in the slope of this line are readily detectable, it is possible that slight changes in the flux-gradient relationships may not be readily detected, particularly if a wide range of gradients or fluxes are recorded.

Concave or convex flux-gradient relationships in a normal linear plot have been reported repeatedly in the literature. The reasons suggested for these deviations have been discussed previously. They range from soil fabric effects (Section 3.4), the presence of osmotic forces (Section 3.5.2), equipment limitations (Section 6.1.3), to real changes in the structure and behaviour of water in clay-water systems (Sections 2.2 and 2.3).

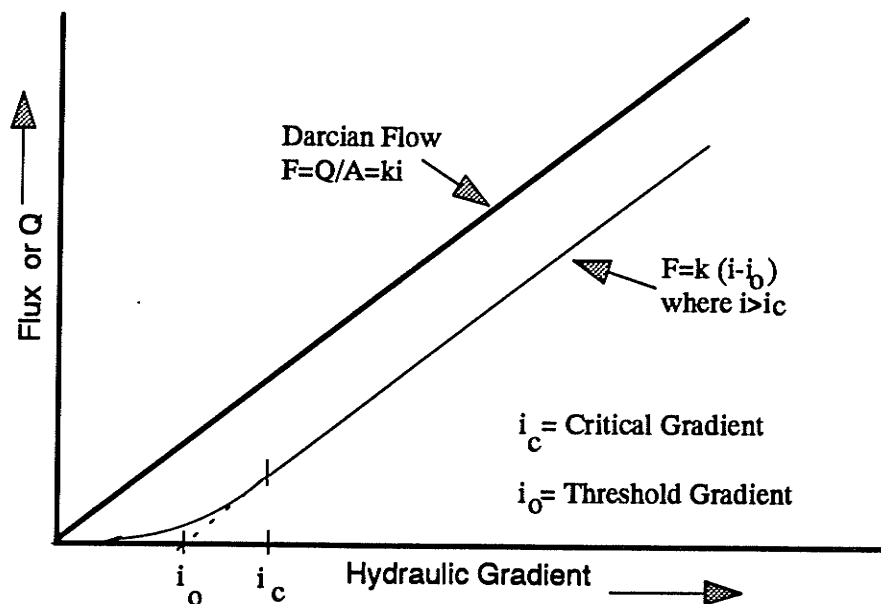


Figure 3.8 Flux-Hydraulic Gradient Relationships Typically Reported (after Yong and Warkentin 1975)

The shapes of potential deviations in the shape of the flux-gradient plot are presented in Figures 3.7 and 3.8. Figure 3.8 simply represents two of the special case rheological models shown in Figure 3.3. The classical Darcy model for Newtonian water flow through a porous medium calls for a straight-line relationship passing through the origin of the graph. Observed deviations from this behaviour have been the cause for much of the past century's debate over the applicability of the Darcy relationship.

If the flux-hydraulic gradient plot is a straight line intersecting the gradient axis in a location other than the origin, this intersect is defined as the threshold gradient ( $i_0$ ) required to initiate flow. The hydraulic gradient at which darcian flow behaviour begins in a flux-gradient relationship which is not a straight-line plot at low gradients, is defined as the Critical Gradient ( $i_c$ ) for flow.

The second technique for presenting flow data is to plot the hydraulic flux versus hydraulic gradient in log-log space. Plotting of the flux-gradient relationship in log-log space has been done by Sri Ranjan and Karthigesu (1992), Sri Ranjan and Gillham (1991), Dixon et al. (1993a) and Karthigesu (1994). This technique presents data in a manner which facilitates the identification of changes in the flux-gradient relationship. A plot of the measured flux versus applied hydraulic gradient should plot as a straight line which has a slope of 1.0. (Figure 3.9). Any change in hydraulic conductivity will result in a vertical shift in the location of this line. This technique provides the clearest display for examining hydraulic conductivity over a wide range of gradients and emphasizes the location of any critical gradients for changes in flow behaviour. However, a log-scale plot does not provide a visual means for detecting the threshold gradients defined by conventional means (zero flux occurs at a gradient equal to zero). These plots are based on the assumption of the

validity of the darcian flow model. A shift in the location of the line is interpreted as a change in the pore space available for flow. If such a shift occurs and provided that no further changes in the pore volume available for flow occurs, then the new flux-gradient relationship will again be a straight line with a slope of 1.0 which is offset from the initial line. The hydraulic conductivity  $k$ , of a plot such as that shown in Figure 3.9 is calculated by either extending the plotted lines backwards (or forward) to the point at which it cuts the hydraulic gradient of 1.0. The flux at this gradient is defined as the hydraulic conductivity. Alternatively, any value of the flux located along the regions showing Darcian flow behaviour can be divided by the hydraulic gradient applied to obtain this measured flux.

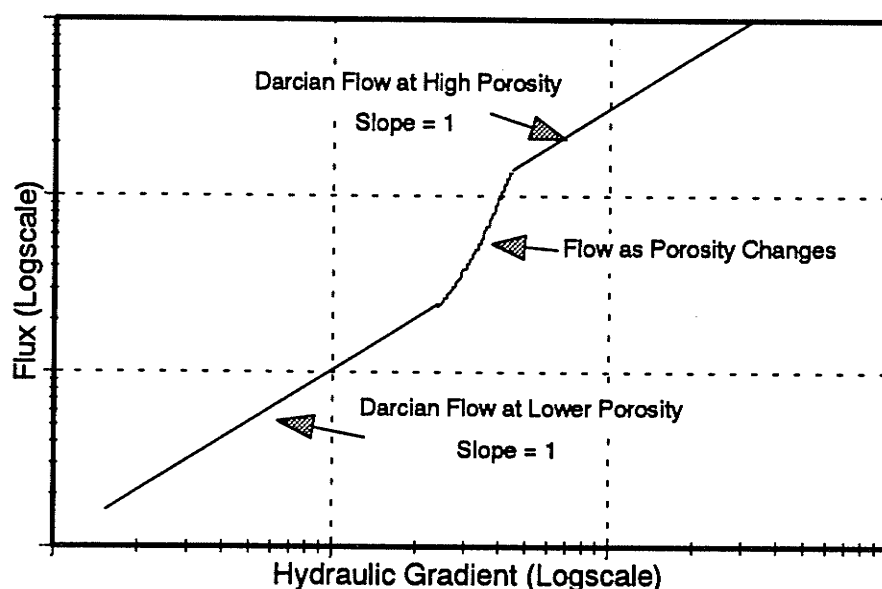


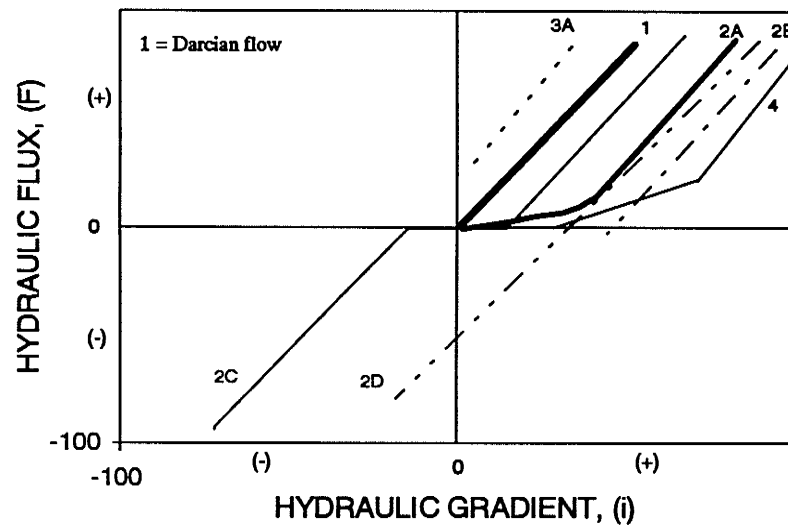
Figure 3.9 Plot of Log-Flux versus Log Hydraulic Gradient

In order to generate a good estimate of the potential changes in the hydraulic conductivity of a soil specimen both of these plots should be used. The linear plot provides a visual

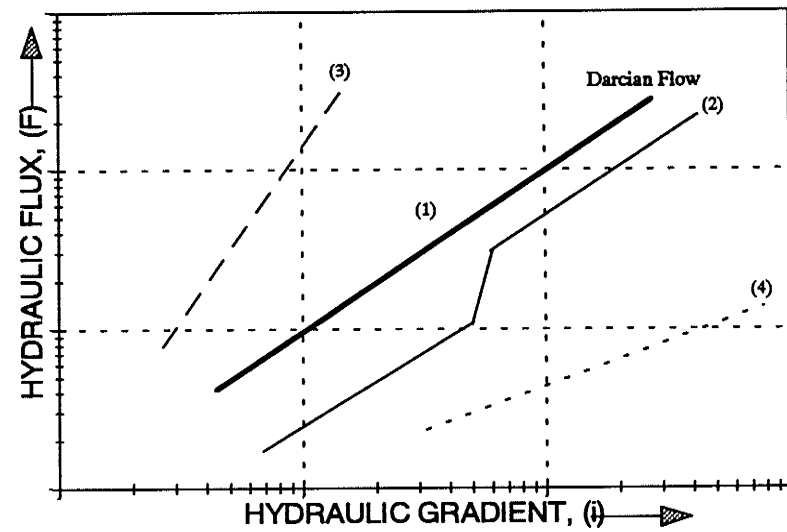
record of the presence of threshold and or critical gradient(s). The log-log plot provides a sensitive means to detect subtle changes in the pore space available for flow.

### **3.6.2 Classification of Flow Behaviour Observed in Soils**

The possible variations in the shape of a plot of flux-hydraulic gradient plots are numerous and have been discussed in Section 3.6.1. When dealing with a large number of tests it is easier if the shape of the plots can be classified as to type for easy data tabulation and subsequent comparison. The data collected as part of this thesis represents some 50+ tests and so a classification procedure has been developed for use in presenting the results. As discussed in Section 3.6.2, there are two means of presenting the flux-hydraulic gradient data, log-scale or linear-scale. As a result of the two plotting techniques there are two sets of flow-type classifications which have been defined, one for linear and one for log plots. Figure 3.10 presents the flow-type classifications defined. These definitions are used in Chapter 7 to classify the flow behaviour observed in sand, illite and bentonite materials.



(a) Linear-Scale Plot



(b) Log-Scale Plot

Figure 3.10 Flow-Type Classifications For Water Movement Through Soils

### **3.6.3 Review of Opinions on Darcy's Law**

The behaviour of water at low gradients ( $<100$ ) is of most practical importance in civil and geotechnical engineering because it is in this range of gradient that most natural systems operate. Many researchers have investigated the movement of water through compacted, fine-grained soil materials in efforts to determine the validity of the Darcian flow model. These investigators have obtained a wide range of results, ranging from complete agreement with the Darcy flow model through to the types of deviations in flow behaviour outlined in the preceding sections. There is no clear precedent for deciding in advance how the sand-bentonite mixtures or highly compacted bentonites proposed for use in the Canadian Nuclear Fuel Waste Management Program will behave. This forms the justification for this research program.

Table 3.5 illustrates the wide range of views on the subject of Darcy's law and the meaning of deviations from its predictions. The remainder of this thesis presents the results of studies to examine the validity of these suppositions and to determine the controlling influences on the behaviour of compacted bentonite clay materials. Chapter 4 describes the mineralogical, chemical and physical properties of the clays examined in this study. Chapter 5 describes the results of a thermal expansion study, intended to qualitatively determine the structure of water near the surface of clay particles. The data presented in Chapters 4 and 5, along with the review of literature presented in Chapters 2 and 3 provide a foundation for the detailed investigation of the hydraulic behaviour of soil materials presented in Chapters 6 and 7.

Table 3.5      Darcy's Law: Results of Experimental Studies On Very Fine Grained and High Activity Clays

RESEARCH FINDINGS AND OPINIONS OF RESEARCHERS

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1) Darcy's Flow Equation is Valid For Most Soils

Olsen (1960, 1965), Chan & Kenney (1973, 1974), Smiles (1978), Mitchell (1976), Tavenas et al. (1983), Peterson & Kelkar (1983), Matyas (1967)

2) Non-Darcy Flow is the Result of Equipment Limitations

Olsen (1960, 1965)

3) Non-Darcy Flow is the Result of Bacterial Action

Gupta & Swartzendruber (1962)

4) Non-Darcy Flow is the Result of Osmosis, Reverse Chemical Osmosis and Counter-Gradients

Kemper (1960), Olsen (1969, 1985), Kemper and Rollins (1966), Graf (1982), Barbour and Fredlund (1989)

5) Non-Darcy Flow is the Result of Complex Coupled Processes

Kemper (1960), Bolt & Groenevelt (1969), Kemper and Rollins (1966), Olsen (1985), Groenevelt & Bolt (1969a,b)

6) Non-Darcy Flow is the Result of Water Structuring and Chemical Influences

Low (1960, 1961), Swartzendruber (1962a,b, 1968), von Englehardt & Tunn (1955), Henniker (1952), Sri Ranjan and Karthigesu (1992), Karthigesu (1994)

7) Non-Darcy Flow is the Result of Experimentally-Induced Changes in Soil Structure, either chemical or physical in nature.

Terzaghi (1925), Lutz & Kemper (1959), Martin (1962), Mitchell (1976), Miller & Low (1963), Hansbo (1960, 1973), Mitchell and Younger (1967), Garion & Swartzendruber (1975), Pane et al. (1982)

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## **4.0 MATERIAL CHARACTERIZATION: PHYSICAL AND CHEMICAL PROPERTIES**

### **4.1 Experimental Program**

The materials examined in this thesis have a wide range of physical and chemical properties. In order to establish what type of materials were being studied, a comprehensive series of characterization tests were conducted. Knowledge of the physical, mechanical and chemical properties is essential for developing an understanding of the behaviour of water as it percolates through soil materials. These data, together with the mineralogical analyses presented in Section 2.2, provide a basis for material comparison and ensure there is no uncertainty regarding the specific clays examined.

The materials selected for examination are; (1) rounded silica sands with a narrow range of particle size, (2) crushed illitic shale, and (3, 4) two commercially available sodium bentonite clays. Details of the particle size distributions of these materials are provided in Table 4.1. These materials are expected to exhibit a wide range of mineralogical, physical, mechanical and chemical properties. The fact that these three materials are very different mineralogically was established in Section 2.2 and so their examination provides opportunities to examine the effect of mineralogy on hydraulic behaviour. This chapter presents the results of tests to determine the physical characteristics (Section 4.2.1), mechanical properties (Section 4.2.2), pore structure (Section 4.2.3) and the chemical properties (Section 4.3.1) of the clays. As each of these materials contain at least some water soluble materials and this has a potential to influence their hydraulic behaviour, the nature of this component is examined in Section 4.3.



## 4.2 Physical and Mechanical Characteristics

### 4.2.1 Physical Properties

Characterization tests were conducted to determine potential influences on the hydraulic characteristics of the soils examined in the testing program.

Table 4.1 presents some of the basic physical properties of the materials examined. Material characterization involved the following physical tests; particle size analysis, consistency limits determination (liquid limit and plasticity index), and free swell capacity. Much of this information has already been published in reports and papers (Gray et al. 1984, 1985; Dixon and Gray 1985; Dixon and Woodcock 1986; Dixon et al. 1984, 1985, 1992a,b, 1993a,b; and Dixon and Miller 1995). A summary of the results is presented in Table 4.1.

Table 4.1 Physical Properties of Soil Materials Investigated

| Material                                | Sand/Silt/Clay<br>Content<br>ASTM (1992)<br>Technique<br><br>(% Mass) | Sand/Silt/Clay<br>Content<br>Laser Sizing<br>Technique<br><br>(% Mass) | Liquid<br>Limit<br><br>(%) | Plasticity<br>Index | Moisture<br>Content<br>For<br>Maximum<br>Compacted<br>Density<br>(%) | Free<br>Swell<br>Volume<br>*<br><br>(cm <sup>3</sup> /g) |
|-----------------------------------------|-----------------------------------------------------------------------|------------------------------------------------------------------------|----------------------------|---------------------|----------------------------------------------------------------------|----------------------------------------------------------|
| Silica Sand                             | >92/<8/0                                                              | NC                                                                     | NP                         | NP                  | NC                                                                   | <1                                                       |
| Illite                                  | 18/50/32                                                              | 2/81/17                                                                | 31                         | 11                  | 14                                                                   | <1                                                       |
| Na-bentonite<br>Saskatchewan<br>Wyoming | <3/20/>77                                                             | <1/80/20<br><1/84/16                                                   | 257<br>537                 | 208<br>496          | 10                                                                   | >9<br>13                                                 |
| Sand/Bentonite<br>50/50 Mixture         | 52/9/39                                                               | 50/40/10                                                               | 120                        | 100                 | 10                                                                   | 5                                                        |

Note: NP Non-plastic, test is not appropriate for this material  
 NC Not Conducted, test is not appropriate for this material  
 \* Volume occupied by 1 gram of dry soil when allowed to swell to its full potential in 50 cm<sup>3</sup> of a 0.15 Molar solution of NaCl (Dixon et al. 1992a)

The consistency limits (Liquid Limit and Plasticity Index) of the materials examined show that they range from a non-plastic sand, to a low plasticity Illite and finally to high and very high plasticity Saskatchewan and Wyoming bentonites respectively. The particle size gradations of these materials also represent a wide range of sizes, from the pure sand specimens through to the clayey-silt illite and the silty clay bentonite materials. The sand and coarse silt sized materials were dry sieved or wet sieved, as was appropriate, based on the specifications of ASTM standards (ASTM 1992). The finer silt and clay size materials were analyzed using both the hydrometer test for chemically dispersed, fine-grained soils (ASTM 1992) and using a laser light technique to determine the particle size distribution in clay materials (Dixon and Miller 1995). The results for the particle size analyses conducted using the ASTM technique are presented in Figure 4.1. The results for the particle size analyses conducted using the Laser Light technique are presented in Figure 4.2

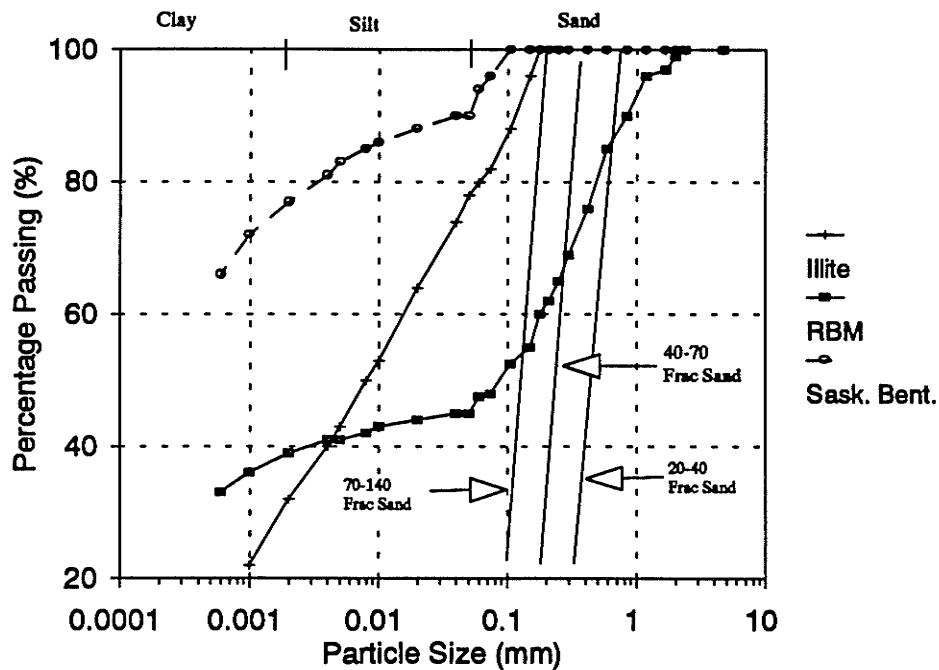


Figure 4.1 Particle Size Distribution Obtained Using ASTM Techniques

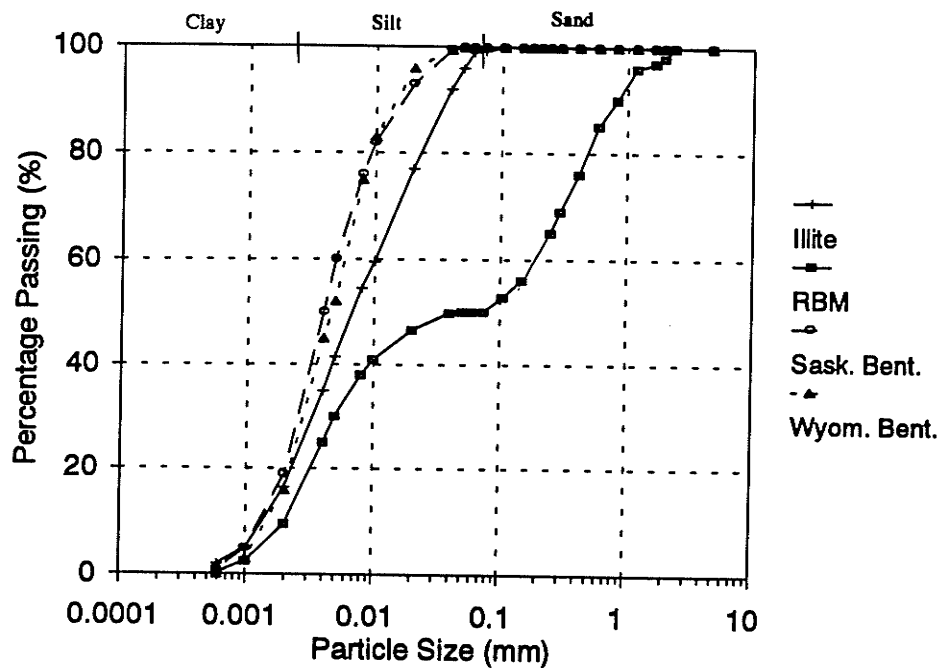


Figure 4.2 Particle Size Distribution Obtained Using Laser Light Technique

The laser light particle sizing was conducted using clay specimens suspended in a solution of sodium hexametaphosphate for 24 hours prior to testing. This particle sizing device takes a small sample of the dispersed clay and further suspends the clay in a large volume of water (approximately 0.1g in 0.25L). The resultant solution is ultrasonically dispersed and a laser light is passed through the resultant solution. The diffraction of the beam passing through the suspension is used to calculate the diameter of the particles in solution. As with the traditional hydrometer test for fine-grained materials (ASTM 1992), this technique assumes that the particles are spherical rather than platy. Advantages of the laser technique for analyzing bentonites are numerous and include,

- speed, test duration is 5 minutes versus several weeks using a hydrometer
- the effects of thixotropic gel formation in the particles is avoided
- a negligible temperature effect on fluid viscosity and density due to short test time
- since the test is automated many of the potential sources of reading inaccuracy are eliminated.

As can be seen in Table 4.1 and Figures 4.1 and 4.2, the hydrometer results can be significantly different than those obtained using the laser technique. The differences are less significant for non-swelling clays such as the illitic clay than for bentonite materials. Laser particle sizing shows that the two bentonite materials examined in this program have similar particle size distributions, with approximately 80% of the material being silt-sized ( $2\mu\text{m}$  to  $76\mu\text{m}$ ) and the remainder being clay-sized ( $<2\mu\text{m}$ ). Very little sand-sized ( $>76\mu\text{m}$ ) material was found in the bentonite samples.

A much higher proportion of coarse material (silt) was recorded for bentonite specimens tested using the laser technique. The differences in the results are attributed to the development of large hydrated clay flocs in the settlement columns used for hydrometer tests. These large, lower density flocs settle at slower rate than is predicted using the assumptions of spherical mineral particles. As a result of the larger, slower settling flocs, the results of particle-size analysis interprets this material to be fine-grained and a high clay content is calculated. The laser technique with its ultrasonic bath prevent the formation of such large flocs. Hence, the sizes determined by the laser system are probably more representative of the actual particle sizes present.

In most situations, clays will not consist of the dispersed and fully hydrated particles analyzed using the hydrometer and other types of particle size test. Commercially purchased clays are normally composed of small aggregates (micro-peds), which are actually composed of a number of individual clay platelets. These micro peds were created by the drying and mechanical crushing of the clay shales which are the parent materials for commercial clays. Clay shales were formed in marine environments and so these parent materials are typically highly anisotropic. The crushing process will reduce

the average particle size considerably but not to the point of completely disaggregating the clay. Mixing of commercially purchased clays with other soil materials or with a sand and then compacting these materials will not alter the basic anisotropy of the individual particles. The clay micropeds will continue to exist within the soil matrix and so the compacted soil will be composed of a compacted mass of anisotropic particles. This type of structuring was described by Gray et al. (1985) and results in an overall isotropic behaviour for the soil but on the microscopic level the soil would remain composed of anisotropic micropeds (static compaction in a rigid mould may produce anisotropic stress-strain behaviour, Graham et al. 1989). Such anisotropic soil substructure will likely have an impact on the conduction of water. As has previously been discussed in Section 3.4, water may be channelled through the limited number of macro pores formed between the micro peds.

Measurement of the free swell potential of clays may provide an indication of the potential for the clay particles and micropeds to hydrate and fill pore spaces of a soil. Since bentonite clay particles are best able to hydrate and disaggregate, the volume ultimately occupied by a swelling clay may provide an indication of both the bentonite content and purity of the clay. Soils containing mixed layer clays such as montmorillonite-illite, montmorillonite-chlorite or other combinations of clay units should have a lower free swell capacity than a pure montmorillonitic clay which is fully dispersed and hydrated.

As was expected for non-hydrating minerals, the sand and illitic clay materials showed no measurable volumetric swelling capacity, (Table 4.1). The two bentonite materials examined both showed a high free swell capacity. The lower free swell volume of the Saskatchewan bentonite might be attributed to the presence of more non-clay components

and the presence of mixed layer clays in the Saskatchewan material (Chapter 2.2). This explanation for variations in free-swell capacity was studied in considerable detail by Resche (1991) and, Dixon and Miller (1995) and found to be inadequate to explain the differences between the behaviour of very similar bentonite materials. Dixon and Miller (1995) examined the mineralogical composition, physical properties of, free swell capacity, hydraulic conductivity and swelling pressure developed by 16 different bentonite clay specimens. These materials were collected from bentonite producers from Canada the USA and Japan. It was found that the free-swell capacity of bentonite clays cannot be predicted based on apparent mineral purity, or any other index property.

#### **4.2.2 Mechanical Properties**

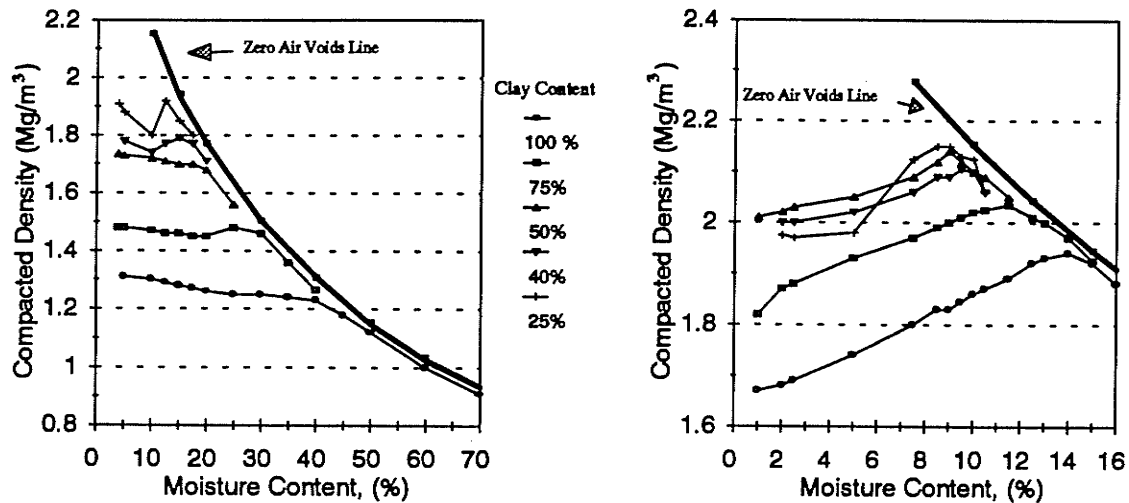
The compaction curves presented in Figure 4.3 can provide useful information on the mechanical behaviour and sensitivity of clays and sand-clay mixtures to changes in the moisture content and type. Gray et al. (1985), Dixon and Gray (1985) examined the compaction properties of most of the materials examined in this thesis.

In these papers it was found that:

- 1) mixing sand with clay will increase the density attainable by compaction (Figure 4.3),
- 2) water type has little influence on the compaction density attainable for bentonite clay-sand mixtures,
- 3) bentonite/sand mixtures (clay content >25%) showed little effect of compaction moisture content on the compaction density attainable until nearly saturated. (Figure 4.3).

The compaction behaviour presented in Figure 4.3 for sand-bentonite mixtures containing greater than 50% (by dry mass) of clay is similar to that reported by Gray (1972) and Pusch (1983). Compaction trials were conducted using both Wyoming and Saskatchewan

bentonites and the results obtained were essentially identical. As a result only the set of data obtained using the Saskatchewan bentonite is presented in Figure 4.3.



(A) Bentonite and Bentonite-Sand Mixtures

(B) Illite and Illite-Sand Mixtures

Figure 4.3 Compaction-Moisture Content Relationships For Clays and Clay-Sand Mixtures (from Dixon et al. 1985)

The dry density-water content relationship observed in Figure 4.3 is attributed to clay-water interaction. The water associated with the clay particle surfaces is assumed to be strongly bonded to the particles and hence have a higher viscosity than free water. The compaction curve is interpreted as showing that the compaction energy applied to systems containing more than 50% clay was insufficient to overcome the shearing resistance of the bonded water. Once sand content exceeded approximately 50 % the compaction curves obtained for sand-bentonite mixtures indicate that the applied energy was sufficient to overcome the shearing resistance. There may also be a more efficient distribution of

compaction energy at higher sand content (Dixon et al. 1985). Compaction curves for illitic clay and sand- illitic clay mixtures showed none of the evidence of a higher viscosity water phase observed for the bentonitic materials. This has been interpreted as meaning that there is little or no change in the structure of water (Chapter 3), in illitic clay-water systems and that the applied energy is sufficient to overcome any shearing resistance of the water component.

#### **4.2.3 Measured Pore Size Distribution In Compacted Specimens.**

Central to the study of the movement of fluids, contaminants or biological organisms is an understanding of the porosity of the soil. Sections 3.2 through 3.5 have already discussed the roles of surface charge, structured water and mechanical compaction on the pore space available for flow. Recently, Choi and Oscarson (1994) have measured the pore size distribution in compacted bentonite, while Wan (1994) has measured the same parameters for a sand-bentonite (50/50 sand/bentonite (RBM)) mixture. These data provide valuable information on the nature of the porosity available for the movement of water, contaminants and perhaps bacteria. The size of the pores available for flow in compacted clays may have a very significant impact on the ability of these materials to act as semi-permeable membranes and thereby limit contaminant migration, and maintain pore pressure differences within and across the soil.

Choi and Oscarson (1994) investigated sodium saturated and calcium saturated Saskatchewan bentonite. These clays were produced by replacing all the exchangeable cations present with either sodium to generate a sodium bentonite, or calcium to obtain a calcium bentonite. These materials were compacted to a dry density of  $1.3 \text{ Mg/m}^3$ . These clay specimens were saturated with either a solution of 0.1 Molar NaCl or 0.05



Molar  $\text{CaCl}_2$  to produce clays containing only one type of exchangeable cation. These specimens were then gradually dried (to minimize disruption of pore structure during drying), using a series of chambers. Each successive desiccation chamber had a lower relative humidity. Following the drying these specimens were examined by mercury (Hg) intrusion porosimetry to a maximum pressure of 414 MPa. At this pressure the Hg should be able to enter pores with a diameter as small as  $0.0036\mu\text{m}$  (3.6nm). The results obtained indicate that 20% to 25% of the porosity of these materials were smaller than  $0.0036\mu\text{m}$  (the amount smaller is unknown). This portion of the porosity was present as smaller pores, occluded pores and otherwise immobile water.

In addition to the limited porosity available for Hg displacement, the porosimetry tests established that the pore sizes present in the sodium bentonite, calcium bentonite, RBM and illite were limited to a few narrow size ranges. Sodium bentonite compacted to a dry clay density of  $1.3 \text{ Mg/m}^3$  contained pores in the  $0.0036\mu\text{m}$  to  $0.036\mu\text{m}$  (average  $0.01\mu\text{m}$  (10nm)) range and little of any larger size (Choi and Oscarson 1994). Calcium bentonite showed a bimodal pore size distribution with pores in the  $0.0036\mu\text{m}$  to  $0.036\mu\text{m}$  (average  $0.01\mu\text{m}$ ) range as well as at  $0.100\mu\text{m}$  (Choi and Oscarson 1994). Choi and Oscarson (1994) attributed the bimodal distribution observed in the Ca-bentonite to the presence of two pore types, interparticle pores (formed between micropeds when the clay is compacted) and smaller intraparticle pores (within exterior outlines of individual particles). The RBM tested by Wan (1994), exhibited a trimodal size distribution with pores in the same range as was observed for the Ca-bentonite as well as at the size range of  $5\mu\text{m}$  to  $50\mu\text{m}$ . (Two sets of specimens were tested, compacted to (1)  $1.41 \text{ Mg/m}^3$ ; and (2)  $1.68 \text{ Mg/m}^3$ , both were compacted at 17.6% gravimetric moisture content. The illitic specimens were compacted to  $1.84 \text{ Mg/m}^3$  and  $2.03 \text{ Mg/m}^3$  and had the majority of their pores in the

.02 $\mu\text{m}$  to 1.0 $\mu\text{m}$  range. The data presented in Figure 4.4 show examples of the type of porosity distributions observed for all four materials studied.

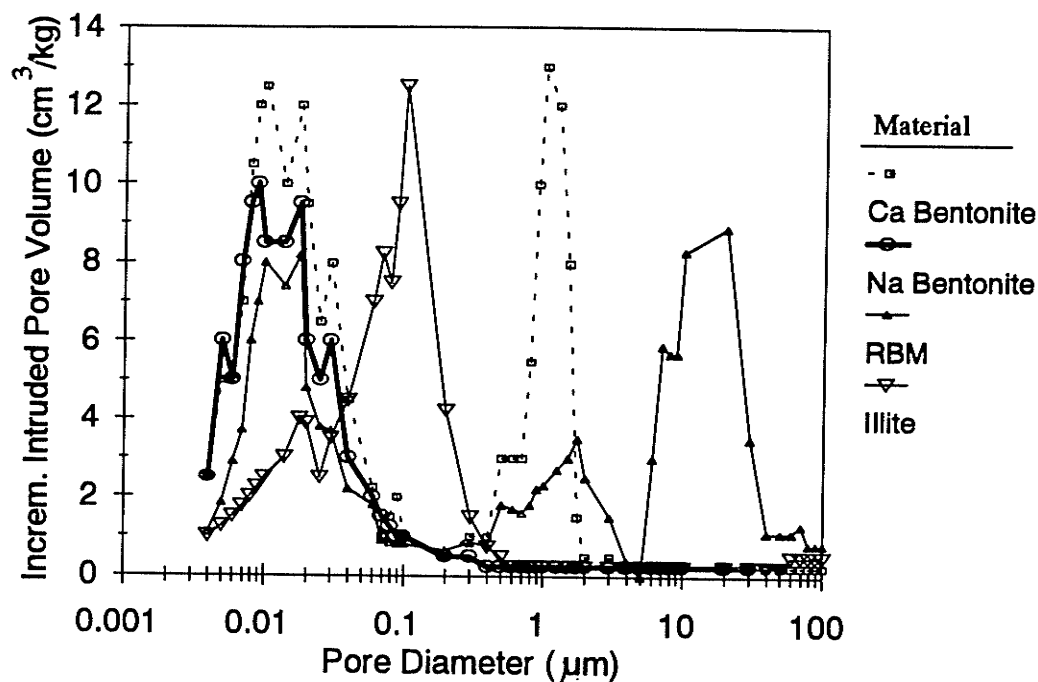


Figure 4.4 Pore Size Distribution Present in Na-, Ca- bentonites and the RBM (After Choi and Oscarson 1994; Wan 1994)

Four further porosimetry analyses were conducted on sodium bentonite specimens tested as part of the hydraulic conductivity studies described in Chapters 6 through 8. These specimens had dry clay densities of 0.59  $\text{Mg}/\text{m}^3$ , 0.76  $\text{Mg}/\text{m}^3$ , and 1.18  $\text{Mg}/\text{m}^3$ . The two specimens with density 1.18  $\text{Mg}/\text{m}^3$  exhibited similar pore size distribution to the higher density sodium bentonite specimens described above. The two lower density specimens exhibited a different type of pore structure. Consistent with the higher density specimens a major portion of the pores ranged from 0.003 $\mu\text{m}$ -0.04 $\mu\text{m}$  however, a second pore size was also observed in these specimens at 50 $\mu\text{m}$ -150 $\mu\text{m}$ . If this large pore mode is real

rather than an artifact of the testing procedure it can have a considerable impact on the hydraulic behaviour of low-density bentonites. The larger pores, if interconnected, can provide a preferential pathway for water transportation, contaminant movement and bacterial migration. The significance of a large-pore component is discussed in Chapter 8 with reference to the hydraulic behaviour of these materials (presented in Chapter 7).

The cause of the largest pore size found in the RBM is uncertain. These large pores may be induced by the compaction process, or by the interaction of the sand and clay particles during the compaction process. Alternatively they may simply be the result of desiccation cracks or small pull-out craters (small pores created as the result of small sand particles being pulled from the specimen surface), created during the preparation of the buffer specimens for porosimetry testing. The later explanation is supported by the findings of Dixon et al. (1993b) who observed that RBM materials initially prepared at significant moisture content can exhibit considerable shrinkage (2% to 8%), and notable cracking during the desiccation process. Additionally, further work by Wan (1994) has found that the presence of this large pore size was present irregardless of initial compaction density and drying technique. The paper by Choi and Oscarson (1994) did not provide any measurement of the drying shrinkage while Wan (1994) reported that shrinkage induced by drying resulted in approximately 6% shrinkage for a specimen initially compacted to  $1.68 \text{ Mg/m}^3$  at a gravimetric moisture content of 17.8%. If however, the larger pore size observed for the RBM is present in saturated materials, it could have a significant effect on the hydraulic behaviour of this material. A large pore mode might provide preferential flow paths for water and contaminants through the barrier. The significance of this large pore mode is discussed in detail in Chapter 8.

The results of porosimetry tests on bentonite clays with dry densities greater than  $1.18 \text{ Mg/m}^3$  indicated that there are some pores of  $0.01 \mu\text{m}$  and a limited number of others which reached  $0.10 \mu\text{m}$  average diameter. These pores are large enough to contain unstructured water but should be much too small for an active bacterium to occupy (minimum bacterium size is approximately  $0.1 \mu\text{m}$ , Section 3.5.4). The data from the RBM and low density bentonites are somewhat less conclusive regarding the potential to contain bacteria. If the larger pore size of the RBM ( $5 \mu\text{m}$  to  $150 \mu\text{m}$ ) observed by Wan (1994) is actually present and interconnected in a hydrated buffer, it might be possible for some biological intrusion to occur in the buffer. Such an intrusion could be in the form of bacterial movement through the specimen, or biofilms could form on the outer surfaces of the specimen. Biofilm formation could result in these pores becoming unusable for water movement and retard the movement of contaminants (Stroes-Gascoyne and West 1994). If biofilm generation in the specimens tested in this thesis were a significant issue, it should be detectable as a time-dependant reduction in the flux which can pass through the RBM. This reduction would be observed as the bacterial materials gradually filled and plugged the macropores.

As bacterial growth has the potential to affect water flow through clays, time dependent changes in the flux observed under constant gradient conditions were examined. Typical results obtained in these flux-time tests are presented in Figure 4.5 and they show that there were no consistent time-dependant changes in the hydraulic conductivity through either the clay or RBM specimens despite testing times as high as 10500 hrs (438 days). A detailed examination of the flux-hydraulic gradient performance of all these materials is presented in Chapter 7. The lack of systematic change in the hydraulic conductivity of these specimens means that despite the presence of significant biological activity in the

pore fluid above and below the specimen there was no significant reduction in the ability of fluid to move through compacted clays. The question of bacterial content and activity is examined later in Section 4.3.

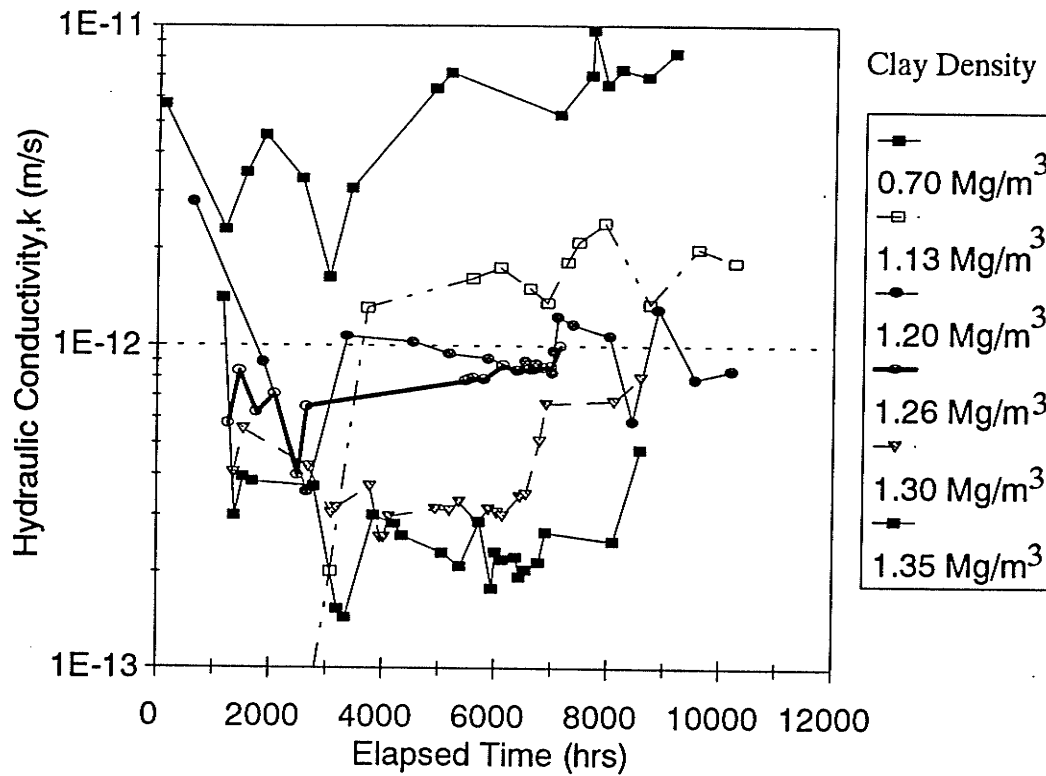


Figure 4.5 Change in Hydraulic Conductivity with Time in Compacted Clays

#### 4.2.4 Properties Associated With Surface Chemistry

The surface chemistry of clays is difficult to establish, partially because of the very small particles involved and partially due to the complexity of the systems involved. Clay materials are typically composed of plate-like particles which may be singular or may be present as particle aggregations which may or may not be hydrated. The crystal structure of clay minerals is variable, with differing surface charge intensity potentially existing at different locations along the surface of each clay platelet (resulting from isomorphous

lattice substitutions or empty lattice sites (Section 2.1)). The surface properties of clay minerals are usually related to a measured physical surface area per unit mass of dry clay ( $\text{m}^2/\text{g}$ ) or, the ability of the clay to sorb and release cations (Cation Exchange Capacity (CEC)), expressed as  $\text{meq}/100\text{g}$  of dry soil. Table 4.2 presents a summary of the material characteristics which are closely associated with the surface chemistry of the minerals.

Table 4.2 Surface Chemistry Properties of Soil Materials Investigated

| Property                                              | Silica Sand          | Illitic Clay         | Sodium Bentonite (Sask.) | Sodium Bentonite (Wyoming) | Sand/Sask Bentonite Mixture |
|-------------------------------------------------------|----------------------|----------------------|--------------------------|----------------------------|-----------------------------|
| Specific Weight                                       | 2.66-2.70<br>(2.65)* | 2.74-2.79<br>(2.75)* | 2.71-2.91<br>(2.84)*     | 2.84*                      | 2.75*                       |
| Specific Surface ( $\text{m}^2/\text{g}$ )            | <1                   | 43-81                | 519-631                  | 750                        | 260-315                     |
| Cation Exchange Capacity ( $\text{meq}/100\text{g}$ ) | <<1                  | 10-15                | 71-82                    | 76                         | 35-45                       |
| Dominant Mineral(s)*                                  | Quartz               | Illite               | Bentonite                | Bentonite                  | Quartz-Bentonite            |

(Data Previously Published in; Dixon and Woodcock 1986; Dixon et. al 1986; and Oscarson and Dixon 1989)

\* For details see below

Specific Weight (G), is a measure of density of the solids portion of a soil (weight of solids/weight of same volume of water). The specific weight of a soil considers only the mineral component and does not include any mass or volume occupied by water or voids. While the measurement of G for minerals which do not have a hydrated component is not difficult, the presence of water layers around or within the minerals makes determination of the mineral specific weight difficult. The specific weight of soil minerals is also affected by the type of minor components present, making it difficult to attain accurate measurements. For most applications an estimate to within 0.05 is adequate, however in high surface area materials such as bentonites this leads to considerable uncertainty

in the actual porosity, and therefore to the difficulty in defining the pore space available for conducting fluids.

The specific weight of bentonitic clay is reported in the literature to vary from approximately 2.4 to 2.9 with the majority of literature reporting the  $G$  calculated from crystal structure as 2.7 (Lambe and Whitman 1979) to 2.8 (van Olphen and Fripiat 1974). Data on the specific weight of illitic clays is less variable with a range of 2.7 to 2.9 reported in the literature. Low values for  $G$  reported in the literature can be attributed to the presence of one or more layers of adsorbed water being included as part of the mineral phase. The presence of adsorbed water layers is the result of testing oven dried clay materials (dried at 110°C as defined by ASTM (1992) standards). These clays are not entirely dry, they still contain measurable quantities of water, in the form of water adsorbed to the mineral surfaces.

Thermal Gravimetric Analyses presented in Section 2.2.3 showed that there was a moisture content of approximately 3 % by dry weight (weight after drying to 700°C) present in both bentonites and illites after drying at 110°C. Illitic clays lost this water beginning at approximately 400°C but the magnitude of the loss was equivalent to that observed for the bentonite clays (Figure 2.9). While dried illitic clay will regain little of the moisture content lost by oven drying, bentonite clay can gain 10%, or more, (by dry weight) of moisture directly from the air.

It is essential that the influence of water structuring in bentonite clays be examined in terms of the absolute moisture content present. If the specific weight of the clay ( $G_s$ ), is adjusted to account for the presence of this structural water, the value will increase from

the 2.75 commonly reported for oven (110°C) dried material to approximately 2.84 for completely dehydrated clay. As the adsorbed water component is important when determining the influence of surface charge on water structure and pore space available for flow, the higher of these  $G_o$  values is more appropriate for use in calculations involving porosity. The values of specific weight selected for use in the calculations for illitic and bentonite clays used in this thesis are 2.75 and 2.84 respectively.

The specific surface ( $S_o$ ), and cation exchange capacity (CEC) of soil materials are also means of predicting the likely behaviour of clays. Cation exchange capacity provides a measure of the ability of a soil to exchange cations in solution with cations held on the surface of the mineral component. The specific surface of a soil is the exposed surface area of the mineral particles per gram of dry soil. As the materials used in this thesis have very little organic material (Oscarson and Cheung 1983) the CEC and  $S_o$  measured are functions of the minerals present.

The CEC and  $S_o$  values measured for the materials examined are indicative of three very different types of soil (Table 4.2). First, the silica sand is a coarse-grained low surface area mineral with little or no CEC, indicative of a very low surface charge. Second, the illitic clay is relatively coarse-grained, but because of its tabular form and degree to which it has been ground it has a measurable CEC and  $S_o$ . Finally, the bentonitic clays represent very fine-grained particles with a high surface charge and hence the high CEC and  $S_o$ . The Saskatchewan and Wyoming bentonites exhibit notably different CEC and  $S_o$  values (Table 4.2). The differences can be attributed to the presence of larger quantities of non-bentonite minerals and mixed-layer clays in the material from Saskatchewan.



The Free-Swell, CEC and  $S_o$  data obtained for these materials suggest strongly that if water structure and mobility is affected by surface charged mineral particles, the Wyoming and Saskatchewan clays would be the materials where this would be most evident. Materials such as illitic clay and quartz sand are less likely to affect water structure, since they have low surface area or CEC. With the establishment of the nature of the surface activities of the materials examined in this thesis it will be possible to discuss the results of hydraulic conductivity tests in terms of the differences in the surface chemistry.

### **4.3 Pore Fluid Chemistry and Bacteriology**

#### **4.3.1 Pore Fluid Chemistry**

The pore fluid chemistry of clay-water systems can affect the mass transport properties. As was discussed in Chapters 2.3 and 3.5, the presence of ions, particularly cations, can have a significant effect on the pore water structure and mass transport. The clays and sand materials examined in this thesis were examined to determine the quantity and type of soluble compounds available.

An analysis was first conducted to determine the approximate quantity and composition of the soluble salts present. This was accomplished by placing approximately 2.5 grams of dry soil in contact with 250 cm<sup>3</sup> of deionized water. This mixture was vigorously shaken for one minute initially and this mixing was repeated approximately 10 more times over a 48 hour period. The resultant suspension was then centrifuged to separate out the solid and liquid portions. The supernatant liquid was microfiltered and submitted for chemical analysis to determine the quantity of Na<sup>+</sup>, K<sup>+</sup>, Ca<sup>+2</sup> and Mg<sup>+2</sup> cations and Cl<sup>-</sup>,

$\text{SO}_4^{2-}$  and  $\text{CO}_3^{2-}$  anions present as readily soluble components (Table 4.3). The high  $\text{Mg}^{+2}$  content apparently present in the soluble ion analyses is more likely the result of ultra-fine particles of clay which passed through the filters used. The Mg is most likely the structural Mg present within the clays. This interpretation is supported by the apparently higher Mg content in soluble salts analyses than is present as exchangeable Mg.

Table 4.3 Soluble and Exchangeable Ions Present in Clay Materials

| Ion                                               | Illitic Clay        | Saskatchewan                | Bentonite           | Wyoming                     | Bentonite           |
|---------------------------------------------------|---------------------|-----------------------------|---------------------|-----------------------------|---------------------|
|                                                   | Soluble Ion Content | Exchangeable Cation Content | Soluble Ion Content | Exchangeable Cation Content | Soluble Ion Content |
| Sodium ( $\text{Na}^+$ )<br>(meq/kg clay)         | 7.7                 | 453                         | 214                 | 492                         | 177                 |
| Potassium ( $\text{K}^+$ )<br>(meq/kg clay)       | 10                  | 26                          | 4.4                 | 9.8                         | 2.9                 |
| Calcium ( $\text{Ca}^{+2}$ )<br>(meq/kg clay)     | 6.6                 | 350                         | 32.5                | 285                         | 21.5                |
| Magnesium ( $\text{Mg}^{+2}$ )<br>(meq/kg clay)   | 6.1                 | 52                          | 126                 | 46                          | 104                 |
| Chlorine ( $\text{Cl}^-$ )<br>(meq/kg clay)       | 3.2                 |                             | 18.7                |                             | 2                   |
| Sulphate ( $\text{SO}_4^{2-}$ )<br>(meq/kg clay)  | 5.6                 |                             | 176                 |                             | 64                  |
| Carbonate ( $\text{CO}_3^{2-}$ )<br>(meq/kg clay) | 12.8                |                             | 20.5                |                             | 78                  |
| Total                                             | 30.4                | 881                         | 377                 | 832.8                       | 306                 |

The data presented in Table 4.3 provides an indication of the total amount of readily soluble material present as well as the total quantity of exchangeable cations present, not just those which are readily put into solution during the percolation process. These data provide a means of determining the effect of fresh water percolation through compacted clay. It will now be possible to estimate the proportion of the soluble salts remaining in

a specimen at the end of testing and to determine what, if any chemical gradient has been induced by water percolation through the clays examined.

Table 4.3 also clearly shows that the content of soluble salts in the illitic clay is low (30.4 meq/kg). This is approximately one tenth the soluble ion content of the bentonites. The Saskatchewan bentonite has the highest content of soluble material with 377 meq/kg, with the Wyoming material having 306 meq/kg.

The high soluble salts content of the bentonite clays have the potential to induce chemical gradients across these soils. In an attempt to limit the influence of such a gradient, the specimens were all prepared with either deionized water or a brine solution known as the Standard Canadian Shield Saline Solution (SCSSS) as the initial pore fluid. To minimize the influence of salt movement into or out of the specimens, large reservoirs of the same fluid as was used to prepare the specimen were located at either end of the specimen. In some longer term tests, the reservoir fluid was replaced and the cell base was flushed with the same pore fluid as was initially used in specimen preparation. This was done to ensure that any chemical gradients formed by the dissolution of pore fluid salts, diffusion of salts, or the flushing action induced by through flow of permeant was limited.

Previously, Saskatchewan bentonites have been studied to determine the type of soluble salts present and the rate at which they are removed by percolation with deionized water. Oscarson and Dixon (1989) and Oscarson et al. (1990) examined soluble salt removal in unprocessed and intact specimens of sodium bentonite clay shale from Saskatchewan. Water was percolated parallel or normal to the bedding planes of this clay-shale and the effluent was periodically collected for analysis (Figure 4.6).

Unprocessed bentonite specimens which were percolated along their bedding planes exhibited the most rapid removal of their soluble salts. Specimens percolated normal to the bedding planes showed a very much lower rate of leaching. These percolation/leaching tests were conducted until between 3 and 8 pore volumes had been flushed through the specimens using high hydraulic gradients (typically 1500 to 3000). Even with high volumes of pore fluid having been passed through the specimens, only about 50 % of the soluble salts identified as being present in these materials were removed at the end of testing (Figure 4.6).

Figure 4.6 provides support to the interpretation previously presented regarding the source of the apparently high  $Mg^{+2}$  content in the processed bentonites. This ionic content is the result of damaged clay crystals. Tests to determine the  $Mg^{+2}$  content of the unprocessed Saskatchewan bentonite conducted by Oscarson and Dixon (1989) found that the  $Mg^{+2}$  removed by percolation with deionized water was very limited (Figure 4.6). Likewise, the removal of sulphate from the unprocessed bentonite specimens was much lower than was observed for the processed clay. This reduced removal may indicate a time-dependence of sulphate removal rather than a flushing action. If the sulphate is removed by bacterial action, the limited removal by percolation of intact clay, relative to that achieved by limited percolation of fresh water through processed clay has two possible explanations. First, there is no significant bacterial activity within the intact clay, thereby limiting sulphate removal, whereas the processed material has enough internal bacterial activity to reduce the sulphate content. This explanation is not consistent with the porosimetry results presented previously which indicated that there were insufficient pore spaces of adequate size in 100% clay specimens to allow bacterial intrusion and activity.

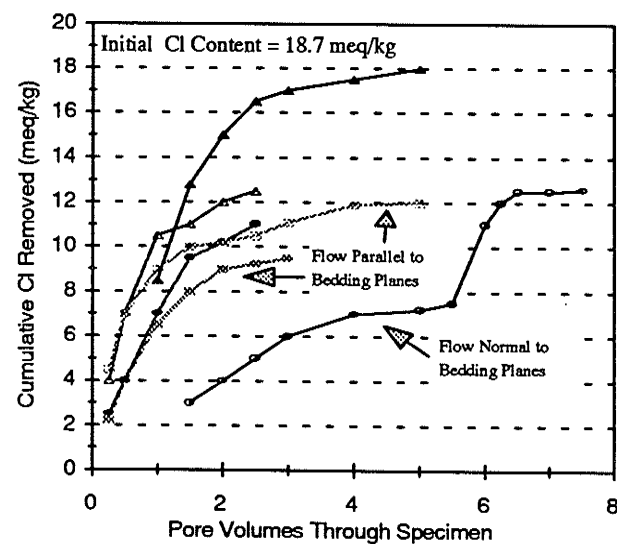
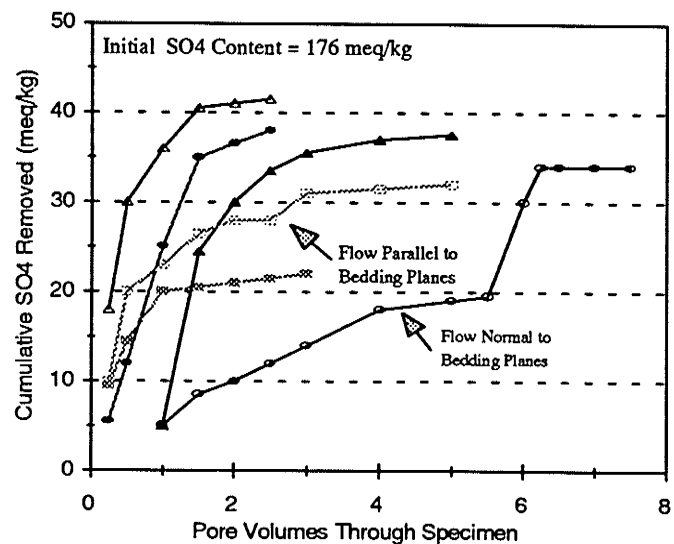
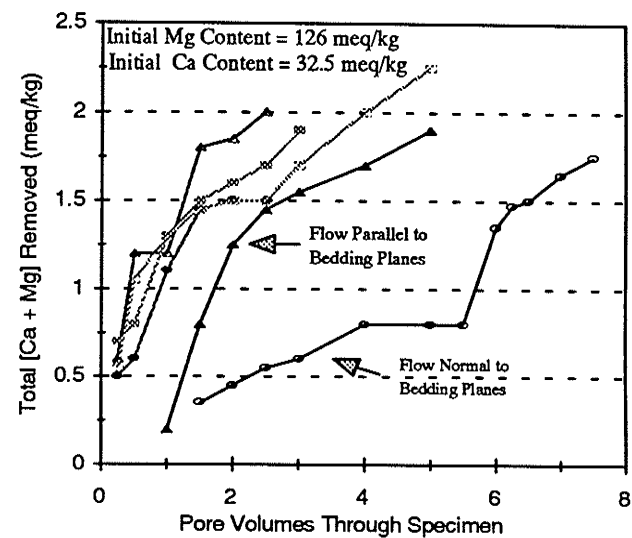
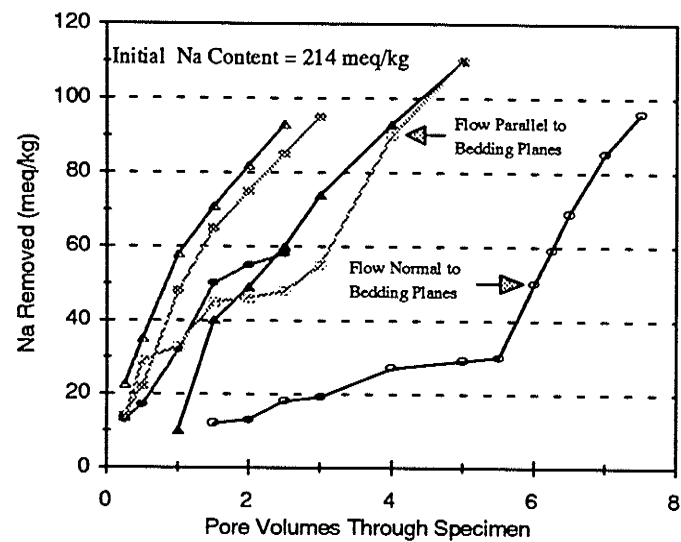


Figure 4.6 Cumulative Ionic Removal By Fresh Water Percolation of Unprocessed Bentonite Clay (From Oscarson & Dixon 1989)

The second possible explanation for the sulphate removal observed in Figure 4.6 is related to the testing time. The intact specimens were tested over a relatively short time, while the processed materials were tested over a much longer time. If removal of the sulphate by bacteria is time dependent and related to chemical diffusion from the specimen, then greater depletion in the processed materials is expected.

It will be shown later that the hydraulic conductivity of the specimens of unprocessed and intact bentonitic clay-shale specimens of  $1.2 \text{ Mg/m}^3$  dry density were measured to be in the order of  $10^{-12} \text{ m/s}$ . This value of  $k$  is not dissimilar to those measured for processed bentonitic clay (Oscarson et al. 1990). If the data obtained by testing natural bentonitic shale material is used to estimate the time required to establish both a constant rate of flow and chemical equilibrium state in densely compacted bentonites, it would be impossible to complete a test in less than several decades.

To determine the actual chemistry within the clay specimens following water percolation, a number of bentonite specimens were selected for sectioning and chemical analysis. At the end of hydraulic conductivity testing these specimens were carefully extruded from the sample holder and then sliced to provide 3 to 5 sections for chemical analysis. Each of these sections were then oven dried to determine their mass. Then 2.5 g, or less of these subsamples were placed in  $100 \text{ cm}^3$  of deionized water per gram of clay, and were prepared in the same manner as was used to determine the initial chemical composition of the clays (Table 4.3).

The results of the two chemical analyses of the sectioned clay specimens are presented in Table 4.4. These data show that there is no clear chemical gradient created across the

specimen, although there is an apparent reduction in the ionic concentration present in the clay closest to the inflow and outflow reservoirs for all the cations excepting Na. In all but the specimen of 1.14 Mg/m<sup>3</sup> density it appears that the sodium ions are gradually being flushed through the specimens in the densest specimen.

The only consistent trends in ionic concentrations observed in Table 4.4 are found in the anion concentrations. There is a very clear reduction in the sulphate content of these specimens. At the end of testing, the sulphate content (actually the total sulphur content expressed as sulphate), is only a small fraction of its original level. The highest remaining sulphate contents were observed in the regions closest to both the fluid reservoirs. Depletion was nearly complete in the central regions of the clay specimens. Also observed was an overall increase in the carbonate content of the clays, with concentration increasing as the outflow end of the specimen is approached.

One explanation for the sulphate and carbonate concentrations observed is microbial activity. Biochemical gradients may cause the sulphate initially present in the specimens to diffuse outwards and to be metabolized by bacteria present at the interface of specimen and the filter stones. The sulphur associated with this bacterial action is sufficient to provide higher sulphate concentrations at the ends of the specimens (because total S is expressed as SO<sub>4</sub><sup>2-</sup>). However, this is still at considerably depleted levels relative to the initial internal concentrations (the remainder having been lost as H<sub>2</sub>S<sub>(gas)</sub>). The additional sulphate may have been transported into the reservoirs, either by bacterial action, diffusional or advective transportation. The apparent removal of the sulphates from the core of the specimen can be interpreted as indicating a limited bacterial population within the specimens. An active bacterial population throughout the specimen itself should

metabolize the sulphur and would tend to limit redistribution since a sulphate gradient would not occur because  $\text{SO}_4$  would be used up throughout the specimen. The presence of very small residues of the original sulphur content can be interpreted as indicating that little biological activity is occurring within the specimen. The elevated carbonate concentrations observed may be byproducts of the respiratory processes carried out by the bacteria. The actual results of bacterial investigations of clay specimens are presented in Section 4.3.2.

The bacteriological explanation provided for the anion distributions shown in Table 4.4 are speculative in nature but would result in the distributions observed. Significant bacterial populations would need to be present for the type of ionic redistribution observed to have occurred. To test this explanation for the chemical distribution observed, samples were taken of the fluid present at the upper and lower surfaces of four specimens and bacterial counts were made. These specimens had been tested as part of the hydraulic conductivity testing program described in Chapters 6 and 7. The bacterial counts were made to provide an indication of the type and relative health of the microbial population at or near the surface of bentonite specimens. Section 4.3.2 and Table 4.5 presents the results of bacterial analyses.

Tests to determine pore water chemistry showed that pore fluid equilibration will take an extremely long time and/or require the movement of a considerable number of pore volumes of permeant. As these options are not feasible given the very low permeability of the materials examined, efforts must be made to limit the potential for chemical changes within the specimens during testing. This was accomplished by minimizing the volume of permeant passing through the specimens. Minimizing the generation of



chemical concentration gradients is accomplished by use of a displacement measuring system which is capable of measuring very low displacements and allowing very long duration tests to be conducted at low applied hydraulic gradients (Sections 6.1 and 6.2).

Table 4.4 Analysis of Soluble Salt Content Remaining at the End of Hydraulic Conductivity Testing

| Ion | Initial Conc. in Clay | Clay at Inflow End | Lower Mid | Mid | Upper Mid | Clay at Outflow End | Outflow Fluid |
|-----|-----------------------|--------------------|-----------|-----|-----------|---------------------|---------------|
|-----|-----------------------|--------------------|-----------|-----|-----------|---------------------|---------------|

Wyoming Bentonite: 1.14 Mg/m<sup>3</sup>,  
Ionic Content Remaining after 1.25 Pore Volumes of Fresh Water Percolation(meq/kg soil)

|                 |      | Distance From Inflow (mm) |  |      |  |      |       |
|-----------------|------|---------------------------|--|------|--|------|-------|
|                 |      | 1.52                      |  | 5.03 |  | 8.60 | 10.17 |
| Na              | 194  | 172                       |  | 162  |  | 151  |       |
| K               | 1.5  | 1.6                       |  | <1   |  | 1.7  |       |
| Ca              | 54.7 | 64                        |  | 75   |  | 53   |       |
| Mg              | 213  | 204                       |  | 249  |  | 148  |       |
| Cl              | 4    | 2.2                       |  | 1.5  |  | 2.2  |       |
| SO <sub>4</sub> | 62.2 | 8.7                       |  | 1.2  |  | 16   |       |
| CO <sub>3</sub> | 89.6 | 111                       |  | 118  |  | 123  |       |

Wyoming Bentonite: 1.34 Mg/m<sup>3</sup>,  
Ionic Content Remaining after 1.25 Pore Volumes of Fresh Water Percolation(meq/kg soil)

|                 |      | Distance From Inflow (mm) |      |  |      |       |       |
|-----------------|------|---------------------------|------|--|------|-------|-------|
|                 |      | 2.50                      | 6.70 |  | 9.66 | 12.04 | 13.17 |
| Na              | 194  | 106                       | 145  |  | 149  | 177   |       |
| K               | 1.5  | 1                         | 1.1  |  | 1.4  | 2     |       |
| Ca              | 54.7 | 40                        | 66   |  | 65   | 54    |       |
| Mg              | 213  | 129                       | 205  |  | 200  | 154   |       |
| Cl              | 4    | 1.3                       | 1.2  |  | 1.4  | 3.8   |       |
| SO <sub>4</sub> | 62.2 | 24                        | 5.2  |  | 1.4  | 20.2  |       |
| CO <sub>3</sub> | 89.6 | 70                        | 103  |  | 121  | 134   |       |

The procedure adopted for testing the hydraulic properties of bentonitic specimens minimizes, so far as is possible, ionic advection and allows time for pore fluid ions to diffuse within each specimen, minimizing the magnitude of the chemical gradients within the specimens. Most of the hydraulic conductivity tests conducted as part of this research program involved total pore water volume exchanges of less than 0.75 pore volumes, and many had less than 0.1 pore volumes (See Section 6.3 for data on permeability testing). This means that less than 15 % of the soluble salts are likely to have been flushed from the soil (with the possible exception of sulphate) with no discernable chemical gradient having been developed across these specimens. These data provide confidence in the ability to conduct hydraulic conductivity tests on compacted bentonite clay specimens without inducing large chemical gradients across the specimens. The role of bacterial action on the measured hydraulic properties has been examined in Section 4.2.3 and an actual bacterial analysis is presented in Section 4.3.2.

#### **4.3.2 Bacteriological Characteristics of Bentonite Specimens**

Four specimens were sampled to determine the type and distribution of bacteria associated with bentonite and bentonite-sand materials. These specimens had been installed for durations ranging from 390 days to 450 days prior to their dismantling and sampling for bacteria. The first two specimens were tested under anaerobic conditions. They were sampled to determine the nature of the bacterial population present in the water above the interface between the specimen and the filterstones. One of these specimens had been percolated with distilled and deionized (DD) water and the other with a brine solution. The results of these analyses are presented in Table 4.5. The third specimen was a clay specimen which was tested under aerobic conditions and was then tested to determine the bacterial populations in the fluid at the outflow interface. The

specimen was also sampled to try and determine the type and size of the bacterial populations present at the surface and the core of the specimen. The final specimen was a bentonite-sand material which had been tested under anaerobic conditions and was sampled and tested in the same manner as the third specimen. The results of bacterial analyses on the third and fourth specimens are presented in Table 4.6.

Table 4.5 Bacterial Populations Present at the Surface of Compacted Bentonite Clays

| Location                | Bacterial Populations Present in Bacteria/cm <sup>3</sup> of Fluid |                      |      |                      |
|-------------------------|--------------------------------------------------------------------|----------------------|------|----------------------|
|                         | Bacteria Type                                                      |                      |      |                      |
|                         | AO                                                                 | IRB                  | SRB  | SLYM                 |
| DD Water at Inflow      | 3.13x10 <sup>6</sup>                                               | NM                   | NM   | NM                   |
| DD Water at Outflow     | 5.64x10 <sup>6</sup>                                               | 2.50x10 <sup>5</sup> | 2500 | 2.80x10 <sup>5</sup> |
| Saline Water at Outflow | 2.84x10 <sup>3</sup>                                               | 0                    | 0    | 0                    |

Note: AO = Total Bacterial Count, using Acridine Orange (AO) Staining  
 IRB= Iron Reducing Bacteria      SRB= Sulphate Reducing Bacteria  
 SLYM= Slime Bacteria

The AO counts presented in Table 4.5 represent a total count of both living and dead bacteria. The plate counts presented in Table 4.6 are of living and viable bacteria. However, the plate counts generally only represent from 1% to 10% of the total bacteria actually present. This is a result of the inability to grow the entire range of bacteria in a single artificial growth medium (Stroes-Gascoyne 1994).

The plate counts presented in Table 4.5 indicate the presence of a healthy and thriving bacterial population in the anaerobic fluid associated with the bentonite specimen percolated with distilled and deionized water. The Sulphate Reducing Bacteria (SRB) count is considerably higher than is normally found in groundwater environments (Stroes-Gascoyne and West 1994) and could result in metabolization and reduction of the

sulphate content of the system, as was observed in the chemical analyses presented in Table 4.4. The somewhat lower bacterial population at the inflow is likely the result of a smaller space at inflow end of the specimen for the bacteria to grow (the design of the cell is presented in Chapter 6). The data in Table 4.5 also show a much lower bacterial population is present in a highly saline environment. Although lower in absolute count, the numbers presented for the total population in this saline solution are indicative of a relatively active bacterial environment.

Previous paragraphs described bacterial action in water-filled regions immediately above and below the specimens. In contrast, Table 4.6 presents results of measuring the bacterial populations actually within and on the surfaces of a compacted bentonite clay and a clay-sand mixture. These specimens were tested using the same type of permeameter used for testing the specimens presented in Table 4.5, excepting that the outflow lines (at top of specimens), exited to a fluid reservoir which was open to the atmosphere. This means that the specimen was aerobic (at least at the outflow end)

The data presented in Table 4.6 generally show a reduced bacterial content (both aerobic and anaerobic) in the central regions of the specimens. This could be expected as the outermost sections include the interfaces between the specimen and the filterstones which are the regions most favourable for bacterial growth. There is also a higher concentration of anaerobes and SRB bacteria in the base of the specimens, relative to the concentration at the top. This can be attributed to the more anaerobic conditions which would be present furthest away from the oxygen source (outflow end of specimens) (Hamon, 1994). These data show that there are bacteria present and alive in all regions of the specimen but not their relative health or ability to move within the specimens. The relative scarcity

of bacteria in the central regions of the specimens may be an indication that these organisms do not move readily through these materials or that they don't have the space needed to multiply and grow. Alternatively, the bacteria recorded as being present in the central regions may be those initially present in the soil prior to its compaction. These organisms may or may not have been active in the soil during the test.

Table 4.6 Bacteriological Characteristics of Bentonite Clay and Bentonite-Sand Specimens

| Material                                              | Location         | Plate Counts (CFU/cm <sup>3</sup> ) |                      | CFU/cm <sup>3</sup><br>SRB |
|-------------------------------------------------------|------------------|-------------------------------------|----------------------|----------------------------|
|                                                       |                  | Aerobic                             | Anaerobic            |                            |
| Bentonite Clay Aerobic (1.10 Mg/m <sup>3</sup> )      | Water Above Clay | 79300                               | 13400                | 0                          |
|                                                       | Upper Quarter    | 35000                               | 1.35x10 <sup>7</sup> | 79                         |
|                                                       | Upper Middle     | 156000                              | 3.11x10 <sup>6</sup> | 158                        |
|                                                       | Lower Middle     | 1120                                | 1.67x10 <sup>6</sup> | 100                        |
|                                                       | Lower Quarter    | 307                                 | 1.73x10 <sup>7</sup> | 250                        |
| Bentonite-Sand Aerobic (1.68/1.22 Mg/m <sup>3</sup> ) | Water Above Clay | 5.33x10 <sup>6</sup>                | 15800                | 79                         |
|                                                       | Top Layer        | 9.80x10 <sup>5</sup>                | 2.19x10 <sup>5</sup> | 79                         |
|                                                       | Mid Specimen     | 600                                 | 4920                 | 79                         |
|                                                       | Bottom Layer     | 6900                                | 1.29x10 <sup>6</sup> | 158                        |

Note: CFU - colony forming units (usually 1 bacterium/unit)

The data presented in Tables 4.5 and 4.6 show that there is considerable bacterial action in the interfacial regions of bentonite and bentonite-sand specimens. This type of activity was likely present in all the specimens examined in the course of hydraulic conductivity

investigations. However, the results presented in Figure 4.5 indicated that there was no clear time-dependent change in the hydraulic properties of compacted bentonitic materials. This infers that bacterial activity is not a dominating influence on the flow of water through the specimens examined in this thesis.

Since chemical and biological influences on the movement of water through the compacted clays examined in this thesis are apparently limited, it is possible to move forward to laboratory investigations of the actual structure of the pore water in these systems (Chapter 5). Once the actual water structure in these soils is established experimentally, it will then be possible to examine and interpret fluid movement through compacted clays under conditions of low applied hydraulic gradients (Chapters 6 and 7).

## **5.0 THERMAL EXPANSION TESTING**

### **5.1 Purpose of Thermal Expansion Testing**

Literature which predicts and reports variations in the structure and behaviour of water in clay-water systems was reviewed in Sections 2.2 and 2.3. To estimate the influence of water structure on water flow through a clay, it is necessary to determine the amount of structuring actually present. Direct measurement of the structure of water in compacted clay-based materials is extremely difficult as it deals with atomic and molecular levels of measurement. A number of techniques have been developed which allow estimates of the magnitude of water structuring in compacted clays. Two of these techniques are Nuclear Magnetic Resonance (NMR) (or associated high energy physics-based techniques) and thermal expansion testing. NMR has typically been used to look at slurries or clay suspensions and has not been used to examine dense clays. Thermal expansion testing has been used on slurries and dense soils (but not bentonites) to estimate the degree of water structuring present. Because there was no ready access to NMR equipment and no evidence that the NMR technique could be used successfully, the technique selected for the research described in this thesis was thermal expansion testing.

Thermal expansion testing assesses deviations from the theoretical thermal expansion, (or contraction) of the water portion of clay-water systems. The thermal expansion of bulk (free) water is well documented and can be obtained from the literature. As with the water component, the thermal expansion of the mineral component of clay soils can be calculated using published values. What is missing is information on the thermal expansion of combined clay-water systems. For a given temperature increment, the

volume change calculated for the water phase can be added to the volume change calculated for the mineral phase. The resulting theoretical volume change can then be compared with measured volume change. Any discrepancies between these two separate estimates of volume change can be attributed to differences in the thermal expansion properties of structured water associated with clay particle surfaces.

The compacted densities of the soil-water systems examined here are higher than any previously published results from mineralogically similar systems. As a result there is no data available to permit comparison of the results. The tests were conducted at high back pressures (1.5 MPa), thereby ensuring full specimen saturation. Deviation from the thermal expansion predicted using theoretical values can be used to suggest an appropriate structural model (or models) for the water phase. The selected model(s) can then be used in interpreting the results of the hydraulic conductivity testing in Chapter 7, with the objective of developing a comprehensive model for water structure and water movement in clay soils.

## **5.2 Measurement of the Thermal Expansion of Mineral-Water Systems.**

### **5.2.1 Calculation of Thermal Expansion**

Calculation of thermal expansion of mineral-water systems requires careful defining of the parameters used. The most important of these are the coefficients of thermal expansion,  $\beta_w$  and  $\beta_m$  for the water and mineral components respectively.



The thermal expansion properties of water are well known (Table 5.1 (Weast 1976)). The specific volumes ( $V_T$ ) of water initially of unit volume at 0°C and then heated are presented in Column 2 of Table 5.1 and in Figure 5.1. From the specific volumes of water, the coefficients of thermal expansion ( $\beta_w$ ), can be calculated (column 3 in Table 5.1), (Weast 1976). The coefficient  $\beta_w$  is defined as the thermally-induced volume change ( $dV_T$ ) per unit volume of water (at 0°C), per increment in temperature  $dT$ , ( $^{\circ}\text{C}^{-1}$ ). The "Global"  $\beta_w$  values obtained from Weast (1976) are the average thermal expansion coefficients for the temperature range of 0°C to the specified temperature. For example the  $\beta_w$  calculated for water at 50°C is the total change in specific volume ( $dV_T$ ) occurring as the result of a temperature change from 0°C to 50°C (column 2 in Table 5.1) divided by the temperature change ( $^{\circ}\text{C}$ ). These "Global" coefficients represent the average thermal expansion value for the entire temperature change considered rather than incremental changes resulting from small changes in system temperature. This means that significant changes in thermal expansion behaviour occurring over a narrow range of temperature may be lost as the result of the averaging done in this technique.

Two modifications have been made to the definitions commonly used in calculating specific volume ( $V_T$ ) and the thermal expansion coefficient ( $\beta_w$ ) of water. These redefinitions simplify the computation of pore fluid volume changes in tests on clay - water systems but do not alter the volume changes obtained for a given temperature change. The first modification defines the specific volume of water ( $V_T'$ ) as 1.0000 at 25°C, this was the starting temperature in the test program. The second modification uses an average ( $\beta_w'$ ) coefficient for each 10°C increment in temperature. The result of these modifications on the resultant specific volume of water is presented in Figure 5.1.

Table 5.1 Coefficient of Volumetric Thermal Expansion For Free Water

| 1<br>Temperature<br>(°C) | 2<br>Specific<br>Volume<br>$V_T$<br>(m <sup>3</sup> /Mg) | 3<br>Global<br>$\beta_w$<br>(x10 <sup>-6</sup> )<br>(m <sup>3</sup> /m <sup>3</sup> /°C) | 4<br>Adjusted<br>Spec. Vol.<br>$V_T'$<br>(m <sup>3</sup> /Mg) | 5<br>Adjusted<br>$\beta_w'$<br>(x10 <sup>-6</sup> )<br>(m <sup>3</sup> /m <sup>3</sup> /°C) |
|--------------------------|----------------------------------------------------------|------------------------------------------------------------------------------------------|---------------------------------------------------------------|---------------------------------------------------------------------------------------------|
| 0                        | 1.00                                                     | 0                                                                                        | 0.9936                                                        |                                                                                             |
| 25                       | 1.00643                                                  | 257                                                                                      | 1.0000                                                        | 595                                                                                         |
| 30                       | 1.00943                                                  | 314                                                                                      | 1.00298                                                       | 595                                                                                         |
| 40                       | 1.01541                                                  | 385                                                                                      | 1.0477                                                        | 645                                                                                         |
| 50                       | 1.02288                                                  | 457.6                                                                                    | 1.0165                                                        | 785                                                                                         |
| 60                       | 1.03140                                                  | 523                                                                                      | 1.0250                                                        | 878                                                                                         |
| 70                       | 1.04111                                                  | 590                                                                                      | 1.02969                                                       | 937                                                                                         |
| 75                       | 1.04596                                                  | 612.8                                                                                    | 1.0395                                                        | 1067                                                                                        |
| 80                       | 1.05154                                                  | 640                                                                                      | 1.04036                                                       | 1067                                                                                        |
| 90                       | 1.0627                                                   | 696                                                                                      | 1.0563                                                        | 1119                                                                                        |
| 100                      | 1.07501                                                  | 750.1                                                                                    | 1.0686                                                        | 1158                                                                                        |

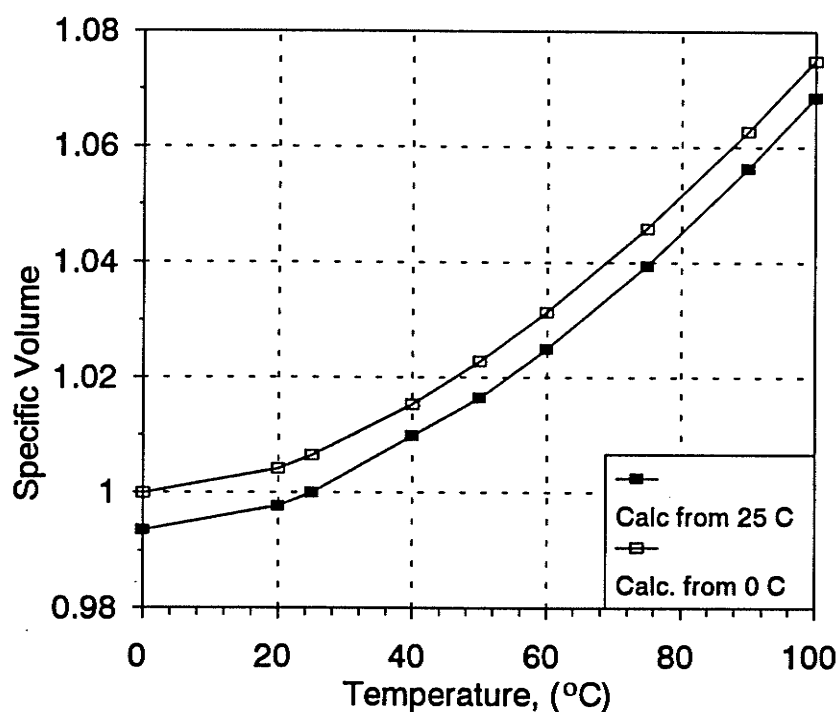


Figure 5.1 Specific Volume Calculated Using Conventional ( $\beta_w$ ) and the Adjusted ( $\beta_w'$ ) Coefficients of Thermal Expansion

The  $\beta_w'$  values presented in Column 5 of Table 5.1 were calculated using the incremental technique for handling changes in temperature. This technique was presented by Dixon et al. (1993a). It allows a greater degree of data resolution than was possible in the analysis reported by Gray et al. (1990). The coefficient  $\beta_w'$  is assumed to be a constant within each temperature range listed in the table.

The technique of using the  $\beta_w'$  coefficients to estimate the volume change of the fluid portion of a specimen over a temperature change from say 25°C to 75°C sees volume change calculated as a series of steps. The first is a 5°C step from 25°C to 30°C using  $\beta_w' = 595 \times 10^{-6} \text{ m}^3/\text{m}^3/^\circ\text{C}$ . The next step is the 10 degree step from 30°C to 40°C using  $\beta_w = 645 \times 10^{-6} \text{ m}^3/\text{m}^3/^\circ\text{C}$  for the volume initially present at 30°C. The third step is the 10°C step from 40°C to 50°C using  $\beta_w = 785 \times 10^{-6} \text{ m}^3/\text{m}^3/^\circ\text{C}$  for the volume initially present at 40°C. This process is continued until the final increment from 70°C to 75°C is calculated. Use of such stepped  $\beta_w'$  values also facilitates identification of changes in thermal expansion behaviour with temperature change. Provided that the pore fluid behaves as a "pure" water, the same volume change is predicted using either technique (Figure 5.1).

Table 5.2 presents the thermal expansion coefficients ( $\beta_m$ ), for the minerals known to be present in the clays that were tested. The range of  $\beta_m$  values for these materials is relatively narrow, and so even large inaccuracies in the assumed composition of the specimens will have only a small effect on net thermal expansions. Comparison with Table 5.1 shows that the thermal expansion coefficient for water is 10 to 70 times higher than that for the minerals examined. Such differences in the  $\beta$  values for the mineral and fluid components mean that the calculated volume changes for the whole specimen are relatively insensitive to assumptions made about its mineralogy. The large differences

between the thermal expansion coefficients for the water and minerals also mean that volume changes are dominated by the volume straining of the water component. Volume changes of the mineral components are second-order factors in the volume straining of the total specimen. Hence, any differences in the thermal expansion properties of bound water associated with mineral surface activity (in contrast with the water), will not be masked by difficulties in determining the quantitative mineralogy of the specimens.

Table 5.2 Thermal Expansion Coefficients For Minerals

| Mineral           | Temperature<br>(°C) | $\beta_m \cdot 10^6$<br>(m <sup>3</sup> /m <sup>3</sup> /°C) |
|-------------------|---------------------|--------------------------------------------------------------|
| Quartz*           | 20-50               | 57.6                                                         |
|                   | 50-100              | 38                                                           |
| Feldspar*         | 20-100              | 11.3-17.5                                                    |
| Illite**          | 25-600              | 22-28                                                        |
| Kaolinite**       | 25-400              | 24-34                                                        |
| Montmorillonite** | 25-400              | <39                                                          |
| Water             | 0-100               | 750                                                          |
| Ice***            | <0                  | 52                                                           |

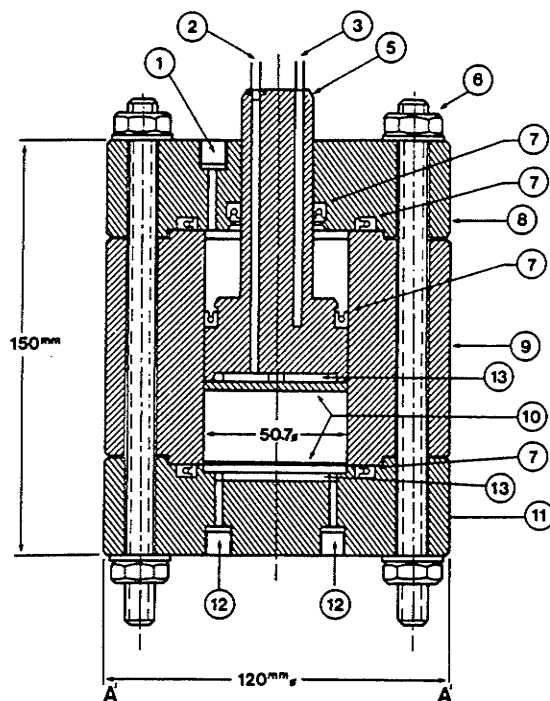
Source: \* Skinner (1966); \*\* McKinstry (1965); \*\*\* Michel (1978)

### 5.2.2 Equipment Utilized and Technique Adopted to Measure the Thermal Expansion of Mineral-Water Systems.

Two rigid-walled cells of the type shown in Figure 5.2 were constructed and used to measure the thermal expansion of mineral-water systems. In order to measure changes in specimen volume, the cells were designed to allow fluid to escape while the specimens were heated. The volume of the expelled pore fluid was monitored, to determine thermally-induced volume changes in the specimen. High pore water pressure (1.5 MPa), was maintained throughout all testing, including calibrations, to ensure full specimen saturation and prevent steam generation. To maintain a constant temperature and limit

temperature gradients across the specimens, the outside of each cell was wrapped with heater tape and insulated (not shown in Figure 5.2). Temperatures were monitored and controlled using 2 thermocouples installed on the outer wall of the cell and in a thermocouple mounted in a well inside the piston.

Temperatures within the cells were increased in increments of approximately 5°C, until the maximum test temperature of approximately 100°C was reached. After each increment of temperature, constant temperature was maintained until expulsion of pore fluid ceased. After achieving maximum temperature, the specimen was cooled in steps of 5°C and the accompanying fluid movement into the cell was measured.



#### DESIGN DETAILS

1. Hydraulic Fluid Supply
2. 1/8" Stainless Steel Tubing
3. Thermocouple Well
4. LVDT Seat
5. Piston
6. Threaded Steel Rods
7. Pressure Activated Seals
8. Top Cap
9. Specimen Sleeve
10. Sintered Stainless Steel Filter Stones
11. Bottom Plate
12. Bottom Water Line
13. Grooved Water Flushing Platen

Figure 5.2 Thermal Expansion Cell

For each temperature change, calculation was made of the corresponding volume change that could be anticipated from the volume of solid particles and water present at the beginning of that increment using the corresponding thermal expansion coefficients ( $\beta_m$  and  $\beta_w$ ). These calculations were made using the assumption that the water was all "free" water. Only the fluid and mineral materials actually in the cell at the beginning of each 5°C temperature change are considered as participating in the thermal expansion/contraction process. The adopted technique allows water to enter or leave the system while retaining the physical dimensions of the specimen. This measurement and calculation procedure was used to avoid inducing cumulative volume-change errors. Any volume lost through expansion is not available for any subsequent volume expansion during the heating portion of the cycle. Other assumptions lead to errors in estimating the expansion which should occur.

Calibration of the cells was conducted using well characterized materials (Quartz sand saturated with deionized and de-aerated water). The properties of these materials are taken from Weast (1976); Skinner (1966); and McKinsty (1965). Calibration was done in two steps. One, the thermally-induced volume changes for the quantities of quartz sand and free water present in each cell were calculated using literature-derived coefficients of thermal expansion (Tables 5.1 and 5.2). Two, a thermal expansion test was conducted using these materials in the test cell.

Several heating and cooling cycles were conducted during each calibration test on the cells. Cycling of the temperature checked the reproducibility of the readings and the calibrations developed for each cell. In order to compare theoretical with measured changes in water volumes, the mineral component ( $dV_{min}$ ) was subtracted from the total

measured volume ( $dV_{TOT}$ ). This generated a "measured" change in pore water volume ( $dV_w$ ) which could then be compared to the change in pore water volume predicted using literature coefficients of thermal expansion for water. Differences between the measured volume change and theoretical volume change for each cell were used to determine a correction for the cell, which takes account of the effects of thermal expansion of the cell and its components. The two cells were calibrated separately and had slightly different calibrations. Results are presented in Figure 5.3.

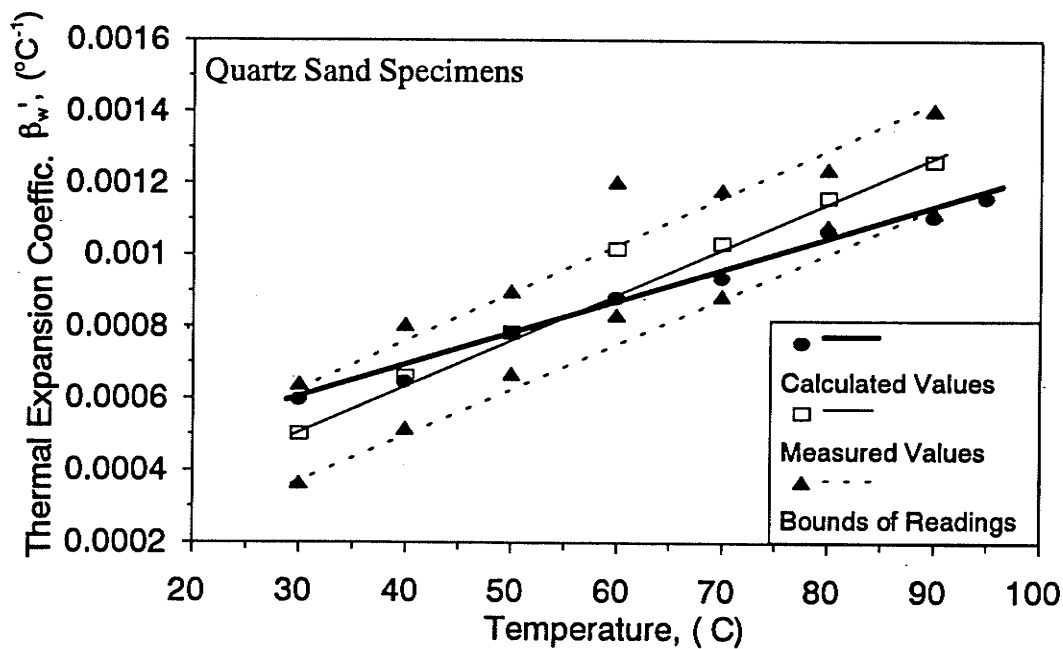


Figure 5.3 Thermal Expansion Properties of Water Associated with Quartz Sand

The data obtained, as well as the best fit line through these calibration data for quartz sand are shown in Figure 5.3. The data presented in this figure show the average value obtained as well as the bounds of the readings. These data show that there is some scatter of the measured thermal expansion coefficient of the water ( $\beta_w'$ ) from the predicted values. This scatter can be used to establish the limits of accuracy of the equipment and

the technique used for reducing the results. Figure 5.3 establishes that deviations in the  $\beta_w'$  coefficient must exceed more than .0001 from the theoretical  $\beta_w'$  before they can be considered as being outside the range of variability of the measuring device. This corresponds to approximately 10% at 90° C.

Once the calibration factors had been established for the cells, clay specimens were installed and back pressured. Volume changes induced by heating or cooling of the specimens were then measured and used to determine the thermal expansion coefficient for the pore water component.

### **5.3 THERMAL EXPANSION TESTS**

#### **5.3.1 Test Results**

As mentioned in the preceding section, thermal expansion testing began with examination of water-saturated quartz sand specimens. Figure 5.3 presented the results of six tests on quartz sand specimens used for cell calibrations. Following development of the calibrations, three illitic clay specimens were tested. The results of these tests are presented in Figure 5.4, together with the best fit line for the water component measured in quartz sand specimens.

Table 5.3 shows values of the ratio of  $\beta_w'$  (measured) to  $\beta_w'$  (calculated) for each 10°C temperature change. For each temperature, the calculated volume change for the mineral component ( $dV_{min}$ ) was subtracted from the total displacement measured ( $dV_{TOT}$ ). This generated a "measured" change in pore water volume ( $dV_w$ ) which could be compared to



corresponding volume predicted using the values of  $\beta_w'$  in Table 5.1 for the thermal expansion of water. The theoretical thermal expansion coefficient ( $\beta_w'$ ) has been precalculated for each pre-defined temperature range (Table 5.1). The measured change in pore water volume ( $dV_m$ ), for each of the temperature increments listed in Table 5.1 and then a "measured"  $\beta_w'$  calculated by dividing  $dV_m$  by  $dT$ . It will be remembered that any deviation in the  $\beta_w'$  of less than 10% at 90° C cannot be separated from uncertainty in the calibrations.

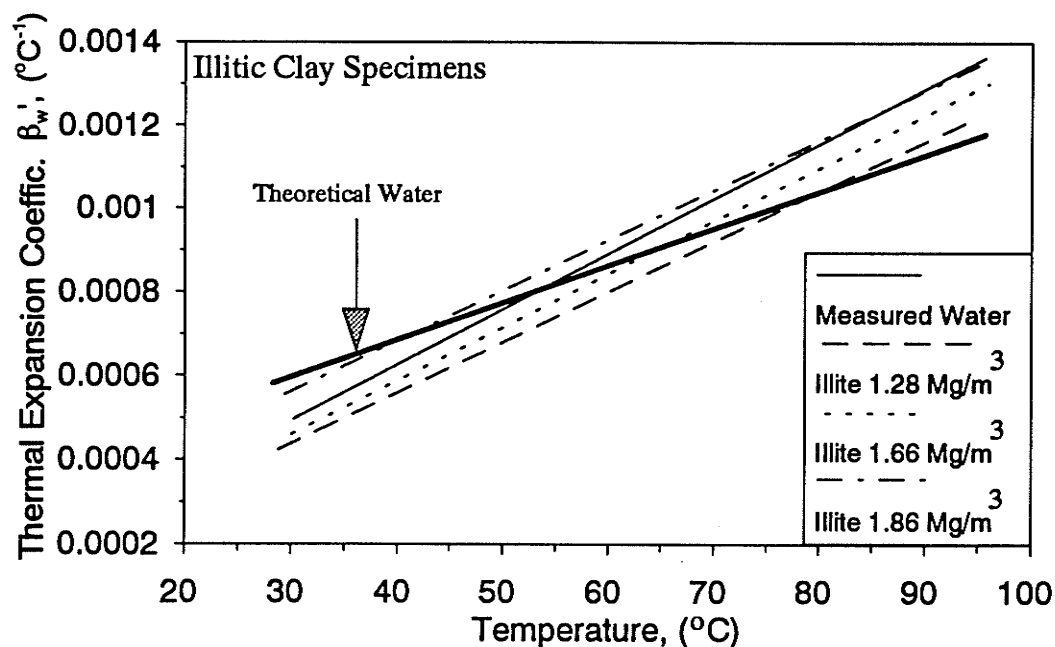


Figure 5.4 Thermal Expansion Coefficient of Water Associated With Illitic Clay

The thermal expansion coefficients ( $\beta_w'$ ) measured for the pore water in illitic clay specimens were of similar magnitude to those for the quartz sand-water specimens (Table 5.3). In Figure 5.4 all three illitic clay specimens with exhibited straight-line relationships which roughly paralleled the predicted  $\beta_w'$  - T relationship for bulk water. These data indicate that the water in these specimens is no more structured than "free" water. There

is an apparent trend towards increasing thermal expansion coefficient with increasing compacted density, but this is a weak relationship given the limits of measuring accuracy.

Table 5.3 Percentage of Predicted Pore Water Thermal Expansion Coefficient Developed by Mineral-Water Systems.

(Measured  $\beta_w'$ /Calculated  $\beta_w'$ ) \* 100% For Pore Water

TEMPERATURE RANGE (°C)

| Material                | 25-35 | 35-45 | 45-55 | 55-65 | 65-75 | 75-85 | 85-95 | 95  | 95-100 | 100+ |
|-------------------------|-------|-------|-------|-------|-------|-------|-------|-----|--------|------|
| <u>Quartz</u>           | 84    | 102   | 100   | 109   | 97    | 109   | 108   | NM  | NM     | NM   |
| <u>Illite</u>           |       |       |       |       |       |       |       |     |        |      |
| 1.28 Mg/m <sup>3</sup>  | 74    | 101   | 90    | 89    | 95    | 97    | 94    | NM  | 103    | NM   |
| 1.66 Mg/m <sup>3</sup>  | 83    | 97    | 68    | 83    | 101   | 116   | 102   | 117 | NM     | NM   |
| 1.86 Mg/m <sup>3</sup>  | 96    | 58    | 68    | 106   | 117   | 105   | 113   | NM  | 115    | NM   |
| <u>Na-Bentonite</u>     |       |       |       |       |       |       |       |     |        |      |
| 0.211 Mg/m <sup>3</sup> | 47    | 54    | 58    | 60    | 77    | 63    | 68    | 77  | NM     | NM   |
| 0.234 Mg/m <sup>3</sup> | 107   | 71    | 83    | 80    | 77    | 69    | 67    | 70  | NM     | NM   |
| 0.309 Mg/m <sup>3</sup> | 64    | 78    | 70    | 62    | 75    | 67    | 73    | 68  | NM     | NM   |
| 0.341 Mg/m <sup>3</sup> | 58    | 73    | 70    | 70    | 71    | 72    | 73    | 74  | 84     | 104  |
| 0.354 Mg/m <sup>3</sup> | 70    | 88    | 57    | 84    | 88    | 79    | 81    | 79  | NM     | NM   |
| 0.780 Mg/m <sup>3</sup> | 88    | 75    | 84    | 66    | 76    | 73    | 64    | 83  | 93     | 88   |
| 1.054 Mg/m <sup>3</sup> | 111   | 117   | 97    | 88    | 96    | 86    | 81    | 78  | 78     | 117  |

NM = Not Measured

Thermal expansion coefficients were also measured for the pore water components of seven bentonite specimens. Six of these specimens, (tested at temperatures from 25°C to 90°C), exhibited  $\beta_w'$  values which were consistently lower than those of bulk water (Figure 5.5, Table 5.3). These coefficients appear to be related to clay density, with the lowest expansion coefficients for a particular temperature usually being observed for the lowest density systems.

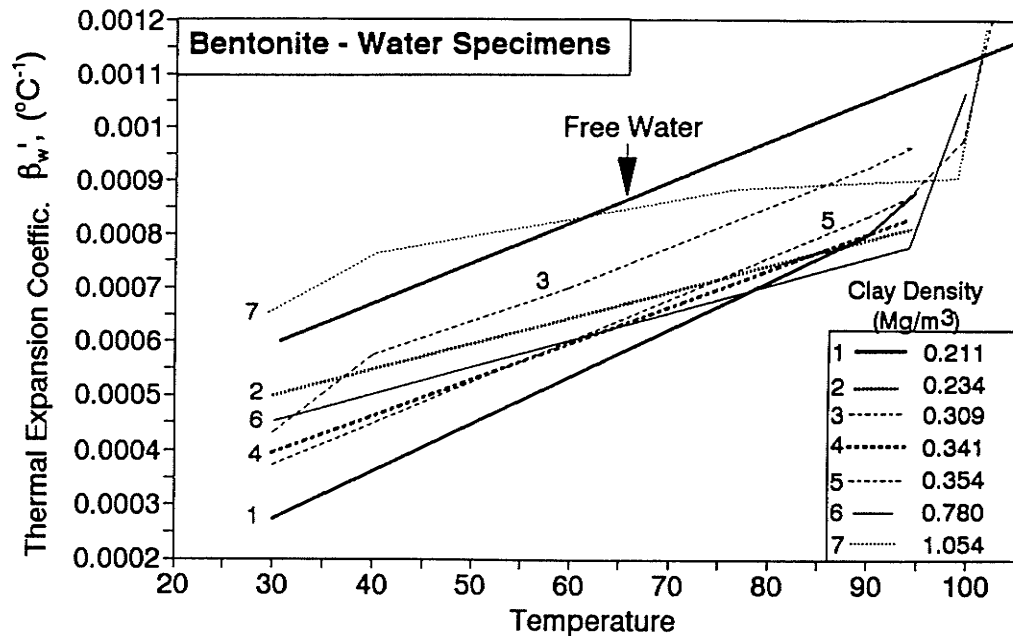


Figure 5.5 Thermal Expansion Coefficient Of Water Associated With Bentonite Clays (From Dixon et al. 1993)

The densest bentonite specimen examined ( $1.05 \text{ Mg/m}^3$ ), exhibited a  $\beta_w'$  -  $T$  relationship that generally followed the predictions for bulk water until the temperature exceeded approximately  $70^\circ\text{C}$ . Between  $70^\circ\text{C}$  and  $95^\circ\text{C}$  this specimen exhibited a lower  $\beta_w'$  than was predicted for bulk water. At approximately  $100^\circ\text{C}$  the measured thermal expansion coefficient increased significantly and actually exceeded the value predicted for bulk water.

Three of the bentonite specimens were tested (with back pressures of  $1.5 \text{ MPa}$ ) at temperatures above the  $100^\circ\text{C}$  limit originally planned for this study (Figure 5.3). They all exhibited sharp increases in  $\beta_w'$  at approximately  $95^\circ\text{C}$  which continued at the highest temperatures examined. The remaining four bentonite specimens examined had maximum testing temperatures of  $95^\circ\text{C}$ , and so any change in the shape of the  $\beta_w'$  -  $T$  plot at higher temperatures was not recorded for these specimens.

### 5.3.2 Interpretation of Thermal Expansion Measurements

As discussed in the preceding section, the thermal expansion properties of the quartz sand-water specimens were defined from the literature as the sum of the two components. These data were used to develop calibration factors for the thermal expansion cells used. This technique permitted the cells to be calibrated to allow thermal expansion coefficients to be measured to within 10% of the theoretical values (Table 5.3).

Over a portion of the temperature range examined, the three illitic clay specimens exhibited values of  $\beta_w'$  that were slightly below predicted values of bulk water. At higher temperatures, the values of  $\beta_w'$  for illitic specimens were slightly higher (5% to 15%), than were predicted in Table 5.1. This suggests that the majority of the pore water in the illitic systems has the structure of free water but at lower temperatures there may be some weak structuring. There is apparently a tendency for  $\beta_w'$  coefficients for a given temperature to increase with increasing clay density. However, the magnitude of the deviations from the predicted  $\beta_w'$  coefficients are only slightly larger than the values recorded for the quartz sand - water specimens.

Tests on bentonitic clays measured  $\beta_w'$  values as much as 40 % lower than would be measured for bulk water. These data support the suggestion by Anderson and Low (1958) that the presence of charged particle surfaces increases the proportion of structured water, and decreases its average density. There is also an apparent trend for the magnitude of the  $\beta_w'$  deviation at a given temperature to decrease with increasing clay density. Reasons for this trend are uncertain, but a possible explanation may be found in the work of Oster and Low (1963), referred to in Section 2.3.5. In this model, the water

in dense clay-water systems is less structured than in lower density systems. These differences in water structure with changing clay density were attributed to the presence of cations which break down the structure of water. At higher clay density, cations are in close association with the clay surface and act to prevent water structuring in the clay interlayers (Oster and Low, 1963). Using this concept, the thermal expansion of the pore water of dense bentonite clays should be closer to that of bulk water. Lower density specimens would contain structured water and would thereby exhibit measurable deviations from the predicted thermal expansion. The data presented in Figure 5.3 support these predictions.

The behaviour of the three bentonites tested at temperatures exceeding 95°C also confirms the results reported by Borsetto et al. (1986), Baldi et al. (1988) and Derjaguin et al. (1986;1987). These researchers all reported changes in thermal expansion of pore fluid at elevated temperatures. These changes were attributed to destructuring of water at temperatures exceeding approximately 90°C, and predicted that fluid destructuring would be accompanied by an increase in  $\beta_w'$ . The data obtained in this study indicate the presence of pore fluid structuring at temperatures lower than approximately 90°C. Once this temperature is exceeded, destructuring of the fluid begins.

The program of thermal expansion testing suggests, as expected, that quartz sand and illitic clay have little or no bonded or structured pore water. Hence, these materials can be expected to behave like true porous media and so should conduct water in accordance with Darcian flow rules. It is possible there may be some weak water structuring in dense illitic clay systems at temperatures below approximately 50°C and this might be reflected in some deviations from ideal Darcian flow at very low hydraulic gradients. Low-density

bentonitic clay specimens exhibited significant reductions in the thermal expansion coefficients of their pore water. The pore water appears to be a structured material and so may not exhibit the Newtonian fluid behaviour required for the application of the Darcy equation. The measured thermal expansions suggest that few of the required conditions for the validity of Darcy's law (Table 3.2) are appropriate in bentonitic clays and that deviations from this relationship might be expected. The apparent destructuring of pore fluid at elevated densities and temperatures suggest that measured deviations from Darcian flow behaviour might be most pronounced in relatively low density specimens. In contrast, the hydraulic behaviour of dense bentonites may well be Darcian in nature, though of course the absolute values of hydraulic conductivity may be very low.

This information on the possible water structuring in clays provides a conceptual framework for the examination of the hydraulic behaviour of compacted sands and clays presented in Chapters 6, 7 and 8.

## **6.0 HYDRAULIC CONDUCTIVITY MEASUREMENT- EQUIPMENT AND TECHNIQUES**

### **6.1 A Review and Discussion of Current Technology**

#### **6.1.1 Introduction**

Sources of inaccuracy in the measurement of hydraulic flow and their influence on efforts to measure flow through low permeability soils have dominated discussions on the validity of the Darcian flow model. Discussion has been particularly intense on techniques used to measure flow through low permeability materials while applying low hydraulic gradients. There are almost as many opinions on what technique is best for testing as the large number of researchers listed in Sections 3.6.3, 6.1.4 and in the list of references provided with this thesis.

As complete specimen saturation is a requirement of any study of the validity of the Darcy equation, techniques used to achieve this condition have been the topic of numerous studies. Section 6.1.2 presents and discusses a number of these saturating techniques. Along with the development of the technologies to saturate and then measure water movement through these soils (Sections 6.1.2 and 6.1.3), has come the recognition that there are limitations to the accuracy in the readings obtained using these techniques (Section 6.1.4).

Just as important as ensuring that the specimen is saturated and selecting the most appropriate equipment to measure flow, is establishing when steady-state flow has been achieved. Section 6.1.5 reviews the literature available and procedures recommended to ensure that steady-state flow has been achieved during testing. On completion of the

reviews presented in Sections 6.1.2 through 6.1.5, the information available is summarized and the technique selected for use in this thesis is justified (Section 6.1.6).

### **6.1.2 Techniques Used to Ensure Specimen Saturation**

Preparation of specimens for hydraulic conductivity testing will almost inevitably result in the presence of entrapped air. Unless the specimen is actually formed by consolidation from a slurry and then installed in a cell submerged under water, some degree of air entrainment is unavoidable. As slurry preparation and submerged construction is impractical or inappropriate for most situations, (especially in clays having a high swelling capacity), alternative means have been developed to install near-saturated specimens and then force the specimen into a state of complete saturation.

The most commonly used technique to achieve saturation is to form the specimen as close to saturation as is practical and then use water under pressure (referred to as back pressuring) to force the remaining air into solution (Mitchell et al., 1965; Lowe and Johnson, 1960). Immediately following this back pressuring, a substantial hydraulic gradient is typically applied in an effort to circulate the dissolved air - water solution out of the specimen and replace it with deaerated pore fluid. This approach is described in considerable detail by Black and Lee (1973) who include a discussion on the time required to accomplish this saturation. This type of saturation process can be undertaken on any specimen, provided the specimen volume is kept constant and a source of pressurized, deaerated water is available.

There are certain limitations to using the back pressuring technique to achieve specimen saturation. The application of pressure to the pore spaces of a specimen can lead to



straining of the soil fabric as the pore fluid forces its way through the specimen and into entrapped air pockets. This may cause the generation of macro or micro channels which can allow easier water conduction through the specimen. The applied back pressure must, in most low permeability materials, be maintained for the duration of the test. Any reduction in back pressure can lead to dissolved gases coming out of solution, creating new voids and potentially acting as obstacles to fluid movement. Depressurizing the specimen can also induce specimen strain as the pore volume increases.

Triaxial or flexible walled permeameter specimens are commonly tested for degree of saturation by use of a "B-test" (Lee et al. 1969; Skempton 1954). This test involves increasing the confining pressure on the specimen and monitoring the pore pressure response through the closed end drains in the specimen. Assuming the validity of the effective stress concept, the change in the total stress of the specimen should be exactly equal to the change in the water pressure. In the "B-test", large changes in the confining pressure can result in macroscopic strains and/or microstrains within the soil. Such strains could change the soil fabric, and hence the hydraulic behaviour of the specimen. The time required to saturate a specimen will vary with the amount of pore air present, the pressure applied, and the rate at which the pore water can enter the specimen to dissolve and remove the entrapped air (Braden and Sides 1967; Lee et al. 1969). Black and Lee (1973) provide a good review of this technique and discuss their attempt to develop a time-based criterion for defining specimen saturation. This study concluded that saturation was potentially a slow process and it might be appropriate to accept some degree of unsaturation in triaxial testing rather than wait for "full" saturation to be achieved.

A test similar to the "B-test" can be conducted on specimens which are rigidly confined. An increase is made in the pore water pressure at one end of an undrained specimen and pore pressure transfer (PPT) is monitored at a pore pressure transducer mounted on the other end of the specimen. Alternatively, this test can be conducted by monitoring the total stress of the specimen in a cell where no drainage is allowed. The time required for either the pore pressure or the total stress change to equal the change in applied pore pressure provides a measure of how close the specimen is to full saturation. A specimen with air voids present should exhibit a slower rate of pressure transfer than a saturated material with its very low compressibility. As in the "B-test", the PPT test can, in extreme cases, induce macroscopic compressive strains or induce microfabric strains as the result of pore pressure application on an unsaturated material. Both of these techniques have the same basic limitations, they are subjective and they have the potential to induce specimen strain.

Considerable discussion of the significance of the strains induced by testing technique to the subsequently measured hydraulic conductivity of soils is present in the technical literature (Edil and Erikson 1985; McIntyre et al. 1979; and Pane et al. 1982). It is generally agreed that straining is most significant to the hydraulic performance of materials which either have a brittle micro or macro-structure, or where changes in stress were applied rapidly or on one end only. More elastic or plastic materials (such as bentonites) may not be as severely affected by microstrains.

### **6.1.3 Determining Steady-State Flow In Soils**

In the interests of developing standardized techniques for use in testing of clay liners, considerable effort has been expended in trying to define when saturation is achieved

(Section 6.1.2), and when flux through the specimen is constant. Researchers such as Pierce and Witter (1986), Anderson (1982) and Zimmie (1981) have all attempted to develop empirical techniques to define when steady state flow is reached. Pierce and Witter (1986) called for one to five pore volumes to be passed through the soil and constant  $k$  to be recorded before assuming specimen saturation is achieved. This type of criterion may be appropriate for the relatively high hydraulic conductivities they examined (approx.  $10^{-6}$  m/s). However, a material of hydraulic conductivity of  $10^{-12}$  m/s would require an unacceptably long time to meet these requirements. There would also be an additional risk of inducing significant changes to the pore fluid chemistry as the result of such extensive flushing.

An example of the time scale involved in achieving a fixed number of pore volumes displacement can be illustrated using a 10mm thick specimen of  $1.25 \text{ Mg/m}^3$  sodium bentonite. Testing of this material using a hydraulic gradient of 100 (assuming the validity of the Darcian flow model and full saturation), would require approximately 1,157 days (3 years) to transmit one pore volume of fluid. This type of flow test would not allow examination of the effect of very low gradient, or changing hydraulic gradients on flow through this material in a practical time frame.

With the impracticality of using a preset number of pore volumes to determine steady-state flow, it has been necessary to develop alternative techniques to examine the hydraulic conductivity of clays. Techniques typically used to measure very low flow rates have been described by Dixon et al. (1987,1992a,b), Sri Ranjan and Karthigesu (1992), and Haug and Wong (1992). These techniques generally involve construction of nearly saturated specimens. The specimen was then either percolated until enough fluid had been added

to fill the gas-filled pore spaces or, the specimen was back pressured to dissolve out any air. The specimens were then percolated until steady-state flow is achieved.

Testing conducted in this thesis involved either monitoring of inflow only, or both inflow and outflow. Monitoring continued until the flux into and out of (if both inflow and outflow were monitored) the specimen was constant. If the inflow was the only displacement monitored, then percolation was continued until the flux was constant for an extended time period (more than 10 days). The details of the techniques used in this thesis are presented in greater detail in Section 6.2.

#### **6.1.4 Measurement of Saturated Hydraulic Conductivity**

A large number of inherent sources of uncertainty and error in the results of hydraulic conductivity testing have been reported (Edil and Erikson 1985; McIntyre et al. 1979; Olsen 1965; Olsen and Daniel, 1981; Pane et al. 1982; Pierce et al. 1987a,b; and Tavenas et al. 1983). Table 6.1 presents the most commonly reported sources of error or inaccuracy in the measurement of water movement through soils. The causes of inaccurate flow measurement range from improper sample preparation and installation through to chemical and biological activity. The key to proper hydraulic conductivity testing is recognition of potential sources of inaccuracy in the measurements made and then taking the steps necessary to avoid inducing these sources of error. The information presented in Table 6.1 was used in the planning and conduct of the experiments presented in this thesis.

Table 6.1 Potential Sources of Error in Hydraulic Conductivity Measurement

| <u>Error Source</u>                                                      | <u>Effect on Flow</u>                                                                                                                                  |
|--------------------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------|
| Incomplete Saturation-occluded pores reducing volume available for flow  | -difficulty in determining steady-state (SS) flow<br>-extending time required to achieve SS flow                                                       |
| <u>In low activity clays</u>                                             | -increasing $k$ as the specimen saturates,                                                                                                             |
| <u>In high activity clays</u> (bentonites)                               | -decreasing $k$ as osmotic suction forces decrease and saturation is approached.                                                                       |
| Flow Along Cell Walls-Especially important in low activity soils         | -flow along the interface is higher than flow through core so higher average flow values measured<br>-significance depends on the cross-sectional area |
| Line Leakage                                                             | -Depends on location and magnitude of leak;<br>-inaccurate displacement readings occur.                                                                |
| Air Bubbles in System-Air lock in systems with low applied gradient      | -Inaccurate displacement measurements<br>-Temperature changes can result in bubble volume changes                                                      |
| Very High Gradients                                                      | -Flow channelling through or around specimen<br>-Pressure induced strain of specimen<br>-Particle reorientation or erosion due to high flow velocity   |
| Membrane Leakage                                                         | -Inaccurate displacement measurements<br>-Changes in specimen chemistry<br>-Specimen straining                                                         |
| Specimen Strain                                                          | -Changes in soil fabric and structure<br>-Generation of strain-induced hydraulic gradients                                                             |
| Non-Uniform Samples-Preferential flow and inability to reproduce results |                                                                                                                                                        |
| Voids Within Sample                                                      | -In small specimens they can result in higher $k$<br>-Voids can collapse, resulting in fabric changes                                                  |
| Smear Zones                                                              | -Reduce specimen entry porosity and hence limit flow giving a much lower than actual value for $k$                                                     |

Table 6.1 (Continued) Potential Sources of Error in Hydraulic Conductivity Measurement

| <u>Error Source</u>                 | <u>Effect On Flow</u>                                                                                                                                                                                                                                                                                                         |
|-------------------------------------|-------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| Alterations in clay chemistry       |                                                                                                                                                                                                                                                                                                                               |
| <u>In low activity soils</u>        | <ul style="list-style-type: none"> <li>-Soil fabric changes can occur, result of changes depends on the particular chemical change occurring</li> <li>-Fissuring and flow channelling may occur</li> <li>-Fabric cementation or de-cementation, resulting in a weaker, stronger, more brittle or less brittle soil</li> </ul> |
| <u>In high activity soils</u>       | <ul style="list-style-type: none"> <li>-Can be significant, especially in low density systems</li> <li>-Can cause specimen strain</li> <li>-effects already mentioned for low activity soils</li> </ul>                                                                                                                       |
| Micro-Organism Growth               | <ul style="list-style-type: none"> <li>-Can block pores and restrict flow, or form biofilms on ends restricting water entry to soil, thereby lowering measured flux.</li> <li>-Can generate chemical gradients across soil</li> </ul>                                                                                         |
| Meniscus Effects in Capillary Tubes | <ul style="list-style-type: none"> <li>-Meniscus friction can increase resistance to flow through tubes, resulting in a flux which is a function of equipment not the soil.</li> </ul>                                                                                                                                        |
| Temperature Variations              | <ul style="list-style-type: none"> <li>-Thermal expansion or contraction of specimen can result in displacements which are not a function of gradient.</li> </ul>                                                                                                                                                             |
| Stress Changes                      | <ul style="list-style-type: none"> <li>-Volume strains and associated fabric changes</li> </ul>                                                                                                                                                                                                                               |
| Flow Direction                      | <ul style="list-style-type: none"> <li>-Should not affect measured flux</li> <li>-Can result in changes in soil fabric due to particle movement under applied gradient</li> </ul>                                                                                                                                             |

The results of experiments on mass transport of water through clay soils have been reported for many decades. As technology has improved, so has the range of materials whose mass transport properties can be reliably measured and reported. The equipment and techniques described in the literature fall into the following four general categories;

- i) rigid-walled, constant volume systems with either, a constant hydraulic head (gradient), or a falling hydraulic head,
- ii) rigid-walled, constant volume systems with a fixed flow-rate.

- iii) flexible walled systems where the specimen volume is controlled by adjusting confining pressures and applying a predetermined hydraulic gradient,
- iv) rigid-walled consolidation cells, where consolidating specimens are tested using either a fixed or falling hydraulic gradients.

Each of these techniques is briefly discussed below. They are then critically compared and their applicability to the testing of swelling soils with very low hydraulic conductivity is discussed.

The ability to accurately monitor flow through specimens may be influenced by specimen size, and the influence of scale is typically associated with the possibility of higher flow rates along the soil-permeameter wall interface. There are also reports of potential volumetric straining as the result of applying back pressure to rigid wall systems (Edil and Erikson 1985; Pane et al. 1982). It should be noted that these observations were for low activity clay materials at intermediate densities. Swelling clays should not have these limitations, any channels opened as the result of wall irregularities or applied pore pressures would rapidly hydrate and swell to block such channels. Such clays are basically self-sealing. The ultimate flow rates measured for specimens originally having intentionally induced gaps, fissures or voids were found to be equivalent to those of initially intact specimens (Dixon et al., 1993b). Trials were also conducted on bentonite specimens ranging from 32mm to 100mm diameter in an effort to detect any size-dependent changes in the measured fluxes. These tests found no distinguishable differences in the flux-gradient behaviour which could be attributed to cell diameter.

### Rigid-Walled, Fixed -Volume Permeameters: Constant and Falling Head Designs

Specimens tested using these permeameters are rigidly confined to ensure volume straining does not occur. This type of testing is amongst the most common and popular as it requires "uncomplicated" equipment with a minimum of strain and flow monitoring devices. Specimens are typically rigidly confined in a cylindrical sleeve with filters on the ends to ensure uniform wetting and drainage paths. The ends are also rigidly constrained and rigid filter stones are fitted to provide uniform wetting and drainage surfaces. In most relatively high permeability materials this technique provides a quick and consistent means of determining hydraulic conductivity. A simple schematic of this type of test is presented in Figure 6.1. There are two major varieties of rigid-walled tests, the falling head and the fixed head.

Falling head permeability tests have a preset initial hydraulic potential (head) difference applied across the specimen. The hydraulic head difference is allowed to decrease as water flows from the inflow reservoir through the specimen and into the outflow reservoir. The hydraulic gradient applied is defined as the difference in the hydraulic potentials of the inflow and outflow reservoirs, divided by the specimen length. For each time period where displacement was measured, the hydraulic gradient is assumed to be the average of the potential at the beginning and the end of the increment, divided by the specimen length. The volume displaced during this time increment is used to calculate the hydraulic conductivity of the soil.

The falling head technique, while the simplest to conduct, has a number of limitations. It assumes that the flow through the specimen is Darcian in nature and so the average hydraulic head is representative of the flow occurring at both the maximum and minimum



hydraulic gradients present during testing. Additionally, this technique only works effectively when the head change and volume displacements are large enough to be monitored accurately. Associated with the measurement of head and displacement is the need to ensure that evaporative volume losses from the reservoirs are minimized or prevented.

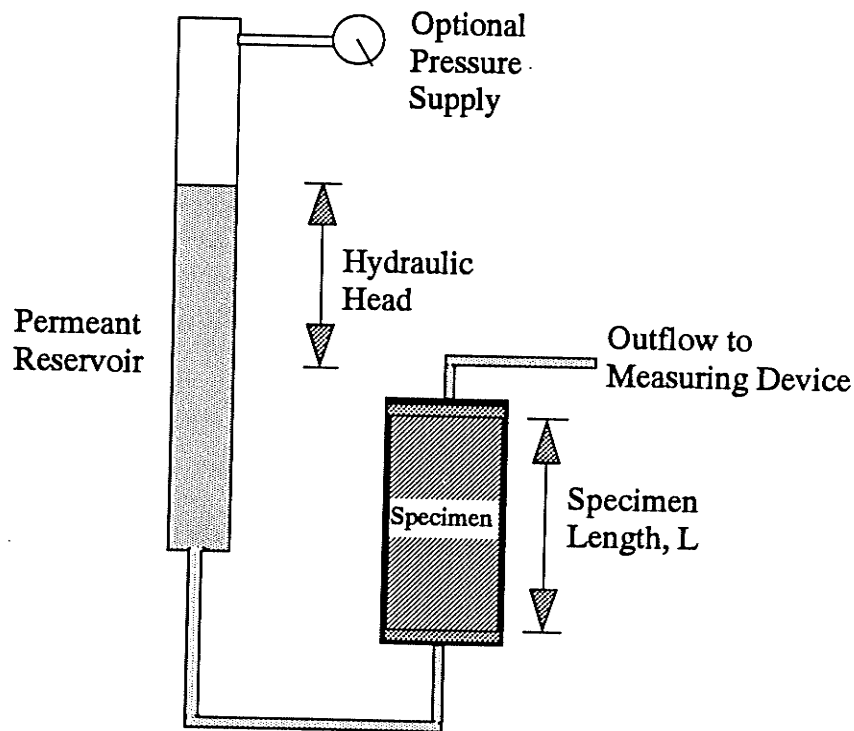


Figure 6.1 Falling Head Permeability Test Using a Rigid Walled Cell: Basic Design

It is possible to use fluid reservoirs with large volumes (especially large diameters) and sensitive displacement gauges to minimize any head changes while monitoring small fluid displacements. In such a system, the hydraulic head will vary by only a few millimetres

over the course of the entire test. This means that the hydraulic gradient was for all purposes a constant. This technique has been used by a variety of researchers to measure flow through low permeability clays (Sri Ranjan and Karthigesu 1992; Karthigesu 1994; Dixon et al. 1986, 1987, 1993a). Hydraulic conductivities as low as  $10^{-14}$  m/s have been reported by Pusch (1980a,b) and Bucher et al. (1986) for materials tested using this technique.

The constant head permeability test is virtually identical to the falling head test, except that the pressure gradient across the specimen is kept constant throughout the test. This constant gradient is commonly achieved by using over-flowing inflow and outflow reservoirs. In this technique a supply of water is supplied to a reservoir at a rate slightly higher than the specimen will transmit the water. The surplus fluid will overflow the reservoir and be lost to the inflow reservoir. Likewise, the outflow reservoir is initially filled to the preset level and the outflow from the specimen will overflow this reservoir, thereby ensuring that the outflow pressure is kept constant. In this manner the applied hydraulic gradient is kept constant. There is a difficulty in using this technique when very high gradients, or back pressuring are used since the overflow systems must be maintained at elevated pressures. Alternatively a bladder-type system can be used to ensure that the hydraulic head is kept constant despite relatively large fluid movements.

#### Rigid-Walled, Constant-Volume and Constant-Rate-of-Flow Permeameter

A modification to the traditional constant-head hydraulic conductivity test was the development of a constant-rate-of-flow testing technique. In this technique, a metering pump is used to inject water at a constant quantity per unit time. This flow rate (flux) is maintained, regardless of the pressure gradient developed across the specimen which can

be measured using pore pressure transducers mounted at each end of the specimen. Alternatively, a differential pressure transducer can be used to measure the pressure difference across the specimen. This technique has a number of advantages to the other rigid-walled testing techniques since it does not require any special displacement gauges or fluid reservoirs. Hence, the constant-rate-of-flow permeameter has fewer connections, less tubing and a lower number of potential sources of leakage. This technique has been used extensively in testing low permeability materials where the flux attainable using traditional pressure supplies is at, or below, the normal level of detection for displacement monitoring devices. Suitable equipment has been described in considerable detail by Olsen (1966), Olsen and Daniel (1981), Olsen et al. (1985) and Pane et al. (1982). A schematic of this type of permeameter is presented in Figure 6.2.

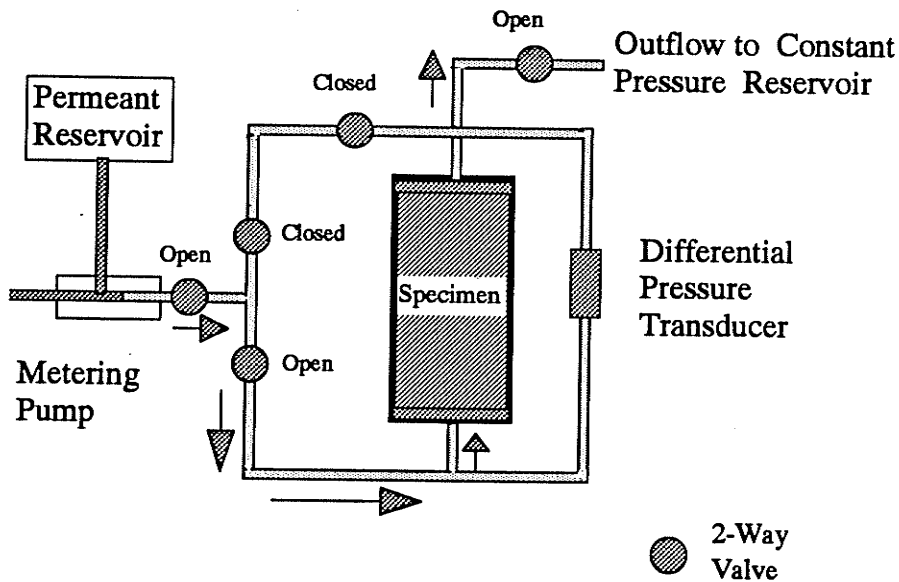


Figure 6.2 Rigid-Walled, Constant-Rate-of-Flow Permeameter: Basic Design

While the constant-rate-of-flow technique has a number of advantages over the falling or constant-head permeameter, there are a number of significant limitations to use of this technique. Olsen (1985) used small specimens (10 cm<sup>2</sup> cross section, 7.7cm length) and the minimum displacement rate measured using their metering pump was  $1.0 \times 10^{-12}$  m<sup>3</sup>/s. This displacement rate translates to a minimum flux of  $1.0 \times 10^{-9}$  m<sup>3</sup>/s/m<sup>2</sup>, and so for a specimen with a  $k$  of  $10^{-12}$  m/s (similar to the materials studied in this thesis), the minimum hydraulic gradient which can be generated is 1000. Olsen et al. (1985) reported that a metering system which was capable of supplying water at  $10^{-13}$  m<sup>3</sup>/s was being developed. This still means that the minimum gradient would be approximately 100. If the specimen cross section were increased to as much as 78.5 cm<sup>2</sup> (100mm diameter) the minimum gradient attainable would be approximately 12.7. This places the minimum gradient well above field conditions and limits the usefulness of this technique in studying flow through materials of very low hydraulic conductivity ( $<10^{-12}$  m/s).

#### Flexible Walled Permeameter

Flexible walled permeameters have been used for a number of years, commonly in association with triaxial compression testing of materials. The equipment used is much the same as that used in confined, drained triaxial tests, excepting that the top and bottom drainage reservoirs are separate and held at different pressures. This induces a hydraulic gradient across the specimen and the flow rate across the specimen can be monitored using traditional displacement gauges. This technique has been used successfully in relatively short duration permeability tests on materials of moderate to low hydraulic conductivity ( $10^{-6}$  to  $10^{-11}$  m/s) (Edil and Erickson 1985 ; Haug and Wong 1992; Haug and Sauer 1993). However, such permeameters have not been used for very long term testing of high swelling capacity specimens with very low hydraulic conductivity.

The general setup for a flexible walled permeameter is presented in Figure 6.3. The advantages, disadvantages and limitations of this type of device are discussed in considerable detail by a large number of researchers including, Black and Lee (1973), Daniel et al. (1984,1985), Bowders (1987), Boynton and Daniel (1985), Carpenter and Stephenson, (1986), Edil and Erikson (1985), Haug and Wong (1992), Haug and Sauer (1993), McIntyre et al. (1979), Olsen and Daniel (1981), Olsen et al. (1985), Peirce et al. (1986) and Tavenas et al. (1983). Most of these researchers prefer the use of a flexible walled permeameter, but Bowders (1987), Daniel et al. (1985), Edil and Erikson (1985) and Peirce et al. (1987b) found that the results obtained using a flexible walled permeameter are essentially the same as those obtained from a rigid walled permeameter. This conclusion was stressed as being particularly valid when testing is done at low hydraulic gradients (Edil and Erikson 1985). At high hydraulic gradients the flexible walled permeameter was preferred to the rigid walled since water channelling between the specimen and the cell wall was seen as a potential mechanism which could affect flow.

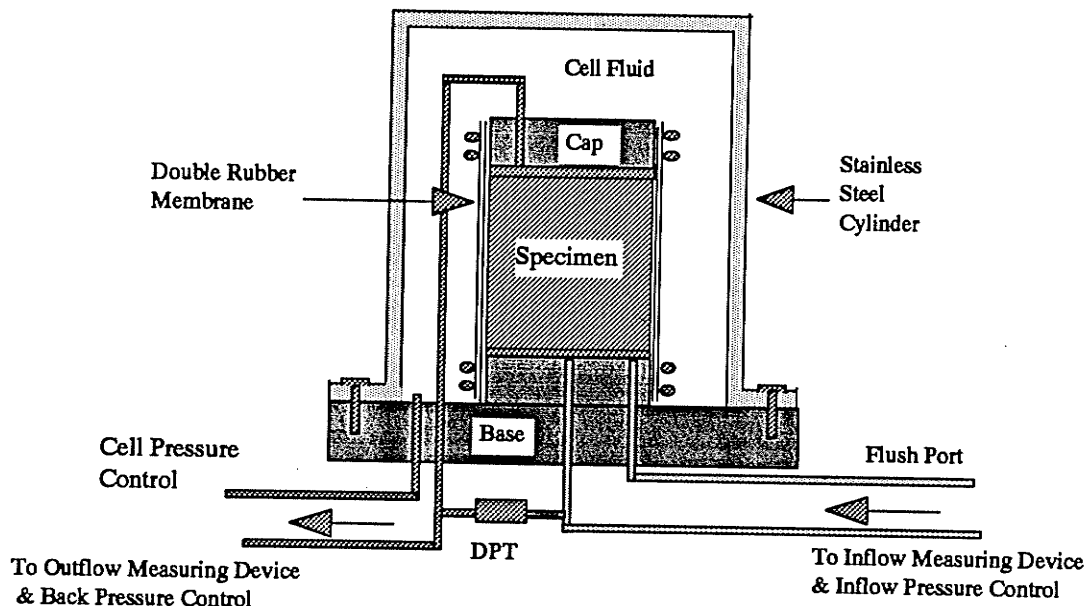


Figure 6.3 Flexible Walled Permeameter: Basic Design (after Haug and Sauer 1993)

The flexible walled permeameter has some limitations in its application to testing very low permeability materials, particularly in terms of potential sources of leakage. (Tavenas et al. 1983). Membranes are not completely impermeable and so for long duration tests, diffusion into or out of the specimen can become significant. Membranes are also subject to chemical attack or mechanical failure if left for long time periods. There is an additional complication in using this technique for bentonitic materials, the cell must be able to provide the 1 MPa to 2 MPa confining pressure needed to prevent specimen swelling (clay densities  $> 1.3 \text{ Mg/m}^3$  would require even higher confining pressures). This means that testing of bentonites would require special triaxial cells capable of providing high pressure confinement. The permeant reservoirs for these systems must also be pressurized and capable of maintaining a small pressure gradient across the specimen.

#### Consolidation Testing to Determine Hydraulic Conductivity

Consolidation testing is still widely used to obtain a measure of the hydraulic conductivity of a soil. This technique was presented by Terzaghi and Peck (1976) as one which could use the measured rate of clay compression, and hence the drainage rate, to calculate hydraulic conductivity. This procedure uses specimen strains to calculate flow, and so is not appropriate for use in determining the mass transport properties under low hydraulic gradients. Straining of the soil skeleton during the consolidation process violates one of the basic requirements of Darcy's law (Table 3.2), that the soil fabric not change during the testing process. As a result, this technique is not appropriate for use in examining the performance of swelling clays under conditions of low applied hydraulic gradient.

### **6.1.5 Selection of Permeameter Type For Use In Testing Dense Clays Having a High-Swelling-Capacity**

The majority of literature dealing with measurement of hydraulic conductivity in clay soils focusses on materials of low swelling capacity and relatively high hydraulic conductivity. For these materials it is generally accepted that either rigid-walled or flexible-wall permeameters will produce comparable results (Bowders 1987; Daniel et al. 1985; Edil and Erikson 1985 and Pierce et al. 1987a). However, if there are special environmental concerns (aggressive chemicals, high back pressure) flexible walled systems have some limitations. Constant rate of flow devices have certain advantages in terms of ease of measuring displacement and determining the hydraulic gradient. However, this device is limited in terms of the minimum measurable hydraulic conductivity and the hydraulic gradients generated are higher than are required for this thesis.

The final consideration in the process of selecting the most appropriate type of permeameter for use in this project was the nature of the materials being investigated. The swelling clays examined in this research program contain a considerable content of soluble and potentially corrosive salts (Section 4.3.1). Additionally, the low hydraulic conductivity for these materials had already been established ( $k < 10^{-11}$  m/s), and as a result the time required to complete each test was known to be in the order of 6 to 18 months. A flexible walled system therefore contained a larger number of potential sources of time-dependent leakage or failure owing to the membranes used to confine the specimen. A rigid walled permeameter system was simple to construct and contained a lower number of potential sources of mechanical failure.

After considering the options available for the design and operation of permeameters, a rigid-walled permeameter and a near-constant-head pore pressure source was selected

as the best compromise of reliability and accuracy. A system of ten stainless steel permeability cells, complete with stainless steel tubing was designed and built for use in this research program. Such systems provide the best combination of ability to resist the aggressive nature of the pore fluid present while maintaining a nearly constant hydraulic gradient across the specimen.

## **6.2 Equipment Design**

### **6.2.1 Introduction**

The review of potential permeameter designs presented in Section 6.1 suggested that a rigid-walled permeameter was the most appropriate for use in measuring flow through dense, low permeability, swelling clays. Specifically, the permeameter needed for this project had to meet the operational requirements presented in Table 6.2.

**Table 6.2 Requirements of Permeameter For Use in Tests Conducted at Low Hydraulic Gradients**

- 1) Withstand high internal stresses (swelling pressures)
- 2) Resist attack by saline pore fluid
- 3) Maintain anaerobic conditions
- 4) Maintain stable pressure gradient
- 5) Apply a wide range of pressure gradients
- 6) Apply no or high back pressures
- 7) Measure very small pore fluid displacements
- 8) Exhibit no, or very low leakage for long duration tests



These requirements led to the design and construction of several sizes of permeameter cells, briefly described by (Dixon et al. 1987, 1992a,b), and a displacement gauge capable of measuring very small rates of flow.

### **6.2.2 The AECL Permeameter**

To meet the testing requirements outlined in Table 6.2, special permeameter cells, displacement gauges and flow controls were developed. All the tubing and non-glass materials used in the system were stainless steel. This was to limit the effects of aggressive pore fluid, to limit tubing strain due to pressure and to prevent water diffusion through the walls of the tubing. The steel tubing allows very high back pressures or gradients to be applied to the specimens without concern for system leakage or failure. This type of permeameter has previously been used in studies of the effective stress concept and were found to operate reliably at applied pore pressures as high as 10 MPa. They can withstand at least 14 MPa total internal pressure (Graham et al., 1986). Although capable of operating at these pressures, the cells were typically operated at either a nominal back pressure (10 to 20 kPa), or at 1.5 MPa. These back pressures were selected to allow comparison of the effect of back pressure on the measured hydraulic conductivity of swelling clays. The results of these comparisons are presented in Chapter 7.

Four different sizes of cell, of two basic designs were constructed with internal diameters of 32mm, 50mm, 75mm or 95mm. The cells were capable of holding specimens of 5mm to 60mm in height. Figures 6.4 and 6.5 provide schematics of the two basic cell types used in this research. The particular cell selected for use in each test was selected on the basis of the estimated minimum flux (flow volume per second per unit cross-sectional area of specimen), which would be measured in the course of testing. For testing at low hydraulic

gradient, the larger cells had sufficient cross-sectional area to permit the small fluxes present to be detected with the displacement gauges available.

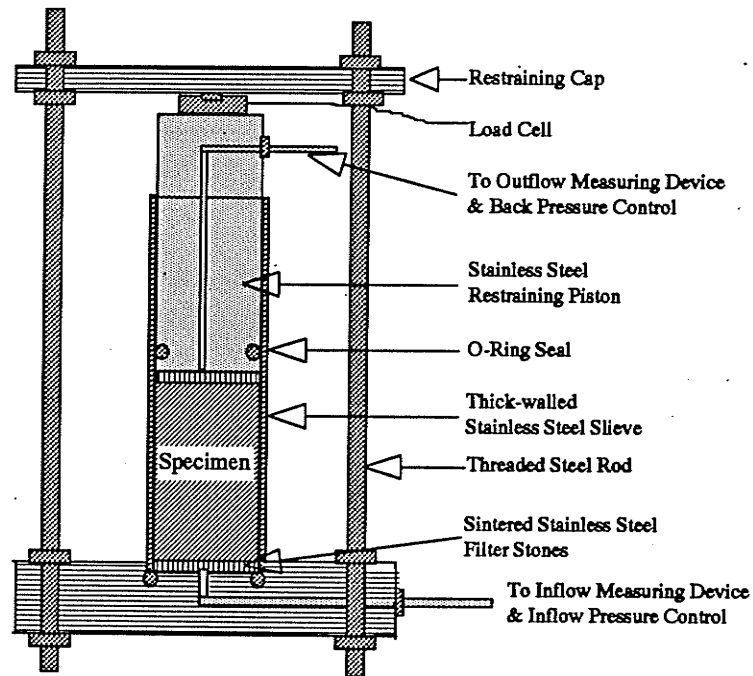


Figure 6.4 Design of Cells Used in Hydraulic Conductivity Testing (32mm & 50mm diameter Cells)

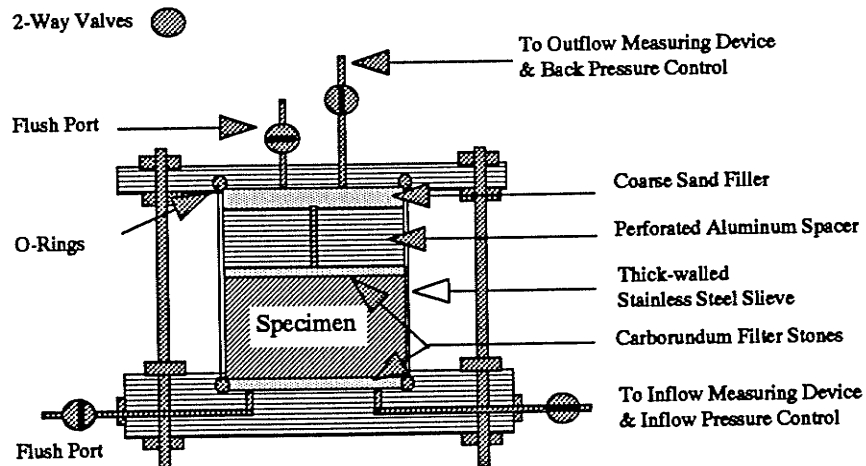


Figure 6.5 Design of Cells Used in Hydraulic Conductivity Testing (75mm & 95mm diameter Cells)

The gauges used in conjunction with the permeameters had one of two possible volumes, either 2.0 ml or 3.5 ml (with 0.005 ml resolution). It was important to match the gauge capacity and the cross-sectional area of the cell with the expected flux through each sample prior to specimen construction. This ensured the best selection of displacement capacity and minimized the number of changes in gauge flow direction. Fluid reservoirs with large capacity were used to minimize changes in applied hydraulic gradient with time. Typically the fluid level in the reservoirs varied by 2mm to 5mm for each gradient examined. The reservoir levels were routinely monitored throughout the tests and were adjusted as necessary to minimize the effects of changing fluid levels on hydraulic gradient. Such a variability in the fluid level represented a variation in the applied gradient of 0.2 to 0.5 for a 10mm long specimen (magnitude decreased with increasing specimen length). This magnitude of reservoir level change was typically observable only when high fluxes were occurring, and the reservoir levels were notably lowered by this displacement. Tests conducted at lower hydraulic gradients typically showed reservoir level changes of less than 2mm (gradient change of  $<0.2$ ). These gauges were under the same pore pressure as the specimen to prevent any effects of fluid degassing or gas compression or expansion within the specimen.

The displacement monitoring systems were constructed using stainless steel components and a high pressure glass tube was installed to permit monitoring of fluid movement. Displacement was monitored by recording the location of a volume of coloured paraffin oil visible through the glass tubing. As water moved into or out of the specimen the oil was displaced and this displacement was measured using a graduated volumetric scale mounted behind the glass tubing. These gauges were constructed in a manner which

permitted the direction of oil movement to be reversed without interfering with water movement into and out of the specimen or disrupting the established hydraulic head.

Two basic displacement gauge orientations were developed for use in this research project. The differences between these two systems resulted from the inherent limitations of using a single type of gauge to measure flow at low hydraulic gradients. A number of systems were constructed with the displacement gauges mounted so that the oil level was measured as upwards or downwards displacement (Figure 6.6). These systems were used for materials where the hydraulic gradients examined exceeded 50. These gauges were used for two reasons. First, the rate of flow at high gradients was considerable and a vertically mounted gauge was less likely than a horizontally mounted gauge to exhibit a breakup of the oil column when the flow rate was high. The second reason for using these gauges at higher applied gradients was that the paraffin oil used to monitor displacement has a lower density than water (0.876 versus 1.00), and so will influence the hydraulic pressure actually applied to the specimen.

The effect of the length of the column of paraffin oil on the hydraulic gradient applied to the specimen can be estimated. The maximum length of the paraffin column is 0.38m and 0.57m for the 2ml and 3.5ml gauges respectively, and this could then be used in calculating the buoyant forces present. At full extent, the buoyant force of the oil is equivalent to 0.047m to 0.062m (the difference in the density of the fluids over the length of the column). This buoyant force translates to a maximum change in the hydraulic gradient actually applied to the specimens of 1.0 to 6.2, depending on the particular specimen being tested. As the oil position was continuously monitored, it is possible to apply a correction to the hydraulic head to account for the effects of this force. At higher

hydraulic gradients ( $>200$ ), the significance of this effect became negligible and gradient corrections were not applied to the data.

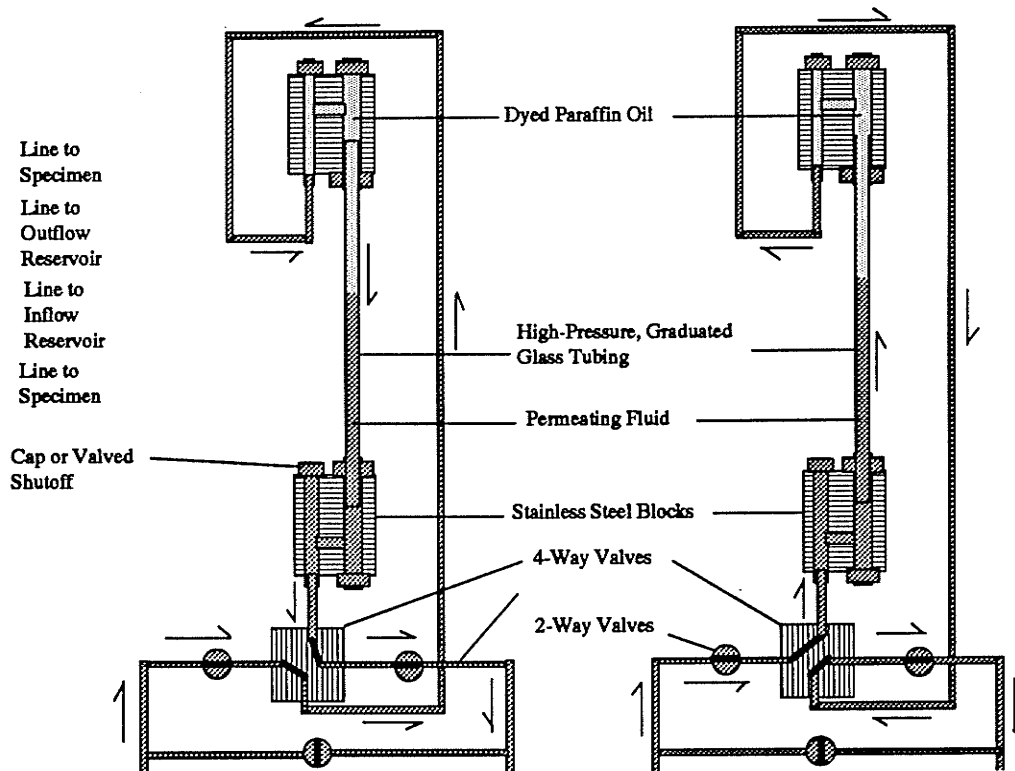


Figure 6.6 Displacement Gauge Used For Testing Hydraulic Conductivity at Applied Gradients Exceeding 50

For specimens tested at low hydraulic gradients ( $<50$ ) a second type of displacement monitoring system was utilized. Flow through these materials was measured using horizontally mounted displacement gauges (Figure 6.7). This orientation minimized the influence of buoyant forces of the oil in the gauges to a maximum of 0.004m. This represented an induced gradient variability of less than 0.35 (for a 1 cm thick specimen). The actual variability of the hydraulic gradient caused by oil buoyancy was usually

considerable less than this worst-case value. As the measurement of the applied hydraulic head in these systems was critical to the determination of the hydraulic gradient, glass tubes were mounted in parallel to the main fluid reservoirs. These tubes allowed direct and accurate measurement of the water levels at the inflow and outflow reservoirs thereby ensuring that the desired hydraulic gradient was the same as was actually applied to the specimen.

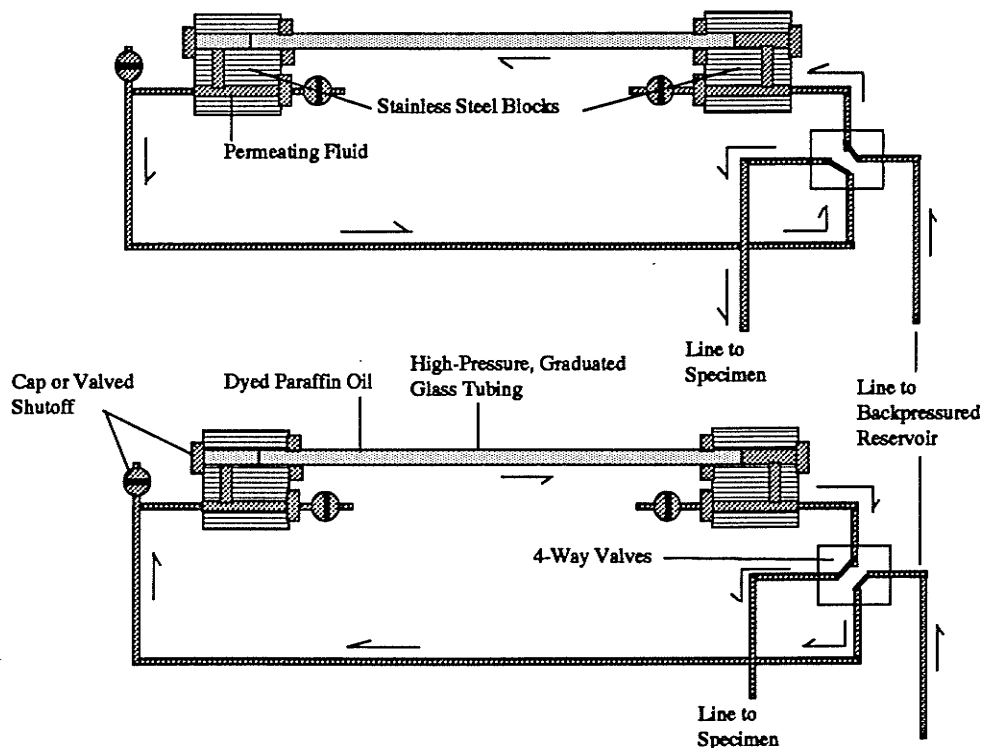


Figure 6.7 Displacement Gauge Used To Monitor Flow At Low Applied Hydraulic Gradients

In tests where there was either a need for back pressure or the applied gradient exceeded approximately 150, the permeant fluid reservoirs were pressurized by use of an inert gas (Argon). Argon minimized the oxygen content of the system and induced an anaerobic (low oxygen content) environment within the system. Anaerobic conditions also limited

the growth of many of the aerobic bacteria and algae which could adversely affect the displacement monitoring system, thereby limiting some of the potential difficulties outlined in Table 6.1. This method of fluid pressurizing does not prevent the growth of anaerobic bacteria or other biota which prefer an oxygen depleted environment. The potential influence of these bio-organisms on flow through these clay soils has previously been presented in Sections 3.5.4 and 4.3.2. Anaerobic conditions within the specimen also simulate the conditions which are likely to exist in the deep geological environment following the resaturation of a nuclear fuel waste disposal vault (Stroes-Gascoyne and West, 1994).

### **6.2.3 Qualification of the AECL Permeameter Systems**

As was outlined in Table 6.3, one of the key requirements of the permeameters used in this project was that they operate reliably for extended times. Prior to each test, the permeameter to be used was inspected and leak tested. If leakage was detected the system was repaired or, if the leakage source could not be found, the system was either rebuilt or the leakage rate was calibrated into the displacement calculations. If the system developed a leak in the course of testing, the leaks were either repaired and the system leak tested prior to test resumption, or the test was terminated. At the end of each test the system was rechecked to ensure no leakage had developed in the course of the experiment, or that the previously determined leakage rate had not changed.

While no system was entirely leak proof, trials on these permeameters measured very small displacements, which expressed as a hydraulic conductivity equivalent, were much less than  $10^{-15}$  m/s. Most of the hydraulic conductivities measured in this research were in the range of  $10^{-10}$  to  $10^{-13}$  m/s, which puts the leakage at less than 1% of the measured

hydraulic conductivity. Leakage at key interfaces within the cell (between the sleeve and end caps, or the sleeve and piston), and within the displacement monitoring system (the seals between the glass tubing and the mounting blocks), was minimized by the use of O-ring seals. At the end of each test these O-rings were visually inspected, if they showed any indication of deformation or damage they were replaced.

In the course of this research there were only three occasions where uncontrollable cell leakage was detected and on a few other occasions small leaks were detected in fittings on the displacement gauges. The weakest points in the entire system were found to be the stems of the pin valves or around the swage fittings used to join the components of the system. Such leaks or failures were typically only detected in systems that had been in service for three or more years and resulted from repeated pressurizing and depressurizing, or corrosive attack by saline pore fluids. These leaks could usually be corrected without terminating the test, either by tightening the appropriate joint to reseal the fitting or, replacing the affected portion of the tubing.

The two most important factors influencing the pore fluid displacement readings were found to be air pockets in the displacement gauges and variations in the laboratory temperature. If the gauge blocks were not correctly deaired small air bubbles could be left behind in some of the drainage lines. These bubbles did not directly affect the flow measurements but changes in the applied gradient resulted in changes in pore water pressure and as a result these bubbles would expand or contract. Such volume strains were reflected in the gauge readings, evidencing themselves as sudden volume changes on application of a new gradient. Another source of reading variability was the effect of laboratory temperature variations. In a tightly sealed system, such as these



permeameters, changes in the ambient temperature resulted in expansion or contraction of the cell and its contents. These volume changes could be detected in the displacement gauges and if temperature was not held stable, could have made interpretation of the data difficult. This effect was noted prior to the commencement of the thesis research and was addressed by moving the laboratory to a location where temperature could be more carefully controlled. The laboratory temperature was targeted to be within 1.5 °C of 20°C. Based on the  $\beta_w$  values presented in Chapter 5 ( $\beta_w = 1.785 \times 10^{-6} \text{ m}^3/\text{m}^3/^\circ\text{C}$ ), a 3°C change in the temperature of a water saturated specimen would result in less than 0.001cm<sup>3</sup> change in the specimen volume. This displacement is based on a 95mm diameter by 20mm high specimen (142ml, the largest used in this thesis) compacted to a density of 0.5 Mg/m<sup>3</sup> (the lowest used in this thesis). Such a specimen would have the highest potential for volume change with temperature change (volume water = 117ml, volume solids = 25ml), since it contains the highest water content.

The accuracy of displacement monitoring gauge readings was 0.005ml , some five times higher than the thermally-induced change in the volume of the pore fluid. Hence, this temperature control should have induced no measurable volumetric fluctuation and so a 3°C range in room temperature was deemed suitable for obtaining "constant" temperature flow measurements.

All the bentonite clay specimens tested in this project were statically compacted directly into the test cells using a vertical ram to compress a premeasured mass of material to a preselected volume. This technique ensured a good bond between the specimen and the cell wall, thereby minimizing the potential for leakage along this interface. It is recognized that this technique has the potential to induce preferential particle orientation especially

at higher degrees of compaction (Gray et al. 1984, 1985) and may induce some anisotropy in the stress-strain behaviour of bentonite-sand specimens (Graham et al., 1986). However, based on a compilation of the swelling pressure - clay density data available from their own tests and literature Gray et al. (1984, 1985) determined that the fabric of compacted bentonite specimens produced by static compaction was isotropic to clay dry densities approaching  $1.6 \text{ Mg/m}^3$  and was not noticeably affected by the moisture content at the time of compaction. Since the density of the bentonite materials examined in this thesis did not exceed  $1.5 \text{ Mg/m}^3$  an assumption of fabric isotropy is justifiable. Section 7.4.4 presents the details of trials which confirmed that the initial degree of saturation did not effect the ultimate hydraulic conductivity of these specimens.

For the sake of consistency and ease in describing the results of hydraulic conductivity testing, a set of definitions was developed for the direction of flow and the "inflow" and "outflow" directions. The standard manner of water percolation was from the cell base to the top of the cell. Flow in this direction was defined as being positive, while flow from the top to the bottom of the cell was defined as negative. The hydraulic head difference (and hence gradient), was defined as being positive when the fluid pressure at the cell base exceeded that at the top of the cell. A negative hydraulic head difference (and hence gradient), was defined as being a condition where the fluid pressure at the cell top exceeded that at the base. These conventions were maintained throughout the entire testing program and permitted plotting of "reversed" flow direction. The significance of these sign conventions becomes clear in Section 7.4 where the results of testing are presented.

To further check the operation of the displacement measurement system used in this thesis, the flux-gradient relationships developed using this permeameter design were compared with those obtained using an independent laboratory and a different operator. This check was conducted using the displacement monitoring system established at the Agricultural Engineering Dept. at the University of Manitoba (UM) in 1992 and subsequently used by Karthigesu (1994). Two illitic clay specimens were first tested at Whiteshell Laboratories (WL), where the testing for this thesis was conducted. The cells with the specimens still inside were then transferred and tested at UM. The operator at the UM had no knowledge of the results obtained at WL and only when all testing was completed were the results compared. The results of this comparison were published by Dixon et al. (1992) and provide confidence in the reproducibility of the tests conducted using the permeameters used in this research.

## **7.0 HYDRAULIC CONDUCTIVITY TESTING**

### **7.1 Selection of Test Conditions**

An ambitious series of hydraulic conductivity tests was planned and conducted for this project. To a previously existing data base of hydraulic conductivity tests conducted by this researcher, and data obtained from literature sources (100 tests), a new set of tests was conducted to provide a complete range of density and hydraulic gradient conditions. Tests done previous to this project were largely performed using high hydraulic gradients, typically in excess of 1000 and in some cases as high as 200,000 (see for example Westsik et al. 1982, 1983).

The hydraulic conductivity tests conducted for this project consisted of 3 specimens of silica sand, 9 specimens of illitic clay, 24 specimens of sodium bentonite and 3 specimens of sand-bentonite buffer. In addition to the hydraulic conductivity data obtained for the bentonite and buffer materials, a further 11 bentonite-sand specimens and 11 bentonite specimens had been tested earlier by the author as part of other research projects (Dixon et. al, 1987). These earlier tests were found to contain data (obtained at applied hydraulic gradients  $> 1000$ ), that have been included in the thesis to provide a broader data-base for behavioral comparison.

Silica sand specimens were included to validate the permeameter design for this project by confirming the Darcy equation in a material which is known to exhibit Darcian flow behaviour. Details of the test procedures and results are presented in Sections 7.2 and 7.3 respectively.

Illitic clay specimens provided the first test of the ability of the permeameters to measure low flow rates and provided a check on the flux-hydraulic gradient behaviour of dense, but low surface area clay materials. A total of 9 illitic clay specimens were formed and tested. The dry densities of these specimens ranged from  $1.6 \text{ Mg/m}^3$  to  $2.1 \text{ Mg/m}^3$ . This range was selected to study the influence of decreasing porosity on the rate of water flow through these clays.

The majority of the specimens composed of 100% bentonite clay were constructed from BaraKade Standard® bentonite, produced by Bentonite Corporation, or Civil Engineering Grade® bentonite, produced by Canadian Clay Products Inc.. A few specimens were constructed of other brands of Wyoming bentonite. Work by Dixon and Miller (1995) established that these materials were of similar mineralogical, swelling and hydraulic character and would produce hydraulic data which was indistinguishable from other Wyoming bentonites. A range of specimen densities and initial degrees of saturation was studied. Clay density varied from  $0.55 \text{ Mg/m}^3$  to  $1.46 \text{ Mg/m}^3$ , and the initial degree of saturation ranged from less than 5% (oven-dry state) to greater than 90%. As with the illitic clay, a range of initial density and degree of saturation was selected to determine the effect of initial moisture content on the ultimate flow behaviour of compacted bentonite specimens. While most of these specimens were prepared using, and percolated with, distilled deionized water (DDW), 3 of the tests were conducted using SCSSS brine solution as the conditioning and percolating fluid. This brine simulates the ground water composition found at 1000m depth in a granitic pluton within the Canadian Shield (Dixon and Woodcock, 1986). It contains such a high concentration of cations (Na, Ca, Mg) and anions (Cl and  $\text{SO}_4$ ) that the diffuse double layer (DDL) should be minimized (see Section 2.3.4). Any observed changes in the flux-hydraulic gradient relationship for specimens of

equal density but differing pore fluid composition could be attributed to the effects of changes in water structure. Details of the method used to prepare and test bentonite clay specimens are provided in Section 7.3.2, and the results of these tests are presented in Section 7.4.

Three specimens composed of equal dry weight proportions of silica sand and sodium bentonite were also examined in this project, and the results combined with data generated by eleven previous tests on bentonite-sand mixtures. This mixture of equal dry weight proportions of sand and bentonite clay is the reference buffer material (RBM) proposed for use in the Canadian Nuclear Fuel Waste Management Program's (CNFWMP) conceptual disposal vault. The physical, mechanical and hydraulic properties of this material have been examined extensively by Gray et al. (1984, 1985), Cheung et al. (1985, 1987), Oscarson and Dixon (1989), Oscarson et al. (1990), Dixon and Gray (1985), Dixon and Miller (1995), Dixon et al. (1984, 1985a, 1987, 1992a,b, 1993b, 1994a), Graham et al. (1986, 1989), Radhakrishna and Chan (1985), and others. Early in the buffer development program it was determined that when the bentonite content exceeds approximately 25% by mass, the swelling pressure and the hydraulic conductivity are largely controlled by the clay portion (Gray et al. 1984; Dixon et al. 1987). This clay content has been expressed as the effective clay dry density (ECDD,  $\gamma_c$ ) (Gray et al. 1984, 1985). Equation 7.1 presents the means by which the  $\gamma_c$  of a sand-bentonite mixture is calculated.

$$\gamma_c = (m_c / (V_T - (m_s / G_s))) \quad (7.1)$$

where  $m_c$  is the initial dry mass of bentonite,  $V_T$  is the total volume of the specimen,  $m_s$  is the dry mass of the sand component and  $G_s$  is the specific gravity of the sand.

Oscarson and Cheung (1983), suggested that the mass diffusion coefficient is highly dependent on the effective porosity parameter ( $n_{eff}$ ), described below. As mentioned in Section 3.2, Cheung et al. (1987) predicted that the thickness of the bound-water layer on a Na-bentonite platelet would be between 0.1nm and 0.4nm (averaging 0.25nm, or one water layer). Previously Pusch (1980b), estimated that the thickness of mechanically stable water layers on the surfaces of clay platelets would be in the range of 0.5nm to 1.0 nm (2 to 4 water layers). The structure of water associated with clay surfaces was discussed previously in Section 3.2. It was decided to use the bound-water layer thickness provided by Cheung et al. (1987) to develop an expression for effective porosity in clay-sand systems. The presence of a single bound-water layer is a more conservative assumption as it allows a larger porosity to be available for flow.

Data from the RBM and other clay-sand specimens have been examined to establish the validity of using the  $\gamma_c$  and  $n_{eff}$  parameters for predicting pore fluid flow under conditions of low applied hydraulic gradient. Calculated values of the  $\gamma_c$  and  $n_{eff}$  parameters are presented Section 7.2. Based on the relationships developed to describe  $n_{eff}$ ,  $d$  and  $d'$  in pure clays (Equations 3.7 through 3.11), it is possible to estimate the effective porosity available for flow in clay-sand mixtures by use of Equation 7.2.

$$n_{eff} = 1 - \gamma_d [(1/G_{mix}) + (0.15P/(1+P))] \quad (7.2)$$

where  $G_{\text{mix}}$  is the average specific weight of the mixture, and  $P$  is the mass ratio of clay to sand in the mixture. The specific surface measured for Na-bentonite was presented in Table 4.2 and is assumed to be  $600 \text{ m}^2/\text{g}$ . The sand is assumed not to absorb water. The value of  $n_{\text{eff}}$  is always less than the absolute porosity ( $n$ ) given by the Equation 7.3.

$$n = 1 - \gamma_d / G_{\text{mix}} \quad (7.3)$$

Pusch (1980b) reported results from a limited number of tests that examined the effects of changing hydraulic gradient on the Darcian hydraulic conductivity of dense bentonites. He reported that deviations from Darcian flow behaviour occurred with changes in applied hydraulic gradient and predicted that increasing hydraulic gradients would result in increases in the hydraulic conductivity. His conclusion was that most flow occurred in regions further than  $1 \text{ nm}$  from the particle surfaces. This means that the effective porosity parameter would not be a constant and so should not provide a means for predicting the hydraulic behaviour of bentonitic soils. In contrast, the same type of bentonite was studied by Bucher et al. (1986) who observed no significant changes in hydraulic conductivity with changing hydraulic gradients. Detailed analysis of the applicability of using the  $n_{\text{eff}}$  and  $\gamma_c$  parameters for describing the hydraulic performance of bentonite clays and clay-sand mixtures is presented in Sections 7.4 and Chapter 8.



## **7.2 Specimen Preparation and Testing Procedures**

### **7.2.1 Silica Sand Specimens**

Sands were tested primarily to confirm the accuracy of the permeameters. It can be expected that clean, uniform sand will exhibit Darcy-type flow (Yong and Warkentin 1975).

Three different sizes of rounded sand were examined in this thesis. These sands were,

- (1) a 20-40 mesh (95% by weight sized between 0.84mm and 0.42mm diameter),
- (2) a 40-70 mesh sand (95% by weight was sized between 0.42mm and 0.21mm diameter), and
- (3) a 70-140 mesh sand (95% by weight was sized between 0.21mm 0.105mm diameter).

These samples were installed in the cells by displacing water in water-filled sleeves with clean, wet sand, followed by tamping and vibrating the emplaced material to densify the sand and release entrained air. A hydraulic gradient was then applied across the specimen and flow was monitored until the flux was constant. The applied hydraulic gradient was increased in a stepwise fashion until the maximum flow rate through the gauges was reached (approximately  $1.5 \times 10^{-8} \text{ m}^3/\text{s}$ ). When the maximum achievable hydraulic gradient was achieved, the hydraulic gradient was decreased and the flux was again measured. This was done to ensure that there was no hysteresis in the results obtained. At the end of testing, the specimen dimensions and mass were determined and the sand density was calculated. The results of the testing of these sands are presented in Section 7.3.

### **7.2.2 Illitic Clay Specimens**

Six specimens of illitic clay (LHI02A;B;C and LHI03A;B;C) were constructed by statically compacting the clay using a hydraulic ram. The specimens were constructed to a range

of initial moisture contents, (oven dried through to 90% of saturation). These conditions were used to determine whether initial moisture content had any influence on the ultimate hydraulic conductivity of the clay. A further three specimens (LHI01A;B;C) were produced by consolidation of illitic clay slurries using a dead weight load frame. These specimens were consolidated until the desired densities were obtained. The consolidation cells used in this process were specially designed to fit the base and top caps used in the permeability cells. At the end of consolidation, the specimens were transferred directly into the permeability testing systems without the need for further trimming. This technique avoided the possibility of specimen disturbance.

The rate of water movement through these clays limited the maximum hydraulic gradient that could be applied to 125, and usually the applied hydraulic gradient was considerably less than 100. The initial hydraulic gradient applied to the illitic clays was fairly low (2 to 10). When the flux through the specimen stabilized for a particular hydraulic gradient, the head was increased until the maximum attainable flux was reached. The applied hydraulic gradient was then decreased in a step-wise manner until the hydraulic gradient applied was lower than that initially imposed on the specimens. This was to examine whether there was any hysteresis in the flux-hydraulic gradient behaviour for the clay. Hysteresis in the plot would indicate that there had been some fundamental change in the hydraulic behaviour of the soil, perhaps as the result of incomplete saturation or fabric changes resulting from water percolation. At the end of each test the specimen was measured while still in the sample sleeve. It was then extruded, weighed and oven dried to obtain final masses and moisture contents. The results of these tests on illitic clay materials are presented in Section 7.3.

### 7.2.3 Bentonite Clay Specimens

Two distinctly different groups of bentonite clay specimens were examined, though both were prepared in the same way. The first group consists of a large number of specimens tested prior to the initiation of this doctoral research (file names varied but are presented in Appendix A). They were tested at substantially higher hydraulic gradients than the second group of specimens prepared specifically for this project, and were generally not back pressured. However, they do provide a large body of data on hydraulic flux - hydraulic gradient behaviour at high hydraulic gradients. The later tests are differentiated from earlier tests by their File Names beginning with MICG, BARCG or RBMLH. Many of these specimens were back pressured to approximately 1500 kPa prior to hydraulic testing. This was done to determine what, if any, influence the absolute pore water pressure had on the movement of water.

As with the illitic clay specimens, the bentonite specimens were initially exposed to a low hydraulic gradient and flow was allowed to equilibrate at that gradient. This process often took several months. Hydraulic gradients were then increased in a step-wise manner until the maximum desired gradient was achieved. At each step the flux was monitored until a constant-rate-of-flow was observed. On completion of monitoring at the maximum applied hydraulic gradient, the gradient was decreased in steps to examine whether hysteresis was present in the flux-hydraulic gradient plot. The minimum hydraulic gradient used was different for each specimen and was controlled by the magnitude of flow through the specimen and the ability of the gauges to accurately measure the displacements occurring.

In the course of testing, a number of the bentonite specimens were observed to exhibit non-Darcian flow behaviour when low hydraulic gradients were applied. Details on these tests are presented in Section 7.4. A number of other specimens were also tested under conditions of reversed flow direction. The hydraulic head on the outflow end of the specimen (top), was elevated so that the hydraulic head at the top of the specimen exceeded the head at the base. Such a hydraulic head should result in a reversal of flow direction and ultimately in a flow rate equal in magnitude to that observed previously for upwards flow under the same gradient. Any change in the flux-hydraulic gradient relationship with change in flow direction would indicate a change in the structure of the soil. This would make interpretation of flux-gradient relationships of little value since the soil had somehow changed in the course of testing. Possible mechanisms involved in creating such a situation were discussed in detail in Section 3.4. Results of the tests conducted for this purpose are also presented in Section 7.4.

The effect of pore fluid composition was studied by building and percolating a number of specimens using the SCSSS brine, as defined in Dixon and Woodcock (1985). These tests are identified in the data tables presented in Section 7.4.4 (Tables 7.4 and 7.5) and Appendix D. These tests provided a means of estimating the effect of pore fluid composition on the fluid movement and the results are presented in Section 7.4.4.

### 7.3 HYDRAULIC PROPERTIES OF SAND AND ILLITIC CLAY SPECIMENS

#### 7.3.1 Quartz Sand Specimens

As mentioned previously, quartz sand specimens were tested to establish the validity of the Darcian flow equation and identify the maximum flow rate attainable using the water displacement gauges constructed for this project. The gauges proved capable of measuring water displacement rates of  $1.5 \times 10^{-8} \text{ m}^3/\text{s}$ . This maximum measurable flow rate was achieved in the sand specimens at an applied hydraulic gradient of less than four. Plots of the flux versus applied hydraulic gradient presented in Figure 7.1 (normal scale) and Figure 7.2 (log-log scale) show that the quartz sand specimens exhibited Darcian behaviour.

Tables 7.1 and 7.2 present the material properties and summarized results of regression analyses on the quartz sand specimens. Detailed results of these tests are provided in Appendix A1. Table 7.2 contains the results of a regression analysis of each of these sets of data. Regression analyses were conducted in two ways. In the first, the data were forced to fit a line running through the origin (0,0) in a linear plot and the correlation coefficient ( $R^2$ ) was determined. The second technique involved a regression analysis where the intercept on the flux axis was calculated rather than being forced through the origin. The regressions generated coefficients that included the Standard Error of Y Estimate (deviation of Flux values from a perfectly linear relationship) and the Standard Error of the Coefficients (error estimate of the hydraulic conductivity values generated by a linear regression). Definitions of these parameters, as defined in Borland, (1993) are presented in Appendix B. Use of these statistical parameters permit the range of possible values for the x-intercept and hydraulic conductivity to be determined.

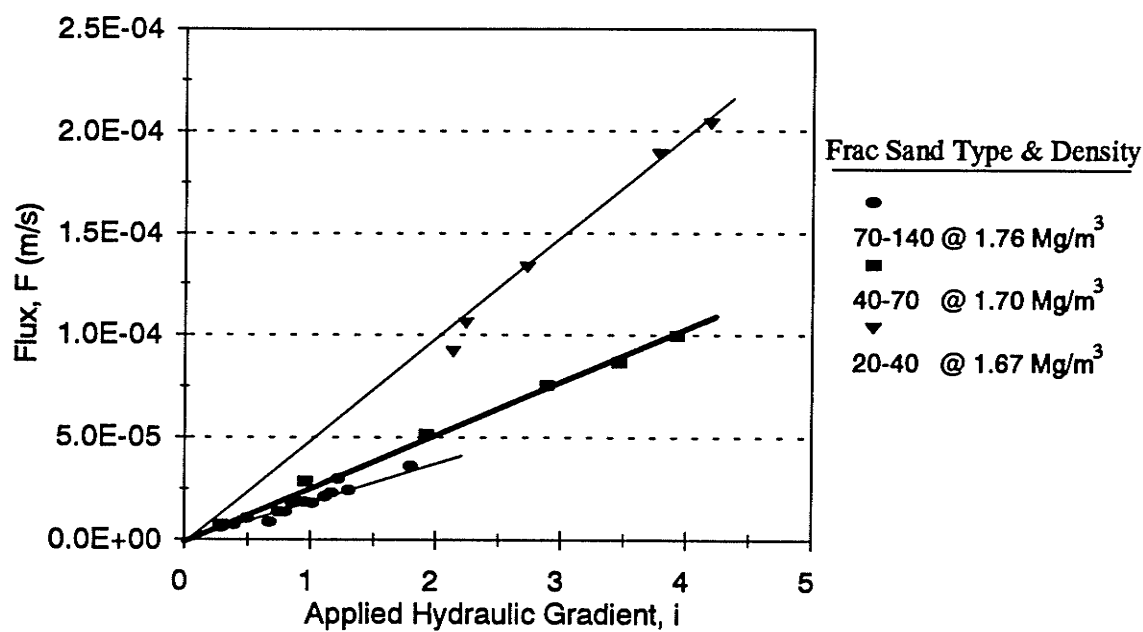


Figure 7.1 Hydraulic Behaviour of Quartz Sand Specimens. (Linear Scale)

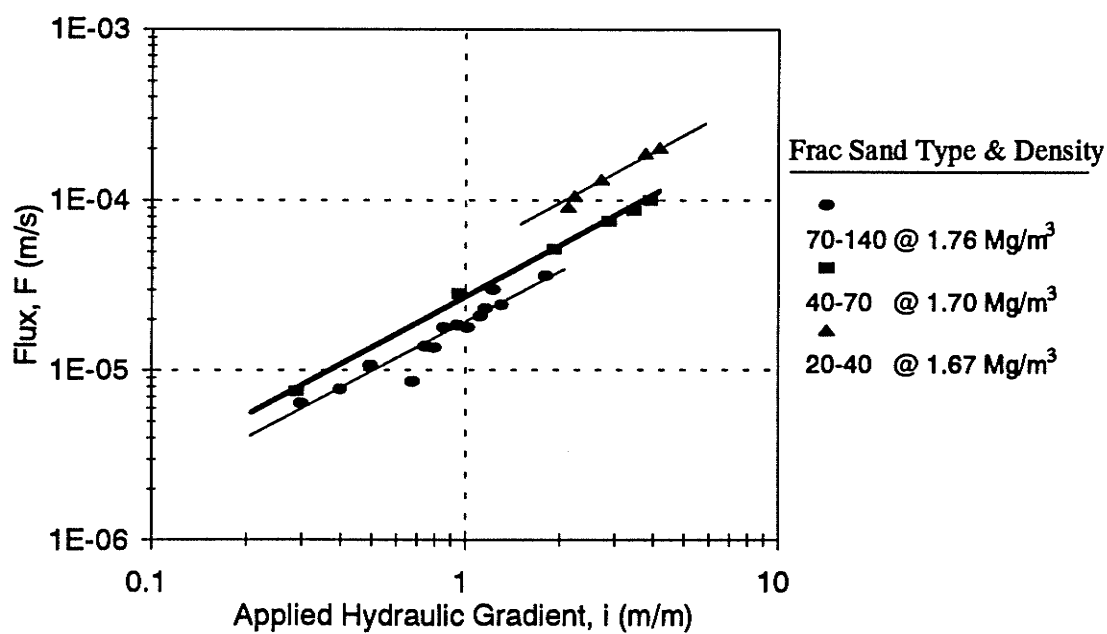


Figure 7.2 Hydraulic Behaviour of Quartz Sand Specimens. (Log - Scale)

Table 7.1 Properties of Quartz Sand Specimens

| File Name | Dry Density<br>(Mg/m <sup>3</sup> ) | Porosity<br>(n) | i<br>Range   | Initial Satn.<br>(%) | EOT Satn.<br>(%) | #<br>i's<br>Tested | Log<br>Plot<br>Flow<br>Code | Linear<br>Plot<br>Flow<br>Code |
|-----------|-------------------------------------|-----------------|--------------|----------------------|------------------|--------------------|-----------------------------|--------------------------------|
| 20-40 FS  | 1.67                                | 0.370           | 2.1 to 4.2   | 100                  | 100              | 5                  | 2                           | 3                              |
| 40-70 FS  | 1.70                                | 0.359           | 0.29 to 3.92 | 100                  | 100              | 7                  | 2                           | 3                              |
| 70-140FS  | 1.76                                | 0.336           | 0.30 to 1.81 | 100                  | 100              | 14                 | 2                           | 3                              |

Table 7.2 Statistical Analysis of Hydraulic Behaviour in Quartz Sand Specimens

| File Name                               | Dry Density<br>(Mg/m <sup>3</sup> ) | Porosity<br>$n_{eff}$ | x<br>Intcpt.<br>(i <sub>o</sub> ) | Statistical<br>Range For<br>x-Intcpt.<br>(Gradient) | R <sup>2</sup> | Hydraulic<br>Conductivity<br>(x10 <sup>-5</sup> m/s) |
|-----------------------------------------|-------------------------------------|-----------------------|-----------------------------------|-----------------------------------------------------|----------------|------------------------------------------------------|
| Forced Fit To Darcy's Law               |                                     |                       |                                   |                                                     |                |                                                      |
| 20-40FS                                 | 1.67                                | 0.370                 | 0                                 | +0.14                                               | .9815          | 4.84+-0.10                                           |
| 40-70FS                                 | 1.70                                | 0.359                 | 0                                 | +0.20                                               | .9950          | 2.52+-0.05                                           |
| 70-140FS                                | 1.76                                | 0.367                 | 0                                 | +0.11                                               | .9269          | 1.95+-0.06                                           |
| Regression With Calculated x-Intercept. |                                     |                       |                                   |                                                     |                |                                                      |
| 20-40FS                                 | 1.67                                | 0.370                 | 0.32                              | 0.23 to 0.46                                        | .9918          | 5.37+-0.28                                           |
| 40-70FS                                 | 1.70                                | 0.359                 | -0.12                             | -0.14 to -0.26                                      | .9974          | 2.42+-0.07                                           |
| 70-140FS                                | 1.76                                | 0.336                 | 0.06                              | -0.05 to 0.16                                       | .9308          | 2.10+-0.16                                           |

The data for quartz sand specimens confirmed the ability of the permeameters to monitor specimens having high flow rates. The data also confirmed the ability of the permeameters to detect Darcian flow in a material where it is known to exist. On the strength of these results it was reasonable to extend the testing program into the less permeable illitic clay specimens with confidence that any observed deviations from Darcian flow would not be the result of the permeameter itself.

### 7.3.2 Illitic Clay Specimens

A total of 9 specimens of illitic clay were tested to determine the flux-hydraulic gradient of clay materials having a relatively low surface area (Table 7.3). Three of these specimens (LHI01A,B,C) were tested using materials consolidated from slurries and then back pressured to approximately 500 kPa prior to testing. Back pressuring was done to ensure saturation and to examine the effect of pore pressure on the ultimate hydraulic behaviour of these specimens. Three other specimens (LHI02A,B,C) were statically compacted and then back pressured (to 500 kPa) prior to testing. The final three specimens (LHI03A,B,C) were statically compacted and tested without back pressure. Plots of hydraulic flux versus applied hydraulic gradient obtained for these illitic clay specimens are presented in Figures 7.3 through 7.11. In some cases the flux was monitored at both ends of the specimen. In such specimens the data obtained from monitoring the inflow and outflow was plotted using separate symbols (Figures 7.6, 7.7, 7.8). The similarity of these results provide confidence in the measurements obtained for specimens where flow displacements were monitored at only one end of the specimen.

Table 7.3 presents the initial and end-of-test properties of the illite specimens while Table 7.4 presents the statistical analysis of this data. Included in Table 7.3 is the Flow-Type classification for each of the tests and was obtained using Figure 3.10 as the basis for comparison. The various types of fluid flow possible were discussed and defined in Section 3.6. The original data used in the plotting of flux-hydraulic gradient relationships are presented in Appendix A2

Of the nine illitic clay specimens examined in this thesis and presented as Figures 7.3 through 7.11, seven exhibited some degree of non-Darcian flow behaviour at low hydraulic



gradient. The two remaining specimens (LHI02C and LHI03A, Figures 7.8, 7.9), showed no evidence of non-Darcian behaviour and exhibited a higher than usual degree of data scatter, particularly at lower hydraulic gradients.

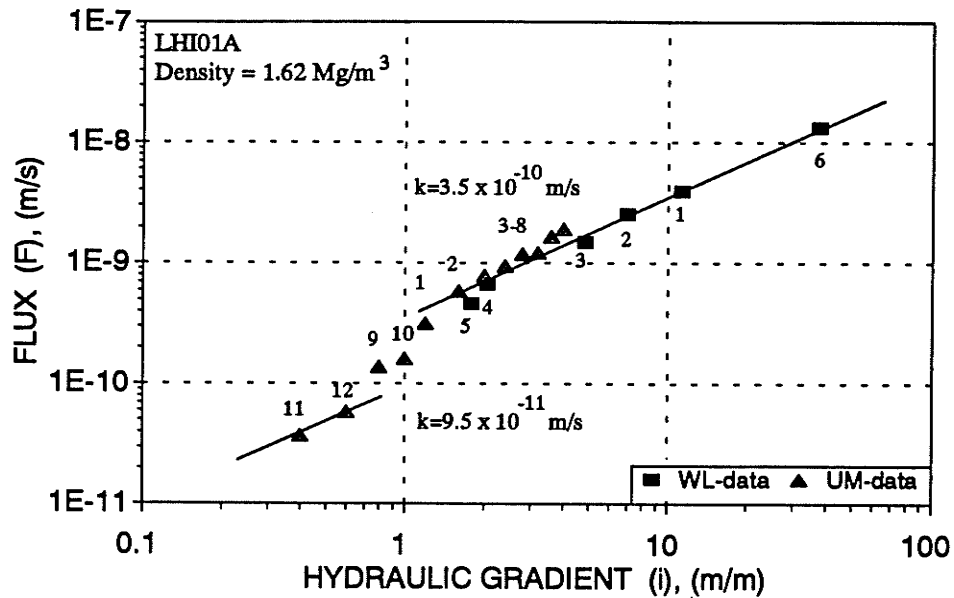


Figure 7.3 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI01A (Density =  $1.62 \text{ Mg/m}^3$  ; Consolidated from Slurry; 500 kPa Back Pressure)

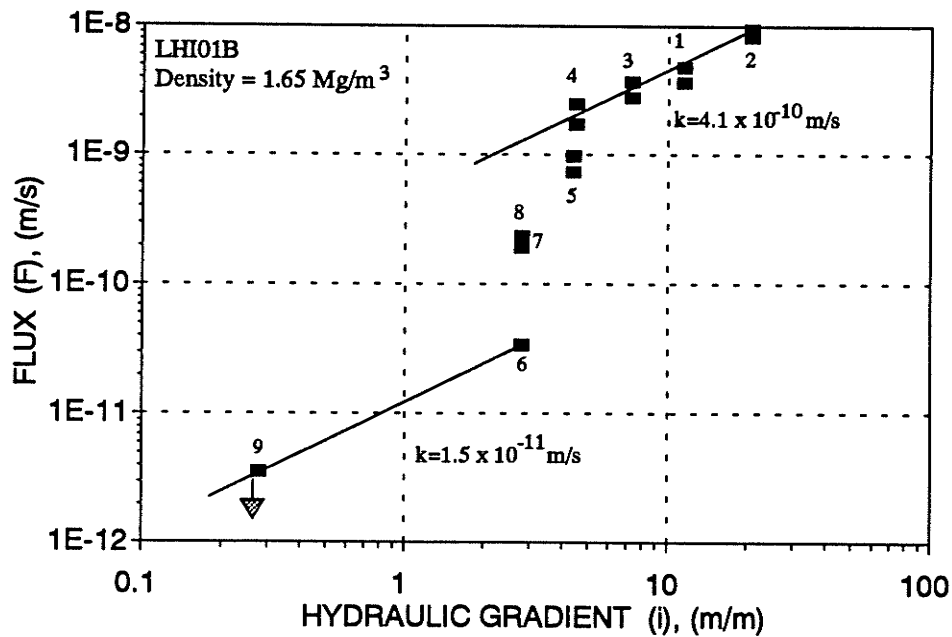


Figure 7.4 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI01B (Density =  $1.65 \text{ Mg/m}^3$  ; Consolidated from Slurry; 500 kPa Back Pressure)

Table 7.3 Initial and End-of-Test Properties of Illitic Clay Specimens

| File Name | Dry Density<br>(Mg/m <sup>3</sup> ) | Effective Clay Dry Density<br>(Mg/m <sup>3</sup> ) | Porosity<br>n | Range of<br>i | Initial Sat.<br>(%) | End of Test Sat.<br>(%) | # Pore Vols. Into Sample | Test Time<br>(Hrs) | # Grads. Tested | Flow Type For a Log Plot <sup>***</sup> | Flow Type For a Linear Plot <sup>***</sup> | i <sub>CH</sub> <sup>**</sup> |
|-----------|-------------------------------------|----------------------------------------------------|---------------|---------------|---------------------|-------------------------|--------------------------|--------------------|-----------------|-----------------------------------------|--------------------------------------------|-------------------------------|
| LHI01A*   | 1.62                                | 1.62                                               | 0.411         | 0.4 to 37.5   | 100                 | >97                     | >0.4                     | 2800               | 19              | 2                                       | 2A                                         | 0.8 - 1.5                     |
| LHI01B*   | 1.65                                | 1.65                                               | 0.400         | 1.1 to 20.9   | 100                 | >98                     | >0.5                     | 2800               | 6               | 2                                       | 2A                                         | 3                             |
| LHI01C*   | 1.77                                | 1.77                                               | 0.356         | 2.4 to 35.4   | 100                 | >97                     | >0.5                     | 3260               | 5               | 2                                       | 2A                                         | 5                             |
| LHI02A**  | 1.81                                | 1.81                                               | 0.342         | 0.1 to 28.7   | 90                  | 107                     | 1.58                     | 5240               | 12              | 2                                       | 2A                                         | 6                             |
| LHI03A*   | 1.84                                | 1.84                                               | 0.331         | 0 to 64.1     | 97                  | >99                     | 1.35                     | 8324               | 14              | 1                                       | 1                                          | ---                           |
| LHI03C*   | 1.84                                | 1.84                                               | 0.331         | -48 to 51.2   | 74                  | 100                     | 3.77                     | 6785               | 12              | 2                                       | 2A                                         | 9 - 10                        |
| LHI02B**  | 1.93                                | 1.93                                               | 0.298         | 1.6 to 118    | 71                  | 104                     | 1.74                     | 6213               | 18              | 2                                       | 2A                                         | 8 - 10                        |
| LHI03B*   | 1.96                                | 1.96                                               | 0.287         | 2.1 to 83.2   | 54                  | 100                     | 3.14                     | 9000               | 12              | 2                                       | 2A                                         | 21                            |
| LHI02C**  | 2.03                                | 2.03                                               | 0.262         | 1.9 to 39.5   | 74                  | 103                     | 0.88                     | 4989               | 12              | 1/2 ?                                   | 1/2A ?                                     | 12 - 17                       |

Note: \* Specimens consolidated from slurries and back pressured to 500 kPa.  
 \*\* Specimens compacted and tested under 500 kPa back pressure  
 \*\*\* As defined in Section 3.6  
 + Specimens compacted and tested without back pressure  
 \*\*Transitional Hydraulic Gradient (gradient at which a change in hydraulic conductivity was noted).

Table 7.4 Statistical Analysis of Hydraulic Flux - Hydraulic Gradient Test Results

|                                       |                                         |                 | Data Regression With A Forced<br>Fit to Darcian Flow |                                     |                                    |                                                                         | Regression With Calculated x-Intercept |                                            |                                    |                                                                         |
|---------------------------------------|-----------------------------------------|-----------------|------------------------------------------------------|-------------------------------------|------------------------------------|-------------------------------------------------------------------------|----------------------------------------|--------------------------------------------|------------------------------------|-------------------------------------------------------------------------|
| File<br>Name                          | Clay<br>Density<br>(Mg/m <sup>3</sup> ) | Porosity<br>(n) | X-<br>incpt<br>(i <sub>o</sub> )                     | Statistical<br>Range of<br>X-incpt. | R-<br>Squared<br>(R <sup>2</sup> ) | Hydraulic<br>Conductivity<br>(k), (m/s)                                 | X-<br>incpt<br>(i <sub>o</sub> )       | Statistical<br>Range of<br>X-incpt.        | R-<br>Squared<br>(R <sup>2</sup> ) | Hydraulic<br>Conductivity<br>(k), (m/s)                                 |
| LHI01A* (High i)<br>(Low i)           | 1.62                                    | 0.411           | 0<br>0                                               | + -0.6<br>+ -0.01                   | 0.9959<br>0.9934                   | 3.5x10 <sup>-10</sup><br>9.5x10 <sup>-11</sup>                          | 0.24<br>0.04                           | -0.4 to 0.9<br>ID                          | 0.9963<br>ID                       | 3.5x10 <sup>-10</sup><br>1.0x10 <sup>-10</sup>                          |
| LHI01B* (High i)<br>(Low i)           | 1.65                                    | 0.4             | 0<br>0                                               | + -1.8<br>ID                        | 0.9469<br>ID                       | 4.1x10 <sup>-10</sup><br>3.6x10 <sup>-10</sup>                          | 0.4<br>ID                              | -1.6 to 2.1<br>ID                          | 0.9344<br>ID                       | 4.3x10 <sup>-10</sup><br>1.5x10 <sup>-11</sup>                          |
| LHI01C* (High i)<br>(Low i)           | 1.77                                    | 0.356           | 0<br>0                                               | + -1.5<br>ID                        | 0.9855<br>ID                       | 1.4x10 <sup>-10</sup><br>1.0x10 <sup>-10</sup>                          | 1.7<br>2.9                             | 0.8 to 2.6<br>ID                           | 0.9949<br>ID                       | 1.5x10 <sup>-10</sup><br>ID                                             |
| LHI02A** (High i)<br>(Low i)          | 1.81                                    | 0.342           | 0<br>0                                               | + -2.3<br>+ -0.9                    | 0.8984<br>0.8984                   | 1.3x10 <sup>-10</sup><br>3.6x10 <sup>-11</sup>                          | -1.4<br>0.3                            | -4.4 to 1.2<br>-0.6 to 1.4                 | 0.9052<br>0.8841                   | 1.2x10 <sup>-10</sup><br>3.9x10 <sup>-11</sup>                          |
| LHI03A* ( all )                       | 1.84                                    | 0.331           | 0                                                    | + -1.2                              | 0.9965                             | 1.1x10 <sup>-10</sup>                                                   | -0.05                                  | -1.2 to 1.3                                | 0.9965                             | 1.1x10 <sup>-10</sup>                                                   |
| LHI03C* (High i)<br>(Low i)           | 1.84                                    | 0.331           | 0<br>0                                               | + -8.1<br>+ -0.5                    | 0.8221<br>0.9831                   | 7.6x10 <sup>-11</sup><br>2.7x10 <sup>-11</sup>                          | 2.5<br>0.6                             | -8.2 to 9.5<br>0.4 to 0.8                  | 0.8260<br>0.9979                   | 8.1x10 <sup>-11</sup><br>2.6x10 <sup>-11</sup>                          |
| LHI02B** (High i)<br>(Low i)          | 1.93                                    | 0.298           | 0<br>0                                               | + -2.9<br>+ -1.4                    | 0.9811<br>0.7564                   | 5.3x10 <sup>-11</sup><br>3.0x10 <sup>-11</sup>                          | -1.48<br>-0.19                         | -4.3 to 1.5<br>-1.3 to 1.0                 | 0.9828<br>0.7583                   | 5.2x10 <sup>-11</sup><br>2.9x10 <sup>-11</sup>                          |
| LHI03B* (High i)<br>(Low i)           | 1.96                                    | 0.287           | 0<br>0                                               | + -9.5<br>+ -4.9                    | 0.8751<br>0.5276                   | 5.7x10 <sup>-11</sup><br>1.1x10 <sup>-11</sup>                          | 11<br>-7.9                             | 6.3 to 18.7<br>-15.6 to -0.2               | 0.9364<br>0.6789                   | 7.4x10 <sup>-11</sup><br>7.9x10 <sup>-12</sup>                          |
| LHI02C** (All)<br>(High i)<br>(Low i) | 2.03                                    | 0.262           | 0<br>0<br>0                                          | + -3.6<br>+ -4.6<br>+ -3.8          | 0.9122<br>0.8753<br>0.3166         | 1.0x10 <sup>-11</sup><br>1.0x10 <sup>-11</sup><br>8.7x10 <sup>-12</sup> | 0.4<br>5.2<br>-5.4                     | -3.2 to 3.9<br>2.2 to 8.2<br>-14.6 to -2.6 | 0.9116<br>0.9174<br>0.5534         | 1.1x10 <sup>-11</sup><br>1.3x10 <sup>-11</sup><br>5.5x10 <sup>-12</sup> |

\* Note: \* Specimens consolidated from slurries and back pressured to 500 kPa. \*\* Specimens compacted and tested at 500 kPa back pressure  
 \* Specimens compacted and tested without back pressure ID - Insufficient Data for statistical analysis

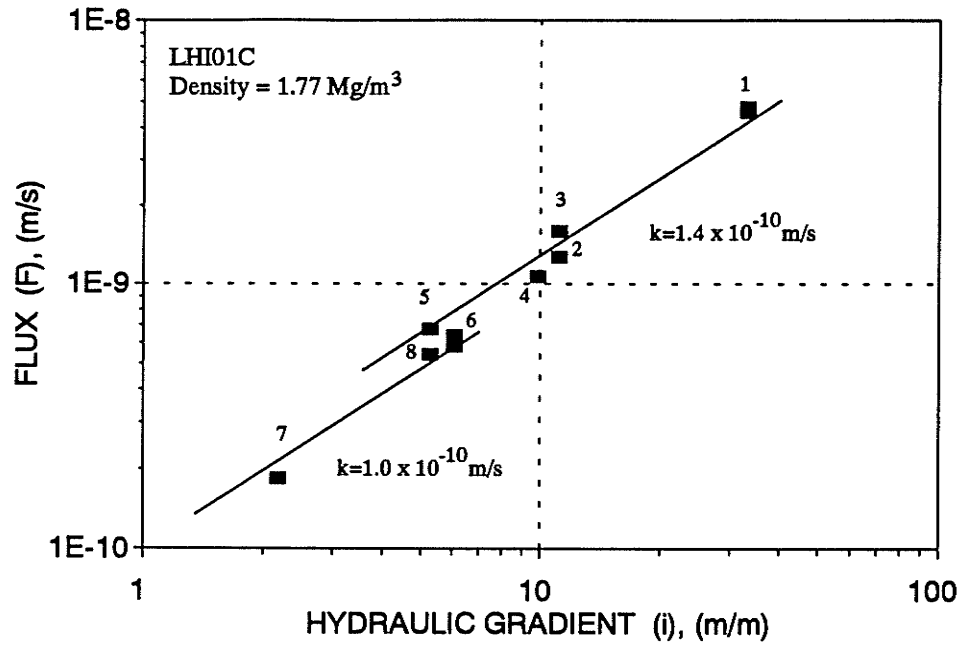


Figure 7.5 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI01C (Density = 1.77 Mg/m<sup>3</sup>; Consolidated from Slurry; 500 kPa Back Pressure)

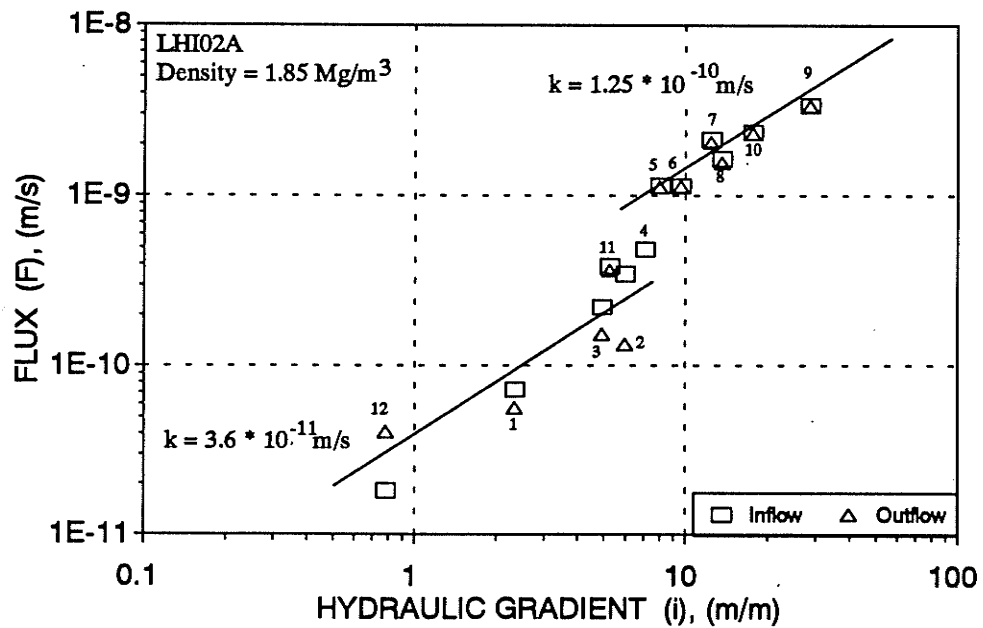


Figure 7.6 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI02A (Density = 1.81 Mg/m<sup>3</sup>; Static Compaction; 500 kPa Back Pressure)

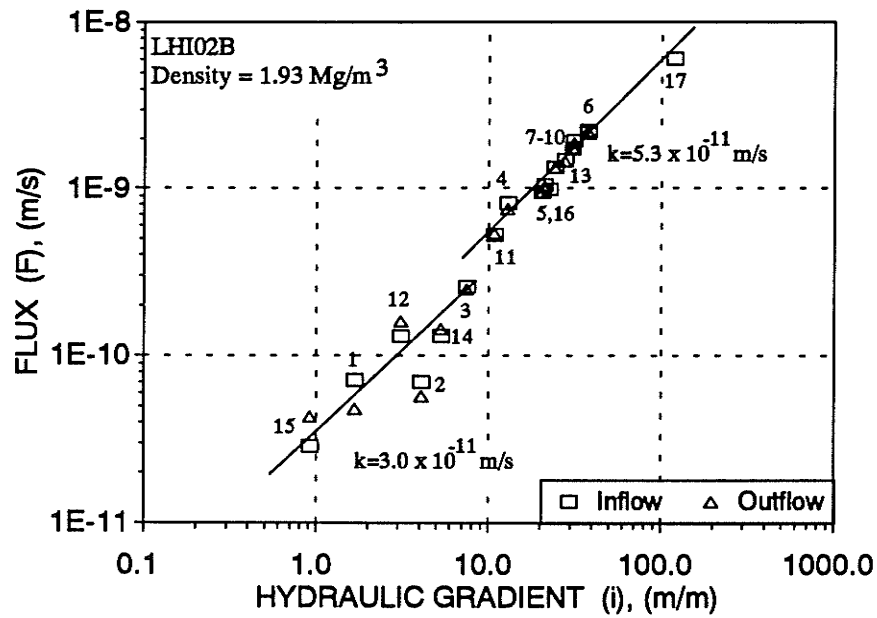


Figure 7.7 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI02B (Density =  $1.93 \text{ Mg/m}^3$  ; Static Compaction; 500 kPa Back Pressure)

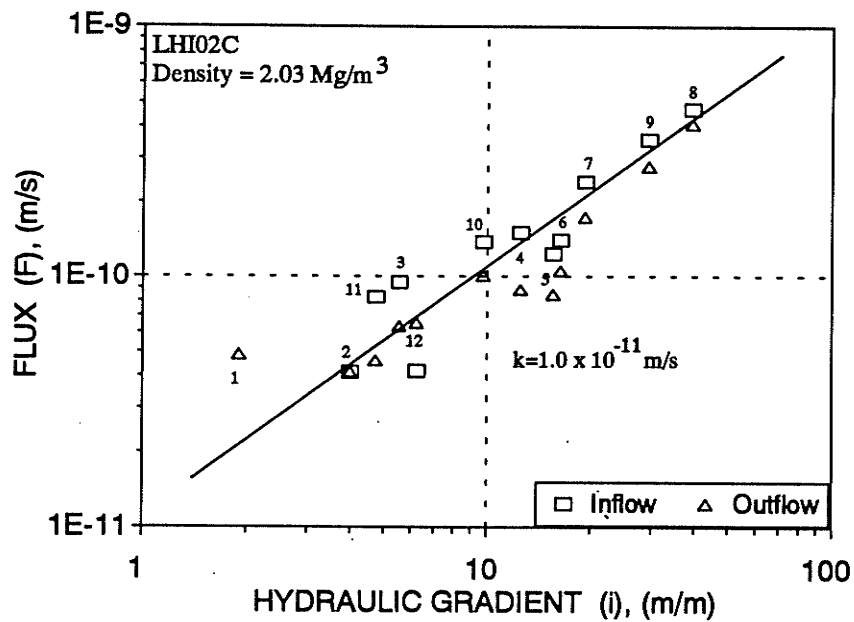


Figure 7.8 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI02C (Density =  $2.03 \text{ Mg/m}^3$  ; Static Compaction; 500 kPa Back Pressure)

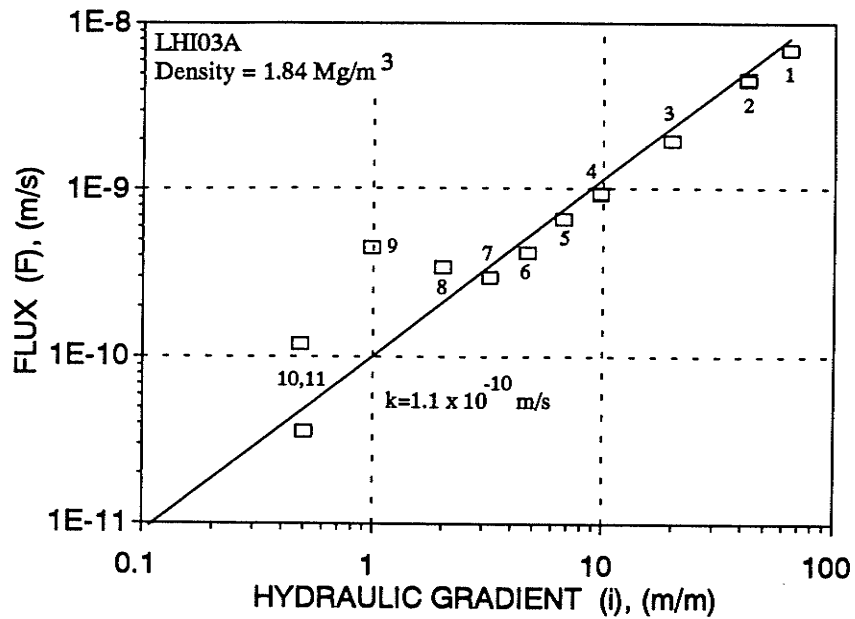


Figure 7.9 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI03A (Density =  $1.84 \text{ Mg/m}^3$ ; Static Compaction; No Back Pressure)

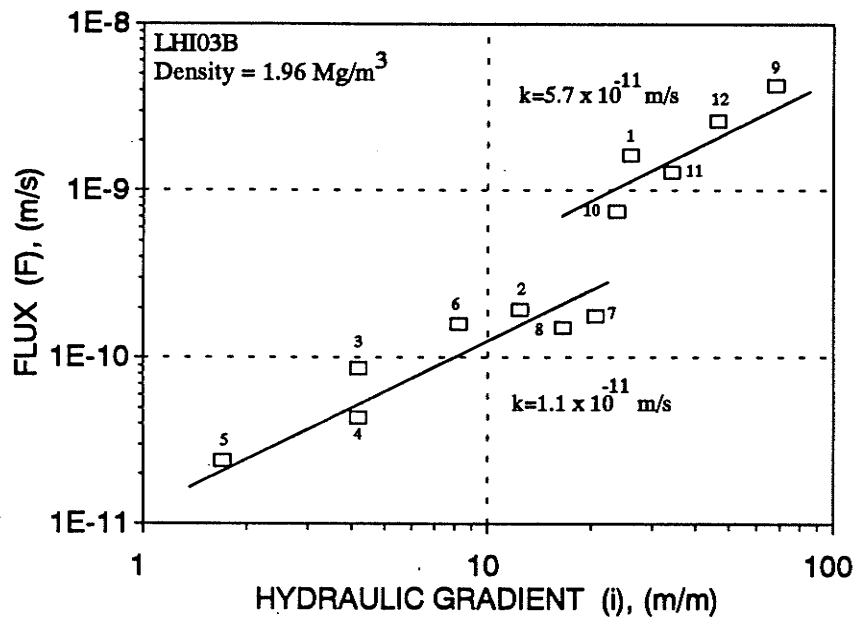


Figure 7.10 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI03B (Density =  $1.96 \text{ Mg/m}^3$ ; Static Compaction; No Back Pressure)

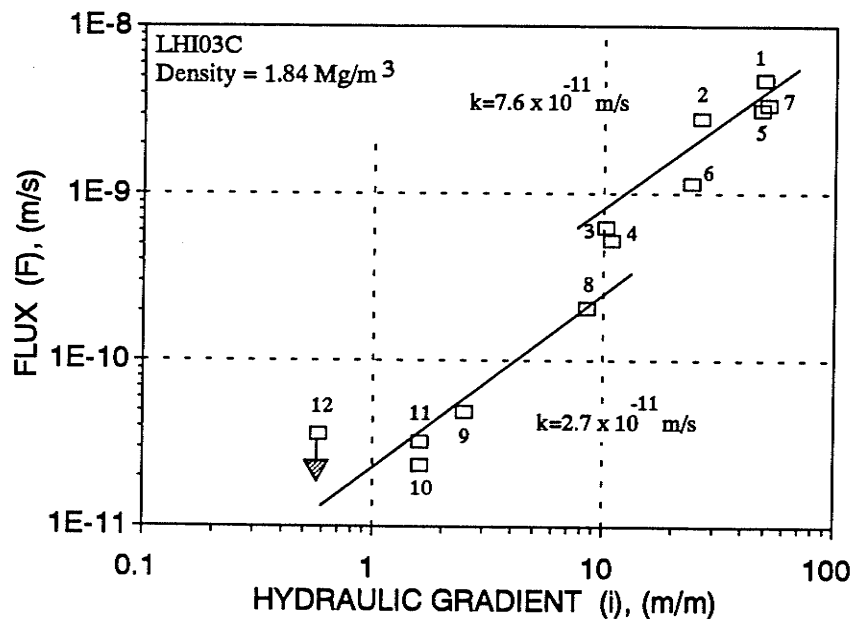


Figure 7.11 Hydraulic Flux Vs Applied Hydraulic Gradient For Clay Specimen LHI03C (Density =  $1.84 \text{ Mg/m}^3$ ; Static Compaction; No Back Pressure)

Deviations from Darcian flow are shown most clearly in plots of log flux ( $\text{m}^3/\text{m}^2/\text{s}$ ), versus log hydraulic gradient, and this format was chosen to present the bulk of the hydraulic flux - hydraulic gradient data in this chapter. Each of Figures 7.3 to 7.7, 7.10, 7.11) show two distinct flux-gradient relationships that are each Darcian in nature. Between each of these relationships is a "transitional " region that perhaps indicates a change in the porosity available for flow. The observed changes in hydraulic conductivity were the same whether the gradients were being increased or decreased. Examples of the independence of the flux to changes in hydraulic gradient are presented in Figures 7.6, 7.7, 7.8 and 7.10 where the increment number is printed in association with the data points.

The transitional gradients can therefore be considered reversible and there is no influence of flow direction or past gradient history on the hydraulic conductivity observed. This non-Darcian flow behaviour results from one of two possible mechanisms, either by fully reversible alteration of soil structure or some type of reversible change in the structure of the pore fluid.

Two potential mechanisms can be used to attribute the observed changes in hydraulic conductivity to changes in the soil fabric. These are,

- (1) water channelling along the cell wall or,
- (2) changes to the pore structure within the specimen.

For either of these explanations to be valid, channels must immediately and completely revert to their initial state when the gradient is reduced. It is difficult to conceive fully reversible channelling of water along the walls or within illitic (non-swelling), specimens. More likely, channels once open should remain at least partially open. The specimens in Figures 7.3 through 7.11 were all compacted directly into, or were consolidated in the same cells that were later used for hydraulic conductivity testing. This should have ensured a tight bond between the cell wall and the specimen and would have limited the potential for wall channelling, especially under the relatively low hydraulic gradients that were used. Water channelling is therefore not likely. No visual evidence of channels could be obtained because extrusion from the cells caused damage to the clay structure at the clay-water interface.

A second possible explanation for the observed hydraulic behaviour is the presence of reversible changes in the pore volume available for flow. This would indicate either a compressible component in the specimens, or a quantity of structured water which only



becomes available for flow when a specific (transitional) hydraulic gradient is exceeded. Three of the specimens were consolidated from slurries and then back pressured (LHI01A,B,C; Figures 7.3, 7.4, 7.5), so they should not have contained any compressible air pockets. Likewise, the second set of three specimens (LHI02A,B,C; Figures 7.6, 7.7, 7.8), were back pressured to ensure water saturation (zero air content), prior to testing. Five of these six specimens exhibited changes in their hydraulic conductivity in the course of testing. These specimens eliminate the argument of incomplete specimen saturation as being a cause of changes in the hydraulic conductivity. This leaves only the explanation of changes in the pore volume available for flow causing of the observed changes in hydraulic conductivity.

Table 7.3 also shows the hydraulic gradients at which the changes in the hydraulic conductivity of the specimens apparently occurred. It is interesting to note in Table 7.3 that the hydraulic gradient at which the hydraulic conductivity changes, is apparently related to the specimen density. Karthigesu (1994), called this gradient the "transitional" gradient, ( $i_{CH}$ ). That is, the hydraulic gradient at which the entire cross-sectional pore area becomes available for the transportation of water. Karthigesu's results are discussed in more detail Chapter 8. As density increased in Table 7.3, so did the transitional gradient. This indicates that denser illite specimens required higher shear stresses to liberate structured water attached to the surfaces of the clay particles. However, the hydraulic gradients at which changes occurred in the pore space available for flow are low relative to the gradients commonly used in hydraulic conductivity testing. These low transitional gradients can be attributed to weak structuring of the pore water closest to illitic clay particles, structuring that can readily break down once sufficiently high hydraulic gradients are applied. Once the transitional gradients were exceeded, the water would be kept in

a free, or unstructured state (Chapter 2). Similar behaviour was observed by Karthigesu (1994) in clay - sand mixtures with less than 10 % bentonite. The hydraulic behaviour in bentonitic systems is presented in Section 7.4.

Figure 7.12 presents the observed relationship between clay density and hydraulic conductivity at hydraulic gradients both below and above the transitional gradient. A clear offset was observed between the hydraulic conductivities above and below the transitional gradient. The data shown in this figure includes the  $k$  calculated by forcing the data through the origin (Forced), and that produced without forcing a fit (No Constraints). As can be seen in this figure it is the gradient applied which is the controlling factor in the hydraulic behaviour, not the manner in which  $k$  was calculated. Section 8.1 discusses the significance of the observed offset as a function of porosity and effective porosity.

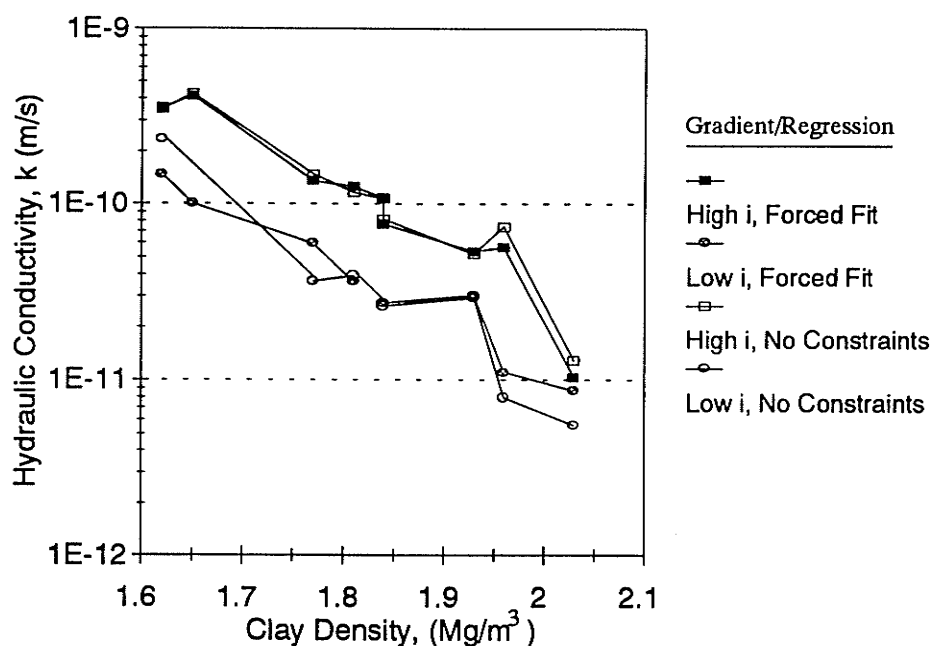


Figure 7.12 Clay Density Vs Hydraulic Conductivity For Illitic Clays  
(High  $i$  = Gradient above the transitional gradient)  
(Low  $i$  = Gradient below the transitional gradient)

## **7.4 Behaviour of Bentonite Clay and Bentonite - Sand Specimens**

### **7.4.1 Test Conditions**

The bulk of the research focused on water flow through bentonite-based materials. The basic flow behaviour of 49 bentonitic specimens is examined in Section 7.4.2 (evidence of Darcian behaviour) and Section 7.4.3 (evidence of non-Darcian behaviour). Initial saturations ranged from oven dry (nominally 0% saturation) to near saturated (>90%). Like the illitic clays discussed in the preceding section, this variety of initial conditions was investigated to determine if any influenced water flow through the material in a significant way. The results of an investigation of the influence of initial degree of saturation are presented in Section 7.4.4 as are the results of a study on the role of pore fluid salinity on measured hydraulic conductivity. The specimens were tested under two pore pressure conditions, one at 1500 kPa back pressure, and the other which applied only atmospheric pressure. The results of back pressuring on the ultimate hydraulic behaviour is also presented in Section 7.4.4. As with the illitic specimens, a number of specimens had the direction of flow reversed in the course of testing and a number of specimens had fluid displacements monitored at both ends. Where flow displacements were monitored at both ends of the specimen, they are plotted as separate data points to provide an indication of the consistency of the measuring technique. Results of the investigation of the effect of changing flow direction are presented in Section 7.4.5. Finally, Section 7.5 discusses the role of bacterial activity on the results of hydraulic conductivity testing.

#### **7.4.2 Evidence of Darcian Flow Behaviour**

Of the 49 bentonite or bentonite-sand specimens included in this project, 31 were tested at gradients which were lower than 100, 24 were tested at gradients less than 50, and 18 at gradients less than 10. Specimens whose hydraulic gradient range included values less than 10 covered the complete range of densities and initial degrees of saturation examined in the program. Tables 7.5 and 7.6 summarize their hydraulic properties.

Of the 49 bentonitic clay and clay-sand specimens examined in this portion of this thesis, 33 exhibited hydraulic gradient - hydraulic flux behaviour that could be described as Darcian in nature. Figures 7.13 through 7.18 present examples of the data obtained in these tests. No transitional gradients similar to those present for illitic materials were observed in these specimens. A summary of the results is presented in Tables 7.5 and 7.6, and a full compilation of the data is provided in Appendix A3. In a number of cases initial plots of the measured flux versus applied hydraulic gradient data indicated that threshold gradients might be present. However, statistical analysis of each set of test data showed that the statistical range for the x-intercept for most of these regressions included the origin. The flow-type classification of these specimens are presented in Table 7.5 and correspond to the definitions presented in Section 3.6. The significance of these data is discussed in Chapter 8.

Table 7.5 Initial and End-of-Test Properties of Bentonite Clay and Bentonite Clay - Sand Specimens

| File Name | Dry Density (Mg/m <sup>3</sup> ) | Clay Density (Mg/m <sup>3</sup> ) | Porosity n | i Range    | Initial Satn. (%) | EOT Satn. (%) | Pore Volumes Through Specimen | Test Duration (Hrs) | # Grads. Tested | Special Notes | Log Plot Flow Code™ | Linear Plot Flow Code™ |
|-----------|----------------------------------|-----------------------------------|------------|------------|-------------------|---------------|-------------------------------|---------------------|-----------------|---------------|---------------------|------------------------|
| BARCG02A  | 0.55                             | 0.55                              | 0.805      | 13-183     | 98                | 100           | 0.15                          | 7466                | 16              |               | 2                   | 4                      |
| BARCG01A  | 0.59                             | 0.59                              | 0.791      | 187-4977   | 98                | >98           | 0.1                           | 7050                | 14              |               | 2                   | 4                      |
| BARCG05A  | 0.66                             | 0.66                              | 0.766      | 1-62       | 73                | >92           | 0.45                          | 2205                | 10              | SCSSS         | 2                   | 4                      |
| BARCG01E  | 0.70                             | 0.70                              | 0.752      | 0-620      | 6                 | >92           | 6.59                          | 10143               | 15              |               | 2                   | 4                      |
| BARCG01C  | 0.76                             | 0.76                              | 0.730      | 4.5-176    | 39                | 87            | 0.34                          | 5036                | 11              | BP*           | 2                   | 4                      |
| BARCG04B  | 0.79                             | 0.79                              | 0.720      | 0-25       | 83                | 102           | NM                            | 2393                | 7               |               | 1                   | 1                      |
| BARCG04BB | 0.79                             | 0.79                              | 0.720      | 2.9-129    | 100               | 103           | 0.55                          | 9257                | 16              | BP*           | 1                   | 1/2D                   |
| BARCG01D  | 0.80                             | 0.80                              | 0.716      | -939-937   | 62                | >95           | 3.03                          | 18106               | 30              | BP*           | 1                   | 1                      |
| BARCG02D2 | 0.89                             | 0.89                              | 0.684      | 2.4-19     | 83                | >98           | 0.07                          | 2762                | 4               | BP*           | NP                  | NP                     |
| BARCG03B  | 0.93                             | 0.93                              | 0.670      | 0-17       | 72                | >98           | 0.06                          | 2241                | 5               | BP*           | 1                   | 1                      |
| BARCG02E  | 0.96                             | 0.96                              | 0.660      | 1-540      | 0                 | >95           | 1.57                          | 2733                | 6               |               | 1                   | 1                      |
| BARCG02C  | 0.96                             | 0.96                              | 0.660      | 2-92       | 98                | 100           | 0.07                          | 3014                | 7               | BP*           | 1                   | 1                      |
| BARCG02BB | 0.99                             | 0.99                              | 0.649      | -1600-2150 | 67                | 100           | 0.49                          | 11723               | 23              | BP*           | 1                   | 1/2D                   |
| BARCG02D  | 1.01                             | 1.01                              | 0.642      | 1.8-61     | 88.2              | >96           | 0.16                          | 2833                | 11              | BP*           | NP                  | NP                     |
| BARCG03A  | 1.01                             | 1.01                              | 0.642      | 14-24      | 98                | 100           | 0.07                          | 2616                | 8               |               | 1                   | 1                      |
| SHC75     | 1.90                             | 1.03                              | 0.455      | 500-16654  | 74                | 93            | NM                            | 3152                | 8               |               | 1                   | 1                      |
| RBML1_P2  | 1.49                             | 1.04                              | 0.455      | 243-1683   | 60                | 100           | 0.58                          | 10300               | 16              |               | 1                   | 1                      |
| BARCG01BB | 1.06                             | 1.06                              | 0.624      | 8-70       | 63                | >95           | 0.55                          | 3050                | 7               | BP*           | 2                   | 4                      |
| BARCG04D2 | 1.06                             | 1.06                              | 0.624      | 171-1207   | 9                 | 100           | 0.34                          | 6622                | 13              |               | 1                   | 1                      |
| BARCG04A  | 1.09                             | 1.09                              | 0.613      | 2.4-418    | 12                | 100           | 0.73                          | 4108                | 13              | BP* SCSSS     | 1                   | 1                      |

| File Name   | Dry Density (Mg/m <sup>3</sup> ) | Clay Density (Mg/m <sup>3</sup> ) | Porosity n | i Range    | Initial Satn. (%) | EOT Satn. (%) | Pore Volumes Through Specimen | Test Duration (Hrs) | # Grads. Tested | Special Notes | Log Plot Flow Code | Linear Plot Flow Code |
|-------------|----------------------------------|-----------------------------------|------------|------------|-------------------|---------------|-------------------------------|---------------------|-----------------|---------------|--------------------|-----------------------|
| S50MC11     | 1.74                             | 1.12                              | 0.360      | 1583-15800 | 54                | >97           | 1.2                           | 3310                | 5               |               | 1                  | 1                     |
| URL115      | 1.12                             | 1.12                              | 0.603      | 36-2720    | 18                | >98           | 1.19                          | 10245               | 12              |               | 1                  | 1                     |
| MICG_9A     | 1.13                             | 1.13                              | 0.599      | 20-169     | 0                 | >98           | 0.72                          | 9124                | 8               |               | 1                  | 1                     |
| BARCG05E    | 1.15                             | 1.15                              | 0.592      | 0.4 - 1369 | 0                 | 100           | 1.1                           | 10795               | 29              |               | 1                  | 1                     |
| URL         | 1.17                             | 1.17                              | 0.588      | 42-3873    | 20                | 102           | 1.64                          | 4200                | 10              | BP*           | 1                  | 1                     |
| BARCG07E    | 1.18                             | 1.18                              | 0.582      | .05-1414   | 0                 | 103           | 0.5                           | 6812                | 19              |               | 1                  | 2D                    |
| BARCG03E    | 1.18                             | 1.18                              | 0.582      | 3-458      | 0                 | >96           | 1.44                          | 8294                | 17              |               | 1                  | 1                     |
| S50MC15     | 1.75                             | 1.18                              | 0.356      | 1580-31610 | 75                | >95           | 0.71                          | 3500                | 7               |               | 1                  | 1                     |
| RBML2_P2    | 1.64                             | 1.19                              | 0.400      | 370-6200   | 83                | >99           | 1.69                          | 10019               | 12              |               | 1                  | 3A                    |
| URL125      | 1.20                             | 1.20                              | 0.574      | 38-4215    | 19                | >96           | 1.69                          | 10246               | 20              |               | 1                  | 1                     |
| THS90B      | 1.20                             | 1.20                              | 0.574      | 766-3064   | 50                | >98           | 1.44                          | 2856                | 4               |               | 1                  | 1                     |
| DW100.42    | 1.22                             | 1.22                              | 0.567      | 643-4825   | 92                | 100           | 0.57                          | 7500                | 5               |               | 1                  | 1                     |
| S50MC17     | 1.72                             | 1.22                              | 0.367      | 468-31200  | 81                | >95           | 0.78                          | 3500                | 8               |               | 1                  | 1                     |
| C50.20WD    | 1.71                             | 1.24                              | 0.375      | 1680-16820 | 80                | 100           | NM                            | 6700                | 3               |               | 1                  | 1                     |
| BARCG03D    | 1.25                             | 1.25                              | 0.557      | 0.6-1373   | 0                 | 100           | 0.6                           | 10198               | 23              | BP*           | 1                  | 2D                    |
| TDCON       | 1.26                             | 1.26                              | 0.553      | 352-35200  | 75                | 98            | 0.52                          | 3624                | 10              |               | 1/2                | 1/4                   |
| SISAVB60/40 | 1.86                             | 1.28                              | 0.324      | 345-34480  | 75                | 99            | 1                             | 3000                | 10              |               | 1                  | 3A                    |
| BAR130      | 1.30                             | 1.30                              | 0.539      | 56-5529    | 22                | 100           | 1.78                          | 8588                | 20              |               | 1                  | 1                     |
| URL135      | 1.31                             | 1.31                              | 0.535      | 32-2821    | 23                | 100           | 0.84                          | 10247               | 18              |               | 1                  | 1                     |
| MICG_9B     | 1.33                             | 1.33                              | 0.528      | 4.4-122    | 0                 | 100           | 0.6                           | 10146               | 12              |               | 1                  | 1                     |
| SSB40A      | 1.78                             | 1.34                              | 0.349      | 57-3485    | 0                 | 100           | 1.25                          | 3408                | 12              |               | 1                  | 1                     |
| S50MC07     | 1.86                             | 1.34                              | 0.316      | 1660-32220 | 42                | >92           | 0.69                          | 3300                | 7               |               | 1                  | 1                     |
| SISAVB25/75 | 1.53                             | 1.34                              | 0.454      | 460-31000  | 17                | >97           | 1.29                          | 3504                | 9               |               | 1                  | 1                     |

| File Name | Dry Density (Mg/m <sup>3</sup> ) | Clay Density (Mg/m <sup>3</sup> ) | Porosity n | i Range    | Initial Satn. (%) | EOT Satn. (%) | Pore Volumes Through Specimen | Test Duration (Hrs) | # Grads. Tested | Special Notes | Log Plot Flow Code** | Linear Plot Flow Code** |
|-----------|----------------------------------|-----------------------------------|------------|------------|-------------------|---------------|-------------------------------|---------------------|-----------------|---------------|----------------------|-------------------------|
| BAR115    | 1.35                             | 1.35                              | 0.521      | 66-6467    | 22                | >98           | 1.73                          | 8589                | 20              |               | 1                    | 1                       |
| SHC25     | 1.55                             | 1.36                              | 0.447      | 314-15680  | 97                | 99            | NM                            | 3304                | 6               |               | 2                    | 4                       |
| RBMLH05   | 1.68                             | 1.22                              | 0.389      | 10-2633    | 0                 | 100           | 2.03                          | 9352                | 19              | BP*           | 1                    | 1                       |
| BARCGEX   | 1.46                             | 1.46                              | 0.482      | 49-4550    | 0                 | 76            | 1.63                          | 5400                | 8               | BP*           | 1                    | 1                       |
| RBM01     | 1.86                             | 1.43                              | 0.320      | 680-33980  | 80                | 100           | 0.74                          | 1950                | 6               |               | 1                    | 1                       |
| SC100.28  | 1.46                             | 1.46                              | 0.482      | 1640-16390 | 86                | >97           | 0.29                          | 7500                | 4               | SCSSS         | 1                    | 1                       |

Note: \* Specimen was back pressured to 1500 kPa

\*\*Flow Type as defined in Section 3.6

Table 7.6 Statistical Analysis of Hydraulic Flux - Hydraulic Gradient Test Results

Regression Line Forced Through Zero (Darcian) No Constraints on Regression Analysis

| File Name        | Clay Density (Mg/m <sup>3</sup> ) | Porosity | X-incpt (i <sub>0</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | X-incpt (i <sub>0</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | Special Notes |
|------------------|-----------------------------------|----------|---------------------------|-------------------------------|----------------|------------------------|---------------------------|-------------------------------|----------------|------------------------|---------------|
| BARCG02A: High i | 0.55                              | 0.806    | 0                         | +8.5                          | 0.9698         | 6.59x10 <sup>-12</sup> | -18.5                     | -29 to -11                    | 0.9847         | 5.9x10 <sup>-12</sup>  |               |
| BARCG02A: Low i  | 0.55                              | 0.806    | 0                         | +7.0                          | 0.9847         | 2.27x10 <sup>-12</sup> | 0                         | -8.1 to 8                     | 0.9218         | 2.26x10 <sup>-12</sup> |               |
| BARCG01A: High i | 0.59                              | 0.792    | 0                         | +475                          | 0.9511         | 5.33x10 <sup>-13</sup> | 494                       | 216 to 888                    | 0.9819         | 6.25x10 <sup>-13</sup> |               |
| BARCG01A: Mid i  | 0.59                              | 0.792    | 0                         |                               | 0.8444         | 1.7x10 <sup>-13</sup>  | 157                       | 14 to 364                     | 0.8719         | 2.04x10 <sup>-13</sup> |               |
| BARCG01A: Low i  | 0.59                              | 0.792    | 0                         | ID                            | ID             | 7.3x10 <sup>-14</sup>  | ID                        | ID                            | ID             | 7.3x10 <sup>-14</sup>  |               |
| BARCG05A: High i | 0.66                              | 0.768    | 0                         | +20                           | 0.6773         | 4.1x10 <sup>-09</sup>  | 15.5                      | 6 to 32                       | 0.8252         | 1.36x10 <sup>-08</sup> | SCSSS         |
| BARCG05A: Low i  | 0.66                              | 0.768    | 0                         | +1.3                          | 0.9390         | 4.03x10 <sup>-10</sup> | 1                         | 0 to 2.4                      | 0.9735         | 4.71x10 <sup>-10</sup> |               |
| BARCG01E: High i | 0.70                              | 0.754    | 0                         | +72                           | 0.8168         | 7.38x10 <sup>-12</sup> | -88                       | -231 to 2                     | 0.8432         | 6.19x10 <sup>-12</sup> |               |
| BARCG01E: Low i  | 0.70                              | 0.754    | 0                         | +26                           | 0.0851         | 2.62x10 <sup>-12</sup> | 2.4                       | -28 to 34                     | 0.8521         | 2.68x10 <sup>-12</sup> |               |
| BARCG01C: High i | 0.76                              | 0.732    | 0                         | +5.5                          | 0.9912         | 2.41x10 <sup>-12</sup> | 2.2                       | 2.2 to 7.8                    | 0.9919         | 2.46x10 <sup>-12</sup> | BP*           |
| BARCG01C: Low i  | 0.76                              | 0.732    | 0                         | +4.9                          | 0.6145         | 1.18x10 <sup>-12</sup> | 4                         | 1.3 to 9.9                    | 0.7133         | 1.79x10 <sup>-12</sup> |               |
| BARCG04B         | 0.79                              | 0.722    | 0                         | +0.7                          | 0.9931         | 8.41x10 <sup>-12</sup> | -0.3                      | -1 to 0.4                     | 0.994          | 8.25x10 <sup>-12</sup> | BP*           |
| BARCG04BB        | 0.79                              | 0.722    | 0                         | +13                           | 0.8924         | 6.22x10 <sup>-12</sup> | 9                         | -0.1 to 18                    | 0.9352         | 7.14x10 <sup>-12</sup> | BP*           |
| BARCG01D         | 0.80                              | 0.718    | 0                         | +109                          | 0.9654         | 3.91x10 <sup>-12</sup> | -83                       | -145 to 4                     | 0.9871         | 3.29x10 <sup>-12</sup> |               |
| BARCG02D2        | 0.89                              | 0.687    | 0                         | ID                            | ID             | 3.91x10 <sup>-11</sup> | -34                       | -41 to -30                    | 0.8867         | 1.12x10 <sup>-11</sup> | BP*           |



| File Name        | Clay Density (Mg/m <sup>3</sup> ) | Porosity | X-incpt (i <sub>o</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | X-incpt (i <sub>o</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | Special Notes |
|------------------|-----------------------------------|----------|---------------------------|-------------------------------|----------------|------------------------|---------------------------|-------------------------------|----------------|------------------------|---------------|
| BARCG03B         | 0.93                              | 0.673    | 0                         | +0.3                          | 0.9921         | 1.02x10 <sup>-11</sup> | -0.1                      | -0.6 to 0.4                   | 0.9922         | 1.01x10 <sup>-11</sup> | BP*           |
| BARCG02E         | 0.96                              | 0.662    | 0                         | +24                           | 0.9814         | 2.42x10 <sup>-12</sup> | 2.4                       | -27 to 30                     | 0.9814         | 2.42x10 <sup>-12</sup> |               |
| BARCG02C         | 0.96                              | 0.662    | 0                         | +16                           | 0.8347         | 2.6x10 <sup>-13</sup>  | 5.7                       | -8 to 18                      | 0.8515         | 2.81x10 <sup>-13</sup> | BP*           |
| BARCG02BB        | 0.99                              | 0.651    | 0                         | +580                          | 0.6961         | 5.02x10 <sup>-13</sup> | 467                       | 324 to 646                    | 0.9701         | 6.01x10 <sup>-13</sup> | BP*           |
| BARCG02D         | 1.01                              | 0.644    | 0                         | NP                            | NP             | NP                     | NP                        | NP                            | NP             | NP                     | BP*           |
| BARCG03A         | 1.01                              | 0.644    | 0                         | NP                            | ID             | 1.61x10 <sup>-11</sup> | ID                        | ID                            | ID             | 2.13x10 <sup>-11</sup> | BP*           |
| SHC75            | 1.03                              | 0.455    | 0                         | +971                          | 0.9752         | 4.47x10 <sup>-13</sup> | -646                      | -1553 to 374                  | 0.9797         | 4.25x10 <sup>-13</sup> |               |
| RBML1_P2         | 1.04                              | 0.455    | 0                         | +100                          | 0.8702         | 6.64x10 <sup>-13</sup> | -18.5                     | -139 to 98                    | 0.8706         | 6.5x10 <sup>-13</sup>  |               |
| BARCG04D2        | 1.06                              | 0.627    | 0                         | +139                          | 0.8900         | 5.01x10 <sup>-13</sup> | 16.7                      | -139 to 176                   | 0.8903         | 5.1x10 <sup>-13</sup>  |               |
| BARCG01BB high i | 1.06                              | 0.627    | 0                         | +5.1                          | 0.9449         | 1.05x10 <sup>-12</sup> | -4.6                      | -13 to -2                     | 0.9516         | 9.7x10 <sup>-13</sup>  | BP*           |
| BARCG01BB low i  | 1.06                              | 0.627    | 0                         | +2.6                          | ID             | 3.39x10 <sup>-13</sup> | -16.8                     | -30 to -23                    | 0.8842         | 1.57x10 <sup>-13</sup> | BP*           |
| BARCG04A         | 1.09                              | 0.616    | 0                         | +26                           | 0.9702         | 1.2x10 <sup>-11</sup>  | 9.4                       | 16 to 35                      | 0.9729         | 1.24x10 <sup>-11</sup> | BP*, SCSSS    |
| S50MC11          | 1.12                              | 0.593    | 0                         | +615                          | 0.9889         | 7.9x10 <sup>-13</sup>  | 283                       | -396 to 1001                  | 0.9901         | 8.12x10 <sup>-13</sup> |               |
| URL115           | 1.12                              | 0.606    | 0                         | +116                          | 0.9752         | 1.34x10 <sup>-12</sup> | -31                       | -155 to 91                    | 0.9763         | 1.3x10 <sup>-12</sup>  |               |
| MICG_9A          | 1.13                              | 0.602    | 0                         | +7                            | 0.9811         | 1.58x10 <sup>-12</sup> | -1.7                      | -9.8 to 6.3                   | 0.9815         | 1.57x10 <sup>-12</sup> |               |
| BARCG05E         | 1.15                              | 0.595    | 0                         | +155                          | 0.9461         | 7.91x10 <sup>-13</sup> | 41                        | -109 to 191                   | 0.95           | 8.03x10 <sup>-13</sup> |               |
| URL              | 1.17                              | 0.588    | 0                         | +82                           | 0.9967         | 1.08x10 <sup>-12</sup> | -61                       | -139 to 15                    | 0.9976         | 1.05x10 <sup>-12</sup> | BP*           |
| BARCG07E         | 1.18                              | 0.585    | 0                         | +576                          | 0.2234         | 4.55x10 <sup>-13</sup> | 566                       | 391 to 796                    | 0.9235         | 4.35x10 <sup>-13</sup> |               |
| BARCG03E         | 1.18                              | 0.585    | 0                         | +72                           | 0.7330         | 1.59x10 <sup>-13</sup> | -45                       | -137 to -34                   | 0.7933         | 1.39x10 <sup>-13</sup> |               |
| S50MC15          | 1.18                              | 0.356    | 0                         | +1716                         | 0.9733         | 2.89x10 <sup>-13</sup> | -152                      | -189 to 1737                  | 0.9734         | 2.87x10 <sup>-13</sup> |               |

| File Name     | Clay Density (Mg/m <sup>3</sup> ) | Porosity | X-incpt (i <sub>o</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | X-incpt (i <sub>o</sub> ) | Statistical Range of x Incpt. | R <sup>2</sup> | k (m/s)                | Special Notes |
|---------------|-----------------------------------|----------|---------------------------|-------------------------------|----------------|------------------------|---------------------------|-------------------------------|----------------|------------------------|---------------|
| RBMLH2_P2     | 1.19                              | 0.581    | 0                         | +572                          | 0.8931         | 1.94x10 <sup>-13</sup> | -945                      | -1428 to -343                 | 0.9293         | 1.64x10 <sup>-13</sup> |               |
| URL125        | 1.20                              | 0.577    | 0                         | +113                          | 0.9918         | 8.33x10 <sup>-13</sup> | -31                       | -143 to 85                    | 0.9921         | 8.42x10 <sup>-13</sup> |               |
| RBMLH05       | 1.22                              | 0.389    | 0                         | +225                          | 0.9352         | 5.12x10 <sup>-13</sup> | 132                       | -45 to 318                    | 0.9581         | 5.37x10 <sup>-13</sup> |               |
| S50MC17       | 1.22                              | 0.367    | 0                         | +2937                         | 0.9169         | 2.86x10 <sup>-13</sup> | -1099                     | -3871 to 2414                 | 0.9232         | 2.70x10 <sup>-13</sup> |               |
| DW100.42      | 1.22                              | 0.570    | 0                         | +306                          | 0.9693         | 3.17x10 <sup>-13</sup> | -113                      | -512 to 275                   | 0.9709         | 3.07x10 <sup>-13</sup> |               |
| THS90B        | 1.23                              | 0.567    | 0                         | +124                          | 0.9847         | 3.13x10 <sup>-13</sup> | -113                      | -532 to 390                   | 0.9709         | 3.07x10 <sup>-13</sup> |               |
| C50.20WD      | 1.24                              | 0.375    | 0                         | +605                          | 0.9928         | 8.37x10 <sup>-13</sup> | -849                      | -1257 to -501                 | 0.9988         | 7.87x10 <sup>-13</sup> |               |
| BARCG03D      | 1.25                              | 0.560    | 0                         | +920                          | 0.1887         | 1.63x10 <sup>-13</sup> | 844                       | 760 to 1013                   | 0.9601         | 2.37x10 <sup>-13</sup> |               |
| TDCON         | 1.26                              | 0.556    | 0                         | +221                          | 0.9885         | 8.11x10 <sup>-13</sup> | 109                       | -104 to 312                   | 0.9898         | 8.34x10 <sup>-13</sup> |               |
| SISAVB60/40   | 1.28                              | 0.324    | 0                         | +922                          | 0.9924         | 1.29x10 <sup>-13</sup> | -1230                     | -1758 to -742                 | 0.9983         | 1.22x10 <sup>-13</sup> |               |
| BAR130        | 1.30                              | 0.542    | 0                         | +336                          | 0.9450         | 2.76x10 <sup>-13</sup> | -238                      | -564 to 127                   | 0.9564         | 2.6x10 <sup>-13</sup>  |               |
| URL135        | 1.30                              | 0.542    | 0                         | +373                          | 0.8325         | 4.82x10 <sup>-13</sup> | 54                        | -333 to 452                   | 0.8341         | 4.99x10 <sup>-13</sup> |               |
| MICG_9B       | 1.32                              | 0.535    | 0                         | +5.4                          | 0.9748         | 3.87x10 <sup>-12</sup> | -2.9                      | -8.7 to 2.6                   | 0.9786         | 3.72x10 <sup>-12</sup> |               |
| SSB40A        | 1.34                              | 0.349    | 0                         | +2700                         | 0.7309         | 2.63x10 <sup>-13</sup> | -1276                     | -1705 to -1158                | 0.8992         | 1.85x10 <sup>-13</sup> |               |
| S50MC07       | 1.34                              | 0.316    | 0                         | +748                          | 0.9953         | 2.31x10 <sup>-13</sup> | 436                       | -276 to 1188                  | 0.9962         | 2.36x10 <sup>-13</sup> |               |
| SISAVB25/75   | 1.34                              | 0.454    | 0                         | +656                          | 0.9950         | 3.15x10 <sup>-13</sup> | -458                      | -1137 to 143                  | 0.9963         | 3.05x10 <sup>-13</sup> |               |
| BAR115        | 1.35                              | 0.525    | 0                         | +525                          | 0.9470         | 2.24x10 <sup>-13</sup> | -170                      | -612 to 250                   | 0.9515         | 2.13x10 <sup>-13</sup> | BP*           |
|               |                                   |          |                           |                               |                |                        |                           |                               |                |                        |               |
| SHC25, high i | 1.36                              | 0.447    | 0                         | +6663                         | 0.8495         | 8.94x10 <sup>-14</sup> | 6532                      | 3125 to 13771                 | 0.9439         | 1.24x10 <sup>-14</sup> |               |
| SHC25, low i  | 1.36                              | 0.447    | 0                         | +1242                         | 0.8681         | 8.1x10 <sup>-15</sup>  | 1754                      | 1333 to 3111                  | 0.9588         | 1.14x10 <sup>-14</sup> |               |
|               |                                   |          |                           |                               |                |                        |                           |                               |                |                        |               |
| RBMO1         | 1.43                              | 0.320    | 0                         | +346                          | 0.9993         | 1.2x10 <sup>-13</sup>  | -176                      | -523 to 180                   | 0.9994         | 1.19x10 <sup>-13</sup> |               |
| SC100.28      | 1.46                              | 0.486    | 0                         | +444                          | 0.9952         | 1.46x10 <sup>-13</sup> | -458                      | -830 to -60                   | 0.9976         | 1.4 x10 <sup>-13</sup> |               |
| BARCGEX       | 1.46                              | 0.486    | 0                         | +281                          | 0.9577         | 1.58x10 <sup>-13</sup> | -404                      | -499 to -327                  | 0.9975         | 1.39x10 <sup>-13</sup> | BP*           |

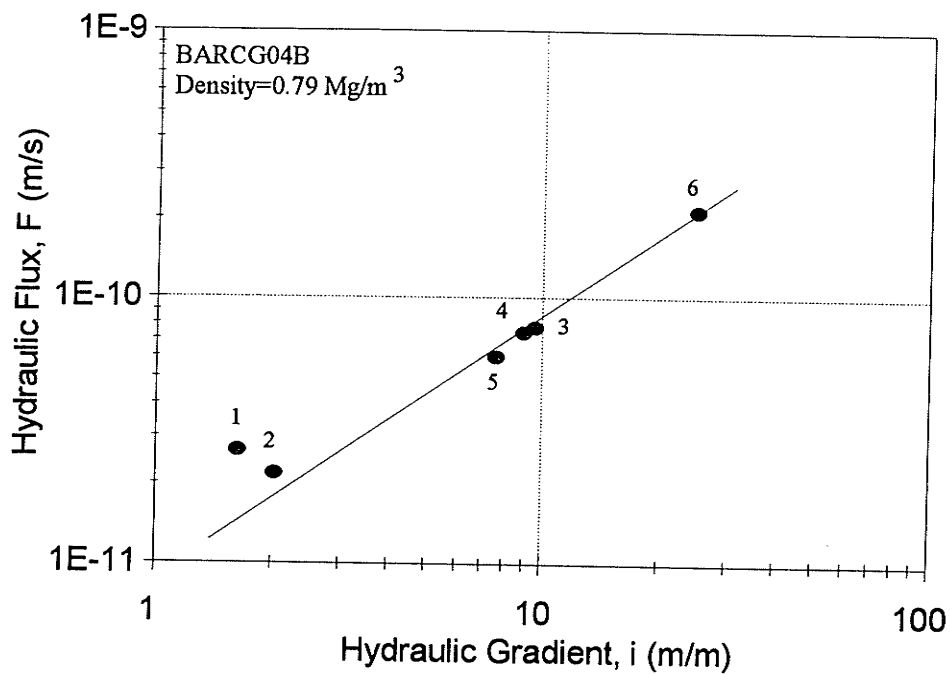


Figure 7.13 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG04B (Density = 0.79 Mg/m<sup>3</sup> ; Static Compaction; 1500 kPa Back Pressure)

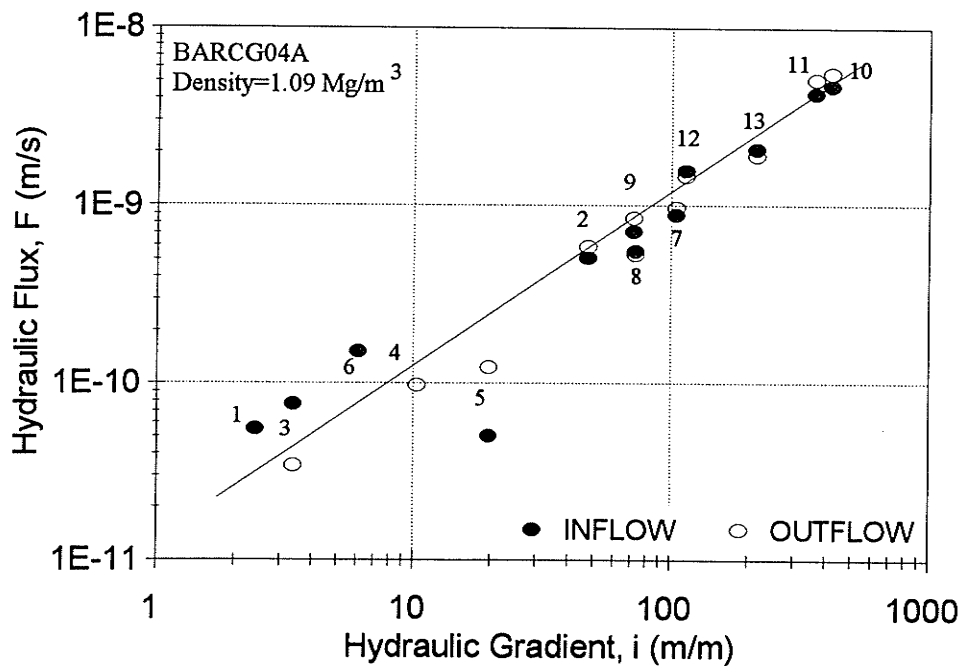


Figure 7.14 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG04A (Density = 1.09 Mg/m<sup>3</sup> ; Static Compaction; 1500 kPa Back Pressure, Saline Fluid)

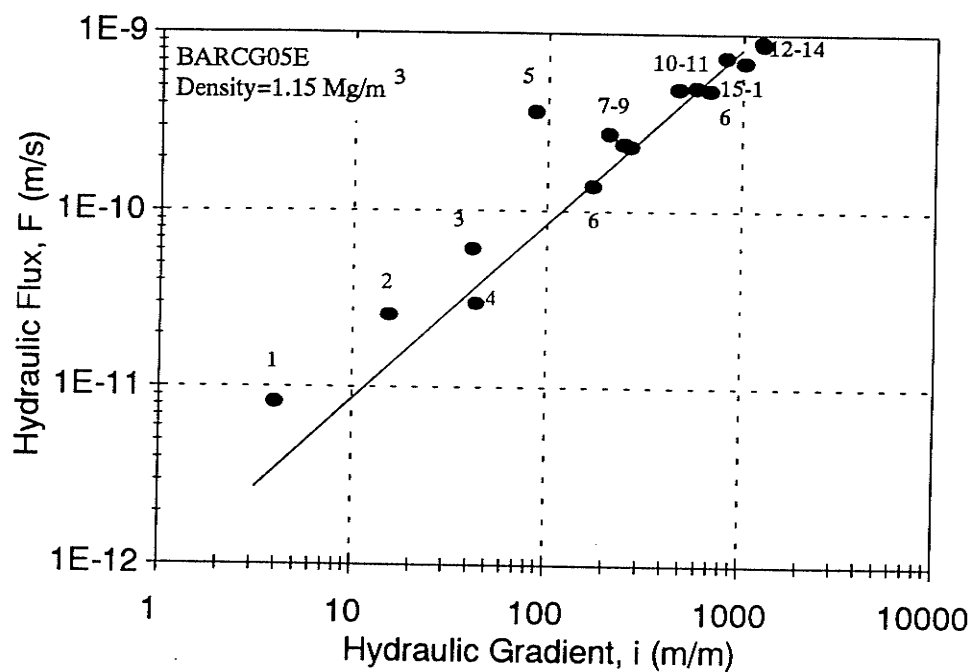


Figure 7.15 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG05E (Density =  $1.15 \text{ Mg/m}^3$  ; Static Compaction; No Back Pressure)

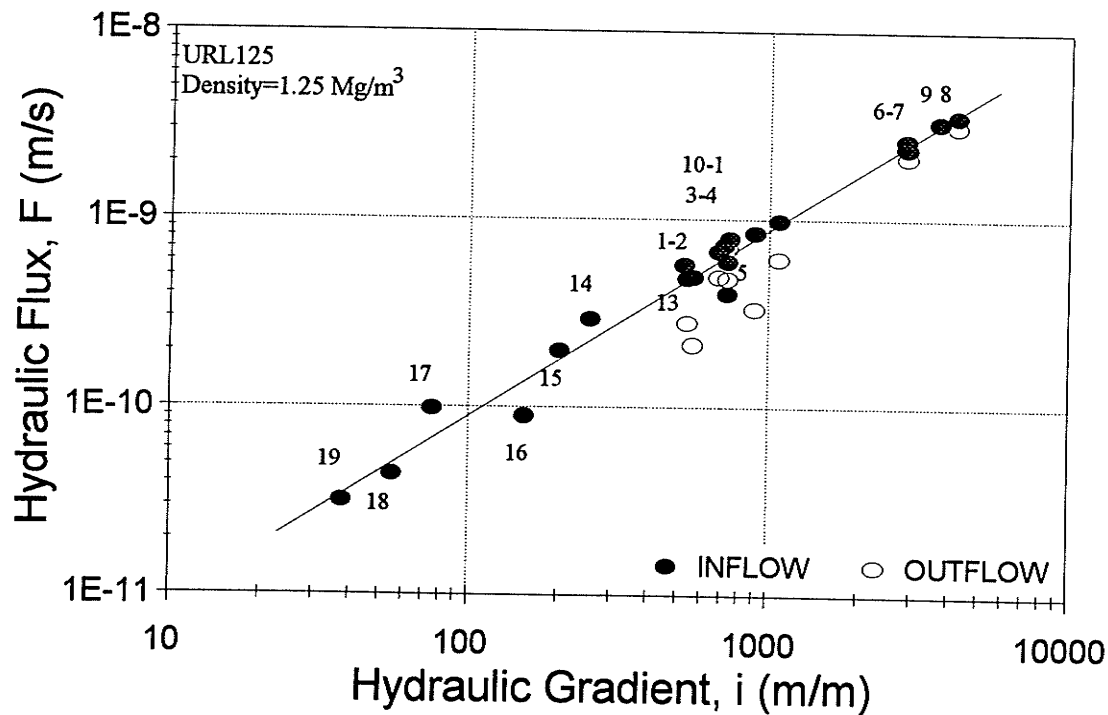


Figure 7.16 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen URL125 (Density =  $1.25 \text{ Mg/m}^3$  ; Static Compaction; No Back Pressure)

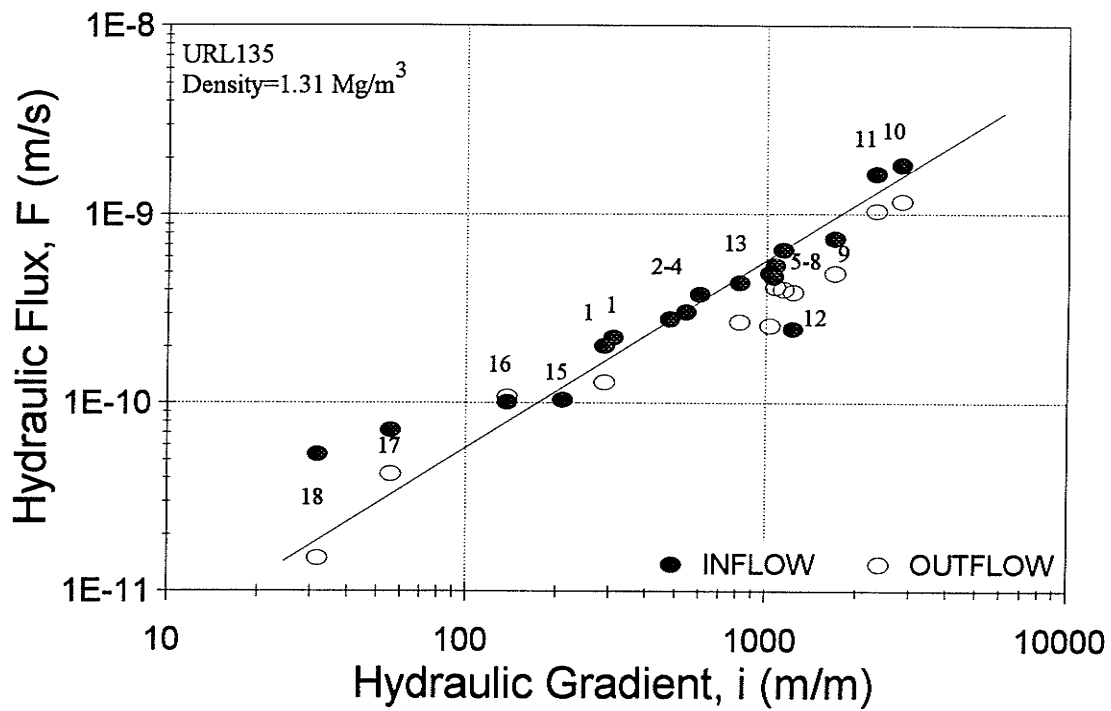


Figure 7.17 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen URL135 (Density = 1.31 Mg/m<sup>3</sup> ; Static Compaction; No Back Pressure)

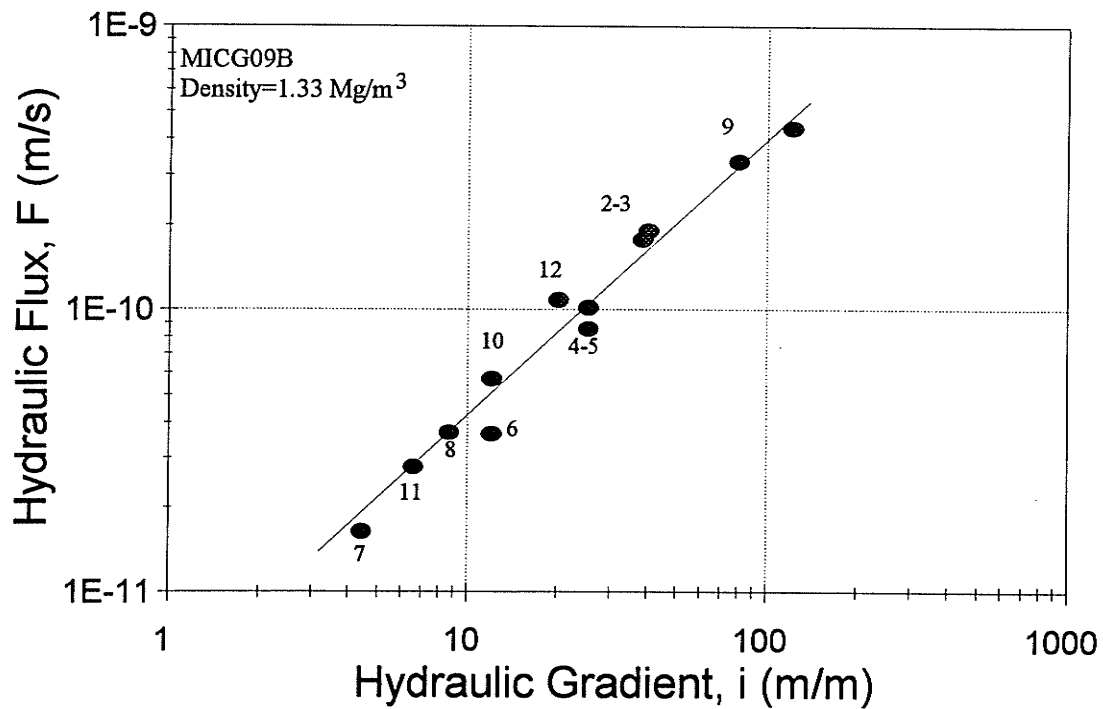


Figure 7.18 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen MICG09B (Density = 1.33 Mg/m<sup>3</sup> ; Static Compaction; No Back Pressure)

#### 7.4.3 Evidence of Non-Darcian Flow Behaviour

A number of the specimens exhibited one of two non-Darcian behaviours, for example those specimens plotted as Figures 7.19 through 7.23, and those plotted as Figures 7.24 through 7.26. These two basic data patterns were observed in the 14 specimens which did not exhibit Darcian flow behaviour. The first type had a transitional gradient in log-log space similar to that seen in some illite specimens, and a bi-linear plot in arithmetic-space plots. These plots corresponded to Flow Type 2 in a log-space plot and Flow Type 4 in a linear plot (Table 7.5, see also Section 3.6.2 and Figure 3.10 for definitions). These specimens exhibited normal Darcian flow over quite a wide range of increasing hydraulic gradients and then exhibited a sharp change in their hydraulic conductivity at the transitional gradients. Once the transitional gradient was exceeded, the flow behaviour was again Darcian, but the hydraulic conductivity had increased. The second type of non-Darcian flow behaviour observed was a straight-line "Darcian" plot in log-log space, but linear plotting of the data in arithmetic space produced a threshold gradient (regression line did not intersect origin).

Of the seven specimens which exhibited a transitional gradient, five were the lowest density materials investigated in this thesis (density  $0.55 \text{ Mg/m}^3$  to  $0.76 \text{ Mg/m}^3$ ). The tests on these low density bentonitic materials are presented in Figures 7.19 through 7.23. These specimens showed shifts in the Darcian flow relationship at low hydraulic gradients (similar to the illitic clay specimens discussed in Section 7.3). This behaviour can be attributed to the specimens undergoing changes in the pore space available for flow when an increase in applied hydraulic gradient exceeded a transitional gradient (as described by Karthigesu (1994) for low bentonite content specimens). Karthigesu (1994) reported the presence of similar transitional gradients in specimens having effective clay dry bulk

densities of  $0.14 \text{ Mg/m}^3$  (5% bentonite clay by dry weight proportion) and  $0.27 \text{ Mg/m}^3$  (10% bentonite clay by dry weight proportion).

The Darcian hydraulic conductivity of the five low density bentonite specimens examined approximately doubled when the transitional gradient was exceeded. As was the case with the illitic specimens exhibiting transitional gradients, the change in "k" was found to be reversible, that is, independent of whether the gradients were increasing or decreasing. This reversible transition is shown, where appropriate in Figures 7.19 through 7.23. This means that the changes in flow were not the result of change in soil structure or flow path which are generally believed to be non-reversible, but must be caused by some other mechanism, such as that described in Section 7.3.2.

Two higher density specimens ( $1.06 \text{ Mg/m}^3$  and  $1.36 \text{ Mg/m}^3$ ), also exhibited transitional gradients and non-Darcian flow in both log-scale and linear plots. These data are presented in Appendix A3. These two specimens were tested at a smaller number of hydraulic gradients (7 and 6 for the lower and higher density specimens respectively) than the specimens previously presented. Most of the other tests involved 10 to >20 different hydraulic gradients. The limited number of gradients examined make it difficult statistically to separate the behaviour into two separate regions of behaviour. The first of these two specimens (BARCG01BB,  $1.06 \text{ Mg/m}^3$ ), exhibited inconsistent inflow behaviour throughout the course of testing and only the outflow data was used to define its flux-gradient behaviour. The poor quality of the data make it inappropriate to consider this specimen's behaviour as being due to any intrinsic material property. Specimen SHC25 ( $1.36 \text{ Mg/m}^3$ ), was tested at very high hydraulic gradients and a transitional gradient was apparently observed at a very high gradient (approximately 10,000). It may be in the denser (>0.76

Mg/m<sup>3</sup>) materials that transitional gradients exist at very high gradients but this was not evidenced in other specimens tested at similar gradients.

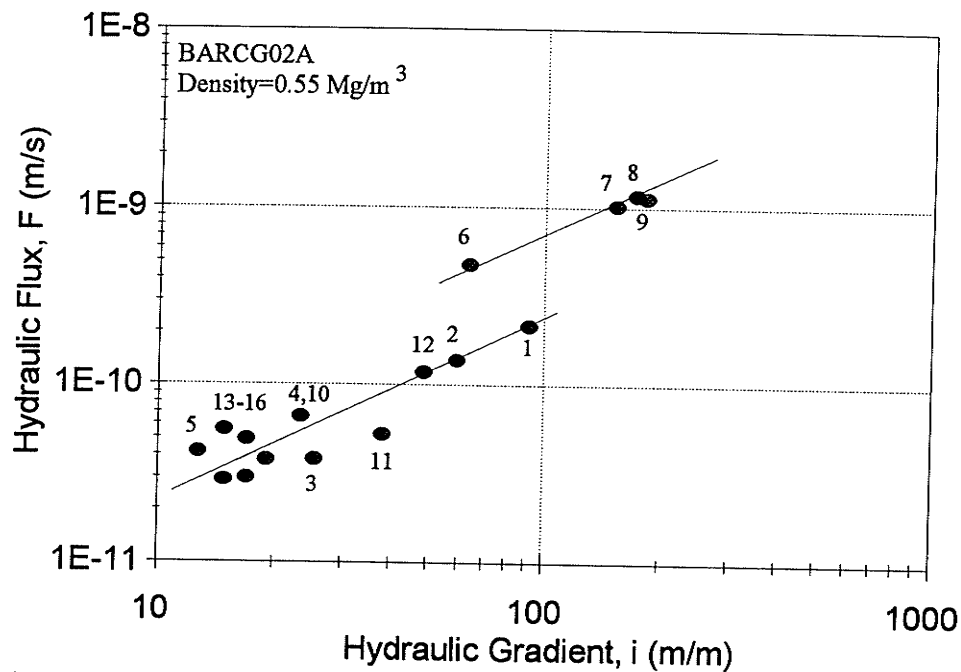


Figure 7.19 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG02A (Density =  $0.55 \text{ Mg/m}^3$  ; Static Compaction; No Back Pressure)

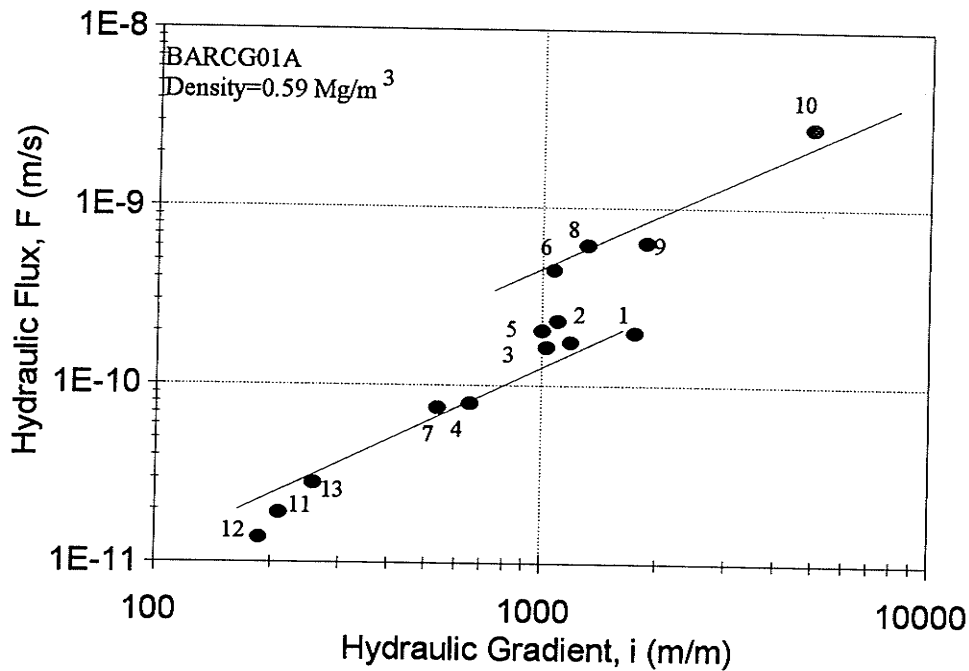


Figure 7.20 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG01A (Density =  $0.59 \text{ Mg/m}^3$  ; Static Compaction; No Back Pressure)



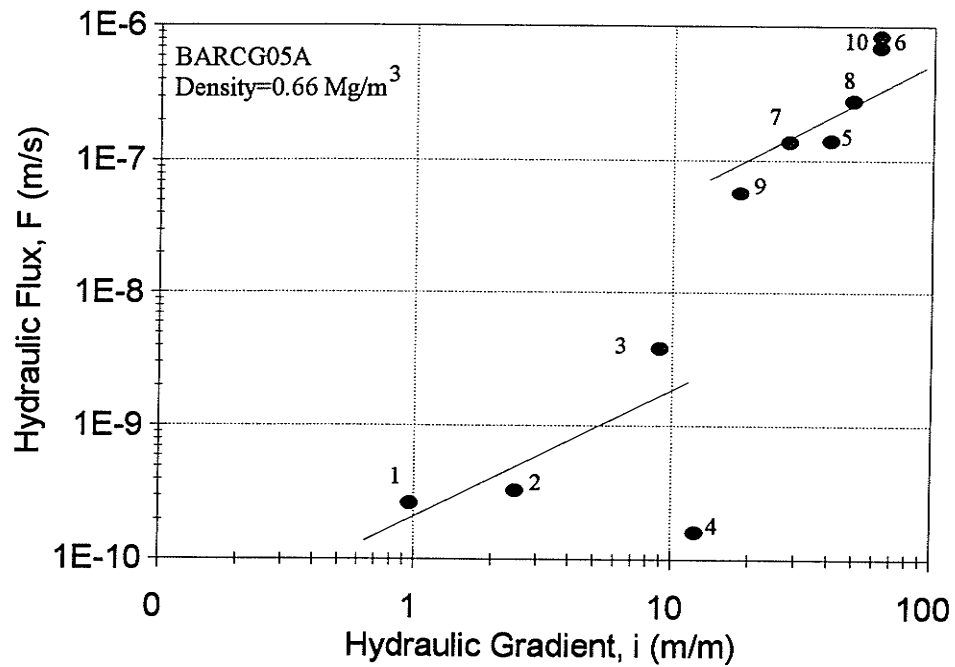


Figure 7.21 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG05A (Density = 0.66 Mg/m<sup>3</sup> ; Static Compaction; No Back Pressure, Saline Fluid)

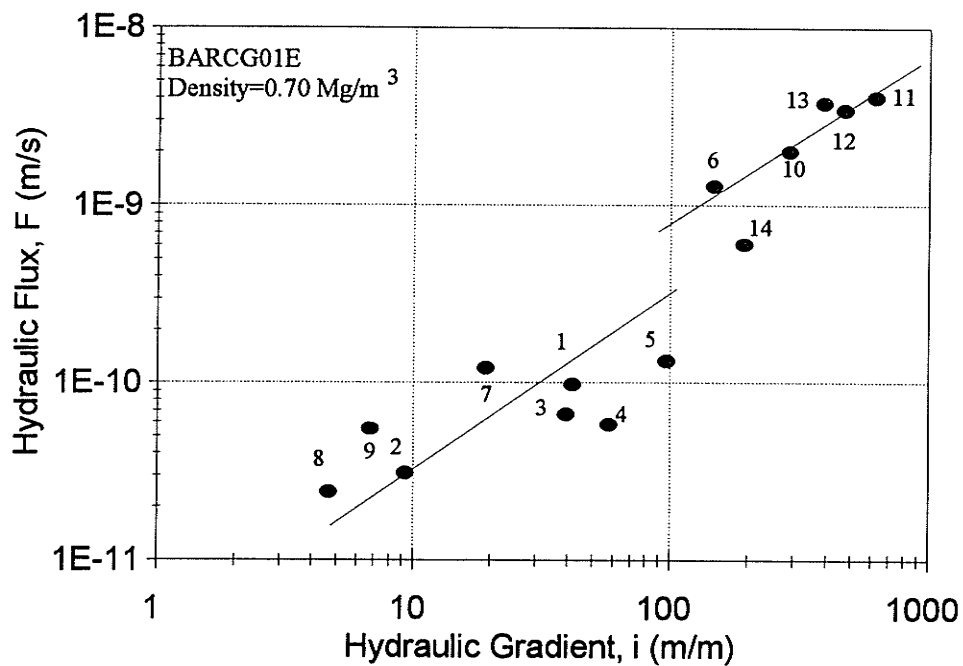


Figure 7.22 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG01E (Density = 0.70 Mg/m<sup>3</sup> ; Static Compaction; No Back Pressure)

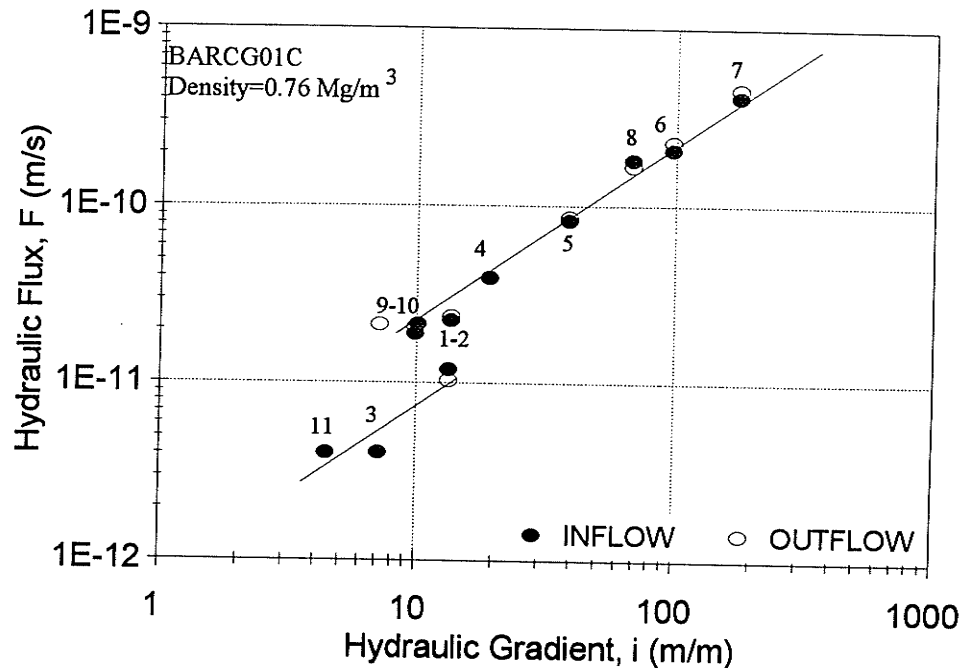


Figure 7.23 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG01C (Density = 0.76 Mg/m<sup>3</sup> ; Static Compaction; 1500 kPa Back Pressure)

The remaining 7 specimens which exhibited non-Darcian flow behaviour had "threshold" gradients which were outside the statistical range calculated for the specimens (see Table 7.6), and no transitional gradients were observed. The presence of threshold gradients implies that quite large gradients were required to cause flow, and indeed reverse flows (against the direction of hydraulic gradient) were apparently observed. These reversed flows could not be related to specimen density, back pressure or initial degree of saturation. Figures 7.24 through 7.26 present plots of the flux-hydraulic gradient data obtained for three of these tests.

The reason for this reverse-flow behaviour is uncertain. Suggested possibilities include, some form of unidentified chemical or biochemical gradient which acts in opposition to a base-to-top flow, or inaccuracies in calibrating pressure transducers. Despite considerable

effort, neither of these possibilities can be confirmed as the source of these deviations from Darcian flow behaviour. No way has been found to predict or quantify chemical or biological mechanisms present, and there appears to be no consistent relationship between the threshold gradients and any measured material parameters. As all specimens were tested in the same style of permeameter, any chemical or biological mechanisms should have been active in all the specimens tested, not just these few. The transducers used to measure the hydraulic heads applied to these specimens were all calibrated prior to test initiation. Errors made in obtaining the transducer calibrations are possible and would explain the inconsistent manner in which the threshold gradients were present. However, given that transducer calibration is a routine part of the laboratory operation, it appears unlikely that this would be the cause of the very large threshold gradients observed. The problem remains unresolved.

As there was no consistent pattern of occurrence of threshold gradients rather than transitional gradients, and no definitive explanation for such behaviour, it was decided to treat them as scatter in the data obtained. The hydraulic conductivities determined for these materials are independent of the observed threshold gradients, and so they can be used in examining relationships between density, porosity, and hydraulic conductivity (Chapter 8).

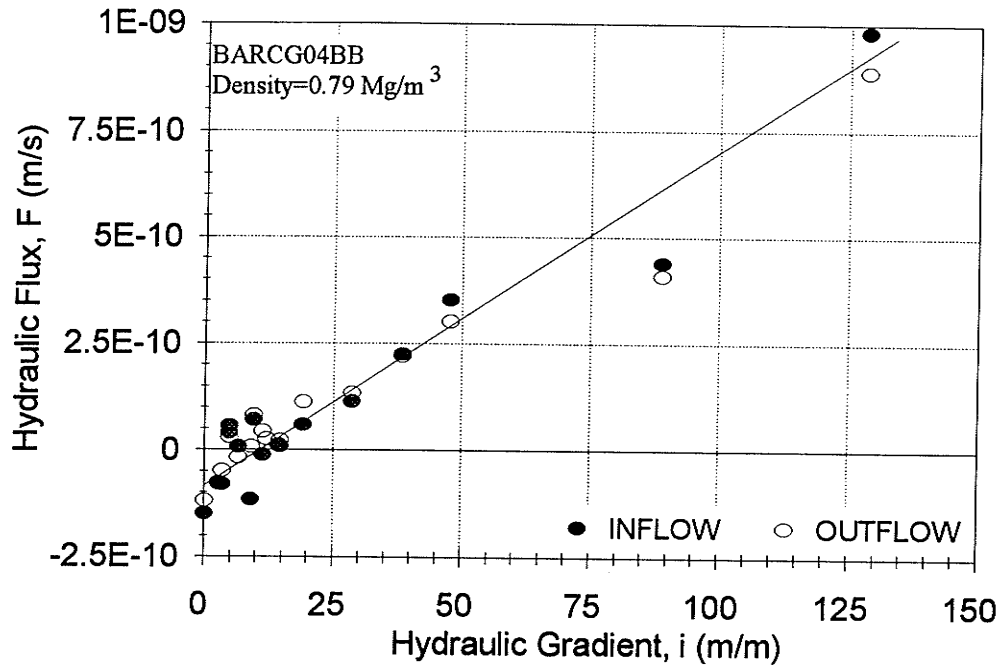


Figure 7.24 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG04BB (Density =  $0.79 \text{ Mg/m}^3$  ; Static Compaction; 1500 kPa Back Pressure)

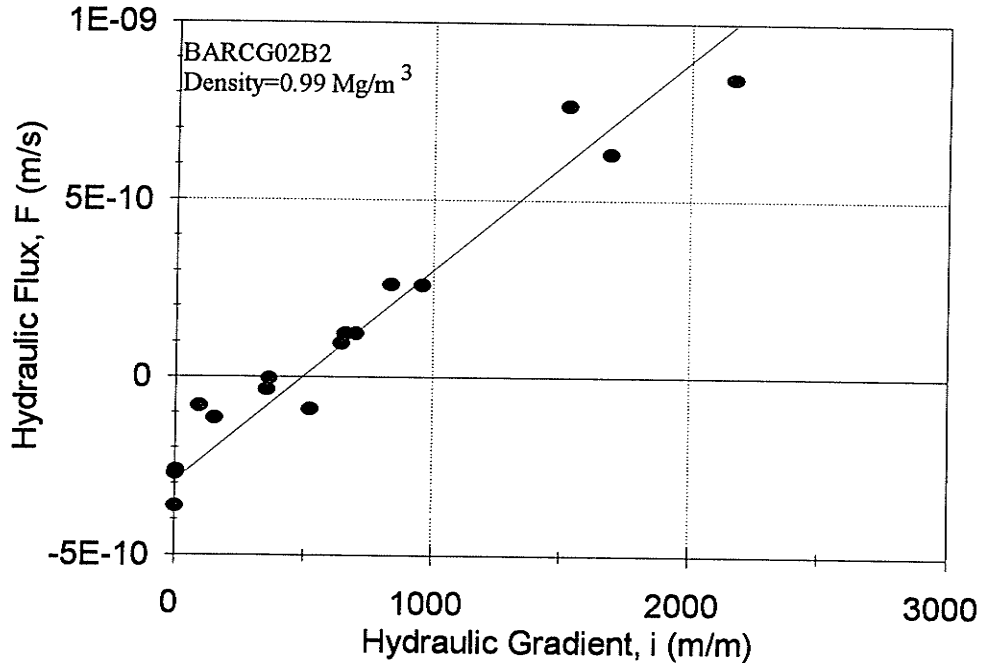


Figure 7.25 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG02B2 (Density =  $0.99 \text{ Mg/m}^3$  ; Static Compaction; No Back Pressure)

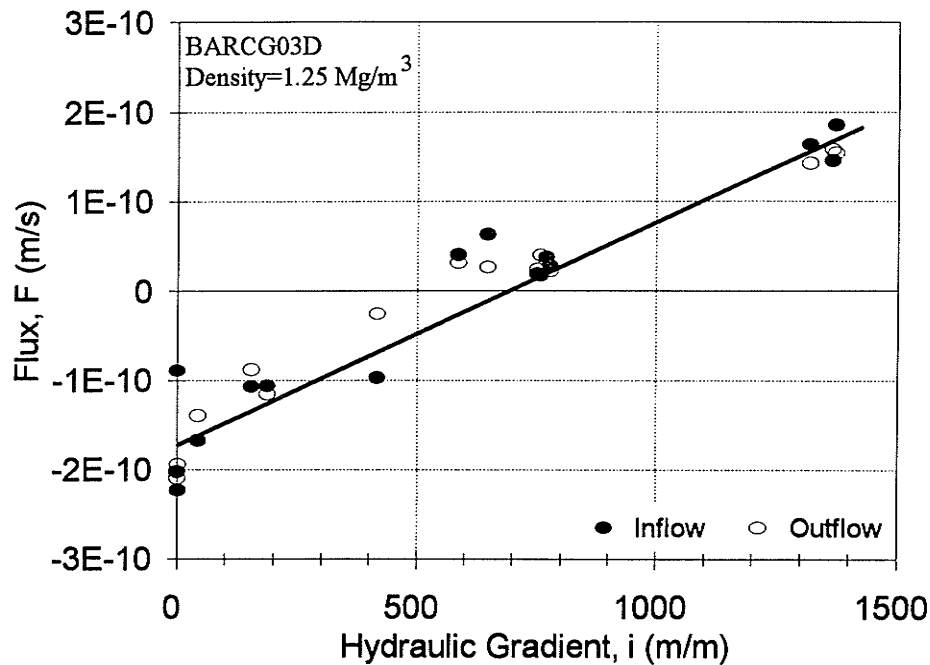


Figure 7.26 Hydraulic Flux Vs Applied Hydraulic Gradient For Specimen BARCG03D (Density = 1.25 Mg/m<sup>3</sup> ; Static Compaction; 1500 kPa Back Pressure)

#### 7.4.4 Influence of Initial Degree of Saturation, Pore Fluid Composition and Back Pressure on Water Flow Through Bentonite and Sand-Bentonite Materials

A series of tests was conducted to determine the influences of, (1) initial degree of specimen saturation, (2) pore fluid composition and, (3) back pressure on the hydraulic performance of bentonite specimens. These tests are important as they assist in identifying whether these parameters could have induced changes in the hydraulic performance of the bentonitic specimens.

As outlined in Tables 7.5 and 7.6, specimens were tested with initial degrees of saturation varying from 0% (oven dried) to greater than 90%. This was done to examine the effect of differing saturations on flow rates through bentonite-based materials. Figure 7.27

presents the results of the hydraulic conductivity measurements versus clay density. As in the illite results shown in Figure 7.12, hydraulic conductivity decreases with increasing clay density. Different symbols in Figure 7.27 indicate the initial degrees of saturation. This figure shows no clear relationship between initial degree of saturation and hydraulic conductivity for these materials.

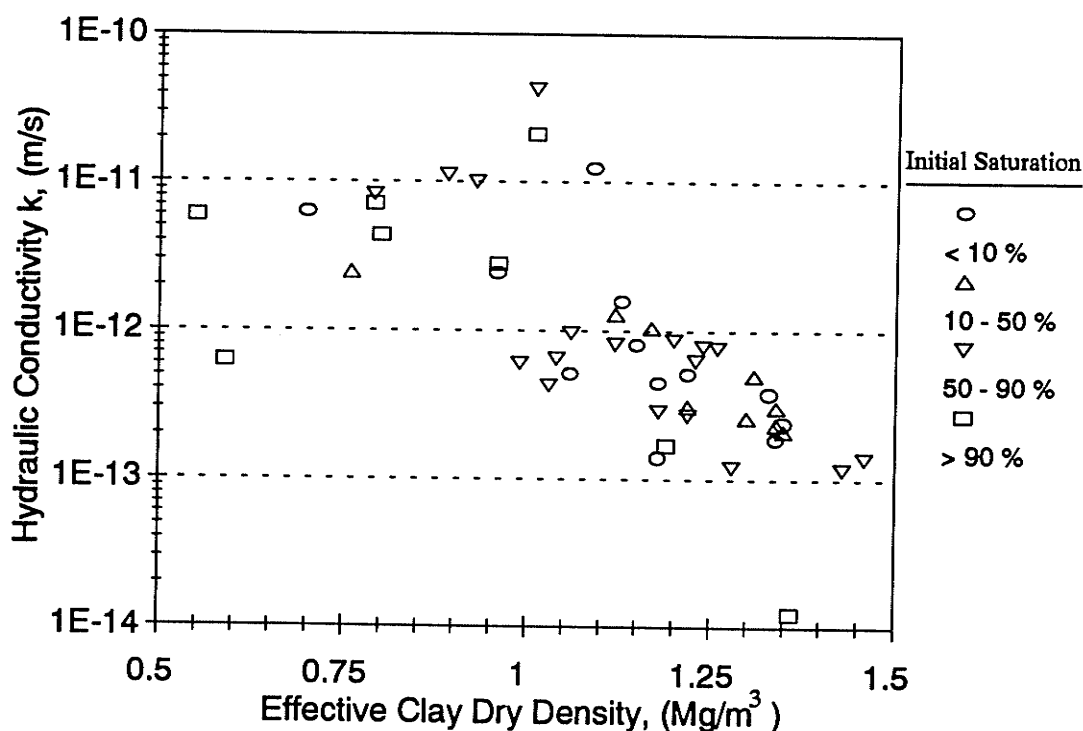


Figure 7.27 Influence of Initial Degree of Saturation on the Ultimate Hydraulic Conductivity of Bentonite and Bentonite-Sand Specimens

The lack of discernable differences in the hydraulic conductivity of specimens having widely different initial degrees of saturation indicate there are no significant differences in the overall soil structure of these specimens. This is consistent with the model presented by Oliphant and Tice (1985) who determined that fluid flow in clays, and in particular, bentonites, is largely controlled by conduction through a very limited number of channels through macro pores (Chapter 3 gave a more detailed explanation of this behaviour). Oliphant and Tice (1985) found that changes in density induced little change in the

pathways taken to conduct the water through bentonites, a finding supported by this study. The small number of macro pores through which water can flow was not influenced by the initial degree of saturation. This can be accounted for by assuming that there is little in the way of true macro pores in any of these materials, the bulk of the porosity is taken up by discontinuous micro pores within individual peds, and spaces between the individual clay platelets.

The bentonite clays used in these tests were not composed of individual platelets. The clay "particles" are actually anisotropic micro peds which have been packed into an essentially isotropic macrostructure (as presented in Section 3.4). Following full hydration, the soil remains isotropic on the specimen scale while retaining its anisotropic microstructure. At very high degrees of compaction where the micro peds are actually broken down, it might be expected that initial degree of saturation can begin to become significant to the hydraulic conductivity measured.

The influence of pore fluid chemistry on hydraulic conductivity was also examined in three specimens. Figure 7.28 shows data from these tests plus data reported previously by Dixon et al. (1987). It separates data from specimens tested using saline permeant from those tested using a distilled and deionized water. This figure also includes data from Pusch 1980a,b, Bucher and Speigl 1984, Bucher et al. 1985, Peterson and Kelkar 1983, Westsik 1982,1983, Radhakrishna and Chan 1985, Couture and Seitz 1983, Wheelwright et al. 1981 and Wood et al. 1982).

Cheung et al. (1987) predicted that a clay density  $<1.25 \text{ Mg/m}^3$  is required before an effective porosity is available for flow or influence of pore fluid chemistry occurs (Section

2.3.4). In general, this idealized model is valid only in a fully dispersed system with parallel clay platelets. Regression analysis of data shown in Figure 7.28 suggests that the boundary at which advective flow begins to be influenced could be reduced to perhaps  $1.00 \text{ Mg/m}^3$  from the  $1.25 \text{ Mg/m}^3$  proposed by Cheung et al. (1987). Specimens having densities greater than about  $1.0 \text{ Mg/m}^3$  exhibit the type of advective flow expected of a soil system in which much of the porosity is unavailable for flow, and only the small remainder is composed of unstructured water in pore spaces which are unaffected by diffuse double layers. It is this remaining porosity through which most of the advective transportation occurs.

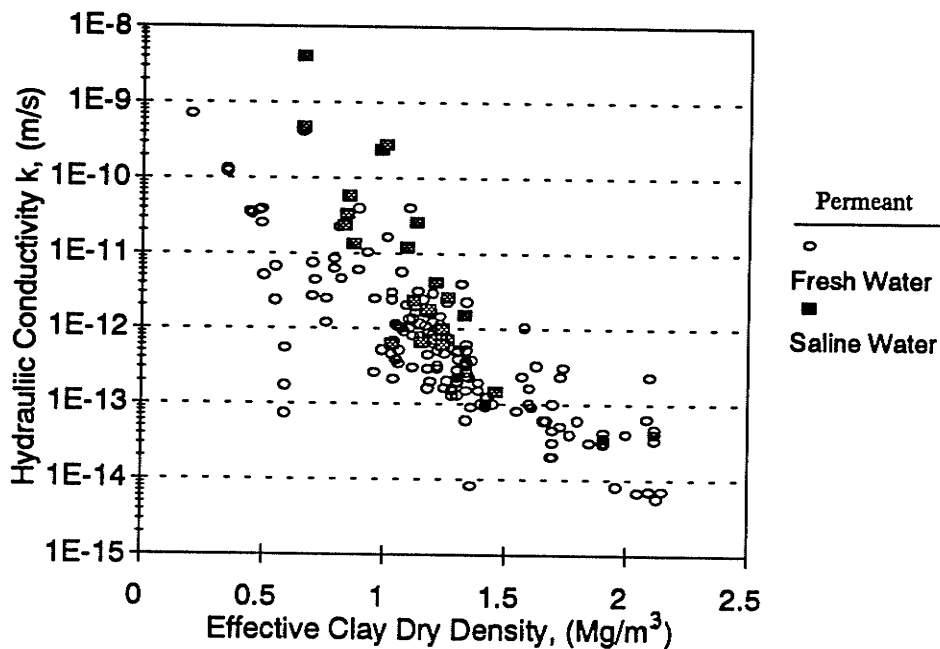


Figure 7.28 Influence of Pore Fluid Salinity on Hydraulic Conductivity of Bentonite

Figure 7.29 shows results of tests to examine how back pressure influences the hydraulic behaviour of bentonitic specimens. The results show that there is no systematic difference in the hydraulic behaviour of these clays that can be related to initial degree of



saturation. Studies of the influence of time on measured flow rates (Figure 4.7) indicated that any occluded or blocked pores are not likely to become active flow paths. This means that the existence of a limited degree of unsaturated porosity will not alter the results of studies on the influence of hydraulic gradient on the movement of water through these bentonitic specimens.

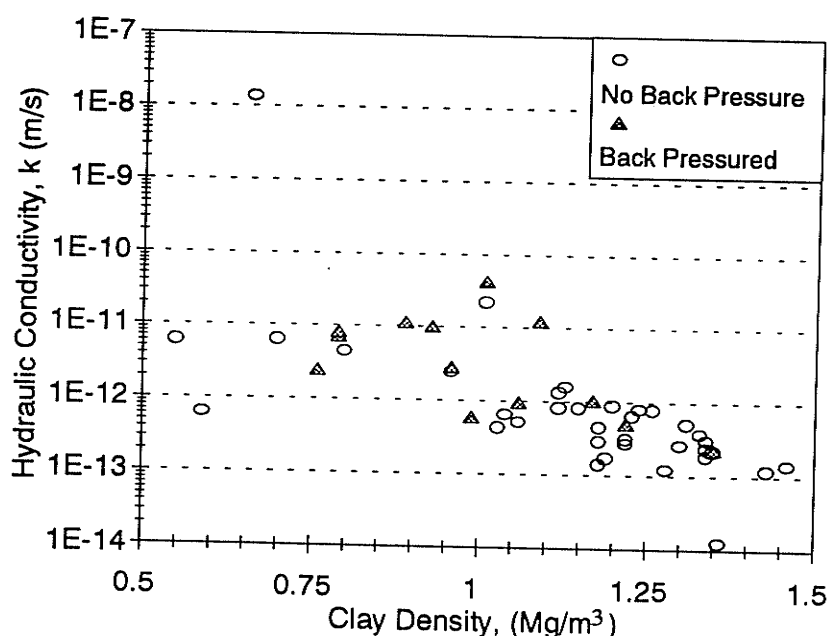


Figure 7.29 Influence of Back Pressure on Hydraulic Conductivity of Bentonite

From investigations into the influences of initial degree of saturation, back pressuring and pore fluid composition, it can be concluded that none of these parameters are likely to significantly alter the performance of these materials at clay densities  $>1.0 Mg/m^3$ . As the Canadian Nuclear Fuel Waste Management Program's (CNFWMP) Disposal Concept calls for the use of buffer materials compacted to a clay density  $>1.25 Mg/m^3$  it is unlikely that hydraulic performance of this barrier will be influenced by these parameters.

At low clay densities ( $<1\text{Mg/m}^3$ ), it is likely that pore fluid composition will influence the hydraulic performance of specimens. At these densities there is a well developed diffuse double layer surrounding the platelets and ionic concentration could become a factor in determining the porosity available for advective flow. The presence of an extensive double layer in low density bentonite specimens is supported by the transitional gradients shown in Figures 7.19 through 7.23. These gradients are interpreted as being the result of an increased porosity available for flow following increases in hydraulic gradient. Section 8.1 discusses the porosity and effective porosity parameters as they relate to the materials examined in this thesis. Section 8.2 will then compare the results obtained in the laboratory portion of this thesis to the results predicted using existing models for advective flow.

#### **7.4.5 Influence of Changing Flow Direction on Hydraulic Behaviour**

Six of the specimens were tested with reversals in the flow direction included in the range of conditions imposed. These changes in the direction of flow were, (1) to examine the possibility of other non-hydraulic gradients that might influence the flow of water through dense bentonites and, (2) to study the possibility of soil fabric changes occurring as the result of a reversal in flow direction.

The hydraulic gradients applied to these specimens were incremented until the desired maximum hydraulic gradient was achieved. Gradients were then reduced to zero and eventually reversed. The magnitude of the reverse gradient was incremented until it reached the maximum value in the other direction. Finally the direction was again reversed to establish reproducibility of the initial flux-gradient relationship. Figures 7.30

through 7.32 present the results from three of these specimens. These figures also include the increment number for each stage of the test

All 6 tests exhibited consistent flow behaviour, with Darcian flow behaviour being present in most tests, although several showed the presence of threshold gradients. Changes in the direction of water flow had no noticeable influence on the flux-gradient relationship, indicating that the soil fabric was not affected by changes in flow direction.

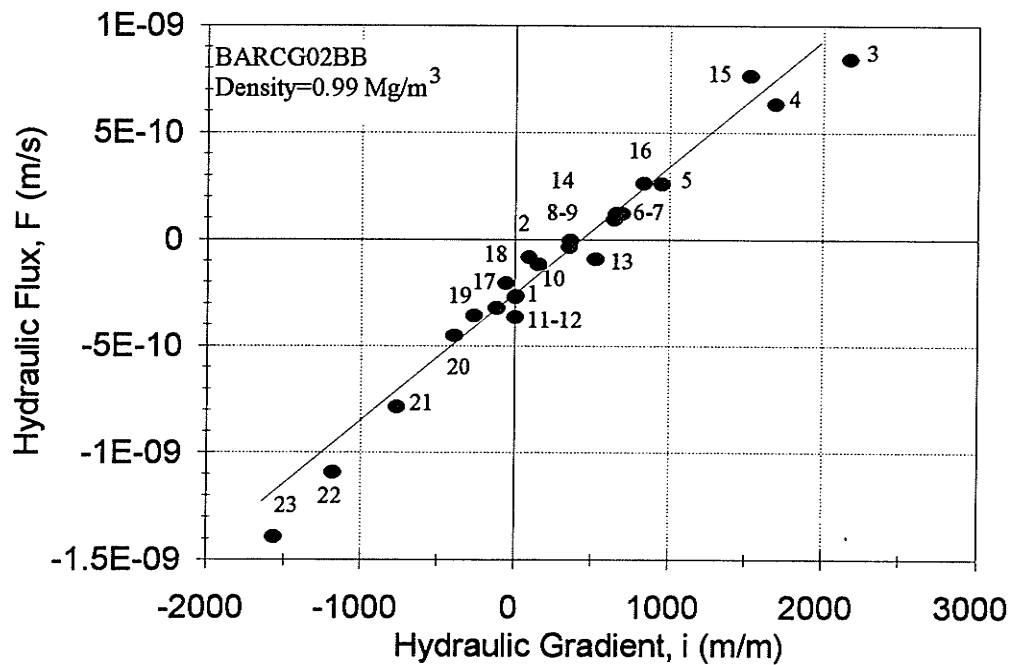


Figure 7.30 Influence of Change in Flow Direction on Bentonite-Based Materials (BARCG02BB; 0.99 Mg/m<sup>3</sup>; Static Compaction; 1500 kPa Back Pressure)

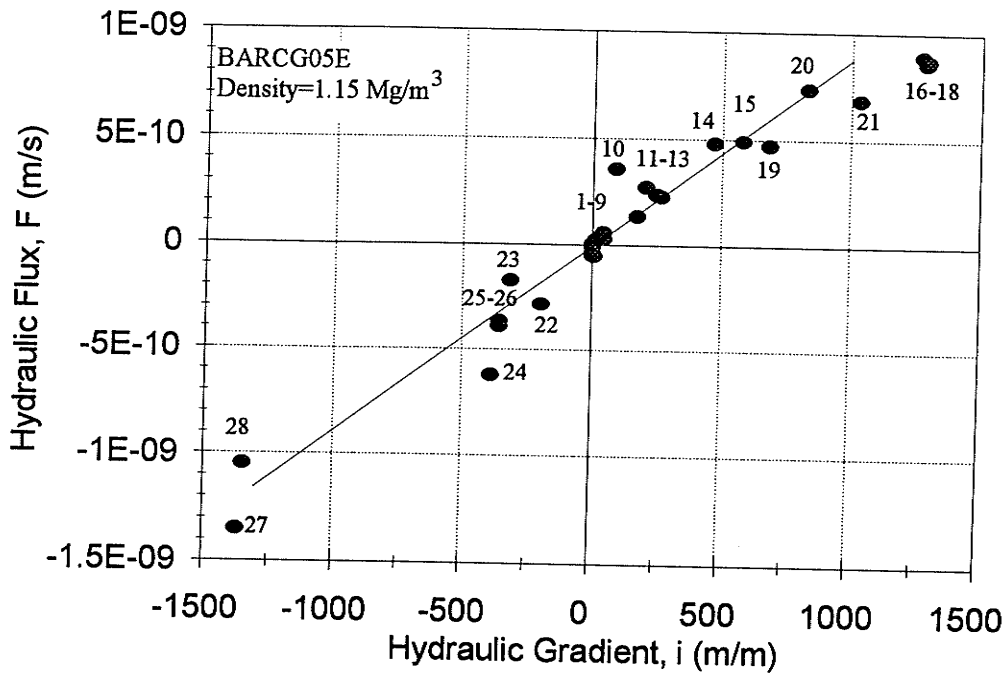


Figure 7.31 Influence of Change in Flow Direction on Bentonite-Based Materials (BARCG05E; 1.15 Mg/m<sup>3</sup>; Static Compaction; 1500 kPa Back Pressure)

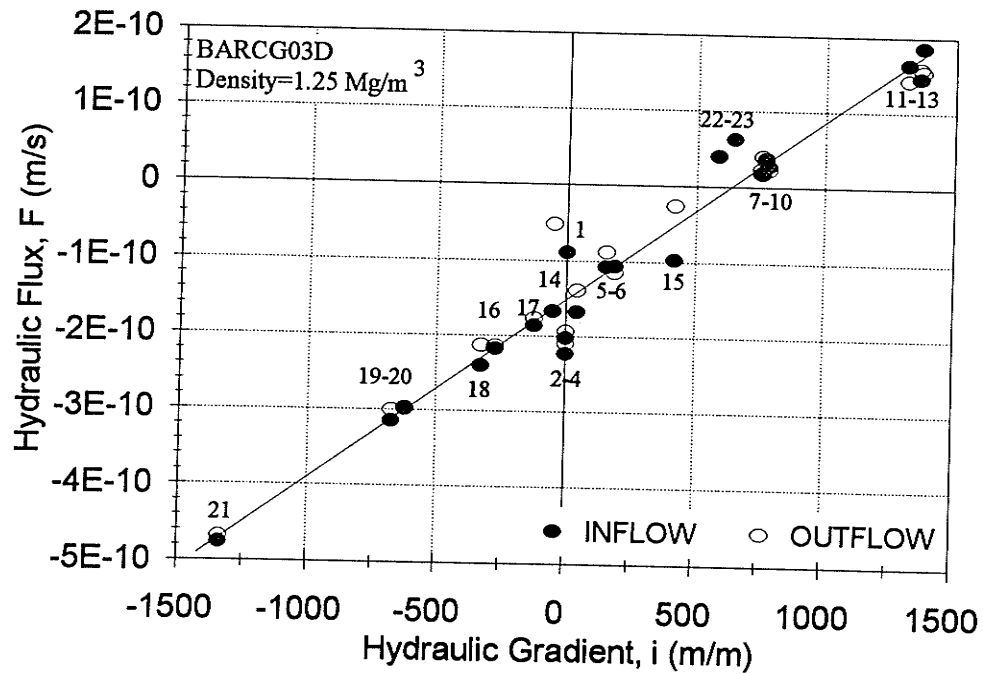


Figure 7.32 Influence of Change in Flow Direction on Bentonite-Based Materials (BARCG03D; 1.25 Mg/m<sup>3</sup>; Static Compaction; No Back Pressure)

## **7.5 Bacterial Activity and Its Influence on the Results of Hydraulic Conductivity Testing**

As discussed in Sections 3.4.4 and 4.3, there are a number of potential influences of bacterial activity on the total flux through clay soils. The tests described here were all very lengthy (durations up to 25 months, and were originally thought to be relatively free of bacterial activity. There was no supply of oxygen to the specimens, argon saturated fluids were used as the permeants, and a food supply sufficient to support a significant bacterial population was not believed to be present. However on dismantling, specimens from tests lasting longer than 4 months which had been percolated with deionized water, exhibited a strong sulphurous smell and contained black residues at the specimen - filter paper - filter stone interfaces. Additionally, nearly complete degradation was observed of the filter papers used to separate the filter stones from the specimens. In contrast, specimens constructed and tested using a brine solution (SCSSS, 70g/L dissolved salts) exhibited none of these features. The filter paper was intact and no discolouration was observed at the specimen-filter stone interface.

The black residue present at the top and base of the specimens rapidly disappeared when the dismantled permeameters were exposed to air. This indicates the presence of an anaerobic sulphide precipitate being oxidized. The sulphide precipitate was most likely formed through bacterial action producing sulphide from sulphate. The specimens were all carefully examined to determine the distribution of the suspected anaerobic bacterial growth. In none of the specimens were any darkened areas observed in any location other than at the surface of the interface between the specimen and the filter stone. Towards the end of the research it was realized that the filter papers used between the specimen and filter stones were not inert materials but were composed of cellulose. This

provided a carbon source for anaerobic bacteria present in an otherwise carbon-poor system. There was also plenty of water and growing space at these interfaces (but not inside the specimen). The bacterial populations measured in these specimens were likely considerably healthier than they would be in a carefully controlled emplacement environment in which a food supply could be denied by limiting the amount of carbon introduced. Previously, Section 4.2.3 established that influence of bacterial action on the hydraulic performance of these materials was not detectable. That is, there was no plugging of the pores, only growth on the top and base of the specimens. This provides added confidence of the ability of bentonites to perform adequately in a disposal vault environment.

The large differences between the vitality of the bacterial populations in the two ground water environments (Section 4.3.2), may reflect positively on the conditions anticipated in a nuclear fuel waste disposal vault. The ground water in a disposal vault located 500m to 1000m depth in the Canadian Shield will not be fresh, and is likely to be moderately to highly saline (Stroes-Gascoyne and West, 1994). Bentonite clays also have a very high soluble salt content (Section 4.3 of this thesis), and so the pore fluid will be saline. Hence, the activity of the anaerobic bacterial population may be severely restricted in the vicinity of the buffer simply as the result of the chemical environment. An additional factor in this entire system is the presence of a high radiation field, originating from the waste containers. This field is sufficient to virtually sterilize the region immediately surrounding the waste containers (Stroes-Gascoyne et al. 1994). In this case, the radiation field and the small size of the pores present in the hydrated regions of the buffer should prevent bacterial penetration into the region of the waste container until resaturation of the buffer is complete. At that time any desiccation cracking which

occurred prior to resaturation of the buffer will have disappeared as the result of clay swelling. This will leave an intact buffer with pore sizes that are too small for bacterially induced movement to occur in the regions immediately adjacent to the waste containers.

Data in Figure 4.5 (Section 4.2.3) showed no consistent changes in the hydraulic conductivity of these specimens with time, and in Section 7.3, it was found that hydraulic gradient also has no effect. As bacterial activity at the ends of the specimens was significant, it might be expected that time-dependent changes in hydraulic conductivity might be observed as bio-films were deposited on the surfaces, potentially blocking water flow into the pores. This was not observed. However, the potential for biologically-induced osmotic or chemical gradients across the specimens is real. It would appear that while such action did apparently result in substantial chemical concentration changes within the specimens (Table 4.4 in Section 4.3), the influence of this process on the movement of water through these materials was minimal. This conclusion is supported by the Darcian flow behaviour of the majority of the specimens. If the bio-chemical or osmotic gradients were driving the system in any specific direction, it should have been evident by the presence of clear threshold gradients throughout the range of materials examined. This was not the case, and there was little evidence for such a feature in these materials. Only at the lowest densities examined was there a consistent deviation from ideal Darcian flow behaviour, and at the lowest gradients examined the threshold gradient approached zero. As the presence of non-Darcian behaviour was dependent on applied hydraulic gradient rather than time, the presence of biofilms or other biologically driven influences would not seem to be significant in these systems.

The influence of bacterial activity on the hydraulic conductivity of these specimens tested has been found to be small or insignificant, although it is recognized that further work should probably be done on this topic. It is therefore now possible to examine the test results in a framework that considers the physical nature of the pore fluid as the determining factor in advective transportation. Chapter 8 discusses the results presented in this chapter and puts them into a context which includes the models for water structure presented in Sections 2.3, 2.4 and Chapter 5. It also develops a framework for predicting advective flow in clays and clay-sand materials of various compositions and densities.



## **8.0 POROSITY, EFFECTIVE POROSITY AND MEASURED ADVECTIVE FLOW IN CLAYS: ANALYSIS OF RESULTS**

### **8.1 Porosity, Effective Porosity, and Measured Flows**

#### **8.1.1 Porosity Parameters in Sand and Illitic Systems**

The results of measuring the hydraulic properties of quartz sand materials were presented in Section 7.3.1. Sand has a very low specific surface area ( $S_o$ ), (Table 4.2) and so it has very little or no measurable quantity of structured water. It was expected that sands would exhibit Darcian flow behaviour, and this was indeed observed (Figures 7.1 and 7.2).

Comparisons of hydraulic conductivities measured in sand specimens with those predicted using the Poiseuille and Kozeny-Carman Equations (Sections 3.3.2 and 3.3.3 respectively), provides a useful initial examination of the appropriateness of using these equations to predict the hydraulic performance of soil materials. It was found that the Kozeny-Carman equation comes closest to fitting the data obtained by laboratory testing (Table 8.1). The measured data fall within an order of magnitude of predictions generated using the Kozeny-Carman equation and in one of the cases, the data match the prediction (Table 8.1). As the density of the sand increased the calculated and measured data comes closer to matching the Kozeny-Carman predictions. The Poiseuille equation consistently predicts values much higher than those measured.

While it may be noted that hydraulic conductivity is a parameter which varies over several orders of magnitude and some degree of deviation can be expected between calculated  $k$  and measured  $k$ , the agreement between calculated and measured data is not as close

as might be hoped. However, the results are considered reasonable given the assumptions for surface area, particle shape and particle size that must be made before the equations can be used. A full discussion of the inherent limitations of the Poiseuille and Kozeny-Carman equations was presented in Section 3.3.5. Sample calculations for these equations are presented in Appendix C.

Table 8.1 suggests that use of the Kozeny-Carman equation to predict the hydraulic behaviour of clean, uniform and well characterized sand can provide results that are generally similar to those found using the laboratory equipment and techniques developed in this laboratory testing program.

Table 8.1 Calculation of Hydraulic Conductivity in Sand using the Poiseuille and Kozeny-Carman Equations

Surface area of Sand = variable\*

Unit Weight of Sand = 2650 kg/m<sup>3</sup> Water Viscosity= 0.001 kg/s/m

| Sand Density<br>( $\gamma$ )<br>(kg/m <sup>3</sup> ) | Porosity<br>(n) | Surface Area<br>(S)<br>(m <sup>2</sup> /m <sup>3</sup> ) | Pore Radius<br>(R)<br>(m) | k Poiseuille<br>(m/s) | k Kozeny-Carman<br>(m/s) | k Measured<br>(k)<br>(m/s) |
|------------------------------------------------------|-----------------|----------------------------------------------------------|---------------------------|-----------------------|--------------------------|----------------------------|
| 1670                                                 | 0.370           | 9.0x10 <sup>3</sup>                                      | 6.5x10 <sup>-5</sup>      | 3.2x10 <sup>-3</sup>  | 5.3x10 <sup>-4</sup>     | 4.8x10 <sup>-5</sup>       |
| 1700                                                 | 0.359           | 1.7x10 <sup>4</sup>                                      | 3.4x10 <sup>-5</sup>      | 8.5x10 <sup>-4</sup>  | 1.4x10 <sup>-4</sup>     | 2.5x10 <sup>-5</sup>       |
| 1760                                                 | 0.336           | 4.0x10 <sup>4</sup>                                      | 1.3x10 <sup>-5</sup>      | 1.2x10 <sup>-4</sup>  | 1.95x10 <sup>-5</sup>    | 2.0x10 <sup>-5</sup>       |

\* varies from 6.5 to 22.6 m<sup>2</sup>/kg, depending on particle sizes present

Illitic clay specimens exhibited different flux versus hydraulic relationships than were observed for the quartz sand. Section 7.3.2 showed that eight of the nine specimens tested exhibited a reversible transitional gradient (Table 7.4). It was then determined

(Figure 7.12) that the difference between the  $k$ 's measured at "high" and "low" hydraulic gradients was consistent throughout the range of densities examined. This was initially considered to potentially result from a constant quantity of structured water associated with the clay surfaces when zero or low hydraulic gradient was present. Once the transitional gradient was exceeded some of this water was mobilized for flow and increased flow rates became possible through newly enlarged flow passages. Hydraulic conductivities measured for illitic materials, and predicted using the Poiseuille and Kozeny-Carman equations are presented in Table 8.2. The limited range of porosity studied necessitated plotting the laboratory data in a semi-log format (Figure 8.1).

Table 8.2 Calculation of Hydraulic Conductivity of Illitic clay using the Poiseuille and Kozeny-Carman Equations

Surface area of clay =  $6000 \text{ m}^2/\text{kg}$ ; Density of Illite =  $2750 \text{ kg/m}^3$ ;

| Clay Density<br>( $\gamma$ )<br>( $\text{kg/m}^3$ ) | Total Porosity<br>( $n$ ) | Surface Area<br>( $S$ )<br>( $\text{m}^2/\text{m}^3$ ) | Using $n$                     |                                       |                                     | Measured<br>( $k$ )<br>(at high $i$ )<br>( $\text{m/s}$ ) | Measured<br>( $k$ )<br>(at low $i$ )<br>( $\text{m/s}$ ) |
|-----------------------------------------------------|---------------------------|--------------------------------------------------------|-------------------------------|---------------------------------------|-------------------------------------|-----------------------------------------------------------|----------------------------------------------------------|
|                                                     |                           |                                                        | Pore Radius<br>( $\text{m}$ ) | $k$<br>Poiseuille<br>( $\text{m/s}$ ) | $k$<br>Koz.-Car<br>( $\text{m/s}$ ) |                                                           |                                                          |
| 1620                                                | 0.411                     | $7.3 \times 10^7$                                      | $9.6 \times 10^{-9}$          | $7.5 \times 10^{-11}$                 | $1.2 \times 10^{-11}$               | $3.5 \times 10^{-10}$                                     | $9.5 \times 10^{-11}$                                    |
| 1650                                                | 0.400                     | $7.4 \times 10^7$                                      | $9.0 \times 10^{-9}$          | $6.5 \times 10^{-11}$                 | $1.1 \times 10^{-11}$               | $4.1 \times 10^{-10}$                                     | $1.5 \times 10^{-11}$                                    |
| 1770                                                | 0.356                     | $8.0 \times 10^7$                                      | $7.0 \times 10^{-9}$          | $3.7 \times 10^{-11}$                 | $6.1 \times 10^{-12}$               | $1.4 \times 10^{-10}$                                     | $5.9 \times 10^{-11}$                                    |
| 1810                                                | 0.342                     | $8.1 \times 10^7$                                      | $6.4 \times 10^{-9}$          | $3.1 \times 10^{-11}$                 | $5.0 \times 10^{-12}$               | $1.3 \times 10^{-10}$                                     | $3.6 \times 10^{-11}$                                    |
| 1840                                                | 0.331                     | $8.3 \times 10^7$                                      | $6.0 \times 10^{-9}$          | $2.7 \times 10^{-11}$                 | $4.3 \times 10^{-12}$               | $1.1 \times 10^{-10}$                                     | ---                                                      |
| 1840                                                | 0.331                     | $8.3 \times 10^7$                                      | $6.0 \times 10^{-9}$          | $2.7 \times 10^{-11}$                 | $4.3 \times 10^{-12}$               | $7.6 \times 10^{-11}$                                     | $2.4 \times 10^{-11}$                                    |
| 1930                                                | 0.298                     | $8.7 \times 10^7$                                      | $4.9 \times 10^{-9}$          | $1.7 \times 10^{-11}$                 | $2.8 \times 10^{-12}$               | $5.3 \times 10^{-11}$                                     | $3.0 \times 10^{-11}$                                    |
| 1960                                                | 0.287                     | $8.8 \times 10^7$                                      | $4.6 \times 10^{-9}$          | $1.4 \times 10^{-11}$                 | $2.4 \times 10^{-12}$               | $5.7 \times 10^{-11}$                                     | $1.1 \times 10^{-11}$                                    |
| 2030                                                | 0.262                     | $9.1 \times 10^7$                                      | $3.9 \times 10^{-9}$          | $9.8 \times 10^{-12}$                 | $1.6 \times 10^{-12}$               | $1.0 \times 10^{-11}$                                     | $8.7 \times 10^{-12}$                                    |

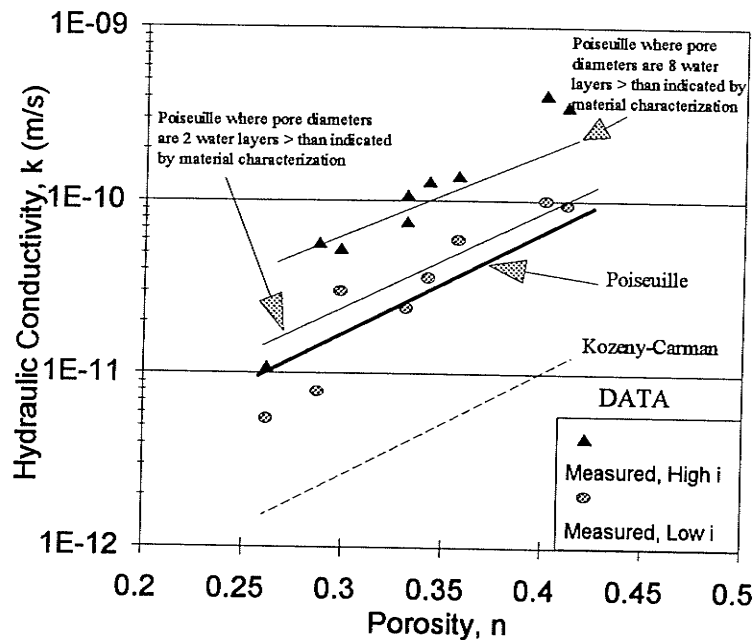


Figure 8.1 Porosity versus Hydraulic Conductivity Relationship for Illitic Clays

Table 8.2 also shows that neither of the numerical solutions provided good predictions for hydraulic conductivity ( $k$ ), at elevated hydraulic gradients. The Poiseuille equation came closer to matching the data obtained by laboratory testing but the match was not particularly good, especially for flow measured under conditions of "high" hydraulic gradient.

Laboratory measurements of  $k$  fell into two well defined and parallel linear relationships (in Log-Log space), for results obtained above and below the transitional gradients (Figure 8.1). Only the densest of the 9 specimens listed in Table 8.2 had a hydraulic conductivity which deviated significantly from these relationships. This high density specimen had a hydraulic conductivity which was similar at high and low applied hydraulic gradients. The hydraulic conductivity measured for this high density specimen closely approximated the

prediction for flow generated using the Poiseuille equation and the line through the remainder of the data generated from specimens tested at gradients below the transitional gradient. This fit may be the result of a reduction in the number of macro-pores present once high density is achieved. A reduced number of macro-pores would result in a greater influence of the smaller pore spaces on the measured hydraulic conductivity, and hence a closer match to one of the primary conditions required for the Poiseuille equation to be valid (uniform pore size (Section 3.3.2)). Alternatively, a significant reduction in the hydraulic conductivity at high density can be interpreted as evidence that there are fewer structured water layers which can be activated for participation in the advective transportation.

The comparisons between experimental and theoretical hydraulic conductivities in Figure 8.1 raise two major questions. The first relates to reasons for the apparent inability of either equation to accurately predict the hydraulic conductivity of illitic clay tested at high hydraulic gradients. The second question has to do with the significance of the two parallel lines representing the hydraulic conductivity above and below the transitional gradient for each specimen. Whatever was the cause of the deviation of the advective flow behaviour measured at high hydraulic gradients, it is evident that at lower applied gradients there is a reduction in the flux through these specimens. This could be accounted for mathematically by assuming that the porosity available for flow decreased when the hydraulic gradient decreased.

Values of hydraulic conductivity predicted using the Poiseuille or the Kozeny-Carman equations show relationships that parallel but considerably under-estimate the hydraulic conductivities measured at elevated gradients. The equations produce values that are

respectively about one-half order and one order of magnitude lower than the laboratory values. However, at gradients below the transitional gradients, the measured hydraulic conductivities came close to predictions from the Poiseuille equation. The significance of these differences in the measured hydraulic conductivity with changing hydraulic gradient is discussed below.

The hydraulic conductivity observed at high gradient, for all but the lowest porosity (highest density) specimen can be described by the Poiseuille equation if it is assumed that the pore radius ( $2d$ ) was 8 water layers wider than was calculated using the material parameters determined for the specimen. The reason for the difference between the Poiseuille prediction and that measured in the laboratory is uncertain. The porosimetry studies discussed in Section 4.2.3 identified the presence of non-uniform pores and perhaps large pore channels dominate the hydraulic properties of the system. This would be consistent with the fact that the illitic clay studied is not composed of individual clay platelets but of micro-peds, each consisting of many clay platelets. As a result, the actual surface area present and available to influence water structure and movement is lower than indicated by the Specific Surface Area ( $S_o$ ) parameter. A lower effective surface ( $S_{eff}$ ), means that the average pore-radius ( $r_p$ ) increases, as will the hydraulic conductivity predicted for a given clay density. In such a situation it would be expected that the hydraulic conductivity measured would be much higher than the predictions of the Poiseuille or Kozeny-Carman equations. Figure 8.1 and Table 8.2 suggest that this was indeed the case.

The difference between hydraulic conductivities measured at hydraulic gradients above and below the transitional gradient for each specimen seems to be independent of

porosity. The previous paragraph showed that the Poiseuille equation permitted estimation of the reduction in the average diameter of channels participating in flow at low hydraulic gradients. This change in effective pore diameter can be interpreted in three ways.

i) Flow at high hydraulic gradients is actually occurring through pores which are 8 water layers larger than was predicted using the material properties available from laboratory testing.

ii) Shearing of previously bonded or structured water increases the available pore radii by about 8 water layers. These layers, once mobilized for flow, would continue to participate in advective flow unless the hydraulic gradient decreased to less than the transitional gradient, at which time they would again become unavailable for flow. At this stage the available radii are approximately equal to those calculated from surface area and moisture content measurements.

iii) The change in hydraulic conductivity results not from a change in the effective radius of the pores conducting flow, but from the activation of pores which had not previously participated in the flow process. If the majority of flow measured at low hydraulic gradient occurs through the macro-pores within the specimen, then a number of micro-pores and the water layers present between some of the clay platelets might not be active in the transportation process. This could be the result of a higher water viscosity due to some limited structuring in response to the surface charge on the clay particles, or to a higher surface tension in these regions resulting from the narrow pore openings. Under these conditions, changes in flow behaviour need not involve shearing of highly structured water. However, as the hydraulic gradient meets and exceeds the transitional gradient, this previously occluded or non-conductive porosity becomes available for flow, resulting in a higher flux and apparently higher hydraulic conductivity. These passages

would close for flow once the gradients decreased to less than the transitional gradient. This may provide a reversible mechanism to explain the observed changes in flow with changing hydraulic gradient.

When the hydraulic conductivity of these illitic clays is considered in conjunction with the thermal expansion results in Chapter 5, it seems that the third explanation in the previous paragraph can provide a likely mechanism to account for change in hydraulic conductivity with changes in hydraulic gradient. It will be remembered that the thermal expansion tests indicated there was little structured water present in the illitic clay specimens which had an average d-spacing which ranged from 12 to 28 water layers. The presence of as many as 4 structured water layers (as indicated by the results of hydraulic conductivity), would therefore represent from 15% (lowest density specimen), to 33% (highest density specimen) of the total porosity of the clay. Given that the accuracy of the thermal expansion measurements is approximately 10% of the total expansion measured at 90°C (Section 5.2), it is not surprising that the thermal expansion testing might fail to identify a change in the water structure of the low density clays. Ice has a thermal expansion rate of approximately 7% of that of bulk water (Michel, 1978). If the water associated with the particle surfaces is assumed to be ice-like in its structure and thermal expansion behaviour, it is possible that the lowest density materials might show no clear deviation between the predicted and measured thermal expansion of the water component, as these deviations would fall within the limits of system accuracy. However, denser clays should have exhibited measured thermal expansion behaviour which differed from that of bulk water, thereby providing an indication that the water layers closest to the surface had a different structure than that of bulk water. Even the presence of water having a "broken down ice structure" as described in Sections 2.3.2 and 2.3.3 should have resulted in some



measurable change in the thermal expansion behaviour of dense illite - water specimens. These thermal expansion findings, together with those of hydraulic conductivity measurements provide a strong argument for an explanation that there is little or no structured water present in the illitic clay. The observed changes in hydraulic conductivity with increased hydraulic gradient are therefore most likely the result of changes in the number of pores active in the flow process, and not from a change in the size of the pores caused by shearing of structured pore fluid.

### **8.1.2 Porosity Parameters in Bentonite and Bentonite - Sand Systems**

In the same manner used in Section 8.1.1 for illitic clay specimens, the measured advective flow through bentonite-based materials has been compared to predictions provided by the Poiseuille and Kozeny-Carman equations, and ultimately to the results of the thermal expansion tests presented in Chapter 5.

Table 8.3 compares the results of the laboratory tests discussed previously in Section 7.4 with the predictions from the Poiseuille and Kozeny-Carman equations. Further data were added from literature sources (Appendix D) to extend the range of porosities available for comparison. This enlarged data base for bentonite-based materials provides a good basis for analyzing advective flow behaviour under high hydraulic gradients. As in the preceding analysis for illitic specimens, the results were first plotted in a semi-log format presenting total porosity versus hydraulic conductivity (Figure 8.2a). The wider range of porosities examined for bentonitic materials made it possible to also plot this data in log-log space (Figure 8.2b). In addition to the predictions of the Poiseuille and Kozeny-Carman

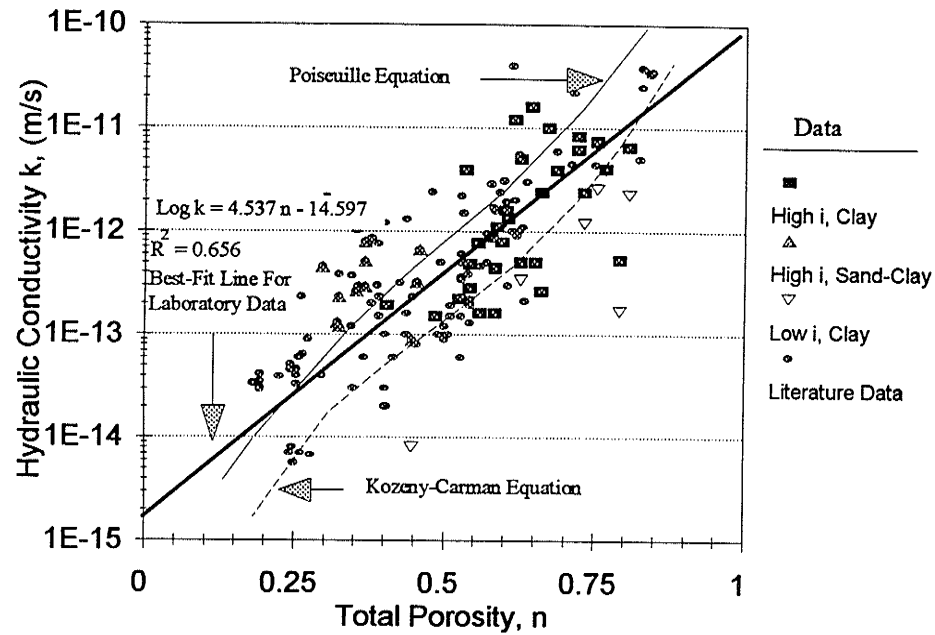
equations and the experimental data points, the regression line through the laboratory data was determined. The combination of semi-log and log-log graphs provides a good basis for examining the role of porosity in controlling hydraulic conductivity.

In Figure 8.2, there are four sets of laboratory data plotted. These data sets are;

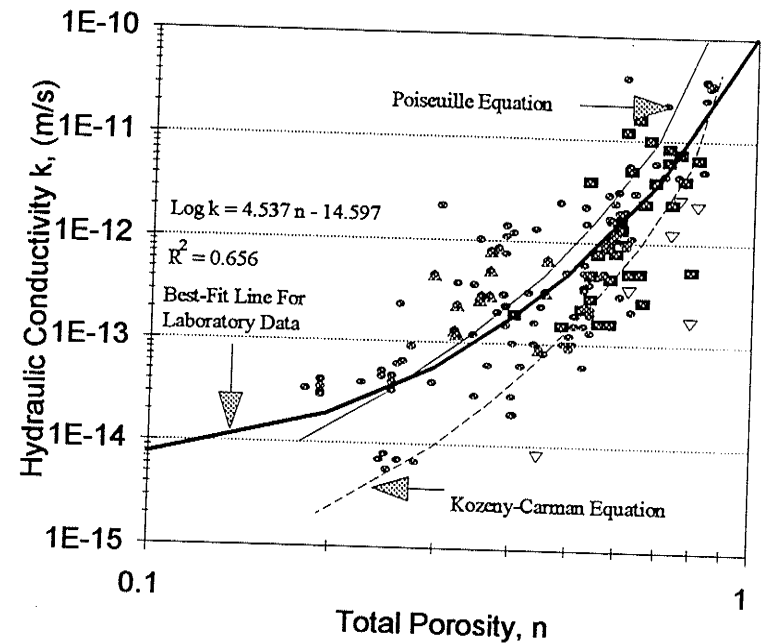
- i) The hydraulic conductivity measured for clay specimens at hydraulic gradients above the transitional gradient (high gradient).
- ii) The hydraulic conductivity measured for sand-clay specimens tested at high hydraulic gradients.
- iii) Literature derived data for specimens tested at high gradients.
- iv) The hydraulic conductivity of specimens tested at hydraulic gradients lower than the transitional gradient (low gradient).

Using the total porosity versus hydraulic conductivity data in Figure 8.2 as the basis for comparison, the theoretical influence of water adsorbed on the particle surfaces can be examined. Figures 8.3a and 8.3b plot the same data as was presented in Figure 8.2, excepting that a single layer of water was assumed to be fixed on the surface of each clay particle and that this resulted in a reduction in the total porosity of the specimen. This reduced porosity is known as the effective porosity ( $n_{eff}$ ). Also presented in Figures 8.3a,b is the best-fit line through the data, providing an excellent means of determining the appropriateness of using an effective porosity parameter in prediction of advective flow through these materials. These different methods of plotting the same data allow examination of the potential effect of a structured layer of water on the hydraulic behaviour of bentonite-based specimens.

The hydraulic conductivity of these bentonite materials clearly increased as the porosity increased (Figure 8.2). Data obtained in this research and those collected from the literature all follow the same general trend, but exhibit a considerable degree of scatter (the standard deviation of the hydraulic conductivity data in Figure 8.2 is approximately one order of magnitude). This scatter does not seem to be related to any intrinsic difference in the bentonites examined (Dixon and Miller, 1995), and so must represent the limitations of the techniques used, or random variations in the microstructure of the specimens. Comparison of the data with predictions of the Poiseuille and Kozeny-Carman equations show that despite many contrary opinions in the literature, both the Poiseuille and Kozeny-Carman equations actually predicted the hydraulic conductivity of bentonite clays and clay-sand mixtures reasonably well. The Kozeny-Carman equation is somewhat less accurate, especially at higher density, but still falls within the general scatter of the data. Given the need for a conservative means of predicting the advective flow of water through clay barriers, use the Poiseuille equation seems more appropriate. This will provide somewhat higher estimates for  $k$  at a given porosity. Most of the available data lie below the line produced by the equation. Both these equations can reasonably be used in low density materials.

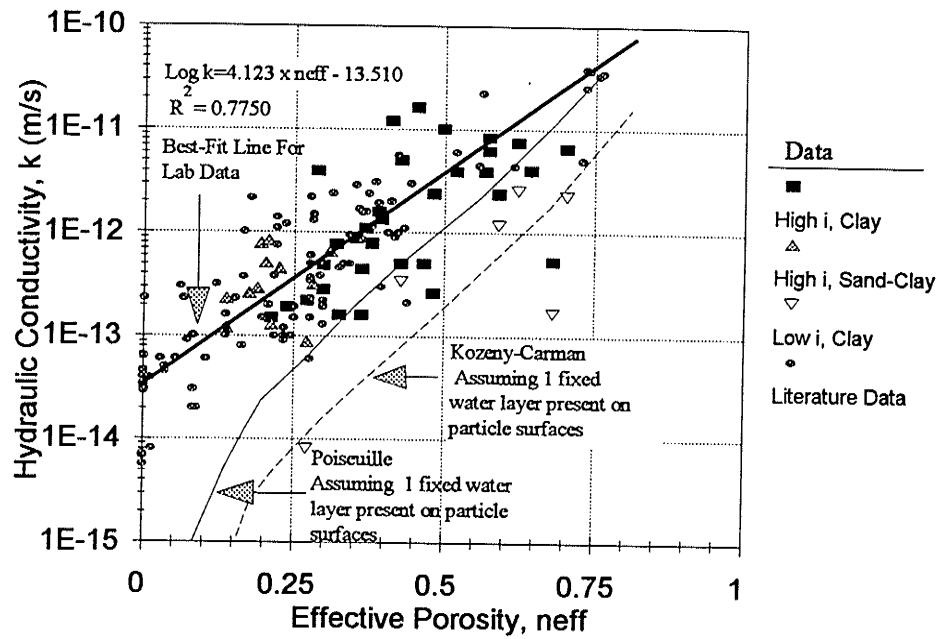


A) Semi-Log Plot

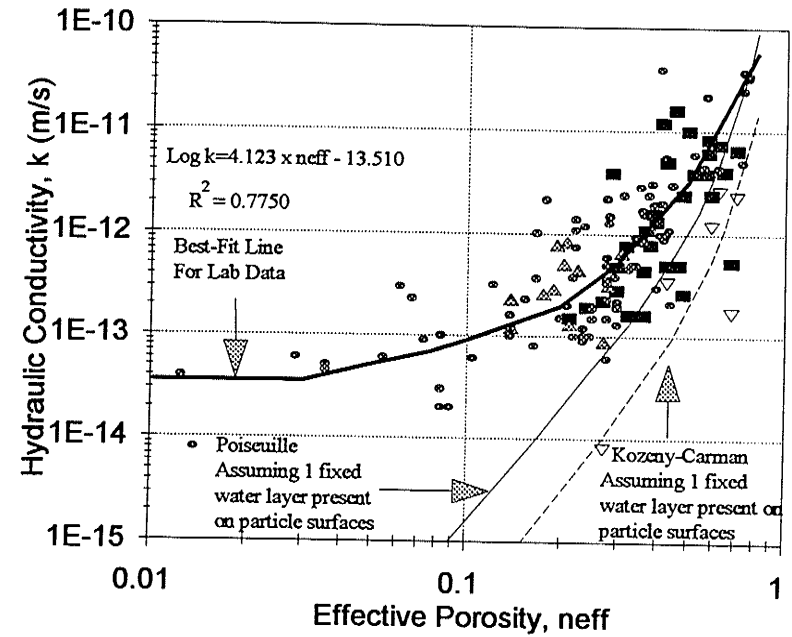


B) Log-Log Plot

Figure 8.2 Relationship Between Porosity and Hydraulic Conductivity Measured in Bentonites and those Predicted Using the Poiseuille and Kozeny-Carman Equations



A) Semi-Log Plot



B) Log-Log Plot

Figure 8.3 Relationship Between Effective Porosity and Hydraulic Conductivity Measured in Bentonites and those Predicted Using the Poiseuille and Kozeny-Carman Equations

Table 8.3 Calculation of Hydraulic Conductivity of Bentonite using the Poiseuille and Kozeny-Carman Equations

Surface area of bentonite= 750,000 m<sup>2</sup>/kg  
Density of bentonite= 2840 kg/m<sup>3</sup>

Water Viscosity= 0.001 kg/s/m  
Potential Change= 0.981 m<sup>2</sup>/s<sup>2</sup>

| Density<br>(kg/m <sup>3</sup> ) | Porosity | Effective Porosity | Surface Area<br>(m <sup>2</sup> /m <sup>3</sup> ) | Using n              |                          |                         | k<br>Measured<br>(m/s) | Using neff           |                          |                         |
|---------------------------------|----------|--------------------|---------------------------------------------------|----------------------|--------------------------|-------------------------|------------------------|----------------------|--------------------------|-------------------------|
|                                 |          |                    |                                                   | Pore Radius<br>(m)   | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |                        | Pore Radius<br>(m)   | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |
| 550                             | 0.806    | 0.600              | 4.1x10 <sup>8</sup>                               | 1.0x10 <sup>-8</sup> | 5.5x10 <sup>-11</sup>    | 9.0x10 <sup>-12</sup>   | 6.6x10 <sup>-12</sup>  | 5.7x10 <sup>-9</sup> | 1.6x10 <sup>-11</sup>    | 2.6x10 <sup>-12</sup>   |
| 590                             | 0.792    | 0.682              | 4.4x10 <sup>8</sup>                               | 8.6x10 <sup>-9</sup> | 4.3x10 <sup>-11</sup>    | 6.9x10 <sup>-12</sup>   | 5.3x10 <sup>-13</sup>  | 4.8x10 <sup>-9</sup> | 1.2x10 <sup>-11</sup>    | 1.9x10 <sup>-12</sup>   |
| 660                             | 0.768    | 0.644              | 5.0x10 <sup>8</sup>                               | 6.7x10 <sup>-9</sup> | 2.8x10 <sup>-11</sup>    | 4.5x10 <sup>-12</sup>   | 4.0x10 <sup>-12</sup>  | 3.7x10 <sup>-9</sup> | 7.0x10 <sup>-12</sup>    | 1.1x10 <sup>-12</sup>   |
| 700                             | 0.754    | 0.622              | 5.3x10 <sup>8</sup>                               | 5.8x10 <sup>-9</sup> | 2.2x10 <sup>-11</sup>    | 3.6x10 <sup>-12</sup>   | 7.4x10 <sup>-12</sup>  | 3.1x10 <sup>-9</sup> | 5.3x10 <sup>-12</sup>    | 8.6x10 <sup>-13</sup>   |
| 760                             | 0.732    | 0.590              | 5.7x10 <sup>8</sup>                               | 4.8x10 <sup>-9</sup> | 1.6x10 <sup>-11</sup>    | 2.6x10 <sup>-12</sup>   | 2.4x10 <sup>-12</sup>  | 2.5x10 <sup>-9</sup> | 3.5x10 <sup>-12</sup>    | 5.7x10 <sup>-13</sup>   |
| 790                             | 0.722    | 0.574              | 5.9x10 <sup>8</sup>                               | 4.4x10 <sup>-9</sup> | 1.3x10 <sup>-11</sup>    | 2.2x10 <sup>-12</sup>   | 8.4x10 <sup>-12</sup>  | 2.3x10 <sup>-9</sup> | 2.9x10 <sup>-12</sup>    | 4.7x10 <sup>-13</sup>   |
| 790                             | 0.722    | 0.574              | 5.9x10 <sup>8</sup>                               | 4.4x10 <sup>-9</sup> | 1.3x10 <sup>-11</sup>    | 2.2x10 <sup>-12</sup>   | 6.2x10 <sup>-12</sup>  | 2.3x10 <sup>-9</sup> | 2.9x10 <sup>-12</sup>    | 4.7x10 <sup>-13</sup>   |
| 800                             | 0.718    | 0.418              | 6.0x10 <sup>8</sup>                               | 4.3x10 <sup>-9</sup> | 1.3x10 <sup>-11</sup>    | 2.1x10 <sup>-12</sup>   | 3.9x10 <sup>-12</sup>  | 2.2x10 <sup>-9</sup> | 2.7x10 <sup>-12</sup>    | 4.4x10 <sup>-13</sup>   |
| 890                             | 0.687    | 0.520              | 6.7x10 <sup>8</sup>                               | 3.3x10 <sup>-9</sup> | 8.1x10 <sup>-12</sup>    | 1.3x10 <sup>-12</sup>   | 3.9x10 <sup>-12</sup>  | 1.6x10 <sup>-9</sup> | 1.5x10 <sup>-12</sup>    | 2.4x10 <sup>-13</sup>   |
| 930                             | 0.673    | 0.498              | 7.0x10 <sup>8</sup>                               | 2.9x10 <sup>-9</sup> | 6.6x10 <sup>-12</sup>    | 1.1x10 <sup>-12</sup>   | 1.0x10 <sup>-11</sup>  | 1.4x10 <sup>-9</sup> | 1.2x10 <sup>-12</sup>    | 1.9x10 <sup>-13</sup>   |
| 960                             | 0.662    | 0.482              | 7.2x10 <sup>8</sup>                               | 2.7x10 <sup>-9</sup> | 5.8x10 <sup>-12</sup>    | 9.4x10 <sup>-13</sup>   | 2.4x10 <sup>-12</sup>  | 1.3x10 <sup>-9</sup> | 9.5x10 <sup>-13</sup>    | 1.5x10 <sup>-13</sup>   |
| 960                             | 0.662    | 0.482              | 7.2x10 <sup>8</sup>                               | 2.7x10 <sup>-9</sup> | 5.8x10 <sup>-12</sup>    | 9.4x10 <sup>-13</sup>   | 2.6x10 <sup>-13</sup>  | 1.3x10 <sup>-9</sup> | 9.5x10 <sup>-13</sup>    | 1.5x10 <sup>-13</sup>   |
| 990                             | 0.651    | 0.466              | 7.4x10 <sup>8</sup>                               | 2.5x10 <sup>-9</sup> | 5.0x10 <sup>-12</sup>    | 8.2x10 <sup>-13</sup>   | 5.0x10 <sup>-13</sup>  | 1.2x10 <sup>-9</sup> | 7.8x10 <sup>-13</sup>    | 1.3x10 <sup>-13</sup>   |
| 1010                            | 0.644    | 0.455              | 7.6x10 <sup>8</sup>                               | 2.4x10 <sup>-9</sup> | 4.6x10 <sup>-12</sup>    | 7.4x10 <sup>-13</sup>   | 1.6x10 <sup>-11</sup>  | 1.1x10 <sup>-9</sup> | 6.8x10 <sup>-13</sup>    | 1.1x10 <sup>-13</sup>   |

Table 8.3(Continued) Calculation of Hydraulic Conductivity of Bentonite using the Poiseuille and Kozeny Carman Equations

| Density<br>(kg/m <sup>3</sup> ) | Porosity<br>n | Effective<br>Porosity<br>neff | Surface<br>Area<br>(m <sup>2</sup> /m <sup>3</sup> ) | Using n               |                          |                         | k<br>Measured<br>(m/s) | Using neff            |                          |                         |
|---------------------------------|---------------|-------------------------------|------------------------------------------------------|-----------------------|--------------------------|-------------------------|------------------------|-----------------------|--------------------------|-------------------------|
|                                 |               |                               |                                                      | Pore<br>Radius<br>(m) | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |                        | Pore<br>Radius<br>(m) | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |
| 1060                            | 0.627         | 0.229                         | 8.0x10 <sup>8</sup>                                  | 2.1x10 <sup>-9</sup>  | 3.6x10 <sup>-12</sup>    | 5.9x10 <sup>-13</sup>   | 5.0x10 <sup>-12</sup>  | 3.7x10 <sup>-10</sup> | 1.1x10 <sup>-13</sup>    | 6.8x10 <sup>-15</sup>   |
| 1060                            | 0.627         | 0.428                         | 8.0x10 <sup>8</sup>                                  | 2.1x10 <sup>-9</sup>  | 3.6x10 <sup>-12</sup>    | 5.9x10 <sup>-13</sup>   | 5.0x10 <sup>-13</sup>  | 9.4x10 <sup>-10</sup> | 4.9x10 <sup>-13</sup>    | 8.0x10 <sup>-14</sup>   |
| 1090                            | 0.616         | 0.412                         | 8.2x10 <sup>8</sup>                                  | 2.0x10 <sup>-9</sup>  | 3.2x10 <sup>-12</sup>    | 5.2x10 <sup>-13</sup>   | 1.2x10 <sup>-11</sup>  | 8.6x10 <sup>-10</sup> | 4.0x10 <sup>-13</sup>    | 6.6x10 <sup>-14</sup>   |
| 1120                            | 0.606         | 0.396                         | 8.4x10 <sup>8</sup>                                  | 1.8x10 <sup>-9</sup>  | 2.8x10 <sup>-12</sup>    | 4.5x10 <sup>-13</sup>   | 1.3x10 <sup>-12</sup>  | 7.8x10 <sup>-10</sup> | 3.3x10 <sup>-13</sup>    | 5.4x10 <sup>-14</sup>   |
| 1130                            | 0.602         | 0.390                         | 8.5x10 <sup>8</sup>                                  | 1.8x10 <sup>-9</sup>  | 2.7x10 <sup>-12</sup>    | 4.3x10 <sup>-13</sup>   | 1.6x10 <sup>-12</sup>  | 7.6x10 <sup>-10</sup> | 3.1x10 <sup>-13</sup>    | 5.0x10 <sup>-14</sup>   |
| 1150                            | 0.595         | 0.379                         | 8.6x10 <sup>8</sup>                                  | 1.7x10 <sup>-9</sup>  | 2.4x10 <sup>-12</sup>    | 4.0x10 <sup>-13</sup>   | 7.9x10 <sup>-13</sup>  | 7.1x10 <sup>-10</sup> | 2.7x10 <sup>-13</sup>    | 4.4x10 <sup>-14</sup>   |
| 1170                            | 0.588         | 0.369                         | 8.8x10 <sup>8</sup>                                  | 1.6x10 <sup>-9</sup>  | 2.2x10 <sup>-12</sup>    | 3.6x10 <sup>-13</sup>   | 1.1x10 <sup>-12</sup>  | 6.7x10 <sup>-10</sup> | 2.3x10 <sup>-12</sup>    | 3.8x10 <sup>-14</sup>   |
| 1180                            | 0.585         | 0.363                         | 8.9x10 <sup>8</sup>                                  | 1.6x10 <sup>-9</sup>  | 2.1x10 <sup>-12</sup>    | 3.5x10 <sup>-13</sup>   | 1.6x10 <sup>-13</sup>  | 6.4x10 <sup>-10</sup> | 2.2x10 <sup>-12</sup>    | 3.6x10 <sup>-14</sup>   |
| 1180                            | 0.582         | 0.363                         | 8.6x10 <sup>8</sup>                                  | 1.6x10 <sup>-9</sup>  | 2.1x10 <sup>-12</sup>    | 3.5x10 <sup>-13</sup>   | 4.4x10 <sup>-13</sup>  | 7.1x10 <sup>-10</sup> | 2.2x10 <sup>-13</sup>    | 3.6x10 <sup>-14</sup>   |
| 1190                            | 0.404         | 0.240                         | 8.9x10 <sup>8</sup>                                  | 7.6x10 <sup>-10</sup> | 3.4x10 <sup>-13</sup>    | 5.5x10 <sup>-14</sup>   | 1.9x10 <sup>-13</sup>  | 3.5x10 <sup>-10</sup> | 4.4x10 <sup>-14</sup>    | 7.1x10 <sup>-15</sup>   |
| 1200                            | 0.577         | 0.352                         | 9.0x10 <sup>8</sup>                                  | 1.5x10 <sup>-9</sup>  | 2.0x10 <sup>-12</sup>    | 3.2x10 <sup>-13</sup>   | 8.8x10 <sup>-13</sup>  | 6.0x10 <sup>-10</sup> | 1.9x10 <sup>-13</sup>    | 3.1x10 <sup>-14</sup>   |
| 1250                            | 0.560         | 0.325                         | 9.4x10 <sup>8</sup>                                  | 1.4x10 <sup>-9</sup>  | 1.6x10 <sup>-12</sup>    | 2.6x10 <sup>-13</sup>   | 1.6x10 <sup>-13</sup>  | 5.1x10 <sup>-10</sup> | 1.3x10 <sup>-13</sup>    | 2.2x10 <sup>-14</sup>   |
| 1260                            | 0.556         | 0.320                         | 9.5x10 <sup>8</sup>                                  | 1.3x10 <sup>-9</sup>  | 1.5x10 <sup>-12</sup>    | 2.5x10 <sup>-13</sup>   | 7.7x10 <sup>-13</sup>  | 5.0x10 <sup>-10</sup> | 1.2x10 <sup>-13</sup>    | 2.0x10 <sup>-14</sup>   |
| 1300                            | 0.542         | 0.299                         | 9.8x10 <sup>8</sup>                                  | 1.2x10 <sup>-9</sup>  | 1.3x10 <sup>-12</sup>    | 2.1x10 <sup>-13</sup>   | 4.8x10 <sup>-13</sup>  | 4.4x10 <sup>-10</sup> | 9.1x10 <sup>-14</sup>    | 1.5x10 <sup>-14</sup>   |
| 1300                            | 0.542         | 0.299                         | 9.8x10 <sup>8</sup>                                  | 1.2x10 <sup>-9</sup>  | 1.3x10 <sup>-12</sup>    | 2.1x10 <sup>-13</sup>   | 2.8x10 <sup>-13</sup>  | 4.4x10 <sup>-11</sup> | 9.1x10 <sup>-14</sup>    | 1.5x10 <sup>-14</sup>   |
| 1320                            | 0.535         | 0.288                         | 9.9x10 <sup>8</sup>                                  | 1.2x10 <sup>-9</sup>  | 1.2x10 <sup>-12</sup>    | 1.9x10 <sup>-13</sup>   | 3.9x10 <sup>-12</sup>  | 4.1x10 <sup>-10</sup> | 7.8x10 <sup>-14</sup>    | 1.3x10 <sup>-14</sup>   |

Table 8.3 (Continued) Calculation of Hydraulic Conductivity of Bentonite using the Poiseuille and Kozeny-Carman Equations

| Density<br>(kg/m <sup>3</sup> ) | Porosity | Effective<br>Porosity | Surface<br>Area<br>(m <sup>2</sup> /m <sup>3</sup> ) | Using n               |                          |                         | k<br>Measured<br>(m/s) | Using neff            |                          |                         |
|---------------------------------|----------|-----------------------|------------------------------------------------------|-----------------------|--------------------------|-------------------------|------------------------|-----------------------|--------------------------|-------------------------|
|                                 |          |                       |                                                      | Pore<br>Radius<br>(m) | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |                        | Pore<br>Radius<br>(m) | v<br>Poiseuille<br>(m/s) | k<br>Koz.-Car.<br>(m/s) |
| 1350                            | 0.525    | 0.272                 | 1.0x10 <sup>9</sup>                                  | 1.1x10 <sup>-9</sup>  | 1.0x10 <sup>-12</sup>    | 1.7x10 <sup>-13</sup>   | 2.2x10 <sup>-13</sup>  | 3.7x10 <sup>-10</sup> | 6.1x10 <sup>-14</sup>    | 9.9x10 <sup>-15</sup>   |
| 1460                            | 0.486    | 0.212                 | 1.1x10 <sup>9</sup>                                  | 8.6x10 <sup>-10</sup> | 6.5x10 <sup>-13</sup>    | 1.1x10 <sup>-13</sup>   | 1.5x10 <sup>-13</sup>  | 2.5x10 <sup>-12</sup> | 2.3x10 <sup>-14</sup>    | 3.7x10 <sup>-15</sup>   |
| Bentonite - Sand                |          |                       |                                                      |                       |                          |                         |                        |                       |                          |                         |
| 1030                            | 0.296    | 0.225                 | 7.7x10 <sup>8</sup>                                  | 5.4x10 <sup>-10</sup> | 1.1x10 <sup>-13</sup>    | 1.8x10 <sup>-14</sup>   | 4.5x10 <sup>-13</sup>  | 3.8x10 <sup>-10</sup> | 4.0x10 <sup>-14</sup>    | 6.5x10 <sup>-15</sup>   |
| 1040                            | 0.458    | 0.309                 | 7.8x10 <sup>8</sup>                                  | 1.1x10 <sup>-9</sup>  | 6.9x10 <sup>-13</sup>    | 1.1x10 <sup>-13</sup>   | 6.6x10 <sup>-13</sup>  | 5.7x10 <sup>-10</sup> | 1.3x10 <sup>-13</sup>    | 2.1x10 <sup>-14</sup>   |
| 1120                            | 0.367    | 0.193                 | 8.4x10 <sup>8</sup>                                  | 6.9x10 <sup>-10</sup> | 2.4x10 <sup>-13</sup>    | 3.9x10 <sup>-14</sup>   | 7.9x10 <sup>-13</sup>  | 2.9x10 <sup>-10</sup> | 2.2x10 <sup>-14</sup>    | 3.5x10 <sup>-15</sup>   |
| 1180                            | 0.356    | 0.189                 | 8.9x10 <sup>8</sup>                                  | 6.2x10 <sup>-10</sup> | 2.0x10 <sup>-13</sup>    | 3.6x10 <sup>-14</sup>   | 2.9x10 <sup>-13</sup>  | 2.6x10 <sup>-10</sup> | 1.9x10 <sup>-14</sup>    | 3.1x10 <sup>-15</sup>   |
| 1220                            | 0.367    | 0.203                 | 9.2x10 <sup>8</sup>                                  | 6.3x10 <sup>-10</sup> | 2.2x10 <sup>-13</sup>    | 3.9x10 <sup>-14</sup>   | 5.1x10 <sup>-13</sup>  | 2.8x10 <sup>-10</sup> | 2.3x10 <sup>-14</sup>    | 3.8x10 <sup>-15</sup>   |
| 1220                            | 0.367    | 0.189                 | 9.2x10 <sup>8</sup>                                  | 6.3x10 <sup>-9</sup>  | 2.2x10 <sup>-13</sup>    | 2.9x10 <sup>-13</sup>   | 2.9x10 <sup>-13</sup>  | 2.5x10 <sup>-10</sup> | 1.8x10 <sup>-14</sup>    | 3.0x10 <sup>-16</sup>   |
| 1240                            | 0.378    | 0.207                 | 9.3x10 <sup>8</sup>                                  | 6.5x10 <sup>-10</sup> | 2.5x10 <sup>-13</sup>    | 4.0x10 <sup>-14</sup>   | 8.4x10 <sup>-13</sup>  | 2.8x10 <sup>-10</sup> | 2.5x10 <sup>-14</sup>    | 4.1x10 <sup>-15</sup>   |
| 1280                            | 0.321    | 0.212                 | 9.6x10 <sup>8</sup>                                  | 4.9x10 <sup>-10</sup> | 1.2x10 <sup>-13</sup>    | 2.0x10 <sup>-14</sup>   | 1.3x10 <sup>-13</sup>  | 2.8x10 <sup>-10</sup> | 2.6x10 <sup>-14</sup>    | 4.3x10 <sup>-15</sup>   |
| 1340                            | 0.353    | 0.175                 | 1.0x10 <sup>9</sup>                                  | 5.4x10 <sup>-10</sup> | 1.7x10 <sup>-13</sup>    | 2.8x10 <sup>-14</sup>   | 2.6x10 <sup>-13</sup>  | 2.1x10 <sup>-10</sup> | 1.3x10 <sup>-14</sup>    | 2.1x10 <sup>-15</sup>   |
| 1340                            | 0.324    | 0.138                 | 1.0x10 <sup>9</sup>                                  | 4.8x10 <sup>-10</sup> | 1.2x10 <sup>-13</sup>    | 2.0x10 <sup>-14</sup>   | 2.3x10 <sup>-13</sup>  | 1.6x10 <sup>-10</sup> | 5.7x10 <sup>-15</sup>    | 9.3x10 <sup>-15</sup>   |
| 1340                            | 0.454    | 0.281                 | 1.0x10 <sup>9</sup>                                  | 8.3x10 <sup>-10</sup> | 5.1x10 <sup>-13</sup>    | 8.3x10 <sup>-14</sup>   | 3.2x10 <sup>-13</sup>  | 3.9x10 <sup>-10</sup> | 7.1x10 <sup>-14</sup>    | 1.1x10 <sup>-14</sup>   |
| 1360                            | 0.446    | 0.272                 | 1.0x10 <sup>9</sup>                                  | 7.9x10 <sup>-10</sup> | 4.6x10 <sup>-13</sup>    | 7.6x10 <sup>-14</sup>   | 8.9x10 <sup>-14</sup>  | 3.9x10 <sup>-10</sup> | 6.1x10 <sup>-14</sup>    | 9.9x10 <sup>-15</sup>   |
| 1430                            | 0.324    | 0.138                 | 1.1x10 <sup>9</sup>                                  | 4.5x10 <sup>-10</sup> | 1.1x10 <sup>-13</sup>    | 1.9x10 <sup>-14</sup>   | 1.2x10 <sup>-13</sup>  | 1.5x10 <sup>-10</sup> | 5.3x10 <sup>-15</sup>    | 8.7x10 <sup>-16</sup>   |



Comparison of the hydraulic conductivity measured to that predicted for systems having even one fixed water layer present inappropriate (Figure 8.3). Even a single layer of adsorbed water caused a significant departure of the predicted flow from that actually measured. This infers that all the pore water is involved in the advective flow process.

The plot of the hydraulic conductivity measured at low applied hydraulic gradient for those specimens showing a transitional gradient shows a weak trend towards fitting the predictions where one adsorbed water layer was assumed to be present on the surface of clay particles during testing at low hydraulic gradients (Figure 8.3). The data collected for specimens having a transitional gradient best fits the Kozeny-Carman equation where a single water layer is assumed to be present on the surface of the relatively low density (high  $n_{eff}$ ), specimens.

Explanations similar to those provided for the hydraulic behaviour of illite specimens can again be applied to interpreting the behaviour of bentonite-based specimens.

i) Flow is actually occurring through pores which are slightly larger than predicted using the material properties available from laboratory testing.

ii) Shearing of previously bonded or structured water increases available pore radii by 1 water layer in specimens having a clay density less than approximately  $0.75 \text{ Mg/m}^3$ . This increased pore size, once mobilized for flow, would continue to participate in advective flow unless the hydraulic gradient decreased to less than the transitional gradient, at which time it would again become unavailable for flow.

iii) The change in hydraulic conductivity results not from a change in the effective radius of the pores conducting flow, but from the activation of pores which had not

previously participated in the flow process. If the majority of flow measured at low hydraulic gradient occurs through the macro-pores within the specimen, then a number of micro-pores and the water layers present between some of the clay platelets might not be active in the transportation process. This could be the result of a higher water viscosity due to some limited structuring in response to the surface charge on the clay particles, or to a higher surface tension in these regions resulting from the narrow pore openings. Under these conditions, changes in flow behaviour need not involve shearing of highly structured water. However, as the hydraulic gradient meets and exceeds the transitional gradient, this previously occluded or non-conductive porosity becomes available for flow, resulting in a higher flux and apparently higher hydraulic conductivity. These passages would close for flow once gradients again decreased to less than the transitional gradient.

In an effort to better understand the hydraulic behaviour of the bentonite specimens, data obtained from thermal expansion testing (Chapter 5) was re-examined. These data indicated that there should be a considerable quantity of structured and therefore less mobile pore water associated with bentonites having low compacted density. At lower densities larger distances exist between the individual platelets, and the largest possible degree of structure could be developed in the pore water. As has been discussed in Section 2.3.5, it is possible that higher density materials may actually have little or no structuring of the pore water. The data presented in Figure 5.5 showed that at densities lower than approximately  $0.75 \text{ Mg/m}^3$ , the thermal expansion of the pore fluid was much less than that of free water. However, by the time a density of  $1.05 \text{ Mg/m}^3$  was achieved the thermal expansion behaviour of the pore fluid was much more like that of free water. This agrees with the findings of the laboratory measurements of hydraulic conductivity. The only region where a gradient-dependent change in hydraulic conductivity was clearly

present in bentonite specimens was for clay densities less than approximately  $0.75 \text{ Mg/m}^3$ . At higher densities there was generally no influence of hydraulic gradient on hydraulic conductivity. The hydraulic conductivity of these specimens remained at a consistently low level throughout testing.

Investigations of both the thermal expansion and hydraulic behaviour of bentonite specimens found that features which can be attributed to a "structured" water component are only detectable in low density systems (clay densities  $<0.75 \text{ Mg/m}^3$ ). At higher densities, the behaviour of the pore fluid cannot be distinguished from that of "normal" water. There are a several explanations for these observations.

- 1) The presence of large quantities of dissolved salts in the bentonites, compared with those present in the illitic clays, has resulted in the disruption or prevention of water structuring in specimens with densities exceeding approximately  $0.75 \text{ Mg/m}^3$ . This concept was discussed in Section 2.3.5 where the presence of mobile cations in the pore fluid of relatively dense systems could result in the system behaving as a porous medium in which ideal Newtonian fluid flow occurs (Oster and Low, 1963). The concept also allows the same materials to contain considerable quantities of structured water at lower densities, which might well then show the presence of transitional gradients as a greater quantity of the structured pore fluid is sheared and takes part in the advective flow process.

- 2) The Poiseuille and Kozeny-Carman equations assume that the particles and pores which constitute the specimens are uniform. However, the particle size and porosimetry data presented in Sections 4.2.1 and 4.2.3 respectively, and the calculations presented in Appendix C, show clearly that these assumptions are at best approximate. The average pore diameter measured for Na-bentonite at  $1.2 \text{ Mg/m}^3$  density was

approximately 15nm (Figure 4.6). In comparison, the pore diameter calculated using the particle surface areas to estimate the thickness of water associated with each face (Equation 3.9) and thereby determine the spacing between parallel platelets, produced predicted pore diameters ( $2d$ ) of 3nm. It is therefore possible that the hydraulic conductivity measured at high applied hydraulic gradients is the result of water being channelled through a limited number of larger pores. The remainder of the specimen would be composed of particles having one or more layers of water adsorbed to their surface and small, normally non-conductive pores between the micro-peds. Only at a combination of low density and elevated hydraulic gradient would a portion of the previously immobilized water become available for participation in advective flow.

## **8.2 Summary of Results of Advective Flow Measurements and Analyses**

Measurement of the advective flow properties of illite and bentonite clays provides evidence that a portion of the pore space of low clay density systems is occupied by structured or normally non-conductive water. This structured or non-conductive water can be mobilized for flow by exceeding the transitional gradient for the specimen. At higher densities in bentonite specimens and possibly very dense illites, there is an apparent lack of non-conductive pore space, or else cationic disruption of the structured water component has occurred. The measurements of advective flow through bentonite clays produced hydraulic conductivities that were equal to or higher than those predicted using either the Poiseuille or Kozeny-Carman equations. This is attributed to the presence of a number of interconnected macro-pores with dimensions significantly larger than average

pore sizes. These channels act as preferential flow paths and so the flux through the specimen in a given time exceeds that predicted using conventional equations.

Three potential mechanisms have been identified which can be used to account for the observed porosity versus hydraulic conductivity relationships, in particular the presence of transitional gradients in low-density specimens have been tentatively explained. Data generated by this project, when combined with those available from the literature allow the determination of a quantitative relationship between total porosity (or clay density), and the flux which can be expected to pass through the specimen in a given time. Chapter 9 summarizes the significance of this relationship to the prediction of advective flow through dense bentonite-based barrier materials.

## CHAPTER 9 CONCLUSIONS AND SUGGESTIONS FOR FUTURE RESEARCH

### 9.1 Conclusions

This research project has examined a number of parameters which may have an influence on the advective transport of water through dense clays. A number of materials were carefully characterized, and the influences of water structuring, temperature, density, pore fluid composition, back pressure, bacterial activity, initial degree of saturation, and hydraulic gradient have all been examined. These parameters have all been reported to potentially influence mass transport through clay barriers and so the magnitude of these influences has been established for densely compacted barriers which have a high clay content. Most importantly, the suitability of conventional flow equations for describing advective transport has been determined. The detailed results of these studies have been presented in the preceding chapters and so are not reproduced here. A brief summary of the key findings of this project is provided below.

The principal conclusions which can be drawn from the research are:

1. The Darcian flow equation can be used to predict advective flow through dense illitic and bentonitic clays. Conventionally defined threshold or critical gradients do not appear to exist in these materials. Hence, advective flow will occur to some degree in all clay materials.
2. Illitic and low density ( $<0.75 \text{ Mg/m}^3$ ), bentonitic specimens have one or more transitional gradients present. These gradients represent shifts in the location of the Darcian flow line in plots of  $\log(\text{flux})$  versus  $\log(\text{hydraulic gradient})$ , and hence a change in the hydraulic conductivity  $k$ . It is important to know the location of these shifts before

trying to predict advective flow in these materials using data generated at hydraulic gradients significantly different than will be encountered in practice. These transitions may represent shearing of structured water or else the opening up of porosity unavailable for advective flow at low hydraulic gradients.

3. Under the testing conditions in this project, bacterial action does not appear to affect advective flow through the compacted bentonite or sand-bentonite materials that have been studied.

4. Backpressure, initial degree of saturation, pore fluid salinity, changes in hydraulic gradient and changes in flow direction have no effect on the ultimate advective flow behaviour of saturated bentonite-based materials having an effective clay dry density greater than approximately  $1.0 \text{ Mg/m}^3$ .

5. Despite the limitations of conventional flow equations, a well characterized bentonite clay material, or a sand-clay mixture containing at least 25% by weight of bentonite clay can have its advective flow predicted relatively accurately using the Poiseuille equation for flow through a tubular pore channel. The Kozeny-Carman equation is less accurate in its predictions, especially at higher densities.

6. Advective flow appears to occur through a limited number of interconnected macropores, as indicated by the ability of the Poiseuille equation to predict the hydraulic conductivity of these materials. The size and distribution of these pores will control the quantity of and rate at which contaminants will move across clay barriers.

7. Only Illites and low density (high porosity) bentonites showed any influence of hydraulic gradient on the hydraulic conductivity. Likewise only low density bentonites showed any affect of pore fluid salinity on the measured hydraulic conductivities.

These findings have significance to the Canadian Nuclear Fuel Waste Management Program as they identify the environmental parameters which are most likely to influence advective flow through clay barriers. The role of groundwater salinity, initial degree of saturation, pore water pressure, bacterial activity and applied hydraulic gradients have all been determined to be of little significance to the ultimate hydraulic properties of densely compacted bentonite clays and sand-clay materials. Items identified as being potentially significant to advective transportation are clay density and pore-size distribution. Further studies are being undertaken at Atomic Energy of Canada Limited's Whiteshell Laboratories to provide more comprehensive information on the bacterial activity.

Changes in advective flow behaviour in low density systems have the potential to influence mass transport in specific regions of a disposal facility (such as the upper backfill (uppermost regions in the tunnels)). Hydraulic conductivity changes of as much as one order of magnitude were observed in low density bentonites as well in illitic clays. These changes in hydraulic conductivity must be taken into account when contaminant release models are used to predict the performance of the vault sealing components.

## **9.2 Suggestions For Future Research**

This research has touched on a number of issues associated with advective transport through dense clays. As there has been little previous work done on advective flow through such materials where low hydraulic gradients are present, this research has left a number of issues unresolved and awaiting future investigation. Among the areas which warrant future investigation are the following five potential projects.



1. The size and number of interconnected macropores present in densely compacted bentonite-based barriers remains to be determined. These pores will control the ability of contaminants to move through and ultimately escape through clay barriers. A comprehensive study to establish the role of pore structure on advective transport would permit this issue to be resolved and lead to a better estimation of the ability to isolate contaminants.
2. Pore size and degree of pore interconnection will also control the ability of bacteria to enter the barrier. The growth of bacteria on the surface of a clay barrier has the potential to affect the contaminant transportation process. Bacteria are capable of entering into pores and either moving through the interconnected macropores of a clay, or forming a biofilm on the surface of compacted clay-based barriers. Such a film can result in a plugging of the pores and generation of a sealing layer of bacterial materials. This sort of testing could be conducted by introducing a species of bacteria which is not present in a specimen (by use of a sterilized specimen) and monitoring the advective flow through the specimen. At the same time the presence of the specially introduced organism could be monitored on the other end of the specimen. This would permit the influence of bacteria on advective flow to be monitored as well as the ability of these organisms to pass through the compacted clay.
- 3) The thermal expansion characteristics of the clay-water systems were examined only briefly in this research project. A more comprehensive set of tests which could be conducted on clay-water systems and such tests might be better able to establish the relationship between specimen density and quantity of structured water. This work could allow a better correlation to be established between specimen density and the presence

and magnitude of transitional gradients in clays. It may be possible to accomplish this using the technique adopted for this research project or to use newer Magnetic Resonance Imaging (MRI) technology which has been developed in the past few years. An MRI technique if usable would allow direct measurement of the bound water layers and hopefully quantify the relationship between clay density and water structure.

4) This project has identified the presence of transitional gradients in low density bentonites. Further detailed testing of the influence of hydraulic gradient on the hydraulic conductivity of low density specimens may permit a clearer relationship between density and the magnitude of the transitional gradients of bentonites. This could allow for the development of a more conclusive model to be developed for the structure of water associated with clay particles.

5) Based on the models for water structure and mobilization for flow adopted in this research, a specimen which exhibits a transitional gradient when percolated with deionized water should lose this transition under conditions of saline permeant. This would be due to the suppression of the diffuse double layers and generation of a larger and unchanging porosity for flow. Such tests would require a very carefully controlled series of hydraulic conductivity testing over a very long duration to clearly establish such a relationship. It is possible that such an undertaking would not be feasible given the limitations of current laboratory technology.

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## **APPENDIX A**

### **DETAILED DATA OBTAINED IN HYDRAULIC CONDUCTIVITY TESTING**

|                                                                      |            |
|----------------------------------------------------------------------|------------|
| <b>Appendix A1: Hydraulic Properties of Quartz Sand Specimens</b>    | <b>263</b> |
| <b>Appendix A2: Hydraulic Properties of Illitic Clay Specimens</b>   | <b>264</b> |
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APPENDIX A1: HYDRAULIC PROPERTIES OF QUARTZ SAND SPECIMENS

| Hydraulic<br>Gradient<br>(i)         | Hydraulic<br>Flux<br>(F)<br>(m3/s/m2) | Hydraulic<br>Conductivity<br>(k)<br>(m/s) | Regression Forced Through Zero (Darcian) |           | No Constraints on Regression Analysis |               |
|--------------------------------------|---------------------------------------|-------------------------------------------|------------------------------------------|-----------|---------------------------------------|---------------|
| <b>SSAND-1 (70-140 Frac Sand)</b>    |                                       |                                           | <b>Regression Output:</b>                |           | <b>Regression Output:</b>             |               |
| Density = 1.76 Mg/m3 height= 51.98mm |                                       |                                           | Constant                                 | 0         | Constant                              | -1.3E-06      |
| Porosity = 0.334 diameter=32mm       |                                       |                                           | Std Err of Y Est                         | 2.333E-06 | Std Err of Y Est                      | 2.36E-06      |
| 0.3                                  | 6.37E-06                              | 2.12E-05                                  | R Squared                                | 0.9269    | R Squared                             | 0.9308        |
| 0.4                                  | 7.62E-06                              | 1.91E-05                                  | No. of Observations                      | 14        | No. of Observations                   | 14            |
| 0.5                                  | 1.06E-05                              | 2.12E-05                                  | Degrees of Freedom                       | 13        | Degrees of Freedom                    | 12            |
| 0.68                                 | 8.47E-06                              | 1.25E-05                                  |                                          |           |                                       |               |
| 0.75                                 | 1.38E-05                              | 1.84E-05                                  |                                          |           |                                       |               |
| 0.8                                  | 1.36E-05                              | 1.70E-05                                  | X Coefficient(s)                         | 1.95E-05  | X Coefficient(s)                      | 2.08E-05      |
| 0.86                                 | 1.78E-05                              | 2.07E-05                                  | Std Err of Coef.                         | 6.24E-07  | Std Err of Coef.                      | 1.63E-06      |
| 0.95                                 | 1.84E-05                              | 1.84E-05                                  |                                          |           |                                       |               |
| 1.02                                 | 1.79E-05                              | 1.75E-05                                  | Range for X-intercept +/-0.11            |           | Calculated X-intercept                | 6.00E-02      |
| 1.12                                 | 2.09E-05                              | 1.87E-05                                  |                                          |           | Range of X-intercept                  | -0.05 to 0.18 |
| 1.17                                 | 2.32E-05                              | 1.98E-05                                  |                                          |           |                                       |               |
| 1.23                                 | 2.98E-05                              | 2.42E-05                                  |                                          |           |                                       |               |
| 1.31                                 | 2.43E-05                              | 1.85E-05                                  |                                          |           |                                       |               |
| 1.81                                 | 3.61E-05                              | 1.99E-05                                  |                                          |           |                                       |               |
| <b>40-70 FRAC SAND</b>               |                                       |                                           | <b>Regression Output:</b>                |           | <b>Regression Output:</b>             |               |
| Density=1.70 Mg/m3 height=50.66mm    |                                       |                                           | Constant                                 | 0         | Constant                              | 2.82E-06      |
| Porosity = 0.359 diameter=32mm       |                                       |                                           | Std Err of Y Est                         | 2.503E-06 | Std Err of Y Est                      | 2.1E-06       |
| 3.93                                 | 9.97E-05                              | 2.54E-05                                  | R Squared                                | 0.9950    | R Squared                             | 0.9974        |
| 2.89                                 | 7.57E-05                              | 2.62E-05                                  | No. of Observations                      | 5         | No. of Observations                   | 5             |
| 1.93                                 | 5.17E-05                              | 2.68E-05                                  | Degrees of Freedom                       | 4         | Degrees of Freedom                    | 3             |
| 0.29                                 | 7.5E-06                               | 2.59E-05                                  |                                          |           |                                       |               |
| 0.96                                 | 2.85E-05                              | 2.97E-05                                  | X Coefficient(s)                         | 2.522E-05 | X Coefficient(s)                      | 2.423E-05     |
| 3.47                                 | 8.67E-05                              | 2.50E-05                                  | Std Err of Coef.                         | 4.701E-07 | Std Err of Coef.                      | 7.207E-07     |
|                                      |                                       |                                           | Range for X-intercept +/-0.20            |           | Calculated X-intercept                | 0.12          |
|                                      |                                       |                                           |                                          |           | Range of X-intercept                  | -0.14 to 0.26 |
| <b>SSAND_04 20-40 FRAC SAND</b>      |                                       |                                           | <b>Regression Output:</b>                |           | <b>Regression Output:</b>             |               |
| Density= 1.67 Mg/m3 height=47.62mm   |                                       |                                           | Constant                                 | 0         | Constant                              | -1.7E-05      |
| Porosity = 0.370 diameter=32mm       |                                       |                                           | Std Err of Y Est                         | 6.769E-06 | Std Err of Y Est                      | 5.2E-06       |
| 2.24                                 | 1.06E-04                              | 4.73E-05                                  | R Squared                                | 0.9815    | R Squared                             | 0.9918        |
| 2.73                                 | 1.33E-04                              | 4.87E-05                                  | No. of Observations                      | 5         | No. of Observations                   | 5             |
| 3.78                                 | 1.89E-04                              | 5.00E-05                                  | Degrees of Freedom                       | 4         | Degrees of Freedom                    | 3             |
| 4.19                                 | 2.04E-04                              | 4.87E-05                                  |                                          |           |                                       |               |
| 2.14                                 | 9.18E-05                              | 4.29E-05                                  | X Coefficient(s)                         | 4.839E-05 | X Coefficient(s)                      | 5.367E-05     |
|                                      |                                       |                                           | Std Err of Coef.                         | 8.681E-07 | Std Err of Coef.                      | 2.817E-06     |
|                                      |                                       |                                           | Range for X-intercept +/-0.14            |           | Calculated X-intercept                | 0.32          |
|                                      |                                       |                                           |                                          |           | Range of X-intercept                  | 0.23 to 0.46  |

APPENDIX A2: HYDRAULIC PROPERTIES OF ILLITIC CLAY SPECIMENS

LH101A density = 1.62  
LH101B density = 1.65  
LH101C density = 1.77

LH102A density = 1.81  
LH103A density = 1.84  
LH103C density = 1.84

LH102B density = 1.93  
LH103B density = 1.96  
LH102C density = 2.03

| Elapsed Time (Hrs)  | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | LINEAR REGRESSION ANALYSES                    |           |                                       |          |
|---------------------|------------------------|--------------------|-------------------|---------------------|--------------------|-----------------------------------------------|-----------|---------------------------------------|----------|
|                     |                        |                    |                   |                     |                    | Regression Forced Through Zero (Darcian Flow) |           | No Constraints on Regression Analysis |          |
| LH101A              |                        |                    |                   |                     |                    |                                               |           |                                       |          |
| Density = 1.62 Mg/m |                        |                    |                   |                     |                    |                                               |           |                                       |          |
| 11.35               | WL Data                |                    | 3.89E-09          |                     |                    | <u>Hydraulic Gradient &gt;1</u>               |           | <u>Hydraulic Gradient &gt;1</u>       |          |
| 7.02                | WL Data                |                    | 2.5E-09           |                     |                    | Regression Output:                            |           | Regression Output:                    |          |
| 4.86                | WL Data                |                    | 1.47E-09          |                     |                    | Constant                                      | 0         | Constant                              | 6.61E-11 |
| 1.80                | WL Data                |                    | 4.64E-10          |                     |                    | Std Err of Y Est                              | 2.11E-10  | Std Err of Y Est                      | 2.12E-10 |
| 2.07                | WL Data                |                    | 6.67E-10          |                     |                    | R Squared                                     | 0.9959021 | R Squared                             | 0.9962   |
| 37.52               | WL Data                |                    | 1.32E-08          |                     |                    | No. of Observations                           | 14        | No. of Observations                   | 14       |
| 1.2                 | UM Data                |                    | 3.16E-10          |                     |                    | Degrees of Freedom                            | 13        | Degrees of Freedom                    | 12       |
| 1.6                 | UM Data                |                    | 5.82E-10          |                     |                    |                                               |           |                                       |          |
| 2                   | UM Data                |                    | 7.8E-10           |                     |                    | X Coefficient(s)                              | 3.52E-10  | X Coefficient(s)                      | 3.49E-10 |
| 2.4                 | UM Data                |                    | 9.36E-10          |                     |                    | Std Err of Coef.                              | 5.16E-12  | Std Err of Coef.                      | 6.22E-12 |
| 2.8                 | UM Data                |                    | 1.19E-09          |                     |                    |                                               |           |                                       |          |
| 3.2                 | UM Data                |                    | 1.22E-09          |                     |                    |                                               |           |                                       |          |
| 3.6                 | UM Data                |                    | 1.65E-09          |                     |                    |                                               |           |                                       |          |
| 4                   | UM Data                |                    | 1.91E-09          |                     |                    |                                               |           |                                       |          |
| 0.8                 | UM Data                |                    | 1.36E-10          |                     |                    | <u>Hydraulic Gradient &lt;1</u>               |           | <u>Hydraulic Gradient &lt;1</u>       |          |
| 1                   | UM Data                |                    | 1.6E-10           |                     |                    | Regression Forced Through Zero (Darcian Flow) |           | No Constraints on Regression Analysis |          |
| 0.4                 | UM Data                |                    | 3.71E-11          |                     |                    | Regression Output:                            |           | Regression Output:                    |          |
| 0.6                 | UM Data                |                    | 5.78E-11          |                     |                    | Constant                                      | 0         | Constant                              | -4.3E-12 |
|                     |                        |                    |                   |                     |                    | Std Err of Y Est                              | 1.19E-12  |                                       |          |
|                     |                        |                    |                   |                     |                    | R Squared                                     | 0.9934    | R Squared                             | 1.0000   |
|                     |                        |                    |                   |                     |                    | No. of Observations                           | 2         | No. of Observations                   | 2        |
|                     |                        |                    |                   |                     |                    | Degrees of Freedom                            | 1         | Degrees of Freedom                    | 0        |
|                     |                        |                    |                   |                     |                    | X Coefficient(s)                              | 9.52E-11  | X Coefficient(s)                      | 1.03E-10 |
|                     |                        |                    |                   |                     |                    | Std Err of Coef.                              | 1.65E-12  |                                       |          |

## APPENDIX A2 (Continued): HYDRAULIC PROPERTIES OF ILLITIC CLAY SPECIMENS

| Elapsed Time        |       |                        |          |                    |          | LINEAR REGRESSION ANALYSES                    |          |                     |                                       |                    |           |
|---------------------|-------|------------------------|----------|--------------------|----------|-----------------------------------------------|----------|---------------------|---------------------------------------|--------------------|-----------|
| Time (Hrs)          |       | Hydraulic Gradient (l) |          | Inflow Volume (cc) |          | Inflow Flux (m/s)                             |          | Outflow Volume (cc) |                                       | Outflow Flux (m/s) |           |
|                     |       |                        |          |                    |          | Regression Forced Through Zero (Darcian Flow) |          |                     | No Constraints on Regression Analysis |                    |           |
| LH101C 1.77 Mg/m3   |       |                        |          |                    |          | Gradient >5                                   |          |                     | Gradient >5                           |                    |           |
|                     |       |                        |          |                    |          | Regression Output:                            |          |                     | Regression Output:                    |                    |           |
| 1032                | 33.3  |                        | 4.72E-09 |                    |          | Constant                                      |          | 0                   | Constant                              |                    | -2.47E-10 |
| 1032                | 33.3  |                        | 4.56E-09 |                    |          | Std Err of Y Est                              |          | 2.03E-10            | Std Err of Y Est                      |                    | 1.28E-10  |
| 1584                | 11.2  |                        | 1.26E-09 |                    |          | R Squared                                     |          | 0.9855047           | R Squared                             |                    | 0.9949    |
| 1584                | 11.2  |                        | 1.59E-09 |                    |          | No. of Observations                           |          | 9                   | No. of Observations                   |                    | 9         |
| 2208                | 9.9   |                        | 1.06E-09 |                    |          | Degrees of Freedom                            |          | 8                   | Degrees of Freedom                    |                    | 7         |
| 2520                | 5.3   |                        | 5.38E-10 |                    |          | X Coefficient(s)                              | 1.35E-10 |                     | X Coefficient(s)                      | 1.47E-10           |           |
| 2520                | 5.3   |                        | 6.74E-10 |                    |          | Std Err of Coef.                              | 3.91E-12 |                     | Std Err of Coef.                      | 3.96E-12           |           |
| 2904                | 6.1   |                        | 5.79E-10 |                    |          |                                               |          |                     |                                       |                    |           |
| 2904                | 6.1   |                        | 6.34E-10 |                    |          |                                               |          |                     |                                       |                    |           |
| 3264                | 2.2   |                        | 1.84E-10 |                    |          | Gradient <5                                   |          |                     | Gradient <5                           |                    |           |
| 2362                | 5     |                        | 3.02E-10 |                    |          | Regression Output:                            |          |                     | Regression Output:                    |                    |           |
| 2362                | 5     |                        | 2.69E-10 |                    |          | Constant                                      |          | 0                   | Constant                              |                    | 1.04E-10  |
|                     |       |                        |          |                    |          | Std Err of Y Est                              |          | 4.27E-11            | Std Err of Y Est                      |                    | 2.33E-11  |
|                     |       |                        |          |                    |          | R Squared                                     |          | 0.5073              | R Squared                             |                    | 0.9265    |
|                     |       |                        |          |                    |          | No. of Observations                           |          | 3                   | No. of Observations                   |                    | 3         |
|                     |       |                        |          |                    |          | Degrees of Freedom                            |          | 2                   | Degrees of Freedom                    |                    | 1         |
|                     |       |                        |          |                    |          | X Coefficient(s)                              | 5.94E-11 |                     | X Coefficient(s)                      | 3.62E-11           |           |
|                     |       |                        |          |                    |          | Std Err of Coef.                              | 5.77E-12 |                     | Std Err of Coef.                      | 1.02E-11           |           |
| LH102A              |       |                        |          |                    |          | Gradient <5                                   |          |                     | Gradient <5                           |                    |           |
| Density = 1.81 Mg/m |       |                        |          |                    |          | Regression Output:                            |          |                     | Regression Output:                    |                    |           |
| 2852.4              | 2.35  | 1.925                  | 7.19E-11 | 1.275              | 5.58E-11 | Constant                                      |          | 0                   | Constant                              |                    | -1.16E-11 |
| 3002.5              | 4.92  | 2.015                  | 2.21E-10 | 1.320              | 1.53E-10 | Std Err of Y Est                              |          | 2.73E-11            | Std Err of Y Est                      |                    | 2.95E-11  |
| 3170.8              | 5.98  | 2.140                  | 3.48E-10 | 1.455              | 1.33E-10 | R Squared                                     |          | 0.8764              | R Squared                             |                    | 0.8841    |
| 3338.9              | 7.10  | 2.365                  | 4.84E-10 | 1.475              |          | No. of Observations                           |          | 6                   | No. of Observations                   |                    | 6         |
| 3459.5              | 8.05  | 2.810                  | 1.14E-09 | 1.620              | 1.12E-09 | Degrees of Freedom                            |          | 5                   | Degrees of Freedom                    |                    | 4         |
| 3700.0              | 9.62  | 3.670                  | 1.14E-09 | 2.420              | 1.13E-09 | X Coefficient(s)                              | 3.6E-11  |                     | X Coefficient(s)                      | 3.9E-11            |           |
| 3819.6              | 12.45 | 4.400                  | 2.13E-09 | 3.135              | 2.04E-09 | Std Err of Coef.                              | 3.5E-12  |                     | Std Err of Coef.                      | 7.07E-12           |           |
| 3963.3              | 13.66 | 5.100                  | 1.65E-09 | 3.815              | 1.55E-09 |                                               |          |                     |                                       |                    |           |
| 4039.9              | 28.76 | 5.720                  | 3.38E-09 | 4.415              | 3.34E-09 |                                               |          |                     |                                       |                    |           |
| 4357.7              | 17.75 | 8.460                  | 2.35E-09 | 7.120              | 2.3E-09  |                                               |          |                     |                                       |                    |           |
| 4567.3              | 5.25  | 8.700                  | 3.86E-10 | 7.385              | 3.62E-10 | Hydraulic Gradient >7                         |          |                     | Hydraulic Gradient >7                 |                    |           |
| 5240.0              | 0.78  | 8.725                  | 1.82E-11 | 7.420              | 4.02E-11 | Regression Forced Through Zero (Darcian Flow) |          |                     | No Constraints on Regression Analysis |                    |           |
|                     |       |                        |          |                    |          | Regression Output:                            |          |                     | Regression Output:                    |                    |           |
|                     |       |                        |          |                    |          | Constant                                      |          | 0                   | Constant                              |                    | 1.61E-10  |
|                     |       |                        |          |                    |          | Std Err of Y Est                              |          | 2.79E-10            | Std Err of Y Est                      |                    | 2.81E-10  |
|                     |       |                        |          |                    |          | R Squared                                     |          | 0.8984              | R Squared                             |                    | 0.9052    |
|                     |       |                        |          |                    |          | No. of Observations                           |          | 13                  | No. of Observations                   |                    | 13        |
|                     |       |                        |          |                    |          | Degrees of Freedom                            |          | 12                  | Degrees of Freedom                    |                    | 11        |
|                     |       |                        |          |                    |          | X Coefficient(s)                              | 1.25E-10 |                     | X Coefficient(s)                      | 1.16E-10           |           |
|                     |       |                        |          |                    |          | Std Err of Coef.                              | 4.83E-12 |                     | Std Err of Coef.                      | 1.13E-11           |           |

## APPENDIX A2 (Continued): HYDRAULIC PROPERTIES OF ILLITIC CLAY SPECIMENS

| Elapsed Time (Hrs)   | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | LINEAR REGRESSION ANALYSES                    |                                       |
|----------------------|------------------------|--------------------|-------------------|---------------------|--------------------|-----------------------------------------------|---------------------------------------|
|                      |                        |                    |                   |                     |                    | Regression Forced Through Zero (Darcian Flow) | No Constraints on Regression Analysis |
| LH103A               |                        |                    |                   |                     |                    |                                               |                                       |
| Density = 1.84 Mg/m3 |                        |                    |                   |                     |                    |                                               |                                       |
| 1584.8               | 64.11                  | 4.170              | 6.92E-09          |                     |                    | <u>All Data</u>                               | <u>All Data</u>                       |
| 2112.7               | 42.34                  | 11.085             | 4.61E-09          |                     |                    | Regression Output:                            | Regression Output:                    |
| 2115.3               | 42.34                  | 11.110             | 4.52E-09          |                     |                    | Constant                                      | 0                                     |
| 2286.1               | 18.76                  | 12.070             | 1.94E-09          |                     |                    | Std Err of Y Est                              | 1.29E-10                              |
| 2640.7               | 9.72                   | 13.090             | 9.43E-10          |                     |                    | R Squared                                     | 0.9965                                |
| 2665.1               | 9.71                   | 13.160             | 9.26E-10          |                     |                    | No. of Observations                           | 14                                    |
| 3030.0               | 6.71                   | 13.860             | 6.63E-10          |                     |                    | Degrees of Freedom                            | 13                                    |
| 3601.3               | 4.69                   | 14.580             | 4.16E-10          |                     |                    |                                               |                                       |
| 4033.5               | 3.21                   | 15.130             | 2.96E-10          |                     |                    | X Coefficient(s)                              | 1.07E-10                              |
| 4820.4               | 2.01                   | 15.890             | 3.42E-10          |                     |                    | Std Err of Coef.                              | 1.41E-12                              |
| 5444.5               | 0.98                   | 16.690             | 4.49E-10          |                     |                    |                                               |                                       |
| 5756.6               | 0.48                   | 17.085             | 1.2E-10           |                     |                    |                                               |                                       |
| 8323.8               | 0.50                   | 18.003             | 3.6E-11           |                     |                    |                                               |                                       |
| 7508.7               | 0.00                   | 18.108             | 2.16E-27          |                     |                    |                                               |                                       |
| LH103C               |                        |                    |                   |                     |                    |                                               |                                       |
| DENSITY = 1.84 Mg/m3 |                        |                    |                   |                     |                    |                                               |                                       |
| 761.8                | 51.19                  | 11.185             | 3.39E-09          |                     |                    | <u>Hydraulic Gradient &gt;9</u>               | <u>Hydraulic Gradient &gt;9</u>       |
| 1270.9               | 26.17                  | 15.855             | 2.81E-09          |                     |                    | Regression Forced Through Zero (Darcian Flow) | No Constraints on Regression Analysis |
| 1937.5               | 10.20                  | 17.465             | 6.31E-10          |                     |                    | Regression Output:                            | Regression Output:                    |
| 3785.4               | 10.82                  | 19.160             | 5.28E-10          |                     |                    | Constant                                      | 0                                     |
| 7313.3               | 49.26                  | 19.360             | 4.78E-09          |                     |                    | Std Err of Y Est                              | 6.79E-10                              |
| 6234.0               | -23.96                 | 17.400             | -1.2E-09          |                     |                    | R Squared                                     | 0.8221                                |
| 6785                 | -47.99                 | 13.250             | -3.2E-09          |                     |                    | No. of Observations                           | 7                                     |
| 5109.0               | -8.45                  | 19.030             | -2.1E-10          |                     |                    | Degrees of Freedom                            | 6                                     |
| 2729.9               | 2.50                   | 17.385             | 4.92E-11          |                     |                    |                                               |                                       |
| 5705.4               | -1.60                  | 19.050             | -2.4E-11          |                     |                    | X Coefficient(s)                              | 7.64E-11                              |
| 5705.4               | -1.60                  | 19.050             | -3.3E-11          |                     |                    | Std Err of Coef.                              | 7.23E-12                              |
| 4105                 | 0.58                   | 19.280             | 3.63E-11          |                     |                    |                                               |                                       |
|                      |                        |                    |                   |                     |                    | <u>Hydraulic Gradient &lt;9</u>               | <u>Hydraulic Gradient &lt;9</u>       |
|                      |                        |                    |                   |                     |                    | Regression Forced Through Zero (Darcian Flow) | No Constraints on Regression Analysis |
|                      |                        |                    |                   |                     |                    | Regression Output:                            | Regression Output:                    |
|                      |                        |                    |                   |                     |                    | Constant                                      | 0                                     |
|                      |                        |                    |                   |                     |                    | Std Err of Y Est                              | 1.12E-11                              |
|                      |                        |                    |                   |                     |                    | R Squared                                     | 0.9832                                |
|                      |                        |                    |                   |                     |                    | No. of Observations                           | 4                                     |
|                      |                        |                    |                   |                     |                    | Degrees of Freedom                            | 3                                     |
|                      |                        |                    |                   |                     |                    |                                               |                                       |
|                      |                        |                    |                   |                     |                    | X Coefficient(s)                              | 2.37E-11                              |
|                      |                        |                    |                   |                     |                    | Std Err of Coef.                              | 1.23E-12                              |
|                      |                        |                    |                   |                     |                    |                                               |                                       |
|                      |                        |                    |                   |                     |                    | X Coefficient(s)                              | 2.62E-11                              |
|                      |                        |                    |                   |                     |                    | Std Err of Coef.                              | 8.46E-13                              |

## APPENDIX A2 (Continued): HYDRAULIC PROPERTIES OF ILLITIC CLAY SPECIMENS

|                                |                        |                    |                   |                     |                    | LINEAR REGRESSION ANALYSES                    |          |                                       |           |
|--------------------------------|------------------------|--------------------|-------------------|---------------------|--------------------|-----------------------------------------------|----------|---------------------------------------|-----------|
| Elapsed Time (Hrs)             | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Regression Forced Through Zero (Darcian Flow) |          | No Constraints on Regression Analysis |           |
| LH102B<br>Density = 1.93 Mg/m  |                        |                    |                   |                     |                    | Gradient <10                                  |          | Gradient <10                          |           |
|                                |                        |                    |                   |                     |                    | Regression Output:                            |          | Regression Output:                    |           |
| 811.4                          | 1.68                   | 1.950              | 7.19E-11          | 0.050               | 4.8E-11            | Constant                                      | 0        | Constant                              | 6.41E-12  |
| 1482.9                         | 4.08                   | 2.070              | 7E-11             | 0.130               | 5.76E-11           | Std Err of Y Est                              | 3.8E-11  | Std Err of Y Est                      | 3.96E-11  |
| 1651.3                         | 7.49                   | 2.220              | 2.57E-10          | 0.265               | 2.47E-10           | R Squared                                     | 0.7564   | R Squared                             | 0.7583    |
| 2443.3                         | 12.95                  | 3.590              | 8.11E-10          | 1.515               | 7.45E-10           | No. of Observations                           | 12       | No. of Observations                   | 12        |
| 2491.4                         | 21.00                  | 3.730              | 1.05E-09          | 1.660               | 1.02E-09           | Degrees of Freedom                            | 11       | Degrees of Freedom                    | 10        |
| 2659.5                         | 20.44                  | 4.200              | 9.53E-10          | 2.135               | 9.47E-10           | X Coefficient(s)                              | 3.03E-11 | X Coefficient(s)                      | 2.9E-11   |
| 2945.4                         | 37.92                  | 5.600              | 2.24E-09          | 3.480               | 2.15E-09           | Std Err of Coef.                              | 2.51E-12 | Std Err of Coef.                      | 5.19E-12  |
| 3113.3                         | 37.41                  | 6.610              | 2.17E-09          | 4.520               | 2.21E-09           |                                               |          |                                       |           |
| 3448.4                         | 31.19                  | 8.545              | 1.85E-09          | 6.430               | 1.89E-09           |                                               |          |                                       |           |
| 3616.0                         | 30.68                  | 9.350              | 1.74E-09          | 7.265               | 1.75E-09           |                                               |          |                                       |           |
| 4000.5                         | 24.21                  | 11.110             | 1.35E-09          | 8.995               | 1.32E-09           |                                               |          |                                       |           |
| 4334.8                         | 10.86                  | 12.010             | 5.26E-10          | 9.885               | 5.35E-10           |                                               |          |                                       |           |
| 4502.6                         | 5.30                   | 12.085             | 1.32E-10          | 9.940               | 1.44E-10           |                                               |          |                                       |           |
| 4626.5                         | 27.73                  | 12.540             | 1.49E-09          | 10.385              | 1.45E-09           |                                               |          |                                       |           |
| 4956.3                         | 3.11                   | 12.750             | 1.31E-10          | 10.565              | 1.59E-10           |                                               |          |                                       |           |
| 5125.9                         | 0.92                   | 12.775             | 2.88E-11          | 10.585              | 4.32E-11           |                                               |          |                                       |           |
| 6181.3                         | 22.50                  | 13.305             | 9.91E-10          |                     |                    |                                               |          |                                       |           |
| 6212.6                         | 119.50                 | 13.965             | 6.07E-09          |                     |                    |                                               |          |                                       |           |
|                                |                        |                    |                   |                     |                    | Gradient >10                                  |          | Gradient >10                          |           |
|                                |                        |                    |                   |                     |                    | Regression Output:                            |          | Regression Output:                    |           |
|                                |                        |                    |                   |                     |                    | Constant                                      | 0        | Constant                              | 7.84E-11  |
|                                |                        |                    |                   |                     |                    | Std Err of Y Est                              | 1.57E-10 | Std Err of Y Est                      | 1.53E-10  |
|                                |                        |                    |                   |                     |                    | R Squared                                     | 0.9811   | R Squared                             | 0.9828    |
|                                |                        |                    |                   |                     |                    | No. of Observations                           | 22       | No. of Observations                   | 22        |
|                                |                        |                    |                   |                     |                    | Degrees of Freedom                            | 21       | Degrees of Freedom                    | 20        |
|                                |                        |                    |                   |                     |                    | X Coefficient(s)                              | 5.34E-11 | X Coefficient(s)                      | 5.17E-11  |
|                                |                        |                    |                   |                     |                    | Std Err of Coef.                              | 9.14E-13 | Std Err of Coef.                      | 1.53E-12  |
|                                |                        |                    |                   |                     |                    |                                               |          |                                       |           |
| LH102C<br>Density = 2.03 Mg/m3 |                        |                    |                   |                     |                    | All Data                                      |          | All Data                              |           |
|                                |                        |                    |                   |                     |                    | Regression Output:                            |          | Regression Output:                    |           |
| 448.5                          | 1.90                   | 1.500              | 0.015             | 4.86E-11            |                    | Constant                                      | 0        | Constant                              | -3.95E-12 |
| 664.7                          | 4.00                   | 1.525              | 4.14E-11          | 0.035               | 4.14E-11           | Std Err of Y Est                              | 3.64E-11 | Std Err of Y Est                      | 3.71E-11  |
| 952.5                          | 6.25                   | 1.565              | 4.19E-11          | 0.015               | 6.49E-11           | R Squared                                     | 0.9112   | R Squared                             | 0.9116    |
| 1340.2                         | 12.50                  | 1.745              | 1.50E-10          | 0.085               | 8.84E-11           | No. of Observations                           | 23       | No. of Observations                   | 23        |
| 1844.2                         | 15.60                  | 1.955              | 1.23E-10          | 0.205               | 8.45E-11           | Degrees of Freedom                            | 22       | Degrees of Freedom                    | 21        |
| 2256.9                         | 16.35                  | 2.115              | 1.40E-10          | 0.315               | 1.05E-10           |                                               |          |                                       |           |
| 2520.2                         | 19.30                  | 2.325              | 2.41E-10          | 0.420               | 1.73E-10           |                                               |          |                                       |           |
| 3478.5                         | 39.50                  | 3.475              | 4.69E-10          | 1.385               | 4.08E-10           | X Coefficient(s)                              | 1.04E-11 | X Coefficient(s)                      | 1.06E-11  |
| 3622.4                         | 29.50                  | 3.620              | 3.56E-10          | 1.520               | 2.76E-10           | Std Err of Coef.                              | 4.24E-13 | Std Err of Coef.                      | 7.19E-13  |
| 3932.1                         | 9.75                   | 3.775              | 1.38E-10          | 1.635               | 1.01E-10           |                                               |          |                                       |           |
| 4484.8                         | 4.75                   | 3.960              | 8.27E-11          | 1.725               | 4.58E-11           |                                               |          |                                       |           |
| 4988.8                         | 5.55                   | 4.075              | 9.47E-11          | 1.775               | 6.28E-11           |                                               |          |                                       |           |

APPENDIX A2 (Continued): HYDRAULIC PROPERTIES OF ILLITIC CLAY SPECIMENS

| Elapsed Time (Hrs)                   | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | LINEAR REGRESSION ANALYSES                    |                                       |
|--------------------------------------|------------------------|--------------------|-------------------|---------------------|--------------------|-----------------------------------------------|---------------------------------------|
|                                      |                        |                    |                   |                     |                    | Regression Forced Through Zero (Darcian Flow) | No Constraints on Regression Analysis |
| <b>LHI03B</b>                        |                        |                    |                   |                     |                    |                                               |                                       |
| Dry Density = 1.96 Mg/m <sup>3</sup> |                        |                    |                   |                     |                    |                                               |                                       |
| 1274.3                               | 12.40                  | 21.230             | 1.95E-10          |                     |                    | <u>Hydraulic Gradient &gt;21</u>              | <u>Hydraulic Gradient &gt;21</u>      |
| 1939.0                               | 4.20                   | 21.465             | 8.67E-11          |                     |                    | Regression Output:                            | Regression Output:                    |
| 2211.8                               | 4.20                   | 21.500             | 4.38E-11          |                     |                    | Constant 0                                    | Constant -8.14E-10                    |
| 3234.9                               | 1.70                   | 21.850             | 2.41E-11          |                     |                    | Std Err of Y Est 4.93E-10                     | Std Err of Y Est 4.06E-10             |
| 4050.8                               | 8.20                   | 24.363             | 1.6E-10           |                     |                    | R Squared 0.8751074                           | R Squared 0.9364473                   |
| 5706.9                               | 20.60                  | 26.103             | 1.79E-10          |                     |                    | No. of Observations 5                         | No. of Observations 5                 |
| 7075.0                               | 16.50                  | 36.848             | 1.52E-10          |                     |                    | Degrees of Freedom 4                          | Degrees of Freedom 3                  |
| 7651.0                               | 68.20                  | 49.838             | 4.3E-09           |                     |                    | X Coefficient(s) 5.65E-11                     | X Coefficient(s) 7.4E-11              |
| 8251.0                               | 23.70                  | 53.998             | 7.52E-10          |                     |                    | Std Err of Coef. 5.14E-12                     | Std Err of Coef. 1.11E-11             |
| 8827.0                               | 34.20                  | 59.158             | 1.3E-09           |                     |                    |                                               |                                       |
| 6243.0                               | 46.50                  | 35.448             | 2.64E-09          |                     |                    | <u>Hydraulic Gradient &lt;21</u>              | <u>Hydraulic Gradient &lt;21</u>      |
| 763.1                                | 26.00                  | 17.845             | 1.64E-09          |                     |                    | Regression Output:                            | Regression Output:                    |
|                                      |                        |                    |                   |                     |                    | Constant 0                                    | Constant 4.33E-11                     |
|                                      |                        |                    |                   |                     |                    | Std Err of Y Est 4.69E-11                     | Std Err of Y Est 4.26E-11             |
|                                      |                        |                    |                   |                     |                    | R Squared 0.5275797                           | R Squared 0.6748934                   |
|                                      |                        |                    |                   |                     |                    | No. of Observations 7                         | No. of Observations 7                 |
|                                      |                        |                    |                   |                     |                    | Degrees of Freedom 6                          | Degrees of Freedom 5                  |
|                                      |                        |                    |                   |                     |                    | X Coefficient(s) 1.1E-11                      | X Coefficient(s) 7.93E-12             |
|                                      |                        |                    |                   |                     |                    | Std Err of Coef. 1.52E-12                     | Std Err of Coef. 2.46E-12             |
| <b>LHI01B</b>                        |                        |                    |                   |                     |                    |                                               |                                       |
| Density = 1.65 Mg/m                  |                        |                    |                   |                     |                    |                                               |                                       |
| 336                                  | 11.6                   |                    | 3.68E-09          |                     |                    | <u>Gradient &gt;4.5</u>                       | <u>Gradient &gt;4.5</u>               |
| 336                                  | 11.6                   |                    | 4.83E-09          |                     |                    | Regression Forced Through Zero (Darcian Flow) | No Constraints on Regression Analysis |
| 720                                  | 20.9                   |                    | 8.29E-09          |                     |                    | Regression Output:                            | Regression Output:                    |
| 720                                  | 20.9                   |                    | 9.42E-09          |                     |                    | Constant 0                                    | Constant -1.84E-10                    |
| 1090                                 | 7.3                    |                    | 2.81E-09          |                     |                    | Std Err of Y Est 7.05E-10                     | Std Err of Y Est 7.83E-10             |
| 1272                                 | 7.3                    |                    | 3.7E-09           |                     |                    | R Squared 0.9335184                           | R Squared 0.9343596                   |
| 1440                                 | 4.5                    |                    | 1.74E-09          |                     |                    | No. of Observations 6                         | No. of Observations 6                 |
| 1440                                 | 4.5                    |                    | 2.5E-09           |                     |                    | Degrees of Freedom 5                          | Degrees of Freedom 4                  |
| 1968                                 | 4.4                    |                    | 7.31E-10          |                     |                    | X Coefficient(s) 4.13E-10                     | X Coefficient(s) 4.25E-10             |
| 1968                                 | 4.4                    |                    | 9.79E-10          |                     |                    | Std Err of Coef. 1.99E-11                     | Std Err of Coef. 5.63E-11             |
| 2808                                 | 2.8                    |                    | 3.37E-11          |                     |                    |                                               |                                       |
| 2808                                 | 2.8                    |                    | 1.91E-10          |                     |                    | <u>Gradient &lt;3</u>                         |                                       |
| 2808                                 | 2.8                    |                    | 2.34E-10          |                     |                    | k < 1.5 E-11 m/s                              |                                       |
|                                      | 0.28                   |                    | 3.54E-12          |                     |                    |                                               |                                       |

APPENDIX A3: HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                                                        | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |                                   |
|---------------------------------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|
|                                                                           |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero | No Constraints on Regression Line |
| <b>BARCG2A</b> Density=0.55 Mg/m3<br>Test Duration 20/11/90 to 21/09/91   |                        |                    |                   |                |                     |                    |                 | <u>High l Data</u>             |                                   |
| 2730                                                                      | 91.5                   | 6.09               | 2.15E-10          | 2.35E-12       |                     |                    |                 | Regression Output:             | Regression Output:                |
| 2826                                                                      | 59.6                   | 6.43               | 1.38E-10          | 2.32E-12       |                     |                    |                 | Constant                       | Constant                          |
| 3162                                                                      | 25.5                   | 7.055              | 3.79E-11          | 1.48E-12       |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
| 3330                                                                      | 17.0                   | 7.370              | 2.97E-11          | 1.48E-12       |                     |                    |                 | R Squared                      | R Squared                         |
| 3666                                                                      | 12.8                   | 8.120              | 4.16E-11          | 3.08E-12       |                     |                    |                 | No. of Observations            | No. of Observations               |
| 3762                                                                      | 63.8                   | 9.280              | 4.78E-10          | 7.49E-12       |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
| 3907                                                                      | 153.2                  | 11.840             | 1.03E-09          | 6.74E-12       |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
| 4002                                                                      | 172.3                  | 14.745             | 1.17E-09          | 6.78E-12       |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |
| 4034                                                                      | 183.0                  | 15.655             | 1.14E-09          | 6.22E-12       |                     |                    |                 |                                |                                   |
| 4362                                                                      | 23.4                   | 21.805             | 6.6E-11           | 2.82E-12       |                     |                    |                 | <u>Low l Data</u>              |                                   |
| 4722                                                                      | 38.3                   | 28.040             | 5.22E-11          | 1.35E-12       |                     |                    |                 | Regression Output:             | Regression Output:                |
| 5035                                                                      | 48.9                   | 28.780             | 1.18E-10          | 2.4E-12        |                     |                    |                 | Constant                       | Constant                          |
| 5851                                                                      | 14.9                   | 30.010             | 5.52E-11          | 3.71E-12       |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
| 6067                                                                      | 17.0                   | 30.290             | 4.88E-11          | 2.87E-12       |                     |                    |                 | R Squared                      | R Squared                         |
| 6210                                                                      | 14.9                   | 30.405             | 2.9E-11           | 1.95E-12       |                     |                    |                 | No. of Observations            | No. of Observations               |
| 7466                                                                      | 19.1                   | 35.395             | 3.74E-11          | 1.96E-12       |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
|                                                                           |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |
| <b>BARCG05A</b> Density= 0.66 Mg/m3<br>Test Duration 13/01/94 to 15/04/94 |                        |                    |                   |                |                     |                    |                 | <u>Gradient&gt;10</u>          |                                   |
| 1098.9                                                                    | 0.96                   | 4.59               | 2.65E-10          | 2.76E-10       |                     |                    |                 | Regression Output:             | Regression Output:                |
| 1314.7                                                                    | 2.48                   | 4.31               | 3.27E-10          | 1.32E-10       |                     |                    |                 | Constant                       | Constant                          |
| 2204.6                                                                    | 9.01                   | 125.94             | 3.83E-09          | 4.25E-10       |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
| 1938.9                                                                    | 12.47                  | 5.27               | 1.6E-10           | 1.28E-11       |                     |                    |                 | R Squared                      | R Squared                         |
| 2018.3                                                                    | 40.43                  | 24.85              | 1.4E-07           | 3.46E-09       |                     |                    |                 | No. of Observations            | No. of Observations               |
| 2037.0                                                                    | 62.36                  | 55.45              | 8.33E-07          | 1.34E-08       |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
| 2042.8                                                                    | 28.04                  | 73.52              | 1.37E-07          | 4.88E-09       |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
| 2113.0                                                                    | 49.11                  | 91.23              | 2.77E-07          | 5.63E-09       |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |
| 2136.6                                                                    | 18.15                  | 119.38             | 5.64E-08          | 3.1E-09        |                     |                    |                 |                                |                                   |
| 2114.1                                                                    | 62.04                  | 110.63             | 6.95E-07          | 1.12E-08       |                     |                    |                 | <u>Gradient &lt;10</u>         |                                   |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Constant                       | Constant                          |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
|                                                                           |                        |                    |                   |                |                     |                    |                 | R Squared                      | R Squared                         |
|                                                                           |                        |                    |                   |                |                     |                    |                 | No. of Observations            | No. of Observations               |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
|                                                                           |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
|                                                                           |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                    |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |          |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|----------|-----------------------------------|-----------|
| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero |          | No Constraints on Regression Line |           |
| BARCG1A Density=0.59 Mg/m3         |                        |                    |                   |                |                     |                    |                 | High Gradient (>1000)          |          | High Gradient (>1000)             |           |
| Testing Duration 20/11/90-10/09/91 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 2658                               | 1752.3                 | 14.635             | 1.98E-10          | 1.13E-13       |                     |                    |                 | Constant                       | 0        | Constant                          | -3.09E-10 |
| 2691                               | 1098                   | 14.885             | 2.3E-10           | 2.09E-13       |                     |                    |                 | Std Err of Y Est               | 2.53E-10 | Std Err of Y Est                  | 1.88E-10  |
| 2730                               | 1004.7                 | 15.100             | 2.03E-10          | 2.02E-13       |                     |                    |                 | R Squared                      | 0.9511   | R Squared                         | 0.9819    |
| 2826                               | 654.2                  | 15.440             | 7.90E-11          | 1.21E-13       |                     |                    |                 | No. of Observations            | 4        | No. of Observations               | 4         |
| 3762                               | 1028.0                 | 18.485             | 1.65E-10          | 1.6E-13        |                     |                    |                 | Degrees of Freedom             | 3        | Degrees of Freedom                | 2         |
| 3834                               | 1191.6                 | 18.870             | 1.75E-10          | 1.47E-13       |                     |                    |                 |                                |          |                                   |           |
| 4146                               | 1074.8                 | 19.731             | 4.45E-10          | 4.14E-13       |                     |                    |                 | X Coefficient(s)               | 5.33E-13 | X Coefficient(s)                  | 6.25E-13  |
| 4362                               | 537.4                  | 20.686             | 7.45E-11          | 1.39E-13       |                     |                    |                 | Std Err of Coef.               | 4.53E-14 | Std Err of Coef.                  | 6E-14     |
| 4506                               | 1308.4                 | 22.276             | 6.13E-10          | 4.69E-13       |                     |                    |                 |                                |          |                                   |           |
| 4530                               | 1869.2                 | 22.666             | 6.32E-10          | 3.38E-13       |                     |                    |                 |                                |          |                                   |           |
| 4554                               | 4976.6                 | 24.416             | 2.84E-09          | 5.71E-13       |                     |                    |                 | Mid Gradient (250 to 1200)     |          | Mid Gradient (250 to 1200)        |           |
| 5226                               | 210.3                  | 1.660              | 1.91E-11          | 9.07E-14       |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 5563                               | 186.9                  | 1.780              | 1.37E-11          | 7.36E-14       |                     |                    |                 | Constant                       | 0        | Constant                          | -3.21E-11 |
| 5851                               | 257.0                  | 1.910              | 2.82E-11          | 1.1E-13        |                     |                    |                 | Std Err of Y Est               | 2.98E-11 | Std Err of Y Est                  | 2.97E-11  |
|                                    |                        |                    |                   |                |                     |                    |                 | R Squared                      | 0.8444   | R Squared                         | 0.8719    |
|                                    |                        |                    |                   |                |                     |                    |                 | No. of Observations            | 7        | No. of Observations               | 7         |
|                                    |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 6        | Degrees of Freedom                | 5         |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 1.70E-13 | X Coefficient(s)                  | 2.04E-13  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 1.28E-14 | Std Err of Coef.                  | 3.50E-14  |
|                                    |                        |                    |                   |                |                     |                    |                 | Low Gradient (<200)            |          |                                   |           |
|                                    |                        |                    |                   |                |                     |                    |                 | k = 7.3 e-14 m/s               |          |                                   |           |
| BARCG01E Density=0.70 Mg/m3        |                        |                    |                   |                |                     |                    |                 | High Gradient                  |          | High Gradient                     |           |
| Test Duration 06/05/92 - 09/08/93  |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 1235.8                             | 41.83                  | 2.940              | 9.74E-11          | 2.33E-12       |                     |                    |                 | Constant                       | 0        | Constant                          | 5.35E-10  |
| 1594.0                             | 9.34                   | 2.920              | 3.08E-11          | 3.3E-12        |                     |                    |                 | Std Err of Y Est               | 5.32E-10 | Std Err of Y Est                  | 5.53E-10  |
| 1906.1                             | 39.49                  | 2.980              | 6.61E-11          | 1.67E-12       |                     |                    |                 | R Squared                      | 0.8068   | R Squared                         | 0.8432    |
| 2553.7                             | 57.98                  | 3.065              | 5.75E-11          | 9.92E-13       |                     |                    |                 | No. of Observations            | 5        | No. of Observations               | 5         |
| 3063.0                             | 97.28                  | 3.195              | 1.32E-10          | 1.36E-12       |                     |                    |                 | Degrees of Freedom             | 4        | Degrees of Freedom                | 3         |
| 3439.5                             | 194.55                 | 3.725              | 6.01E-10          | 3.09E-12       |                     |                    |                 | X Coefficient(s)               | 7.38E-12 | X Coefficient(s)                  | 6.19E-12  |
| 4905.3                             | 19.26                  | 4.685              | 1.20E-10          | 6.23E-12       |                     |                    |                 | Std Err of Coef.               | 5.71E-13 | Std Err of Coef.                  | 1.54E-12  |
| 5073.4                             | 4.67                   | 4.665              | 2.40E-11          | 5.14E-12       |                     |                    |                 |                                |          |                                   |           |
| 7108.6                             | 6.81                   | 5.070              | 5.46E-11          | 8.02E-12       |                     |                    |                 |                                |          |                                   |           |
| 7691.2                             | 391.05                 | 12.305             | 3.78E-09          | 9.67E-12       |                     |                    |                 | Low Gradient                   |          | Low Gradient                      |           |
| 7953.0                             | 620.62                 | 15.315             | 4.06E-09          | 6.54E-12       |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 8192.9                             | 471.79                 | 17.910             | 3.44E-09          | 7.29E-12       |                     |                    |                 | Constant                       | 0        | Constant                          | -6.44E-12 |
| 8673.0                             | 288.33                 | 20.900             | 2.00E-09          | 6.92E-12       |                     |                    |                 | Std Err of Y Est               | 6.71E-11 | Std Err of Y Est                  | 7.09E-11  |
| 9152.8                             | 147.86                 | 22.780             | 1.28E-09          | 8.67E-12       |                     |                    |                 | R Squared                      | 0.8511   | R Squared                         | 0.8520    |
| 10143.1                            | 0.00                   | 23.370             | 1.37E-11          |                |                     |                    |                 | No. of Observations            | 10       | No. of Observations               | 10        |
|                                    |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 9        | Degrees of Freedom                | 8         |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 2.62E-12 | X Coefficient(s)                  | 2.68E-12  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 2.87E-13 | Std Err of Coef.                  | 3.95E-13  |



APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                             | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |          |                                   |           |
|------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|----------|-----------------------------------|-----------|
|                                                |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |          | No Constraints on Regression Line |           |
| BARCG01C<br>Test Duration 27/11/92 to 25/06/92 |                        |                    |                   |                |                     |                    |                 | High Gradient Data             |          |                                   |           |
|                                                |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 907.0                                          | 13.37                  | 2.818              | 1.18E-11          | 8.82E-13       | 2.460               | 1.03E-11           | 7.7E-13         | Constant                       | 0        | Constant                          | -5.4E-12  |
| 1291.5                                         | 13.57                  | 2.808              | 2.25E-11          | 1.66E-12       | 2.545               | 2.35E-11           | 1.73E-12        | Std Err of Y Est               | 1.34E-11 | Std Err of Y Est                  | 1.33E-11  |
| 1627.8                                         | 7.17                   | 2.868              | 4.05E-12          | 5.65E-13       | 2.710               | 2.13E-11           | 2.97E-12        | R Squared                      | 0.9912   | R Squared                         | 0.9919    |
| 2301.3                                         | 19.19                  | 3.588              | 3.89E-11          | 2.03E-12       | 3.585               | 3.91E-11           | 2.04E-12        | No. of Observations            | 15       | No. of Observations               | 15        |
| 2491.3                                         | 38.76                  | 4.013              | 8.3E-11           | 2.14E-12       | 3.950               | 8.61E-11           | 2.22E-12        | Degrees of Freedom             | 14       | Degrees of Freedom                | 13        |
| 2683.5                                         | 97.09                  | 4.993              | 2.07E-10          | 2.13E-12       | 5.130               | 2.3E-10            | 2.37E-12        | X Coefficient(s)               | 2.42E-12 | X Coefficient(s)                  | 2.46E-12  |
| 2923.3                                         | 176.36                 | 7.529              | 4.13E-10          | 2.34E-12       | 7.895               | 4.56E-10           | 2.59E-12        | Std Err of Coef.               | 4.37E-14 | Std Err of Coef.                  | 6.17E-14  |
| 3091.3                                         | 68.22                  | 8.414              | 1.82E-10          | 2.67E-12       | 8.640               | 1.67E-10           | 2.45E-12        |                                |          |                                   |           |
| 3643.3                                         | 9.88                   | 8.961              | 1.88E-11          | 1.9E-12        | 8.980               | 2.04E-11           | 2.06E-12        |                                |          |                                   |           |
| 3667.8                                         | 10.08                  | 8.963              | 2.13E-11          | 2.11E-12       | 9.000               | 2.13E-11           | 2.11E-12        |                                |          |                                   |           |
| 5035.6                                         | 4.46                   | 8.988              | 4.03E-12          | 9.05E-13       | 8.965               | -1.1E-12           | -2.5E-13        |                                |          |                                   |           |
|                                                |                        |                    |                   |                |                     |                    |                 | Low Gradient                   |          |                                   |           |
|                                                |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
|                                                |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | -7.21E-12 |
|                                                |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | 5.84E-12 | Std Err of Y Est                  | 5.52E-12  |
|                                                |                        |                    |                   |                |                     |                    |                 | R Squared                      | 0.6145   | R Squared                         | 0.7133    |
|                                                |                        |                    |                   |                |                     |                    |                 | No. of Observations            | 7        | No. of Observations               | 7         |
|                                                |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 6        | Degrees of Freedom                | 5         |
|                                                |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 1.18E-12 | X Coefficient(s)                  | 1.79E-12  |
|                                                |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 2.04E-13 | Std Err of Coef.                  | 5.09E-13  |
|                                                |                        |                    |                   |                |                     |                    |                 |                                |          |                                   |           |
| BARCG04B<br>Test Duration 03/01/92 to 18/03/92 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 1004.6                                         | 1.63                   | 0.015              | 2.65E-11          | 1.63E-11       |                     |                    |                 | Constant                       | 0        | Constant                          | 2.54E-12  |
| 1267.9                                         | 2.04                   | -0.045             | 2.17E-11          | 1.06E-11       |                     |                    |                 | Std Err of Y Est               | 5.74E-12 | Std Err of Y Est                  | 5.79E-12  |
| 1604.0                                         | 9.58                   | -0.145             | 7.75E-11          | 8.09E-12       |                     |                    |                 | R Squared                      | 0.9931   | R Squared                         | 0.9940    |
| 1723.5                                         | 8.97                   | 0.070              | 7.38E-11          | 8.23E-12       |                     |                    |                 | No. of Observations            | 8        | No. of Observations               | 8         |
| 1896.4                                         | 7.65                   | 0.535              | 5.99E-11          | 7.83E-12       |                     |                    |                 | Degrees of Freedom             | 7        | Degrees of Freedom                | 6         |
| 2392.8                                         | 25.01                  | 1.195              | 2.12E-10          | 8.49E-12       |                     |                    |                 | X Coefficient(s)               | 8.41E-12 | X Coefficient(s)                  | 8.25E-12  |
| 2200.8                                         | 0.00                   | 0.530              | -1.36E-12         |                |                     |                    |                 | Std Err of Coef.               | 1.95E-13 | Std Err of Coef.                  | 2.63E-13  |
| 2224.8                                         | 0.00                   | 0.515              | 2.72E-12          |                |                     |                    |                 |                                |          |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                                                   |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |                                   |  |  |
|-------------------------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|--|--|
| Elapsed Time (Hrs)                                                | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero | No Constraints on Regression Line |  |  |
| BARCG4BB Density=0.79 Mg/m3<br>Test Duration 18/03/92 to 07/09/93 |                        |                    |                   |                |                     |                    |                 |                                |                                   |  |  |
| 1026.8                                                            | 9.53                   | -1.050             | 7.13E-11          | 7.48E-12       | 2.620               | 8.13E-11           | 8.53E-12        |                                |                                   |  |  |
| 1505.7                                                            | 4.86                   | -1.285             | 4.15E-11          | 8.53E-12       | 3.235               | 3.15E-11           | 6.48E-12        |                                |                                   |  |  |
| 1893.3                                                            | 4.86                   | -0.820             | 5.72E-11          | 1.18E-11       | 3.695               | 5.71E-11           | 1.17E-11        |                                |                                   |  |  |
| 2252.2                                                            | 19.07                  | -0.920             | 6.08E-11          | 3.19E-12       | 4.710               | 1.14E-10           | 5.98E-12        |                                |                                   |  |  |
| 2608.6                                                            | 47.66                  | 1.965              | 3.52E-10          | 7.39E-12       | 7.320               | 3.03E-10           | 6.35E-12        |                                |                                   |  |  |
| 3062.5                                                            | 88.94                  | 6.800              | 4.39E-10          | 4.94E-12       | 12.330              | 4.09E-10           | 4.6E-12         |                                |                                   |  |  |
| 3542.8                                                            | 38.51                  | 10.415             | 2.25E-10          | 5.83E-12       | 14.820              | 2.22E-10           | 5.77E-12        |                                |                                   |  |  |
| 3995.2                                                            | 11.25                  | 9.715              | -1E-11            | -9.1E-13       | 15.340              | 4.45E-11           | 3.95E-12        |                                |                                   |  |  |
| 4378.9                                                            | 12.01                  | 13.950             |                   |                | 15.265              | 2.57E-11           | 2.14E-12        |                                |                                   |  |  |
| 5098.7                                                            | 3.43                   | 15.905             | -7.9E-11          | -2.3E-11       | 15.100              | -4.82E-11          | -1.4E-11        |                                |                                   |  |  |
| 5464.9                                                            | 2.86                   | 14.820             | -7.8E-11          | -2.7E-11       | 14.495              | -7.62E-11          | -2.7E-11        |                                |                                   |  |  |
| 6058.8                                                            | 6.58                   | 14.065             | 9.29E-12          | 1.41E-12       | 13.835              | -1.76E-11          | -2.7E-12        |                                |                                   |  |  |
| 6467.4                                                            | 9.06                   | 13.745             | -1.2E-10          | -1.3E-11       | 13.635              | 8.64E-12           | 9.54E-13        |                                |                                   |  |  |
| 7091.2                                                            | 14.59                  | 13.815             | 9.94E-12          | 6.82E-13       | 13.850              | 2.41E-11           | 1.65E-12        |                                |                                   |  |  |
| 7451.9                                                            | 14.39                  | 13.910             | 1.17E-11          | 8.11E-13       | 13.890              | 1.32E-11           | 9.15E-13        |                                |                                   |  |  |
| 8074.9                                                            | 28.69                  | 15.310             | 1.15E-10          | 3.99E-12       | 15.840              | 1.35E-10           | 4.69E-12        |                                |                                   |  |  |
| 8578.9                                                            | 0.00                   | 13.515             | -1.5E-10          |                | 14.475              | -1.18E-10          |                 |                                |                                   |  |  |
| 9257.1                                                            | 128.69                 | 29.370             | 9.82E-10          | 7.63E-12       | 28.735              | 8.88E-10           | 6.9E-12         |                                |                                   |  |  |
|                                                                   |                        |                    |                   |                |                     |                    |                 |                                |                                   |  |  |
| BARCG01D Density=0.80 Mg/m^3<br>Test Duration 13/11/92- 14/12/94  |                        |                    |                   |                |                     |                    |                 |                                |                                   |  |  |
| 10161.7                                                           | -142.59                | -30.410            | -4.19E-10         | 2.94E-12       |                     |                    |                 |                                |                                   |  |  |
| 10569.0                                                           | -236.36                | -35.100            | -7.24E-10         | 3.06E-12       |                     |                    |                 |                                |                                   |  |  |
| 11025.1                                                           | -456.39                | -41.925            | -1.54E-09         | 3.38E-12       |                     |                    |                 |                                |                                   |  |  |
| 11217.0                                                           | -723.26                | -46.315            | -2.30E-09         | 3.18E-12       |                     |                    |                 |                                |                                   |  |  |
| 11409.2                                                           | -704.07                | -52.935            | -2.22E-09         | 3.15E-12       |                     |                    |                 |                                |                                   |  |  |
| 11673.0                                                           | -939.34                | -58.968            | -3.18E-09         | 3.39E-12       |                     |                    |                 |                                |                                   |  |  |
| 14369.5                                                           | -40.40                 | -17.065            | -1.42E-10         | 3.52E-12       |                     |                    |                 |                                |                                   |  |  |
| 14697.0                                                           | -40.40                 | -16.163            | 3.76E-10          | -9.3E-12       |                     |                    |                 |                                |                                   |  |  |
| 15441.0                                                           | 699.56                 | 2.410              | 2.98E-09          | 4.26E-12       |                     |                    |                 |                                |                                   |  |  |
| 15472.0                                                           | 676.99                 | 4.123              | 3.35E-09          | 4.95E-12       |                     |                    |                 |                                |                                   |  |  |
| 16089.0                                                           | 491.94                 | 18.605             | 1.95E-09          | 3.96E-12       |                     |                    |                 |                                |                                   |  |  |
| 16377.0                                                           | 371.76                 | 24.095             | 1.55E-09          | 4.18E-12       |                     |                    |                 |                                |                                   |  |  |
| 17409.0                                                           | 937.65                 | 57.345             | 4.43E-09          | 4.72E-12       |                     |                    |                 |                                |                                   |  |  |
| 18105.5                                                           | 9.98                   | 57.410             | 7.35E-11          | 7.36E-12       |                     |                    |                 |                                |                                   |  |  |
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APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |          |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|----------|-----------------------------------|-----------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |          | No Constraints on Regression Line |           |
| BARCG02D2 Density=0.89 Mg/m3       |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| Test Duration 11/11/92 to 10/03/93 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | 3.81E-10  |
| 1923.0                             | 2.38                   | 0.455              | 2.45E-10          | 1.03E-10       | -0.580              | 4.4E-10            | 1.85E-10        | Std Err of Y Est               | 2.56E-10 | Std Err of Y Est                  | 3.66E-11  |
| 2143.0                             | 4.85                   | 1.645              | 3.28E-10          | 6.75E-11       | 1.195               | 4.17E-10           | 8.59E-11        | R Squared                      |          | R Squared                         | 0.8867    |
| 2445.0                             | 9.90                   | 3.740              | 3.23E-10          | 3.26E-11       | 4.740               | 4.6E-10            | 4.65E-11        | No. of Observations            | 4        | No. of Observations               | 4         |
| 2761.0                             | 19.22                  | 4.820              | 3.18E-10          | 1.65E-11       | 7.065               | 6.13E-10           | 3.19E-11        | Degrees of Freedom             | 3        | Degrees of Freedom                | 2         |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 3.91E-11 | X Coefficient(s)                  | 1.12E-11  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 1.15E-11 | Std Err of Coef.                  | 2.84E-12  |
| BARCG03B Density=0.93 Mg/m3        |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| Test Duration 09/12/91 to 18/03/92 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | 1E-12     |
| 693.3                              | 0.00                   | 0.650              | 2.57E-11          | 0              |                     |                    |                 | Std Err of Y Est               | 4.68E-12 | Std Err of Y Est                  | 5.09E-12  |
| 1387.1                             | 1.51                   | 1.655              | 1.49E-11          | 9.91E-12       |                     |                    |                 | R Squared                      | 0.9921   | R Squared                         | 0.9922    |
| 1391.5                             | 1.51                   | 1.590              | 2.13E-11          | 1.42E-11       |                     |                    |                 | No. of Observations            | 7        | No. of Observations               | 7         |
| 1579.2                             | 6.43                   | 2.025              | 6.91E-11          | 1.07E-11       |                     |                    |                 | Degrees of Freedom             | 6        | Degrees of Freedom                | 5         |
| 1603.2                             | 6.43                   | 2.065              | 6.46E-11          | 1E-11          |                     |                    |                 | X Coefficient(s)               | 1.02E-11 | X Coefficient(s)                  | 1.01E-11  |
| 1868.0                             | 8.28                   | 2.585              | 8.52E-11          | 1.03E-11       |                     |                    |                 | Std Err of Coef.               | 2.08E-13 | Std Err of Coef.                  | 4.01E-13  |
| 1887.9                             | 8.28                   | 2.615              | 7.59E-11          | 9.17E-12       |                     |                    |                 |                                |          |                                   |           |
| 2241.6                             | 16.83                  | 4.195              | 1.75E-10          | 1.04E-11       |                     |                    |                 |                                |          |                                   |           |
| BARCG02E Density=0.96 Mg/m^3       |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| Test Duration 19/11/92 to 05/04/93 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | -5.95E-12 |
| 275.0                              | 1.4                    | 14.93              | 4.66E-11          | 3.33E-11       |                     |                    |                 | Std Err of Y Est               | 5.73E-11 | Std Err of Y Est                  | 6.61E-11  |
| 893.9                              | 1.20                   | 19.925             | 3.52E-11          | 2.93E-11       |                     |                    |                 | R Squared                      | 0.9814   | R Squared                         | 0.9814    |
| 1181.8                             | 0.20                   | 19.940             | 2.95E-12          | 1.48E-11       |                     |                    |                 | No. of Observations            | 5        | No. of Observations               | 5         |
| 1609.0                             | 540.20                 | 23.395             | 1.29E-09          | 2.38E-12       |                     |                    |                 | Degrees of Freedom             | 4        | Degrees of Freedom                | 3         |
| 1710.9                             | 540.20                 | 28.915             | 1.34E-09          | 2.49E-12       |                     |                    |                 | X Coefficient(s)               | 2.42E-12 | X Coefficient(s)                  | 2.43E-12  |
| 2281.5                             | 294.00                 | 36.875             | 6.19E-10          | 2.11E-12       |                     |                    |                 | Std Err of Coef.               | 6.49E-14 | Std Err of Coef.                  | 1.93E-13  |
| 2281.5                             | 294.00                 | 36.875             | 7.59E-10          | 2.58E-12       |                     |                    |                 |                                |          |                                   |           |
| 2521.0                             | 152.00                 | 36.770             | 3.9E-10           | 2.57E-12       |                     |                    |                 |                                |          |                                   |           |
| BARCG02C Density=0.96 Mg/m3        |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| Test Duration 22/06/92 to 11/11/92 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | -1.57E-12 |
| 853.3                              | 2.67                   | 2.915              | 0                 | 0              | -2.405              | 7.89E-12           | 2.95E-12        | Std Err of Y Est               | 4.08E-12 | Std Err of Y Est                  | 4.23E-12  |
| 973.3                              | 2.40                   | 2.895              | -6.5E-12          | -2.7E-12       | -2.350              | 1.11E-11           | 4.63E-12        | R Squared                      | 0.8347   | R Squared                         | 0.8515    |
| 1122.5                             | 9.22                   | 2.900              | 1.31E-12          | 1.42E-13       | -2.315              | 5.78E-12           | 6.27E-13        | No. of Observations            | 7        | No. of Observations               | 7         |
| 1285.3                             | 18.34                  | 2.905              | 1.2E-12           | 6.53E-14       | -2.280              | 5.99E-12           | 3.26E-13        | Degrees of Freedom             | 6        | Degrees of Freedom                | 5         |
| 1722.1                             | 46.27                  | 3.025              | 1.1E-11           | 2.38E-13       | -2.210              | 8.02E-12           | 1.73E-13        | X Coefficient(s)               | 2.55E-13 | X Coefficient(s)                  | 2.81E-13  |
| 2484.8                             | 92.17                  | 3.510              | 2.43E-11          | 2.64E-13       | -2.070              | 2.64E-11           | 2.87E-13        | Std Err of Coef.               | 3.86E-14 | Std Err of Coef.                  | 5.24E-14  |
| 2989.7                             | 9.03                   | 3.635              | 8.15E-12          | 9.02E-13       | -2.185              | 4.87E-12           | 5.39E-13        |                                |          |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                                                   |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |                                   |
|-------------------------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|
| Elapsed Time (Hrs)                                                | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero | No Constraints on Regression Line |
| BARCG02BB Density=0.99 Mg/m3<br>Test Duration 17/11/92 to 21/3/94 |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
| 358.2                                                             | 4.06                   | -0.970             | -2.62E-10         |                |                     |                    |                 | Constant                       | 0                                 |
| 1149.8                                                            | 90.45                  | -0.860             | -8.07E-11         |                |                     |                    |                 | Std Err of Y Est               | 2.9E-10                           |
| 1415.5                                                            | 2171.03                | 2.555              | 8.44E-10          | 3.89E-13       |                     |                    |                 | R Squared                      | 0.6960                            |
| 1559.1                                                            | 1689.75                | 4.005              | 6.33E-10          | 3.74E-13       |                     |                    |                 | No. of Observations            | 23                                |
| 1724.8                                                            | 955.25                 | 4.715              | 2.60E-10          | 2.72E-13       |                     |                    |                 | Degrees of Freedom             | 22                                |
| 1988.8                                                            | 642.79                 | 5.130              | 9.58E-11          | 1.49E-13       |                     |                    |                 | X Coefficient(s)               | 5.02E-13                          |
| 2396.8                                                            | 697.97                 | 5.935              | 1.23E-10          | 1.77E-13       |                     |                    |                 | Std Err of Coef.               | 6.82E-14                          |
| 2757.0                                                            | 361.16                 | 5.930              | -3.17E-12         |                |                     |                    |                 |                                |                                   |
| 3068.8                                                            | 353.05                 | 5.810              | -3.38E-11         |                |                     |                    |                 |                                |                                   |
| 3598.9                                                            | 151.27                 | 5.180              | -1.14E-10         |                |                     |                    |                 |                                |                                   |
| 4722.3                                                            | 0.00                   | 0.650              | -2.70E-10         |                |                     |                    |                 |                                |                                   |
| 5100.2                                                            | 0.00                   | -3.065             | -3.62E-10         |                |                     |                    |                 |                                |                                   |
| 5363.4                                                            | 657.39                 | -3.355             | 1.23E-10          | 1.87E-13       |                     |                    |                 |                                |                                   |
| 5868.1                                                            | 523.48                 | -4.170             | -8.87E-11         |                |                     |                    |                 |                                |                                   |
| 6204.1                                                            | 1525.81                | -0.005             | 7.66E-10          | 5.02E-13       |                     |                    |                 |                                |                                   |
| 7043.8                                                            | 835.95                 | 4.715              | 2.61E-10          | 3.13E-13       |                     |                    |                 |                                |                                   |
| 8603.0                                                            | -118.39                | 6.830              | -3.21E-10         | 2.71E-12       |                     |                    |                 |                                |                                   |
| 9467.4                                                            | -59.79                 | 4.578              | -2.05E-10         | 3.43E-12       |                     |                    |                 |                                |                                   |
| 10211.6                                                           | -262.74                | -0.162             | -3.57E-10         | 1.36E-12       |                     |                    |                 |                                |                                   |
| 10570.9                                                           | -395.93                | -3.087             | -4.52E-10         | 1.14E-12       |                     |                    |                 |                                |                                   |
| 11075.1                                                           | -764.53                | -6.987             | -7.86E-10         | 1.03E-12       |                     |                    |                 |                                |                                   |
| 11459.1                                                           | -1179.43               | -12.782            | -1.09E-09         | 9.24E-13       |                     |                    |                 |                                |                                   |
| 11722.9                                                           | -1561.26               | -18.382            | -1.39E-09         | 8.91E-13       |                     |                    |                 |                                |                                   |
| BARCG02D Density=1.01 Mg/m3<br>Test Duration 12/06/92 to 26/10/92 |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
| 163.0                                                             | 1.8                    | 3.345              | -1.77E-10         | -1E-10         | -9.250              | -1.52E-10          | -8.6E-11        | Constant                       | -1.98E-10                         |
| 259.0                                                             | 1.6                    | 2.825              | -1.90E-10         | -1.2E-10       | -9.795              | -2.63E-10          | -1.7E-10        | Std Err of Y Est               | 5.79E-11                          |
| 474.5                                                             | 2.1                    | 4.505              | -2.70E-10         | -1.3E-10       | -8.275              | -2.96E-10          | -1.4E-10        | R Squared                      | 0.1577                            |
| 763.0                                                             | 2.6                    | 2.685              | -2.32E-10         | -8.9E-11       | -10.465             | -3.22E-10          | -1.2E-10        | No. of Observations            | 22                                |
| 1244.4                                                            | 5.1                    | 2.540              | -9.44E-11         | -1.9E-11       | -10.855             | -1.17E-10          | -2.3E-11        | Degrees of Freedom             | 20                                |
| 1412.5                                                            | 5.2                    | 1.950              | -1.54E-10         | -3E-11         | -11.390             | -1.22E-10          | -2.3E-11        |                                |                                   |
| 1585.2                                                            | 9.6                    | 1.265              | -1.79E-10         | -1.9E-11       | -12.125             | -1.35E-10          | -1.4E-11        |                                |                                   |
| 1820.4                                                            | 10.0                   | 0.270              | -1.68E-10         | -1.7E-11       | -13.185             | -1.84E-10          | -1.8E-11        |                                |                                   |
| 1916.4                                                            | 10.2                   | -0.195             | -1.95E-10         | -1.9E-11       | -13.560             | -1.42E-10          | -1.4E-11        |                                |                                   |
| 2180.6                                                            | 18.7                   | -1.370             | -1.70E-10         | -9.1E-12       | -14.820             | -1.87E-10          | -1E-11          |                                |                                   |
| 2754.8                                                            | 61.0                   | -3.495             | -1.43E-10         | -2.3E-12       | -16.445             | -9.76E-11          | -1.6E-12        | X Coefficient(s)               | 1.46E-12                          |
|                                                                   |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 7.54E-13                          |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                   | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES         |                                    |
|--------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|------------------------------------|------------------------------------|
|                                      |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero     | No Constraints on Regression Line  |
| <b>BARCG3A</b>                       |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| Density = 1.01 Mg/m <sup>3</sup>     |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| Test Duration 14/02/91 to 03/06/91   |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| 764.17                               | 20.8                   | 4.930              | 4.91E-10          | 2.36E-11       |                     |                    |                 | Regression Output:                 | Regression Output:                 |
| 1004.33                              | 21.4                   | 7.705              | 4.51E-10          | 2.11E-11       |                     |                    |                 | Constant                           | Constant                           |
| 1176.25                              | 23.3                   | 9.455              | 4.45E-10          | 1.91E-11       |                     |                    |                 | Std Err of Y Est                   | Std Err of Y Est                   |
| 1316.25                              | 22.5                   | 10.795             | 3.15E-10          | 1.4E-11        |                     |                    |                 | R Squared                          | R Squared                          |
| 1604.25                              | 21.4                   | 12.655             | 2.23E-10          | 1.05E-11       |                     |                    |                 | No. of Observations                | No. of Observations                |
| 1940.17                              | 20.4                   | 14.265             | 1.91E-10          | 9.38E-12       |                     |                    |                 | Degrees of Freedom                 | Degrees of Freedom                 |
| 2207.83                              | 15.0                   | 14.620             | 1.95E-10          | 1.3E-11        |                     |                    |                 | X Coefficient(s)                   | X Coefficient(s)                   |
| 2548.50                              | 14.3                   | 16.295             | 2.27E-10          | 1.59E-11       |                     |                    |                 | Std Err of Coef.                   | Std Err of Coef.                   |
|                                      |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| <b>SHC75</b>                         |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| Density=1.90/1.03 Mg/m <sup>3</sup>  |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| Test Duration 15/10/84 to 21/01/95   |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| 848                                  | 666                    | 0.15               | 5.1E-10           | 7.70E-13       |                     |                    |                 | Regression Output:                 | Regression Output:                 |
| 1304                                 | 3331                   | 3.155              | 2.0E-09           | 5.91E-13       |                     |                    |                 | Constant                           | Constant                           |
| 1832                                 | 4997                   | 5.505              | 2.4E-09           | 4.74E-13       |                     |                    |                 | Std Err of Y Est                   | Std Err of Y Est                   |
| 2360                                 | 8328                   | 8.01               | 3.9E-09           | 4.67E-13       |                     |                    |                 | R Squared                          | R Squared                          |
| 2696                                 | 16656                  | 9.01               | 7.5E-09           | 4.51E-13       |                     |                    |                 | No. of Observations                | No. of Observations                |
| 2984                                 | 16656                  | 10.12              | 7.6E-09           | 4.53E-13       |                     |                    |                 | Degrees of Freedom                 | Degrees of Freedom                 |
| 3056                                 | 8328                   | 10.52              | 2.9E-09           | 3.47E-13       |                     |                    |                 | X Coefficient(s)                   | X Coefficient(s)                   |
| 3152                                 | 500                    | 10.58              | 7.6E-10           | 1.51E-12       |                     |                    |                 | Std Err of Coef.                   | Std Err of Coef.                   |
|                                      |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| <b>RBML1_P2</b>                      |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| Density =1.49/1.04 Mg/m <sup>3</sup> |                        |                    |                   |                |                     |                    |                 |                                    |                                    |
| 6948                                 | 242.9                  | 0.070              | 1.4E-10           | 5.95E-13       |                     |                    |                 | Regression Output:                 | Regression Output:                 |
| 7020                                 | 505.6                  | 0.870              | 3.3E-10           | 6.53E-13       |                     |                    |                 | Constant                           | Constant                           |
| 7116                                 | 470.8                  | 0.950              | 3.6E-10           | 7.69E-13       |                     |                    |                 | Std Err of Y Est                   | Std Err of Y Est                   |
| 7308                                 | 455.0                  | 1.170              | 4.3E-10           | 9.53E-13       |                     |                    |                 | R Squared                          | R Squared                          |
| 7477                                 | 439.1                  | 1.330              | 1.4E-10           | 3.30E-13       |                     |                    |                 | No. of Observations                | No. of Observations                |
| 7790                                 | 714.6                  | 1.920              | 5.9E-10           | 8.20E-13       |                     |                    |                 | Degrees of Freedom                 | Degrees of Freedom                 |
| 7958                                 | 1034.3                 | 2.270              | 6.9E-10           | 6.65E-13       |                     |                    |                 | X Coefficient(s)                   | X Coefficient(s)                   |
| 8126                                 | 1024.8                 | 2.610              | 7.0E-10           | 6.84E-13       |                     |                    |                 | Std Err of Coef.                   | Std Err of Coef.                   |
| 8295                                 | 1015.3                 | 2.960              | 6.7E-10           | 6.64E-13       |                     |                    |                 |                                    |                                    |
| 8482                                 | 958.3                  | 3.370              | 6.5E-10           | 6.81E-13       |                     |                    |                 | Calculated i Incpt.                | Calculated i Incpt.                |
| 8819                                 | 926.7                  | 3.945              | 6.2E-10           | 6.65E-13       |                     |                    |                 | Max i Incpt. (at 1 Std.Devn.)      | Max i Incpt. (at 1 Std.Devn.)      |
| 8988                                 | 910.8                  | 4.215              | 5.6E-10           | 6.13E-13       |                     |                    |                 | Minimum i Incpt. (at 1 Std. Devn.) | Minimum i Incpt. (at 1 Std. Devn.) |
| 9206                                 | 885.5                  | 4.550              | 5.7E-10           | 6.43E-13       |                     |                    |                 |                                    |                                    |
| 9469                                 | 929.8                  | 5.010              | 6.0E-10           | 6.46E-13       |                     |                    |                 |                                    |                                    |
| 9613                                 | 898.2                  | 5.215              | 5.3E-10           | 5.93E-13       |                     |                    |                 |                                    |                                    |
| 10312                                | 1683.3                 | 6.370              | 8.6E-10           | 5.13E-13       |                     |                    |                 |                                    |                                    |

## APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                       |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |          |                                   |           |
|---------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|----------|-----------------------------------|-----------|
| Elapsed Time (Hrs)                    | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero |          | No Constraints on Regression Line |           |
| BARCG01BB Density=1.06 Mg/m3          |                        |                    |                   |                |                     |                    |                 | Hydraulic Gradient >20         |          | Hydraulic Gradient >20            |           |
| Testing Duration 18/03/92 to 26/10/92 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 1028.9                                | 8.30                   | -1.185             | -3.6E-11          | -4.4E-12       | 0.665               | 3.94E-12           | 4.74E-13        | Constant                       | 0        | Constant                          | 4.46E-12  |
| 1321.6                                | 16.12                  | -1.650             | -7.3E-11          | -4.5E-12       | 0.745               | 4.92E-12           | 3.05E-13        | Std Err of Y Est               | 5.33E-12 | Std Err of Y Est                  | 6.12E-12  |
| 1495.6                                | 16.04                  | -1.935             | -3.5E-11          | -2.2E-12       | 0.925               | 5.41E-12           | 3.38E-13        | R Squared                      | 0.9449   | R Squared                         | 0.9516    |
| 1945.4                                | 23.54                  | -2.285             | -3.9E-11          | -1.7E-12       | 1.050               | 2.6E-11            | 1.11E-12        | No. of Observations            | 4        | No. of Observations               | 4         |
| 2429.4                                | 41.02                  | -2.430             | -1.6E-11          | -3.8E-13       | 1.730               | 4.63E-11           | 1.13E-12        | Degrees of Freedom             | 3        | Degrees of Freedom                | 2         |
| 2639.7                                | 69.83                  | -2.280             | 5.1E-11           | 7.31E-13       | 1.970               | 6.6E-11            | 9.45E-13        |                                |          |                                   |           |
| 2972.6                                | 69.83                  | -2.670             | -2.2E-11          | -3.2E-13       | 2.555               | 7.77E-11           | 1.11E-12        | X Coefficient(s)               | 1.05E-12 | X Coefficient(s)                  | 9.70E-13  |
|                                       |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 4.87E-14 | Std Err of Coef.                  | 1.55E-13  |
|                                       |                        |                    |                   |                |                     |                    |                 | Hydraulic Gradient <20         |          | Hydraulic Gradient <20            |           |
|                                       |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
|                                       |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | 2.63E-12  |
|                                       |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | 8.84E-13 | Std Err of Y Est                  | 3.62E-13  |
|                                       |                        |                    |                   |                |                     |                    |                 | R Squared                      | -0.3811  | R Squared                         | 0.8842    |
|                                       |                        |                    |                   |                |                     |                    |                 | No. of Observations            | 3        | No. of Observations               | 3         |
|                                       |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 2        | Degrees of Freedom                | 1         |
|                                       |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 3.39E-13 | X Coefficient(s)                  | 1.57E-13  |
|                                       |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 3.65E-14 | Std Err of Coef.                  | 5.70E-14  |
| BARCG4D2 Density=1.06 Mg/m3           |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| Test Duration 04/10/93 to 07/07/94    |                        |                    |                   |                |                     |                    |                 | Constant                       | 0        | Constant                          | -8.51E-12 |
| 199.1                                 | 789.54                 | 1.785              | 4.82E-10          | 6.11E-13       | 0.895               | 4.18E-10           | 5.29E-13        | Std Err of Y Est               | 6.96E-11 | Std Err of Y Est                  | 7.26E-11  |
| 270.8                                 | 828.63                 | 2.625              | 4.04E-10          | 4.88E-13       | 1.735               | 6.86E-10           | 8.28E-13        | R Squared                      | 0.8899   | R Squared                         | 0.8903    |
| 358.7                                 | 733.23                 | 3.550              | 4.1E-10           | 5.59E-13       | 2.935               | 5.32E-10           | 7.25E-13        | No. of Observations            | 13       | No. of Observations               | 13        |
| 502.7                                 | 668.79                 | 4.680              | 3.07E-10          | 4.59E-13       | 4.215               | 2.87E-10           | 4.3E-13         | Degrees of Freedom             | 12       | Degrees of Freedom                | 11        |
| 910.5                                 | 649.00                 | 6.650              | 1.52E-10          | 2.34E-13       | 3.755               | 2.08E-10           | 3.2E-13         |                                |          |                                   |           |
| 1102.6                                | 972.27                 | 7.810              | 4.42E-10          | 4.55E-13       | 3.945               | 3.38E-10           | 3.47E-13        | X Coefficient(s)               | 5.01E-13 | X Coefficient(s)                  | 5.10E-13  |
| 1414.6                                | 1000.24                | 12.905             | 4.47E-10          | 4.47E-13       | 8.145               | 5.8E-10            | 5.8E-13         | Std Err of Coef.               | 2.51E-14 | Std Err of Coef.                  | 5.40E-14  |
| 1510.4                                | 1206.69                | 14.535             | 6.85E-10          | 5.68E-13       | 9.470               | 6.17E-10           | 5.11E-13        |                                |          |                                   |           |
| 1702.6                                | 1206.61                | 17.660             | 6.33E-10          | 5.25E-13       | 11.450              | 4.01E-10           | 3.33E-13        |                                |          |                                   |           |
| 2279.3                                | 282.74                 | 18.345             | 1.17E-10          | 4.13E-13       | 14.780              | 2.62E-10           | 9.26E-13        |                                |          |                                   |           |
| 2519.3                                | 124.80                 | 18.975             | 4.96E-11          | 3.97E-13       | 16.550              | 3.04E-11           | 2.44E-13        |                                |          |                                   |           |
| 2854.9                                | 133.55                 | 19.480             | 8.13E-11          | 6.09E-13       | 19.070              | 2.21E-10           | 1.66E-12        |                                |          |                                   |           |
| 3358.6                                | 170.80                 | 20.045             | 1.54E-10          | 9.02E-13       | 24.545              |                    |                 |                                |          |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                    |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| BARCG4A                            |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 03/07/93 to 21/12/93 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | -1.17E-10 |
| 380.1                              | -47.58                 | 1.065              | -5.07E-10         | 1.07E-11       | -3.405              | -5.86E-10          | 1.23E-11        | Std Err of Y Est               | 3.12E-10  | Std Err of Y Est                  | 3.04E-10  |
| 1491.5                             | 10.35                  | 1.795              |                   | 0              | 3.725               | 9.74E-11           | 9.41E-12        | R Squared                      | 0.9702    | R Squared                         | 0.9729    |
| 235.8                              | 2.42                   | 2.435              | 5.51E-11          | 2.28E-11       | -1.155              |                    | 0               | No. of Observations            | 24        | No. of Observations               | 24        |
| 958.1                              | 3.38                   | 3.115              | 7.60E-11          | 2.25E-11       | 0.630               | 3.41E-11           | 1.01E-11        | Degrees of Freedom             | 23        | Degrees of Freedom                | 22        |
| 2305.0                             | 19.73                  | 2.030              | 5.01E-11          | 2.54E-12       | 6.195               | 1.23E-10           | 6.23E-12        |                                |           |                                   |           |
| 2635.3                             | 6.09                   | 3.155              | 1.51E-10          | 2.48E-11       | 8.125               |                    | 0               | X Coefficient(s)               | 1.2E-11   | X Coefficient(s)                  | 1.24E-11  |
| 3264.5                             | 104.64                 | 13.670             | 8.83E-10          | 8.44E-12       | 18.730              | 9.75E-10           | 9.31E-12        | Std Err of Coef.               | 3.54E-13  | Std Err of Coef.                  |           |
| 3338.6                             | 72.92                  | 14.450             | 5.52E-10          | 7.57E-12       | 18.175              | 5.30E-10           | 7.27E-12        |                                |           |                                   |           |
| 3619.3                             | 71.57                  | 18.540             | 7.10E-10          | 9.92E-12       | 22.775              | 8.49E-10           | 1.19E-11        |                                |           |                                   |           |
| 3748.5                             | 418.28                 | 21.139             | 4.73E-09          | 1.13E-11       | 25.925              | 5.55E-09           | 1.33E-11        |                                |           |                                   |           |
| 3835.3                             | 362.36                 | 27.199             | 4.27E-09          | 1.18E-11       | 29.105              | 5.11E-09           | 1.41E-11        |                                |           |                                   |           |
| 3979.5                             | 114.02                 | 30.054             | 1.57E-09          | 1.38E-11       | 32.650              | 1.46E-09           | 1.28E-11        |                                |           |                                   |           |
| 4108.0                             | 214.70                 | 32.774             | 2.08E-09          | 9.7E-12        | 35.770              | 1.91E-09           | 8.91E-12        |                                |           |                                   |           |
| 380.1                              | 47.58                  | 1.065              | 5.07E-10          | 1.07E-11       | -3.405              | 5.86E-10           | 1.23E-11        |                                |           |                                   |           |
| S50MC11                            |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
|                                    |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | -2.32E-10 |
| 1100                               | 1583                   | 0.1                | 6.9E-10           | 4.38E-13       |                     |                    |                 | Std Err of Y Est               | 4.86E-10  | Std Err of Y Est                  | 5.31E-10  |
| 1500                               | 3166                   | 3.86               | 2.1E-09           | 6.48E-13       |                     |                    |                 | R Squared                      | 0.9888789 | R Squared                         | 0.9900423 |
| 2075                               | 4749                   | 6.5                | 4.0E-09           | 8.34E-13       |                     |                    |                 | No. of Observations            | 5         | No. of Observations               | 5         |
| 2600                               | 7914                   | 9.545              | 6.8E-09           | 8.64E-13       |                     |                    |                 | Degrees of Freedom             | 4         | Degrees of Freedom                | 3         |
| 2950                               | 15829                  | 11.435             | 1.2E-08           | 7.77E-13       |                     |                    |                 |                                |           |                                   |           |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 7.9E-13   | X Coefficient(s)                  | 8.12E-13  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 2.6E-14   | Std Err of Coef.                  | 4.7E-14   |
| URL115                             |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 14/05/90 to 15/07/91 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | 4.09E-11  |
| 3717.5                             | 601                    | 5.020              | 8.21E-10          | 1.37E-12       | 1.535               | 7.16E-10           | 1.19E-12        | Std Err of Y Est               | 1.56E-10  | Std Err of Y Est                  | 1.56E-10  |
| 5589.3                             | 573                    | 9.955              | 9.52E-10          | 1.68E-12       | 5.460               | 7.09E-10           | 1.24E-12        | R Squared                      | 0.9752441 | R Squared                         | 0.976283  |
| 6075.8                             | 696                    | 11.760             | 1.23E-09          | 1.77E-12       | 6.910               | 1.09E-09           | 1.56E-12        | No. of Observations            | 23        | No. of Observations               | 23        |
| 6598.3                             | 1217                   | 14.735             | 1.84E-09          | 1.51E-12       | 9.410               | 1.74E-09           | 1.43E-12        | Degrees of Freedom             | 22        | Degrees of Freedom                | 21        |
| 6915.3                             | 2720                   | 18.185             | 3.72E-09          | 1.37E-12       | 12.450              | 3.33E-09           | 1.23E-12        |                                |           |                                   |           |
| 7269.8                             | 430                    | 18.940             | 7.84E-10          | 1.82E-12       | 12.945              | 4.58E-10           | 1.07E-12        |                                |           |                                   |           |
| 7389.5                             | 258                    | 19.080             | 4.57E-10          | 1.77E-12       | 13.030              | 3.37E-10           | 1.31E-12        |                                |           |                                   |           |
| 7462.9                             | 229                    | 19.185             | 4.97E-10          | 2.17E-12       | 13.045              | 7.1E-11            | 3.1E-13         | X Coefficient(s)               | 1.35E-12  | X Coefficient(s)                  | 1.32E-12  |
| 7917.1                             | 143                    | 19.615             | 3.45E-10          | 2.41E-12       | 13.205              | 1.63E-10           | 1.14E-12        | Std Err of Coef.               | 3.42E-14  | Std Err of Coef.                  | 4.48E-14  |
| 8733.6                             | 109                    | 20.040             | 1.3E-10           | 1.19E-12       | 13.200              | 5.07E-11           | 4.65E-13        |                                |           |                                   |           |
| 9597.7                             | 57                     | 20.255             | 1.15E-10          | 2.01E-12       | 12.905              | -8.16E-11          | -1.4E-12        |                                |           |                                   |           |
| 10245.5                            | 36                     | 20.330             | 6.55E-11          | 1.83E-12       | 12.955              |                    |                 |                                |           |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |                                   |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero | No Constraints on Regression Line |
| MICG09A Density=1.13 Mg/m3         |                        |                    |                   |                |                     |                    |                 |                                |                                   |
| Test Duration 06/08/91 to 09/11/92 |                        |                    |                   |                |                     |                    |                 |                                |                                   |
| 4848.2                             | 168.56                 | 5.125              | 2.73E-10          | 1.62E-12       |                     |                    |                 |                                |                                   |
| 5207.6                             | 113.88                 | 5.240              | 1.73E-10          | 1.52E-12       |                     |                    |                 |                                |                                   |
| 6172                               | 92                     | 5.25               | 1.32E-10          | 1.43E-12       |                     |                    |                 |                                |                                   |
| 6649.9                             | 48.13                  | 5.290              | 8.17E-11          | 1.7E-12        |                     |                    |                 |                                |                                   |
| 7489.7                             | 64.17                  | 5.635              | 1.02E-10          | 1.58E-12       |                     |                    |                 |                                |                                   |
| 8020.6                             | 29.82                  | 5.675              | 3.76E-11          | 1.26E-12       |                     |                    |                 |                                |                                   |
| 8529.9                             | 29.43                  | 5.935              | 6.78E-11          | 2.3E-12        |                     |                    |                 |                                |                                   |
| 9123.6                             | 19.49                  | 5.860              | 3.08E-11          | 1.58E-12       |                     |                    |                 |                                |                                   |
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
|                                    |                        |                    |                   |                |                     |                    |                 | Constant                       | Constant                          |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
|                                    |                        |                    |                   |                |                     |                    |                 | R Squared                      | R Squared                         |
|                                    |                        |                    |                   |                |                     |                    |                 | No. of Observations            | No. of Observations               |
|                                    |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |
|                                    |                        |                    |                   |                |                     |                    |                 | 1.57E-12                       | 1.55E-12                          |
|                                    |                        |                    |                   |                |                     |                    |                 | 4.56E-14                       | 8.68E-14                          |
| BARCG05E Density=1.15 Mg/m3        |                        |                    |                   |                |                     |                    |                 |                                |                                   |
| Test Duration 22/04/93 to 05/08/94 |                        |                    |                   |                |                     |                    |                 |                                |                                   |
| 1356.6                             | 0.88                   | 3.185              | -4.5E-11          | -5.2E-11       |                     |                    |                 |                                |                                   |
| 1453.4                             | 0.44                   | 3.160              | -1E-11            | -2.3E-11       |                     |                    |                 |                                |                                   |
| 1838.1                             | 2.19                   | 2.860              | -5E-11            | -2.3E-11       |                     |                    |                 |                                |                                   |
| 2131.0                             | 1.84                   | 2.625              | -3.6E-11          | -1.9E-11       |                     |                    |                 |                                |                                   |
| 3740.6                             | 8.95                   | 1.055              | -5.1E-11          | -5.6E-12       |                     |                    |                 |                                |                                   |
| 2989.8                             | 4.04                   | 1.965              | 8.11E-12          | 2.01E-12       |                     |                    |                 |                                |                                   |
| 4140.5                             | 15.61                  | 0.690              | 2.55E-11          | 1.63E-12       |                     |                    |                 |                                |                                   |
| 4644.9                             | 41.84                  | 2.795              | 6.06E-11          | 1.45E-12       |                     |                    |                 |                                |                                   |
| 4812.4                             | 43.68                  | 2.800              | 2.97E-11          | 6.8E-13        |                     |                    |                 |                                |                                   |
| 5052.3                             | 87.63                  | 5.170              | 3.59E-10          | 4.1E-12        |                     |                    |                 |                                |                                   |
| 6253.1                             | 173.68                 | 11.685             | 1.37E-10          | 7.86E-13       |                     |                    |                 |                                |                                   |
| 6828.4                             | 268.42                 | 14.840             | 2.3E-10           | 8.59E-13       |                     |                    |                 |                                |                                   |
| 7044.2                             | 249.45                 | 16.155             | 2.4E-10           | 9.61E-13       |                     |                    |                 |                                |                                   |
| 7188.2                             | 208.36                 | 17.120             | 2.74E-10          | 1.31E-12       |                     |                    |                 |                                |                                   |
| 7404.2                             | 471.13                 | 18.775             | 4.82E-10          | 1.02E-12       |                     |                    |                 |                                |                                   |
| 7506.9                             | 582.06                 | 20.100             | 4.93E-10          | 8.46E-13       |                     |                    |                 |                                |                                   |
| 7742.7                             | 1288.73                | 25.270             | 8.6E-10           | 6.67E-13       |                     |                    |                 |                                |                                   |
| 8107.8                             | 1272.30                | 31.555             | 8.92E-10          | 7.01E-13       |                     |                    |                 |                                |                                   |
| 8268.1                             | 1292.84                | 35.140             | 8.71E-10          | 6.74E-13       |                     |                    |                 |                                |                                   |
| 8774.1                             | 684.77                 | 40.085             | 4.75E-10          | 6.93E-13       |                     |                    |                 |                                |                                   |
| 10717.6                            | 832.68                 | 32.405             | 7.36E-10          | 8.84E-13       |                     |                    |                 |                                |                                   |
| 10795.1                            | 1034.18                | 33.780             | 6.86E-10          | 6.63E-13       |                     |                    |                 |                                |                                   |
| 9115.9                             | -193.98                | 39.150             | -2.8E-10          | 1.46E-12       |                     |                    |                 |                                |                                   |
| 9572.6                             | -315.00                | 38.425             | -1.7E-10          | 5.41E-13       |                     |                    |                 |                                |                                   |
| 9788.6                             | -387.08                | 35.885             | -6.2E-10          | 1.6E-12        |                     |                    |                 |                                |                                   |
| 9932.1                             | -358.14                | 35.135             | -3.7E-10          | 1.02E-12       |                     |                    |                 |                                |                                   |
| 10118.9                            | -358.32                | 33.860             | -3.9E-10          | 1.08E-12       |                     |                    |                 |                                |                                   |
| 10364.6                            | -1369.03               | 31.520             | -1.4E-09          | 9.86E-13       |                     |                    |                 |                                |                                   |
| 10428.1                            | -1346.43               | 29.670             | -1E-09            | 7.78E-13       |                     |                    |                 |                                |                                   |
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
|                                    |                        |                    |                   |                |                     |                    |                 | Constant                       | Constant                          |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | Std Err of Y Est                  |
|                                    |                        |                    |                   |                |                     |                    |                 | R Squared                      | R Squared                         |
|                                    |                        |                    |                   |                |                     |                    |                 | No. of Observations            | No. of Observations               |
|                                    |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | Degrees of Freedom                |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | X Coefficient(s)                  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | Std Err of Coef.                  |
|                                    |                        |                    |                   |                |                     |                    |                 | 0.00                           | -3.31E-11                         |
|                                    |                        |                    |                   |                |                     |                    |                 | 1.23E-10                       | 1.21E-10                          |
|                                    |                        |                    |                   |                |                     |                    |                 | 0.9461                         | 0.9500                            |
|                                    |                        |                    |                   |                |                     |                    |                 | 29                             | 29                                |
|                                    |                        |                    |                   |                |                     |                    |                 | 28                             | 27                                |
|                                    |                        |                    |                   |                |                     |                    |                 | 7.91E-13                       | 8.03E-13                          |
|                                    |                        |                    |                   |                |                     |                    |                 | 3.52E-14                       | 3.54E-14                          |



APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| URL Density=1.17 Mg/m3             |                        |                    |                   |                |                     |                    |                 |                                |           |                                   |           |
| Test Duration 08/04/94 to 30/09/94 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 767.1                              | 3850.80                | 9.315              | 4.21E-09          | 1.09E-12       |                     |                    |                 | Constant                       | 0         | Constant                          | 6.37E-11  |
| 910.8                              | 3872.93                | 10.990             | 4.03E-09          | 1.04E-12       |                     |                    |                 | Std Err of Y Est               | 8.9E-11   | Std Err of Y Est                  | 7.96E-11  |
| 1295.3                             | 1902.69                | 13.290             | 2.03E-09          | 1.07E-12       |                     |                    |                 | R Squared                      | 0.9967    | R Squared                         | 0.9976    |
| 1440.3                             | 1806.76                | 14.120             | 1.98E-09          | 1.09E-12       |                     |                    |                 | No. of Observations            | 10        | No. of Observations               | 10        |
| 1630.6                             | 829.01                 | 14.700             | 1.06E-09          | 1.28E-12       |                     |                    |                 | Degrees of Freedom             | 9         | Degrees of Freedom                | 9         |
| 1966.6                             | 876.98                 | 15.740             | 1.05E-09          | 1.19E-12       |                     |                    |                 |                                |           |                                   |           |
| 2590.6                             | 338.29                 | 17.000             | 3.45E-10          | 1.02E-12       |                     |                    |                 | X Coefficient(s)               | 1.08E-12  | X Coefficient(s)                  | 1.05E-12  |
| 2830.8                             | 149.45                 | 17.120             | 1.83E-10          | 1.22E-12       |                     |                    |                 | Std Err of Coef.               | 1.44E-14  | Std Err of Coef.                  | 1.81E-14  |
| 3358.6                             | 81.48                  | 17.370             | 1.44E-10          | 1.77E-12       |                     |                    |                 |                                |           |                                   |           |
| 4198.6                             | 41.88                  | 17.590             | 8.47E-11          | 2.02E-12       |                     |                    |                 |                                |           |                                   |           |
| BARCG07E Density=1.18 Mg/m3        |                        |                    |                   |                |                     |                    |                 |                                |           |                                   |           |
| Test Duration 14/10/93 to 25/07/94 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 428.5                              | 0.57                   | 0.010              | -2.85E-10         |                | -1.840              | -3.06E-10          |                 | Constant                       | 0         | Constant                          | -2.46E-10 |
| 668.5                              | 0.71                   | -1.135             | -2.95E-10         |                | -3.670              | -4.46E-10          |                 | Std Err of Y Est               | 2.62E-10  | Std Err of Y Est                  | 8.36E-11  |
| 788.8                              | 0.85                   | -1.720             | -3.01E-10         |                | -4.290              | -3.19E-10          |                 | R Squared                      | 0.2233846 | R Squared                         | 0.9234605 |
| 1004.8                             | 2.08                   | -2.725             | -3.00E-10         |                | -5.095              | -3.17E-10          |                 | No. of Observations            | 36        | No. of Observations               | 36        |
| 1268.4                             | 1.94                   | -2.775             | -1.11E-11         |                | -5.955              | -1.26E-10          |                 | Degrees of Freedom             | 35        | Degrees of Freedom                | 34        |
| 1628.3                             | 4.91                   | -3.995             | -2.57E-10         |                | -7.365              | -2.90E-10          |                 | X Coefficient(s)               | 4.55E-13  | X Coefficient(s)                  | 4.35E-13  |
| 2109.0                             | 5.24                   | -5.810             | -2.41E-10         |                | -9.790              | -2.53E-10          |                 | Std Err of Coef.               | 6.73E-14  | Std Err of Coef.                  | 2.15E-14  |
| 2541.2                             | 12.09                  | -7.310             | -2.21E-10         |                | -11.615             | -2.39E-10          |                 |                                |           |                                   |           |
| 3116.5                             | 29.04                  | -9.245             | -7.32E-11         |                | -13.815             | -2.21E-10          |                 |                                |           |                                   |           |
| 3524.5                             | 260.00                 | -9.700             | -7.53E-11         |                | -14.495             | -1.21E-10          |                 |                                |           |                                   |           |
| 3788.3                             | 314.76                 | -10.045            | -7.48E-11         |                | -14.790             | -4.50E-11          |                 |                                |           |                                   |           |
| 4220.3                             | 615.60                 | -9.655             | 6.28E-11          |                | -14.270             | 7.31E-11           |                 |                                |           |                                   |           |
| 4536.1                             | 1354.80                | -7.680             | 3.82E-10          |                | -12.350             | 3.77E-10           |                 |                                |           |                                   |           |
| 4991.8                             | -1419.32               | -10.515            | -6.83E-10         |                | -18.135             | -8.96E-10          |                 |                                |           |                                   |           |
| 5349.3                             | -1410.87               | -13.770            | -8.44E-10         |                | -23.245             | -8.57E-10          |                 |                                |           |                                   |           |
| 5804.3                             | -729.89                | -18.255            | -6.23E-10         |                | -27.555             | -5.91E-10          |                 |                                |           |                                   |           |
| 6337.2                             | -388.94                | -22.585            | -5.04E-10         |                | -31.715             | -4.77E-10          |                 |                                |           |                                   |           |
| 6812.3                             | 733.23                 | -23.040            | -1.56E-11         |                | -31.655             | 2.29E-11           |                 |                                |           |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| BARCG03E Density=1.18 Mg/m3        |                        |                    |                   |                |                     |                    |                 | All Data                       |           |                                   |           |
| Test Duration 06/05/92 to 29/04/93 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 949.8                              | -2.98                  | 2.660              | -2.3E-11          | 7.78E-12       |                     |                    |                 | Constant                       | 0         | Constant                          | 6.26E-11  |
| 1211.8                             | 20.00                  | 2.755              | 6.15E-11          | 3.07E-12       |                     |                    |                 | Std Err of Y Est               | 1.15E-10  | Std Err of Y Est                  | 1.04E-10  |
| 1596.0                             | 5.29                   | 2.810              | 8.36E-11          | 1.58E-11       |                     |                    |                 | R Squared                      | 0.7330    | R Squared                         | 0.7933    |
| 2123.7                             | 15.10                  | 2.785              | 6.07E-11          | 4.02E-12       |                     |                    |                 | No. of Observations            | 19        | No. of Observations               | 19        |
| 2129.4                             | 15.10                  | 2.755              | 2.71E-11          | 1.8E-12        |                     |                    |                 | Degrees of Freedom             | 18        | Degrees of Freedom                | 17        |
| 2387.6                             | 24.71                  | 2.980              | 1.73E-10          | 6.99E-12       |                     |                    |                 |                                |           |                                   |           |
| 2939.6                             | 10.38                  | 3.205              | 1.18E-10          | 1.13E-11       |                     |                    |                 | X Coefficient(s)               | 1.59E-12  | X Coefficient(s)                  | 1.39E-12  |
| 3228.3                             | 4.13                   | 3.460              | 1.15E-10          | 2.78E-11       |                     |                    |                 | Std Err of Coef.               | 1.62E-13  | Std Err of Coef.                  | 1.72E-13  |
| 3731.7                             | 3.08                   | 3.360              | 3.78E-12          | 1.23E-12       |                     |                    |                 |                                |           |                                   |           |
| 4165.0                             | 72.12                  | 3.565              | 2.51E-10          | 3.48E-12       |                     |                    |                 |                                |           |                                   |           |
| 4263.4                             | 72.31                  | 3.505              | 2.45E-10          | 3.39E-12       |                     |                    |                 |                                |           |                                   |           |
| 4500.9                             | 110.67                 | 3.605              | 1.45E-10          | 1.31E-12       |                     |                    |                 |                                |           |                                   |           |
| 4621.4                             | 110.77                 | 3.635              | 1.25E-10          | 1.13E-12       |                     |                    |                 |                                |           |                                   |           |
| 5005.3                             | 226.35                 | 4.145              | 4.19E-10          | 1.85E-12       |                     |                    |                 |                                |           |                                   |           |
| 5291.7                             | 457.69                 | 4.795              | 8.45E-10          | 1.85E-12       |                     |                    |                 |                                |           |                                   |           |
| 5603.7                             | 457.12                 | 5.005              | 5.35E-10          | 1.17E-12       |                     |                    |                 |                                |           |                                   |           |
| 5939.7                             | 10.48                  | 5.310              | 3.04E-10          | 2.9E-11        |                     |                    |                 |                                |           |                                   |           |
| 8053.5                             | 14.81                  | 5.680              | 7.83E-11          | 5.29E-12       |                     |                    |                 |                                |           |                                   |           |
| 7478.3                             | -5.00                  | 5.625              | -1.2E-10          | 2.43E-11       |                     |                    |                 |                                |           |                                   |           |
| S50MC15 Density=1.75/1.18 Mg/m3    |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 1100                               | 1580                   | 0.085              | 7.4E-10           | 4.67E-13       |                     |                    |                 | Constant                       | 0         | Constant                          | 4.35E-11  |
| 1600                               | 3161                   | 1.245              | 8.7E-10           | 2.75E-13       |                     |                    |                 | Std Err of Y Est               | 4.96E-10  | Std Err of Y Est                  | 5.42E-10  |
| 2100                               | 4741                   | 4.095              | 1.3E-09           | 2.74E-13       |                     |                    |                 | R Squared                      | 0.9733329 | R Squared                         | 0.9734441 |
| 2600                               | 7902                   | 5.585              | 2.2E-09           | 2.72E-13       |                     |                    |                 | No. of Observations            | 7         | No. of Observations               | 7         |
| 2950                               | 15804                  | 6.725              | 5.6E-09           | 3.52E-13       |                     |                    |                 | Degrees of Freedom             | 6         | Degrees of Freedom                | 5         |
| 3125                               | 31608                  | 7.555              | 8.8E-09           | 2.79E-13       |                     |                    |                 |                                |           |                                   |           |
| 3175                               | 7902                   | 7.915              | 1.7E-09           | 2.20E-13       |                     |                    |                 | X Coefficient(s)               | 2.89E-13  | X Coefficient(s)                  | 2.87E-13  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 1.32E-14  | Std Err of Coef.                  | 2.12E-14  |
| RBMLH2 Density=1.64/1.19 Mg/m3     |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 21/03/89 to 07/06/90 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 7262                               | 368.8                  | 0.690              | 1.59E-10          | 4.32E-13       |                     |                    |                 | Constant                       | 0         | Constant                          | 1.55E-10  |
| 7502                               | 633.1                  | 0.925              | 3.14E-10          | 4.96E-13       |                     |                    |                 | Std Err of Y Est               | 1.11E-10  | Std Err of Y Est                  | 9.49E-11  |
| 7766                               | 3067.0                 | 2.125              | 7.6E-10           | 2.48E-13       |                     |                    |                 | R Squared                      | 0.8931123 | R Squared                         | 0.9293053 |
| 7862                               | 4572.9                 | 2.415              | 8.67E-10          | 1.9E-13        |                     |                    |                 | No. of Observations            | 12        | No. of Observations               | 12        |
| 8341                               | 5147.5                 | 4.465              | 9.54E-10          | 1.85E-13       |                     |                    |                 | Degrees of Freedom             | 11        | Degrees of Freedom                | 10        |
| 8509                               | 5153.7                 | 4.960              | 1.13E-09          | 2.19E-13       |                     |                    |                 |                                |           |                                   |           |
| 8845                               | 5144.5                 | 5.815              | 8.71E-10          | 1.69E-13       | 0.058               |                    |                 | X Coefficient(s)               | 1.94E-13  | X Coefficient(s)                  | 1.64E-13  |
| 9253                               | 5147.5                 | 6.875              | 9.02E-10          | 1.75E-13       | 0.613               | 7.42E-10           | 1.44E-13        | Std Err of Coef.               | 6.7E-15   | Std Err of Coef.                  | 1.43E-14  |
| 9472                               | 5086.1                 | 7.430              | 9.13E-10          | 1.79E-13       | 1.045               | 7.78E-10           | 1.53E-13        |                                |           |                                   |           |
| 9684                               | 6198.6                 | 8.305              | 1.3E-09           | 2.1E-13        | 1.480               | 1.05E-09           | 1.69E-13        |                                |           |                                   |           |
| 9852                               | 6075.6                 | 8.895              | 1.12E-09          | 1.84E-13       | 1.830               | 9.89E-10           | 1.63E-13        |                                |           |                                   |           |
| 10019                              | 6115.6                 | 9.490              | 1.22E-09          | 1.99E-13       | 2.270               | 9.02E-10           | 1.47E-13        |                                |           |                                   |           |

## APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                                                          | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |                                   |
|-----------------------------------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|
|                                                                             |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero | No Constraints on Regression Line |
| URL125 Density=1.20 Mg/m <sup>3</sup><br>Test Duration 14/05/90 to 15/07/91 |                        |                    |                   |                |                     |                    |                 |                                |                                   |
| 1916.50                                                                     | 562                    | 9.915              | 4.96E-10          | 8.83E-13       | 2.360               | 2.16E-10           | 3.84E-13        | Regression Output:             |                                   |
| 2709.00                                                                     | 539                    | 11.015             | 4.88E-10          | 9.04E-13       | 2.965               | 2.81E-10           | 5.21E-13        | Constant                       | 0                                 |
| 3405.00                                                                     | 742                    | 12.375             | 7.86E-10          | 1.06E-12       | 3.190               |                    |                 | Std Err of Y Est               | 1.75E-10                          |
| 4582.08                                                                     | 714                    | 14.915             | 7.29E-10          | 1.02E-12       | 2.950               |                    |                 | R Squared                      | 0.9757061                         |
| 5229.25                                                                     | 902                    | 16.745             | 8.47E-10          | 9.39E-13       | 3.310               | 3.35E-10           | 3.72E-13        | No. of Observations            | 31                                |
| 5925.75                                                                     | 1082                   | 18.61              | 9.8E-10           | 9.06E-13       | 4.180               | 6.13E-10           | 5.67E-13        | Degrees of Freedom             | 30                                |
| 6453.75                                                                     | 2880                   | 22.06              | 2.4E-09           | 8.33E-13       | 6.435               | 2.14E-09           | 7.43E-13        | Regression Output:             |                                   |
| 6574.00                                                                     | 2852                   | 22.9               | 2.65E-09          | 9.29E-13       | 7.215               | 2.42E-09           | 8.49E-13        | Constant                       | -2.24E-11                         |
| 6717.25                                                                     | 4215                   | 24.36              | 3.55E-09          | 8.43E-13       | 8.465               | 3.15E-09           | 7.46E-13        | Std Err of Y Est               | 1.78E-10                          |
| 6770.75                                                                     | 3675                   | 24.875             | 3.31E-09          | 9.01E-13       | 8.975               | 3.30E-09           | 8.98E-13        | R Squared                      | 0.97591                           |
| 6885.58                                                                     | 731                    | 24.635             | 4.03E-10          | 5.52E-13       | 9.185               | 6.99E-10           | 9.57E-13        | No. of Observations            | 31                                |
| 7053.50                                                                     | 731                    | 24.925             | 5.96E-10          | 8.16E-13       | 9.420               | 4.83E-10           | 6.61E-13        | Degrees of Freedom             | 29                                |
| 7077.92                                                                     | 680                    | 24.97              | 6.74E-10          | 9.91E-13       | 9.455               | 4.94E-10           | 7.27E-13        | X Coefficient(s)               | 8.42E-13                          |
| 7150.67                                                                     | 525                    | 25.12              | 5.73E-10          | 1.09E-12       |                     |                    |                 | Std Err of Coef.               | 2.46E-14                          |
| 7413.67                                                                     | 256                    | 25.435             | 2.96E-10          | 1.16E-12       |                     |                    |                 |                                |                                   |
| 8062.00                                                                     | 202                    | 26.04              | 2E-10             | 9.9E-13        |                     |                    |                 |                                |                                   |
| 8469.83                                                                     | 155                    | 26.345             | 8.99E-11          | 5.82E-13       |                     |                    |                 |                                |                                   |
| 8925.50                                                                     | 76                     | 26.525             | 9.81E-11          | 1.29E-12       |                     |                    |                 |                                |                                   |
| 9597.67                                                                     | 56                     | 26.76              | 4.39E-11          | 7.85E-13       |                     |                    |                 |                                |                                   |
| 10245.58                                                                    | 38                     | 26.82              | 3.16E-11          | 8.34E-13       |                     |                    |                 |                                |                                   |
| THS90B Density=1.23 Mg/m <sup>3</sup>                                       |                        |                    |                   |                |                     |                    |                 | Regression Output:             |                                   |
| 863                                                                         | 766                    | 0.8                | 4.4E-10           | 5.68E-13       |                     |                    |                 | Constant                       | 0                                 |
| 1318                                                                        | 1532                   | 3.1                | 1.1E-09           | 6.92E-13       |                     |                    |                 | Std Err of Y Est               | 7.64E-11                          |
| 2154                                                                        | 2298                   | 8.3                | 1.5E-09           | 6.53E-13       |                     |                    |                 | R Squared                      | 0.9846697                         |
| 3042                                                                        | 3064                   | 12.2               | 1.9E-09           | 6.10E-13       |                     |                    |                 | No. of Observations            | 4                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 3                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 6.33E-13                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 1.82E-14                          |
| Regression Output:                                                          |                        |                    |                   |                |                     |                    |                 | Regression Output:             |                                   |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Constant                       | 3E-11                             |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | 9.2E-11                           |
|                                                                             |                        |                    |                   |                |                     |                    |                 | R Squared                      | 0.9851947                         |
|                                                                             |                        |                    |                   |                |                     |                    |                 | No. of Observations            | 4                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 2                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 6.19E-13                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 5.37E-14                          |
| DW100.42 Density=1.22 Mg/m <sup>3</sup>                                     |                        |                    |                   |                |                     |                    |                 | Regression Output:             |                                   |
| 1300                                                                        | 643                    | 0.3                | 1.9E-10           | 3.00E-13       |                     |                    |                 | Constant                       | 0                                 |
| 3400                                                                        | 800                    | 0.75               | 2.0E-10           | 2.50E-13       |                     |                    |                 | Std Err of Y Est               | 9.71E-11                          |
| 5000                                                                        | 1610                   | 2.1                | 6.9E-10           | 4.30E-13       |                     |                    |                 | R Squared                      | 0.9692504                         |
| 5800                                                                        | 3215                   | 6.1                | 1.0E-09           | 3.10E-13       |                     |                    |                 | No. of Observations            | 5                                 |
| 7500                                                                        | 4825                   | 9.1                | 1.5E-09           | 3.10E-13       |                     |                    |                 | Degrees of Freedom             | 4                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 3.17E-13                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 1.59E-14                          |
| Regression Output:                                                          |                        |                    |                   |                |                     |                    |                 | Regression Output:             |                                   |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Constant                       | 3.47E-11                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Y Est               | 1.09E-10                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | R Squared                      | 0.9709118                         |
|                                                                             |                        |                    |                   |                |                     |                    |                 | No. of Observations            | 5                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 3                                 |
|                                                                             |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 3.07E-13                          |
|                                                                             |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 3.07E-14                          |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                    |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
| Elapsed Time (Hrs)                 | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| SHC50 aka S50MC17                  |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 750                                | 1593                   | 0.085              | 7.2E-10           | 4.54E-13       |                     |                    |                 | Constant                       | 0         | Constant                          | 2.97E-10  |
| 1550                               | 3186                   | 1.6                | 9.0E-10           | 2.84E-13       |                     |                    |                 | Std Err of Y Est               | 8.4E-10   | Std Err of Y Est                  | 8.72E-10  |
| 2070                               | 4778                   | 3.5                | 1.4E-09           | 2.87E-13       |                     |                    |                 | R Squared                      | 0.9169333 | R Squared                         | 0.923161  |
| 2620                               | 7964                   | 5.2                | 2.4E-09           | 2.99E-13       |                     |                    |                 | No. of Observations            | 8         | No. of Observations               | 8         |
| 3125                               | 31855                  | 7.4                | 8.1E-09           | 2.54E-13       |                     |                    |                 | Degrees of Freedom             | 7         | Degrees of Freedom                | 6         |
| 3200                               | 7964                   | 7.7                | 2.2E-09           | 2.72E-13       |                     |                    |                 |                                |           |                                   |           |
|                                    | 478                    | 7.7                | 1.5E-10           | 3.05E-13       |                     |                    |                 | X Coefficient(s)               | 2.86E-13  | X Coefficient(s)                  | 2.7E-13   |
| 2950                               | 15927                  | 6.5                | 6.5E-09           | 4.09E-13       |                     |                    |                 | Std Err of Coef.               | 2.22E-14  | Std Err of Coef.                  | 3.18E-14  |
| C50.20WD                           |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 02/85 to 01/86       |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | 6.68E-10  |
| 1300                               | 1680                   | 2.5                | 1.9E-09           | 1.11E-12       |                     |                    |                 | Std Err of Y Est               | 5.07E-10  | Std Err of Y Est                  | 2.87E-10  |
| 3150                               | 8410                   | 17                 | 7.5E-09           | 8.94E-13       |                     |                    |                 | R Squared                      | 0.9927873 | R Squared                         | 0.998844  |
| 4100                               | 16820                  | 20                 | 1.4E-08           | 8.20E-13       |                     |                    |                 | No. of Observations            | 3         | No. of Observations               | 3         |
| 6700                               | 65                     |                    |                   |                |                     |                    |                 | Degrees of Freedom             | 2         | Degrees of Freedom                | 1         |
|                                    |                        |                    |                   |                |                     |                    |                 | X Coefficient(s)               | 8.37E-13  | X Coefficient(s)                  | 7.87E-13  |
|                                    |                        |                    |                   |                |                     |                    |                 | Std Err of Coef.               | 2.69E-14  | Std Err of Coef.                  | 2.68E-14  |
| BARCG03D                           |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 24/03/93 to 25/07/94 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | -1.51E-10 |
| 863.5                              | 0.61                   | -0.930             | -8.9E-11          | -1.4E-10       | -1.680              | -2.02E-10          | -3.3E-10        | Std Err of Y Est               | 1.47E-10  | Std Err of Y Est                  | 3.3E-11   |
| 1342.3                             | 1.89                   | -1.120             | -2.2E-10          | -1.2E-10       | -3.210              | -1.93E-10          | -1E-10          | R Squared                      | 0.1887    | R Squared                         | 0.9601    |
| 1679.0                             | 0.00                   | -1.175             | -2E-10            |                | -1.150              | -2.09E-10          |                 | No. of Observations            | 46        | No. of Observations               | 46        |
| 2519.6                             | 42.12                  | -3.610             | -1.7E-10          | -4E-12         | -3.335              | -1.39E-10          | -3.3E-12        | Degrees of Freedom             | 45        | Degrees of Freedom                | 44        |
| 2878.2                             | 187.70                 | -3.605             | -1.1E-10          | -5.6E-13       | -2.260              | -1.15E-10          | -6.1E-13        |                                |           |                                   |           |
| 3166.3                             | 154.01                 | -4.105             | -1.1E-10          | -6.9E-13       | -2.755              | -8.76E-11          | -5.7E-13        |                                |           |                                   |           |
| 3335.2                             | 769.21                 | -4.065             | 3.78E-11          | 4.91E-14       | -2.805              | 3.47E-11           | 4.51E-14        | X Coefficient(s)               | 1.63E-13  | X Coefficient(s)                  | 2.37E-13  |
| 3646.4                             | 757.81                 | -4.000             | 1.77E-11          | 2.33E-14       | -2.510              | 4.04E-11           | 5.32E-14        | Std Err of Coef.               | 3.05E-14  | Std Err of Coef.                  | 7.3E-15   |
| 3982.4                             | 778.30                 | -3.815             | 2.77E-11          | 3.56E-14       | -2.460              | 2.27E-11           | 2.92E-14        |                                |           |                                   |           |
| 4150.7                             | 752.01                 | -3.755             | 1.89E-11          | 2.51E-14       | -2.380              | 2.41E-11           | 3.2E-14         |                                |           |                                   |           |
| 4486.3                             | 1372.75                | -2.820             | 1.86E-10          | 1.35E-13       | -1.575              | 1.54E-10           | 1.13E-13        |                                |           |                                   |           |
| 4654.3                             | 1318.25                | -2.475             | 1.64E-10          | 1.24E-13       | -1.145              | 1.43E-10           | 1.08E-13        |                                |           |                                   |           |
| 4918.7                             | 1364.80                | -1.835             | 1.46E-10          | 1.07E-13       | -0.470              | 1.59E-10           | 1.16E-13        |                                |           |                                   |           |
| 5350.9                             | -49.97                 | -3.090             | -1.7E-10          | 3.32E-12       | -1.090              | -5.17E-11          | 1.03E-12        |                                |           |                                   |           |
| 5494.9                             | 417.45                 | -3.435             | -9.7E-11          | -2.3E-13       | -1.545              | -2.52E-11          | -6E-14          |                                |           |                                   |           |
| 5927.1                             | -272.48                | -4.840             | -2.2E-10          | 7.96E-13       | -3.510              | -2.13E-10          | 7.83E-13        |                                |           |                                   |           |
| 6334.3                             | -122.35                | -6.140             | -1.9E-10          | 1.52E-12       | -5.495              | -1.77E-10          | 1.45E-12        |                                |           |                                   |           |
| 7174.2                             | -326.37                | -9.205             | -2.4E-10          | 7.35E-13       | -8.560              | -2.12E-10          | 6.5E-13         |                                |           |                                   |           |
| 7750.5                             | -674.17                | -12.170            | -3.1E-10          | 4.65E-13       | -11.275             | -2.99E-10          | 4.44E-13        |                                |           |                                   |           |
| 8448.2                             | -621.00                | -15.580            | -3E-10            | 4.77E-13       | -14.430             | -2.98E-10          | 4.8E-13         |                                |           |                                   |           |
| 9196.0                             | -1337.24               | -21.125            | -4.8E-10          | 3.56E-13       | -20.135             | -4.69E-10          | 3.51E-13        |                                |           |                                   |           |
| 9793.0                             | 647.27                 | -19.450            | 6.31E-11          | 9.74E-14       | -20.150             | 2.68E-11           | 4.14E-14        |                                |           |                                   |           |
| 10198.2                            | 586.27                 | -19.220            | 4.04E-11          | 6.89E-14       | -20.000             | 3.16E-11           | 5.38E-14        |                                |           |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                  | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |                                   |
|-------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------------------------------|
|                                     |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero | No Constraints on Regression Line |
| TDCON Density=1.26 Mg/m3            |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
| Test Duration 26/05/89 to 20/03/90  |                        |                    |                   |                |                     |                    |                 | Constant 0                     | Constant -9.06E-11                |
| 1271.5                              | 365                    | 5.205              | 2.64E-10          | 7.24E-13       |                     |                    |                 | Std Err of Y Est 1.79E-10      | Std Err of Y Est 1.75E-10         |
| 1460.5                              | 322                    | 5.365              | 2.68E-10          | 8.32E-13       |                     |                    |                 | R Squared 0.9885394            | R Squared 0.9897808               |
| 1772.5                              | 398                    | 5.575              | 2.22E-10          | 5.58E-13       |                     |                    |                 | No. of Observations 15         | No. of Observations 15            |
| 2084.5                              | 250                    | 5.740              | 1.56E-10          | 6.24E-13       |                     |                    |                 | Degrees of Freedom 14          | Degrees of Freedom 13             |
| 2492.4                              | 1088                   | 6.475              | 4.32E-10          | 3.97E-13       |                     |                    |                 |                                |                                   |
| 2660.5                              | 1032                   | 6.800              | 5.46E-10          | 5.29E-13       |                     |                    |                 | X Coefficient(s) 8.11E-13      | X Coefficient(s) 8.34E-13         |
| 5492.0                              | 4982                   | 10.400             | 3.88E-09          | 7.78E-13       |                     |                    |                 | Std Err of Coef. 1.5E-14       | Std Err of Coef. 2.35E-14         |
| 5611.8                              | 4850                   | 11.740             | 3.86E-09          | 7.96E-13       | 0.685               | 3.43E-09           | 7.07E-13        |                                |                                   |
| 5780.8                              | 4334                   | 13.475             | 3.46E-09          | 7.98E-13       | 2.103               | 3.07E-09           | 7.08E-13        |                                |                                   |
| 5852.9                              | 5376                   | 14.195             | 4.62E-09          | 8.59E-13       | 2.723               | 3.59E-09           | 6.68E-13        |                                |                                   |
| 6140.8                              | 4844                   | 17.495             | 3.99E-09          | 8.24E-13       | 5.505               | 3.29E-09           | 6.79E-13        |                                |                                   |
| 6381.0                              | 3230                   | 19.315             | 2.65E-09          | 8.2E-13        | 7.122               | 2.22E-09           | 6.87E-13        |                                |                                   |
| 6788.8                              | 2146                   | 21.750             | 1.80E-09          | 8.4E-13        | 9.137               | 1.47E-09           | 6.84E-13        |                                |                                   |
| 7004.8                              | 1791                   | 22.775             | 1.54E-09          | 8.62E-13       | 9.995               | 1.23E-09           | 6.89E-13        |                                |                                   |
| 7149.5                              | 861                    | 23.105             | 8.58E-10          | 9.97E-13       | 10.197              | 4.80E-10           | 5.57E-13        |                                |                                   |
| SISAVB60/40 Density=1.86/1.28 Mg/m3 |                        |                    |                   |                |                     |                    |                 | Gradient >1000                 |                                   |
|                                     |                        |                    |                   |                |                     |                    |                 | Regression Output:             | Regression Output:                |
| 528                                 | 352                    | 0.03               | 1.7E-10           | 4.86E-13       |                     |                    |                 | Constant 0                     | Constant 1.5E-10                  |
| 1008                                | 1760                   | 1.25               | 4.0E-10           | 2.24E-13       |                     |                    |                 | Std Err of Y Est 1.19E-10      | Std Err of Y Est 6.07E-11         |
| 1464                                | 2640                   | 3.75               | 5.4E-10           | 2.04E-13       |                     |                    |                 | R Squared 0.992368             | R Squared 0.9982893               |
| 1992                                | 4400                   | 6.75               | 6.9E-10           | 1.57E-13       |                     |                    |                 | No. of Observations 8          | No. of Observations 8             |
| 2520                                | 8800                   | 9.25               | 1.2E-09           | 1.41E-13       |                     |                    |                 | Degrees of Freedom 7           | Degrees of Freedom 6              |
| 2856                                | 17600                  | 10                 | 2.3E-09           | 1.3E-13        |                     |                    |                 |                                |                                   |
| 3072                                | 35200                  | 17.3               | 4.5E-09           | 1.27E-13       |                     |                    |                 |                                |                                   |
| 3216                                | 17600                  | 18.5               | 2.2E-09           | 1.27E-13       |                     |                    |                 | X Coefficient(s) 1.29E-13      | X Coefficient(s) 1.22E-13         |
| 3336                                | 8800                   | 19.5               | 1.1E-09           | 1.27E-13       |                     |                    |                 | Std Err of Coef. 2.63E-15      | Std Err of Coef. 2.06E-15         |
| 3504                                | 527                    | 19.7               | 1.7E-10           | 3.26E-13       |                     |                    |                 |                                |                                   |

## APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| BAR130 Density=1.30 Mg/m3          |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 04/06/90 to 28/05/91 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | 6.19E-11  |
| 1363.25                            | 941.5                  | 18.305             | 3.81E-10          | 4.05E-13       | 0.000               |                    |                 | Std Err of Y Est               | 9.4E-11   | Std Err of Y Est                  | 8.48E-11  |
| 1532.33                            | 849.7                  | 18.865             | 4.44E-10          | 5.23E-13       | 0.000               |                    |                 | R Squared                      | 0.9449683 | R Squared                         | 0.9564452 |
| 2684.50                            | 814.0                  | 22.300             | 3.56E-10          | 4.38E-13       | 0.590               | 2.22E-10           | 2.72E-13        | No. of Observations            | 37        | No. of Observations               | 37        |
| 3100.00                            | 1140.2                 | 23.535             | 3.46E-10          | 3.03E-13       | 1.375               | 3.39E-10           | 2.98E-13        | Degrees of Freedom             | 36        | Degrees of Freedom                | 35        |
| 3188.00                            | 1333.9                 | 24.035             | 4.21E-10          | 3.16E-13       | 1.645               | 4.21E-10           | 3.16E-13        |                                |           |                                   |           |
| 3788.25                            | 1094.4                 | 25.950             | 4.02E-10          | 3.68E-13       | 2.365               | 2.14E-10           | 1.95E-13        | X Coefficient(s)               | 2.81E-13  | X Coefficient(s)                  | 2.6E-13   |
| 3964.17                            | 1323.7                 | 26.395             | 3.5E-10           | 2.64E-13       | 2.675               | 3.18E-10           | 2.41E-13        | Std Err of Coef.               | 7.11E-15  | Std Err of Coef.                  | 9.38E-15  |
| 4124.58                            | 1242.2                 | 26.805             | 3.51E-10          | 2.83E-13       | 2.905               | 3.95E-10           | 3.18E-13        |                                |           |                                   |           |
| 4948.50                            | 1323.7                 | 29.105             | 3.94E-10          | 2.97E-13       | 4.150               | 2.84E-10           | 2.14E-13        |                                |           |                                   |           |
| 5420.50                            | 1864.0                 | 30.995             | 5.87E-10          | 3.15E-13       | 5.828               | 5.68E-10           | 3.05E-13        |                                |           |                                   |           |
| 5708.50                            | 2547.0                 | 32.390             | 7.28E-10          | 2.86E-13       | 7.103               | 6.23E-10           | 2.45E-13        |                                |           |                                   |           |
| 5900.25                            | 2725.4                 | 33.600             | 8.5E-10           | 3.12E-13       | 8.218               | 8.48E-10           | 3.11E-13        |                                |           |                                   |           |
| 6044.42                            | 5197.3                 | 34.980             | 1.59E-09          | 3.05E-13       | 9.363               | 1.24E-09           | 2.39E-13        |                                |           |                                   |           |
| 6140.00                            | 5528.6                 | 36.090             | 1.65E-09          | 2.98E-13       | 10.283              | 1.33E-09           | 2.4E-13         |                                |           |                                   |           |
| 6452.42                            | 839.5                  | 36.790             | 2.87E-10          | 3.42E-13       | 10.963              | 2.3E-10            | 2.73E-13        |                                |           |                                   |           |
| 6548.17                            | 1043.4                 | 37.030             | 3.64E-10          | 3.49E-13       | 10.948              |                    |                 |                                |           |                                   |           |
| 6645.42                            | 397.6                  | 37.170             | 1.97E-10          | 4.96E-13       | 11.088              | 2.5E-10            | 6.3E-13         |                                |           |                                   |           |
| 6908.50                            | 367.0                  | 37.545             | 2.42E-10          | 6.6E-13        | 11.348              | 1.22E-10           | 3.33E-13        |                                |           |                                   |           |
| 8108.67                            | 100.9                  | 38.265             | 6.82E-11          | 6.76E-13       | 11.633              | 3.57E-11           | 3.54E-13        |                                |           |                                   |           |
| 8588.33                            | 56.1                   | 38.405             | 4.84E-11          | 8.63E-13       | 11.728              | 3.63E-11           | 6.47E-13        |                                |           |                                   |           |
| URL135 Density=1.31 Mg/m3          |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 14/05/90 to 15/07/91 |                        |                    |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | -2.71E-11 |
| 3357.50                            | 310                    | 6.415              | 2.24E-10          | 7.21E-13       |                     |                    |                 | Std Err of Y Est               | 1.79E-10  | Std Err of Y Est                  | 1.81E-10  |
| 3693.25                            | 601                    | 6.870              | 3.75E-10          | 6.25E-13       |                     |                    |                 | R Squared                      | 0.8324556 | R Squared                         | 0.834073  |
| 4029.83                            | 544                    | 7.155              | 3.03E-10          | 5.57E-13       |                     |                    |                 | No. of Observations            | 31        | No. of Observations               | 31        |
| 4533.75                            | 480                    | 7.575              | 2.78E-10          | 5.8E-13        |                     |                    |                 | Degrees of Freedom             | 30        | Degrees of Freedom                | 29        |
| 5085.58                            | 1142                   | 8.330              | 6.46E-10          | 5.65E-13       | -0.450              | 3.98E-10           | 3.48E-13        |                                |           |                                   |           |
| 5453.75                            | 1072                   | 8.920              | 5.35E-10          | 4.99E-13       | -0.080              | 4.1E-10            | 3.83E-13        | X Coefficient(s)               | 4.82E-13  | X Coefficient(s)                  | 4.99E-13  |
| 5589.25                            | 1030                   | 9.110              | 4.86E-10          | 4.72E-13       | 0.020               | 2.56E-10           | 2.49E-13        | Std Err of Coef.               | 2.6E-14   | Std Err of Coef.                  | 4.13E-14  |
| 6100.83                            | 1227                   | 9.480              | 2.47E-10          | 2.01E-13       | 0.270               | 3.85E-10           | 3.13E-13        |                                |           |                                   |           |
| 6549.67                            | 1692                   | 10.375             | 7.40E-10          | 4.37E-13       | 0.830               | 4.85E-10           | 2.86E-13        |                                |           |                                   |           |
| 6645.42                            | 2821                   | 10.765             | 1.83E-09          | 6.49E-13       | 1.050               | 1.17E-09           | 4.15E-13        |                                |           |                                   |           |
| 6717.25                            | 2319                   | 11.115             | 1.63E-09          | 7.04E-13       | 1.260               | 1.04E-09           | 4.47E-13        |                                |           |                                   |           |
| 6909.75                            | 1058                   | 11.555             | 4.72E-10          | 4.46E-13       | 1.490               | 4.64E-10           | 4.39E-13        |                                |           |                                   |           |
| 7245.50                            | 818                    | 12.020             | 4.33E-10          | 5.29E-13       | 1.805               | 2.68E-10           | 3.28E-13        |                                |           |                                   |           |
| 7413.75                            | 291                    | 12.140             | 2.01E-10          | 6.93E-13       | 1.880               | 1.29E-10           | 4.45E-13        |                                |           |                                   |           |
| 8062.00                            | 212                    | 12.355             | 1.04E-10          | 4.93E-13       |                     |                    |                 |                                |           |                                   |           |
| 8733.58                            | 138                    | 12.535             | 1.01E-10          | 7.31E-13       | 1.950               | 1.08E-10           | 7.82E-13        |                                |           |                                   |           |
| 9573.67                            | 56                     | 12.765             | 7.21E-11          | 1.28E-12       | 1.895               | 4.21E-11           | 7.49E-13        |                                |           |                                   |           |
| 10247.33                           | 32                     | 12.925             | 5.32E-11          | 1.67E-12       | 1.880               | 1.5E-11            | 4.7E-13         |                                |           |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                 | Hydraulic Gradient (l) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                    |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| MICG09B Density=1.33 Mg/m3         |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 06/08/91 to 02/11/92 |                        |                    |                   |                |                     |                    |                 | 0                              |           | Constant 1.08E-11                 |           |
| 5329.5                             | 121.97                 | 5.180              | 4.38E-10          | 3.59E-12       |                     |                    |                 | Std Err of Y Est               | 2.09E-11  | Std Err of Y Est                  | 2.02E-11  |
| 6330.9                             | 40.39                  | 5.670              | 1.90E-10          | 4.7E-12        |                     |                    |                 | R Squared                      | 0.9748419 | R Squared                         | 0.9785878 |
| 6690.3                             | 38.61                  | 5.875              | 1.77E-10          | 4.58E-12       |                     |                    |                 | No. of Observations            | 12        | No. of Observations               | 12        |
| 7297.7                             | 25.44                  | 6.050              | 8.51E-11          | 3.35E-12       |                     |                    |                 | Degrees of Freedom             | 11        | Degrees of Freedom                | 10        |
| 7321.6                             | 25.44                  | 6.050              | 1.01E-10          | 3.98E-12       |                     |                    |                 |                                |           |                                   |           |
| 7631.7                             | 12.12                  | 6.065              | 3.62E-11          | 2.99E-12       |                     |                    |                 | X Coefficient(s)               | 3.88E-12  | X Coefficient(s)                  | 3.72E-12  |
| 7991.0                             | 4.44                   | 6.085              | 1.63E-11          | 3.67E-12       |                     |                    |                 | Std Err of Coef.               | 1.28E-13  | Std Err of Coef.                  | 1.74E-13  |
| 8468.5                             | 8.72                   | 6.115              | 3.66E-11          | 4.2E-12        |                     |                    |                 |                                |           |                                   |           |
| 8634.5                             | 80.78                  | 6.255              | 3.34E-10          | 4.13E-12       |                     |                    |                 |                                |           |                                   |           |
| 9164.7                             | 12.12                  | 5.790              | 5.68E-11          | 4.69E-12       |                     |                    |                 |                                |           |                                   |           |
| 9737.4                             | 6.62                   | 5.845              | 2.76E-11          | 4.17E-12       |                     |                    |                 |                                |           |                                   |           |
| 10146.2                            | 20.19                  | 5.940              | 1.08E-10          | 5.35E-12       |                     |                    |                 |                                |           |                                   |           |
| SSB40A 10/10/89 to 10/4/90         |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Density=1.34 Mg/m3                 |                        |                    |                   |                |                     |                    |                 | Constant 0                     |           | Constant 2.36E-10                 |           |
| 569.7                              | 56.5                   | 3.175              | 7.11E-11          | 1.26E-12       |                     |                    |                 | Std Err of Y Est               | 7.02E-11  | Std Err of Y Est                  | 4.53E-11  |
| 1147.5                             | 1311.0                 | 4.215              | 4.52E-10          | 3.45E-13       |                     |                    |                 | R Squared                      | 0.7308772 | R Squared                         | 0.8992264 |
| 1313.7                             | 2634.8                 | 4.615              | 7.89E-10          | 2.99E-13       |                     |                    |                 | No. of Observations            | 11        | No. of Observations               | 11        |
| 1416.8                             | 2599.6                 | 4.840              | 7.05E-10          | 2.71E-13       |                     |                    |                 | Degrees of Freedom             | 10        | Degrees of Freedom                | 9         |
| 1746.0                             | 2350.2                 | 5.390              | 6.74E-10          | 2.87E-13       |                     |                    |                 |                                |           |                                   |           |
| 1940.5                             | 2343.8                 | 5.780              | 6.87E-10          | 2.93E-13       |                     |                    |                 | X Coefficient(s)               | 2.63E-13  | X Coefficient(s)                  | 1.85E-13  |
| 2346.4                             | 3485.3                 | 6.910              | 9.7E-10           | 2.78E-13       |                     |                    |                 | Std Err of Coef.               | 7.17E-15  | Std Err of Coef.                  | 2.06E-14  |
| 2592.5                             | 3440.5                 | 8.075              | 8.54E-10          | 2.48E-13       |                     |                    |                 |                                |           |                                   |           |
| 2753.7                             | 3411.7                 | 8.480              | 8.31E-10          | 2.44E-13       | 0.130               |                    |                 |                                |           |                                   |           |
| 3425.9                             | 3383.0                 | 10.115             | 8.19E-10          | 2.42E-13       | 0.840               | 4.59E-10           | 1.36E-13        |                                |           |                                   |           |
| 3593.7                             | 3370.2                 | 10.525             | 8.5E-10           | 2.52E-13       | 1.080               | 7.8E-10            | 2.31E-13        |                                |           |                                   |           |
| 4097.8                             | 3328.6                 | 11.740             | 8.12E-10          | 2.44E-13       |                     |                    |                 |                                |           |                                   |           |
| SS0MC07 Density=1.86/1.34 Mg/m3    |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| Test Duration 15/10/84 to 21/01/85 |                        |                    |                   |                |                     |                    |                 | Constant 0                     |           | Constant                          |           |
| 1100                               | 1660                   | 0.04               | 2.9E-10           | 1.74E-13       |                     |                    |                 | Std Err of Y Est               | 1.72E-10  | Std Err of Y Est                  |           |
| 1600                               | 3320                   | 1.5                | 8.9E-10           | 2.67E-13       |                     |                    |                 | R Squared                      | 0.995312  | R Squared                         |           |
| 2100                               | 4980                   | 2.8                | 1.1E-09           | 2.3E-13        |                     |                    |                 | No. of Observations            | 7         | No. of Observations               |           |
| 2600                               | 8305 >4.4              |                    | 1.6E-09           | 1.91E-13       |                     |                    |                 | Degrees of Freedom             | 6         | Degrees of Freedom                |           |
| 2950                               | 16610 >5               |                    | 3.9E-09           | 2.35E-13       |                     |                    |                 |                                |           |                                   |           |
| 3100                               | 32220 >6               |                    | 7.5E-09           | 2.33E-13       |                     |                    |                 |                                |           |                                   |           |
| 3200                               | 8305 >6.2              |                    | 1.7E-09           | 2.08E-13       |                     |                    |                 | X Coefficient(s)               | 2.31E-13  | X Coefficient(s)                  | 2.36E-13  |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed Time (Hrs)                                                   | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|----------------------------------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                                                      |                        |                    |                   |                |                     |                    |                 | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| SISAVB25/75 Density=1.34 Mg/m3<br>Test Duration 26/09/84 to 29/01/85 |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 1010                                                                 | 1550                   | 1.5                | 5.8E-10           | 3.73E-13       |                     |                    |                 | Constant                       | 0         | Constant                          | 1.49E-10  |
| 1477                                                                 | 3100                   | 3.7                | 1.4E-09           | 4.39E-13       |                     |                    |                 | Std Err of Y Est               | 2.1E-10   | Std Err of Y Est                  | 1.92E-10  |
| 2005                                                                 | 4650                   | 6.2                | 1.5E-09           | 3.2E-13        |                     |                    |                 | R Squared                      | 0.9950405 | R Squared                         | 0.9963552 |
| 2528                                                                 | 7750                   | 9.5                | 2.6E-09           | 3.3E-13        |                     |                    |                 | No. of Observations            | 9         | No. of Observations               | 9         |
| 3000                                                                 | 15500                  | 10.5               | 5.2E-09           | 3.36E-13       |                     |                    |                 | Degrees of Freedom             | 8         | Degrees of Freedom                | 7         |
| 3216                                                                 | 31000                  | 15.7               | 9.5E-09           | 3.07E-13       |                     |                    |                 | X Coefficient(s)               | 3.15E-13  | X Coefficient(s)                  | 3.07E-13  |
| 3360                                                                 | 15500                  | 16.8               | 5.0E-09           | 3.2E-13        |                     |                    |                 | Std Err of Coef.               | 5.25E-15  | Std Err of Coef.                  | 7.02E-15  |
| 3456                                                                 | 7750                   | 17.6               | 2.3E-09           | 3E-13          |                     |                    |                 |                                |           |                                   |           |
| 3624                                                                 | 460                    | 17.7               | 1.3E-10           | 2.78E-13       |                     |                    |                 |                                |           |                                   |           |
| BAR115 Density=1.35 Mg/m3<br>Test Duration 04/06/90 to 28/05/91      |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 1171.58                                                              | 87.9                   | 13.270             | 1.23E-10          | 1.4E-12        | 0.000               |                    |                 | Constant                       | 0         | Constant                          | 6.63E-11  |
| 1387.25                                                              | 1059.2                 | 15.615             | 3.15E-10          | 2.98E-13       | 0.000               |                    |                 | Std Err of Y Est               | 1.06E-10  | Std Err of Y Est                  | 9.74E-11  |
| 1532.33                                                              | 981.5                  | 15.995             | 3.87E-10          | 3.94E-13       | 0.000               |                    |                 | R Squared                      | 0.8981613 | R Squared                         | 0.916952  |
| 2780.50                                                              | 939.7                  | 19.025             | 3.21E-10          | 3.41E-13       | 0.240               | 2.44E-10           | 2.6E-13         | No. of Observations            | 36        | No. of Observations               | 36        |
| 3212.17                                                              | 1555.1                 | 20.405             | 2.39E-10          | 1.53E-13       | 1.325               | 4.06E-10           | 2.61E-13        | Degrees of Freedom             | 35        | Degrees of Freedom                | 34        |
| 3356.33                                                              | 1101.0                 | 20.510             | 1.58E-10          | 1.44E-13       | 1.895               | 4.03E-10           | 3.66E-13        | X Coefficient(s)               | 2.02E-13  | X Coefficient(s)                  | 1.83E-13  |
| 3860.25                                                              | 1549.1                 | 22.265             | 4.64E-10          | 3E-13          | 3.285               | 4.02E-10           | 2.59E-13        | Std Err of Coef.               | 6.98E-15  | Std Err of Coef.                  | 9.42E-15  |
| 4197.00                                                              | 1417.7                 | 23.370             | 3.98E-10          | 2.81E-13       | 4.505               | 3.84E-10           | 2.71E-13        |                                |           |                                   |           |
| 4364.58                                                              | 1519.3                 | 23.925             | 3.93E-10          | 2.59E-13       | 4.825               | 3.41E-10           | 2.25E-13        |                                |           |                                   |           |
| 5084.00                                                              | 1537.2                 | 25.840             | 3.52E-10          | 2.29E-13       | 6.565               | 3E-10              | 1.95E-13        |                                |           |                                   |           |
| 5396.33                                                              | 2212.4                 | 27.075             | 4.27E-10          | 1.93E-13       | 7.535               | 5.01E-10           | 2.27E-13        |                                |           |                                   |           |
| 5732.42                                                              | 2033.1                 | 28.255             | 5.79E-10          | 2.85E-13       | 8.555               | 3.93E-10           | 1.93E-13        |                                |           |                                   |           |
| 5955.25                                                              | 3240.1                 | 29.105             | 5.77E-10          | 1.78E-13       | 9.415               | 5.26E-10           | 1.62E-13        |                                |           |                                   |           |
| 6021.00                                                              | 6108.2                 | 29.775             | 1.41E-09          | 2.3E-13        | 9.825               | 1.03E-09           | 1.69E-13        |                                |           |                                   |           |
| 6140.00                                                              | 6466.7                 | 30.990             | 1.41E-09          | 2.18E-13       | 10.715              | 1.03E-09           | 1.59E-13        |                                |           |                                   |           |
| 6284.08                                                              | 969.5                  | 31.150             | 1.98E-10          | 2.04E-13       | 10.920              | 1.78E-10           | 1.83E-13        |                                |           |                                   |           |
| 6548.17                                                              | 1208.6                 | 31.550             | 2.45E-10          | 2.03E-13       | 11.280              | 2.66E-10           | 2.2E-13         |                                |           |                                   |           |
| 6788.42                                                              | 472.0                  | 31.740             | 1.10E-10          | 2.34E-13       | 11.390              | 8.61E-11           | 1.82E-13        |                                |           |                                   |           |
| 8108.67                                                              | 118.3                  | 31.735             | 3.01E-11          | 2.55E-13       | 11.800              | 2.87E-11           | 2.43E-13        |                                |           |                                   |           |
| 8588.33                                                              | 65.7                   | 31.845             | 5.36E-11          | 8.16E-13       | 11.965              | 4.92E-11           | 7.49E-13        |                                |           |                                   |           |
| SHC25 Density = 1.55/1.36 Mg/m3                                      |                        |                    |                   |                |                     |                    |                 | Regression Output:             |           | Regression Output:                |           |
| 1142                                                                 | 314                    | 0.45               |                   |                |                     |                    |                 | Constant                       | 0         | Constant                          | -5.98E-10 |
| 1592                                                                 | 3137                   | 0.54               | 2.05E-11          | 6.5E-15        |                     |                    |                 | Std Err of Y Est               | 5.05E-10  | Std Err of Y Est                  | 3.24E-10  |
| 2168                                                                 | 4705                   | 0.58               | 2.77E-11          | 5.9E-15        |                     |                    |                 | R Squared                      | 0.8333734 | R Squared                         | 0.945304  |
| 2672                                                                 | 7841                   | 0.62               | 7.21E-11          | 9.2E-15        |                     |                    |                 | No. of Observations            | 6         | No. of Observations               | 6         |
| 3318                                                                 | 7841                   | 2.37               | 4.3E-10           | 5.5E-14        |                     |                    |                 | Degrees of Freedom             | 5         | Degrees of Freedom                | 4         |
| 2958                                                                 | 15683                  | 1.1                | 7.2E-10           | 4.6E-14        |                     |                    |                 | X Coefficient(s)               | 8.39E-14  | X Coefficient(s)                  | 1.14E-13  |
| 3102                                                                 | 31363                  | 2.01               | 3.21E-09          | 1.0E-13        |                     |                    |                 | Std Err of Coef.               | 1.36E-14  | Std Err of Coef.                  | 1.39E-14  |



APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

|                                              |                        |                    |                   |                |                     |                    |                 | LINEAR REGRESSION ANALYSES     |          |                                   |           |
|----------------------------------------------|------------------------|--------------------|-------------------|----------------|---------------------|--------------------|-----------------|--------------------------------|----------|-----------------------------------|-----------|
| Elapsed Time (Hrs)                           | Hydraulic Gradient (i) | Inflow Volume (cc) | Inflow Flux (m/s) | Inflow k (m/s) | Outflow Volume (cc) | Outflow Flux (m/s) | Outflow k (m/s) | Regression Forced Through Zero |          | No Constraints on Regression Line |           |
| Buffer RBMLH05      Density =1.68/1.22 Mg/m3 |                        |                    |                   |                |                     |                    |                 |                                |          |                                   |           |
| Test Duration 24/09/93 to 31/10/94           |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 1144.3                                       | 10.06                  | -2.955             | -1.4E-10          | -1.4E-11       | -3.475              | -2.64E-10          | -2.6E-11        | Constant                       | 0        | Constant                          | -7.08E-11 |
| 1847.7                                       | 20.02                  | -5.495             | -1.9E-10          | -9.4E-12       | -5.980              | -1.91E-10          | -9.5E-12        | Std Err of Y Est               | 1.15E-10 | Std Err of Y Est                  | 9.4E-11   |
| 2441.1                                       | 37.95                  | -6.240             | 1.11E-11          | 2.92E-13       | -9.530              |                    | 0               | R Squared                      | 0.9352   | R Squared                         | 0.9581    |
| 2608.8                                       | 36.53                  | -6.330             | -3.8E-11          | -1E-12         | -9.915              | -1.04E-10          | -2.8E-12        | No. of Observations            | 37       | No. of Observations               | 37        |
| 3017.1                                       | 57.12                  | -6.985             | -8.5E-11          | -1.5E-12       | -10.515             | -6.11E-11          | -1.1E-12        | Degrees of Freedom             | 36       | Degrees of Freedom                | 35        |
| 3280.2                                       | 93.83                  | -7.200             | -6.2E-11          | -6.6E-13       | -10.755             | -8E-11             | -8.5E-13        | X Coefficient(s)               | 5.12E-13 | X Coefficient(s)                  | 5.37E-13  |
| 3616.3                                       | 94.40                  | -7.525             | -4.8E-11          | -5E-13         | -11.115             | -7.61E-11          | -8.1E-13        | Std Err of Coef.               | 2.22E-14 | Std Err of Coef.                  | 1.9E-14   |
| 4168.2                                       | 630.96                 | -6.875             | 2.36E-10          | 3.74E-13       | -11.195             | 1.76E-10           | 2.79E-13        |                                |          |                                   |           |
| 4696.2                                       | 1283.78                | -3.970             | 5.07E-10          | 3.95E-13       | -8.515              | 3.38E-10           | 2.63E-13        |                                |          |                                   |           |
| 5032.0                                       | -73.34                 | -4.520             | -9.4E-11          | 1.28E-12       | -9.070              | -1.02E-10          | 1.39E-12        |                                |          |                                   |           |
| 5825.2                                       | -36.81                 | -5.515             | -7.4E-11          | 2.01E-12       | -10.015             | -7.24E-11          | 1.97E-12        |                                |          |                                   |           |
| 6552.7                                       | -599.20                | -9.880             | -3.3E-10          | 5.59E-13       | -14.145             | -3.23E-10          | 5.39E-13        |                                |          |                                   |           |
| 6976.2                                       | -967.09                | -12.570            | -5.4E-10          | 5.62E-13       | -16.825             | -4.86E-10          | 5.02E-13        |                                |          |                                   |           |
| 7288.2                                       | -996.39                | -15.330            | -5.4E-10          | 5.44E-13       | -19.375             | -4.97E-10          | 4.98E-13        |                                |          |                                   |           |
| 7528.3                                       | 1229.10                | -12.510            | 6.5E-10           | 5.29E-13       | -16.875             | 6.11E-10           | 4.97E-13        |                                |          |                                   |           |
| 8008.9                                       | 547.03                 | -9.885             | 3.07E-10          | 5.62E-13       | -14.260             | 3.19E-10           | 5.83E-13        |                                |          |                                   |           |
| 8200.2                                       | 580.78                 | -8.935             | 3.02E-10          | 5.2E-13        | -13.355             | 2.91E-10           | 5E-13           |                                |          |                                   |           |
| 8680.2                                       | 100.67                 | -8.740             | 3.16E-11          | 3.14E-13       | -13.035             | 4.7E-11            | 4.67E-13        |                                |          |                                   |           |
| 9352.2                                       | 2633.07                | -2.250             | 1.45E-09          | 5.52E-13       | -6.105              | 1.51E-09           | 5.74E-13        |                                |          |                                   |           |
| BARCGEX      Density=1.46 Mg/m3              |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          |                                   |           |
| Test Duration 05/04/94 - 17/11/94            |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 1000.0                                       | 4348.00                | 4.060              | 6.49E-10          | 1.49E-13       |                     |                    |                 | Constant                       | 0        | Constant                          | 5.62E-11  |
| 1362.0                                       | 2144.00                | 4.440              | 3.63E-10          | 1.69E-13       |                     |                    |                 | Std Err of Y Est               | 4.44E-11 | Std Err of Y Est                  | 1.17E-11  |
| 1507.0                                       | 2052.00                | 4.600              | 3.45E-10          | 1.68E-13       |                     |                    |                 | R Squared                      | 0.9577   | R Squared                         | 0.9975    |
| 2350.0                                       | 979.00                 | 5.080              | 2.04E-10          | 2.08E-13       |                     |                    |                 | No. of Observations            | 7        | No. of Observations               | 7         |
| 2657.0                                       | 373.00                 | 5.160              | 1.12E-10          | 3E-13          |                     |                    |                 | Degrees of Freedom             | 6        | Degrees of Freedom                | 5         |
| 3401.0                                       | 68.00                  | 6.400              | 4.83E-11          | 7.1E-13        |                     |                    |                 | X Coefficient(s)               | 1.58E-13 | X Coefficient(s)                  | 1.39E-13  |
| 5417.0                                       | 47.60                  | 6.840              | 5.93E-11          | 1.25E-12       |                     |                    |                 | Std Err of Coef.               | 8.26E-15 | Std Err of Coef.                  | 3.07E-15  |
| RBM01      Density=1.86/1.43 Mg/m3           |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          |                                   |           |
|                                              |                        |                    |                   |                |                     |                    |                 | Regression Output:             |          | Regression Output:                |           |
| 600                                          | 680                    | 2.7                | 1.4E-10           | 2.00E-13       |                     |                    |                 | Constant                       | 0        | Constant                          | 2.1E-11   |
| 984                                          | 1699                   | 3.9                | 1.7E-10           | 1.00E-13       |                     |                    |                 | Std Err of Y Est               | 4.15E-11 | Std Err of Y Est                  | 4.22E-11  |
| 1152                                         | 3398                   | 4.4                | 4.1E-10           | 1.20E-13       |                     |                    |                 | R Squared                      | 0.999275 | R Squared                         | 0.9993986 |
| 1488                                         | 6796                   | 6.6                | 8.8E-10           | 1.30E-13       |                     |                    |                 | No. of Observations            | 6        | No. of Observations               | 6         |
| 1824                                         | 16989                  | 11.2               | 2.0E-09           | 1.20E-13       |                     |                    |                 | Degrees of Freedom             | 5        | Degrees of Freedom                | 4         |
| 1944                                         | 33979                  | 14.6               | 4.1E-09           | 1.20E-13       |                     |                    |                 | X Coefficient(s)               | 1.2E-13  | X Coefficient(s)                  | 1.19E-13  |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed<br>Time<br>(Hrs)           | Hydraulic<br>Gradient<br>(i) | Inflow<br>Volume<br>(cc) | Inflow<br>Flux<br>(m/s) | Inflow<br>k<br>(m/s) | Outflow<br>Volume<br>(cc) | Outflow<br>Flux<br>(m/s) | Outflow<br>k<br>(m/s) | LINEAR REGRESSION ANALYSES     |           |                                   |           |
|------------------------------------|------------------------------|--------------------------|-------------------------|----------------------|---------------------------|--------------------------|-----------------------|--------------------------------|-----------|-----------------------------------|-----------|
|                                    |                              |                          |                         |                      |                           |                          |                       | Regression Forced Through Zero |           | No Constraints on Regression Line |           |
| SC100.28                           |                              |                          |                         |                      |                           |                          |                       | Regression Output:             |           | Regression Output:                |           |
| Test Duration 01/04/85 to 20/01/86 |                              |                          |                         |                      |                           |                          |                       | Constant                       | 0         | Constant                          | 6.44E-11  |
| 1639                               |                              |                          |                         |                      |                           |                          |                       | Std Err of Y Est               | 6.48E-11  | Std Err of Y Est                  | 5.63E-11  |
| 3278                               |                              |                          |                         |                      |                           |                          |                       | R Squared                      | 0.9951631 | R Squared                         | 0.9975638 |
| 8194                               |                              |                          |                         |                      |                           |                          |                       | No. of Observations            | 4         | No. of Observations               | 4         |
| 16389                              |                              |                          |                         |                      |                           |                          |                       | Degrees of Freedom             | 3         | Degrees of Freedom                | 2         |
|                                    |                              |                          |                         |                      |                           |                          |                       | X Coefficient(s)               | 1.46E-13  | X Coefficient(s)                  | 1.4E-13   |
|                                    |                              |                          |                         |                      |                           |                          |                       | Std Err of Coef.               | 3.47E-15  | Std Err of Coef.                  | 4.91E-15  |
| OTHER MISC. DATA                   |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| DWNAB0.5                           |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| Density=0.50 Mg/m3                 |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 334                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 796                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 1592                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 3184                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 4776                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| DWNAB0.65                          |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| Density=0.71 Mg/m3                 |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 203                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 338                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 844                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 1688                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 3376                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 5064                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| DWNAB0.8                           |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| Density=0.82 Mg/m3                 |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 398                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 795                                |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 1590                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 3180                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |
| 4770                               |                              |                          |                         |                      |                           |                          |                       |                                |           |                                   |           |

APPENDIX A3 (Continued): HYDRAULIC PROPERTIES OF BENTONITE SPECIMENS

| Elapsed<br>Time<br>(Hrs) | Hydraulic<br>Gradient<br>(i) | Inflow<br>Volume<br>(cc) | Inflow<br>Flux<br>(m/s) | Inflow<br>k<br>(m/s) | Outflow<br>Volume<br>(cc) | Outflow<br>Flux<br>(m/s) | Outflow<br>k<br>(m/s) | LINEAR REGRESSION ANALYSES     |                                   |
|--------------------------|------------------------------|--------------------------|-------------------------|----------------------|---------------------------|--------------------------|-----------------------|--------------------------------|-----------------------------------|
|                          |                              |                          |                         |                      |                           |                          |                       | Regression Forced Through Zero | No Constraints on Regression Line |
| SC50.38                  |                              |                          |                         |                      |                           |                          |                       |                                |                                   |
|                          |                              | Density=0.84 Mg/m3       |                         |                      |                           |                          |                       |                                |                                   |
|                          | 640                          | 3.4                      | 3.4E-08                 | 5.23E-11             |                           |                          |                       |                                |                                   |
|                          | 1598                         | 7.6                      | 9.1E-08                 | 5.68E-11             |                           |                          |                       |                                |                                   |
|                          | 3196                         | 32.1                     | 1.1E-07                 | 3.35E-11             |                           |                          |                       |                                |                                   |
| SC50.20D                 |                              |                          |                         |                      |                           |                          |                       |                                |                                   |
|                          |                              | Density=1.15 Mg/m3       |                         |                      |                           |                          |                       |                                |                                   |
|                          | 639                          | 0.9                      | 6.9E-10                 | 1.08E-12             |                           |                          |                       |                                |                                   |
|                          | 799                          | 1.8                      | 4.6E-10                 | 5.77E-13             |                           |                          |                       |                                |                                   |
|                          | 1598                         | 2.8                      | 1.1E-09                 | 6.57E-13             |                           |                          |                       |                                |                                   |
| DW50.20W                 |                              |                          |                         |                      |                           |                          |                       |                                |                                   |
|                          |                              | Density=1.28 Mg/m3       |                         |                      |                           |                          |                       |                                |                                   |
|                          | 1019                         | 1.6                      | 7.7E-10                 | 7.54E-13             |                           |                          |                       |                                |                                   |
|                          | 1699                         | 3.6                      | 8.2E-10                 | 4.83E-13             |                           |                          |                       |                                |                                   |
|                          | 8495                         | 6.9                      | 2.4E-09                 | 2.87E-13             |                           |                          |                       |                                |                                   |
| SC50.20                  |                              |                          |                         |                      |                           |                          |                       |                                |                                   |
|                          |                              | Density=1.26 Mg/m3       |                         |                      |                           |                          |                       |                                |                                   |
|                          | 1705                         | 5.5                      | 1.4E-09                 | 8.03E-13             |                           |                          |                       |                                |                                   |
|                          | 3409                         | 23.7                     | 2.7E-09                 | 7.81E-13             |                           |                          |                       |                                |                                   |
|                          | 5455                         | 40                       | 3.1E-09                 | 5.73E-13             |                           |                          |                       |                                |                                   |

## APPENDIX B

### REGRESSION ANALYSIS: DEFINITIONS

Definitions as given by Borland (1993) and put into the context they are used in this project

**Constant:** The y-axis intercept of the regression. For Darcian flow this value is zero in a hydraulic flux versus hydraulic gradient plot.

**Degrees of Freedom (DF):** The number of observations minus the number of independent values being computed by the regression. For Darcian flow where the Flux intercept must be zero:

$$DF = \# \text{ Observations} - \# \text{ of Hydraulic Gradients tested}$$

For analyses where the regression lines are not forced through the origin:

$$DF = \# \text{ Observations} - (\# \text{ Hydraulic Gradients tested} + 1)$$

**Standard Error of Y Estimate:** The estimated standard error of the y values (Flux). It represents the deviation of the observed y values from the values of the linear combinations:

$$C + \beta_1 x_1 + \dots + \beta_k x_k + \text{error} \quad (\text{B.1})$$

Where C is the y-intercept (flux), otherwise known as the constant;  $\beta$  is the x-coefficient or slope of the regression line (hydraulic conductivity in a flux-hydraulic gradient plot) and B is the average of the flux observations (average of y values)

The standard error is computed using the square root of the Sum of the Squares (SSE) divided by the Degrees of Freedom. The SSE is defined as:

$$SSE = C + \beta_1 x_1 + \dots + \beta_k x_k - y \quad (\text{B.2})$$

The standard error of Y estimate is a measure of how closely the data conforms to the ideal regression line projected through it.

**R-Squared or Variance:** A statistic that shows the strength of the relationship between the independent and dependent variables. To calculate the R Squared value the parameters SSE, SSR and SST are required. SSE is as defined in Equation B.2. SSR and SST are respectively;

$$SSR = \text{sum of squares of } (C + \beta_1 x_1 + \dots + \beta_k x_k - B) \quad (\text{B.3})$$

$$SST = \text{sum of squares of } (y - B) \quad (\text{B.4})$$

R-Squared for a regression forced through the origin is defined as;

$$R\text{-Squared} = 1 - (SSE / SST) \quad (\text{B.5})$$

For analyses where the y-intercept is calculated,  $SST = SSR + SSE$ , therefore R-Squared is;

$$R\text{-Squared} = SSR / SST \quad (B.6)$$

X-Coefficient(s): These are the coefficients  $A_1, \dots, A_k$  of the independent (x) variables in the model. In this study these are the set hydraulic gradients.

Standard Error of Coefficient: An estimate of the coefficients (the  $A_n$  values in the  $A_n x_n$  terms). This estimate assumes that i) the model is valid and ii) The observed values' deviations from the model is attributable to a Gaussian distribution of errors.

Each coefficient should be interpreted as the given x-value (Hydraulic Gradient) plus or minus the corresponding standard error of that coefficient. It is this range which is referred to in Chapter 7 as the Statistical Range of Hydraulic Conductivity Values

## **APPENDIX C**

### **SOLUTION OF THE POISEUILLE AND KOZENY-CARMAN EQUATIONS**

|                                                                   |     |
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## LIST OF SYMBOLS USED

$S$  = Surface area per kg of soil

$S_T$  = Surface area/ $m^3$  of soil

$S_w$  = Wetted surface =  $S_T/(1-n)$

$n$  = Porosity =  $V_v/V_T$

$V_v$  = Volume occupied by voids within a specimen

$V_T$  = Total specimen volume (voids and solids)

$V_s$  = Volume occupied by solids portion of a specimen

$e$  = Void ratio =  $V_v/V_s$

$r$  = particle radius

$r_p$  = Pore radius =  $n/S_T = n/(S(n-1))$

$\gamma$  = Dry bulk density ( $kg/m^3$ ) =  $w_s/V_T$

$v'$  = Mean effective flow velocity

$v$  = Apparent velocity =  $v'n$  (at  $i = 1.0$  this is  $k$  for a unit cross-sectional area)

$\Psi$  = Change in potential across specimen ( $erg/g$ ) =  $dyne\ cm\ gm^{-1} = (gL)$

$g$  = Gravitational constant, ( $9.81\ ms^{-2}$ )

$L$  = Length of specimen

$L_e$  = Effective flow path through specimen

$C_s$  = Pore shape factor

$T$  = Tortuosity of flow path =  $L_e/L = f^2$

$\eta$  = Fluid viscosity = 0.01002 Poise (Water at 20°C)

## Appendix C1: The Poiseuille Equation For Flow Through A Capillary

The Poiseuille Equation in its basic form is given as:

$$v' = \gamma r_p^2 \Delta\Psi / (8\eta\Delta L) \quad (C-1)$$

a number of these parameters are physical constants; Namely,

$$\eta = 0.01002 \text{ Poise} \quad 1 \text{ Poise} = 0.10 \text{ kgs}^{-1}\text{m}^{-1}$$

$$g = 9.81 \text{ ms}^{-2}$$

$$\Delta\Psi = 9.81 \text{ m}^2\text{s}^{-2} \text{ (potential change across a 1m long specimen given a head of 1m)}$$

Hence,  $v' = 9.81 \gamma r_p^2 / (0.008016) = 1223.8 \gamma r^2 \text{ (m/s)}$  (C-2)  
and,  $v = v'n$

### SAMPLE SOLUTIONS OF POISEUILLE EQUATION:

#### Sample Solution of Poiseuille Equation for a quartz sand specimen.

Quartz Sand Specimen, 70-140 Frac Sand:  $\gamma = 1760 \text{ kg/m}^3$ ,  $S_T = 3.96 \times 10^4 \text{ m}^2$   
 $n = 0.336$

given that pore radius,  $r_p$  can be estimated using the relationship

$$r_p = n / (S(1-n)) \quad (\text{Mitchell, 1976})$$

$$r_p = 0.336 / (3.96 \times 10^4(1-0.336)) = 1.28 \times 10^{-5} \text{ m}$$

hence,  $v' = 1223.8 \times (1.28 \times 10^{-5})^2 \times 1760 = 3.52 \times 10^{-4} \text{ m/s}$   
 $v = 0.336 (3.52 \times 10^{-4}) \text{ m/s}$   
 $= 1.18 \times 10^{-4} \text{ m/s}$

The actual flow velocity measured for this specimen was  $2.0 \times 10^{-5} \text{ m/s}$ , approximately 1/20th that predicted using the Poiseuille Equation.

The primary reason for the difficulty in using this equation lies with the need to accurately know the total surface area (per  $\text{m}^3$ ) of sand. The Frac Sand considered was a 70-140 grade, that is the diameter of the particles ranged from 0.21mm to 0.105mm. While this is a very narrow range of size in a practical sense, it will result in a considerable range of  $S_T$ .

For example; Given, surface area of a sphere =  $4\pi r^2$   
volume of a sphere =  $4\pi r^3/3$



Given the potential range in particle radius  $r$ , the volume  $V$ , surface area  $s$ , and mass  $m$ , of the individual particles can range from.

$$\begin{array}{llll} r = 1.05 \times 10^{-4} \text{ m} & V = 4.85 \times 10^{-12} \text{ m}^3 & s = 1.39 \times 10^{-7} \text{ m}^2 & m = 1.29 \times 10^{-9} \text{ kg} \\ r = 5.25 \times 10^{-5} \text{ m} & V = 6.06 \times 10^{-13} \text{ m}^3 & s = 3.46 \times 10^{-8} \text{ m}^2 & m = 1.61 \times 10^{-9} \text{ kg} \end{array}$$

The total number of spheres  $\#$ , and the surface area ( $S$ ) present in a  $1 \text{ m}^3$  specimen having a dry bulk density of  $1760 \text{ kg/m}^3$  will range from

$$\begin{array}{lll} r = 1.05 \times 10^{-4} \text{ m} & \# = 1.32 \times 10^{11} & S = 1.66 \times 10^4 \text{ m}^2 \\ r = 5.25 \times 10^{-5} \text{ m} & \# = 1.25 \times 10^{12} & S = 3.96 \times 10^4 \text{ m}^2 \end{array}$$

This will provide a final solution for the Poiseuille equation which gives an estimated flow velocity  $v'$  range of  $3.5 \times 10^{-4}$  to  $8.5 \times 10^{-4} \text{ m/s}$ . The presence of even a small number of finer particles can therefore cause a very significant reduction in the hydraulic conductivity predicted using this relationship.

The Poiseuille equation is clearly limited in its ability to accurately predict the hydraulic conductivity of even ideal spherical granular media. When finer and non-spherical materials such as clays are considered the assumptions inherent in this equation become even more significant. Once again of primary importance in the surface area of the particles and the assumption that particles are spherical (they are not).

#### Sample Solution of Poiseuille Equation for an Illitic Clay Specimen.

Specimen, LHI02B  $\gamma = 1930 \text{ kg/m}^3$ ,  $S_T = 3.96 \times 10^4 \text{ m}^2$   $n = 0.336$

Given average particle diameter  $= 7 \times 10^{-6} \text{ m}$  then  $r = 3.5 \times 10^{-6} \text{ m}$ .

Individual Particle Volume  $= 5.39 \times 10^{-16} \text{ m}^3$  Particle Surface Area  $= 5.13 \times 10^{-11} \text{ m}^2$

Particle Mass  $= 5.39 \times 10^{-16} \times 2750 = 1.48 \times 10^{-12} \text{ kg}$

# Particles  $= 1930 / 1.48 \times 10^{-12} = 1.30 \times 10^{15}$  Total Surface Area  $= 6.67 \times 10^4 \text{ m}^2$

$$r_p = n / (S_T(1-n)) \quad r_p = .336 / (6.67 \times 10^4 (.664)) = 7.6 \times 10^{-6} \text{ m}$$

$$v' = 1223.6 \times 1930 \times (7.6 \times 10^{-6})^2 = 1.79 \times 10^{-5} \text{ m/s}$$

$$v = 0.336 \times 1.79 \times 10^{-5} = \underline{6.01 \times 10^{-6} \text{ m/s}}$$

This compares to a measured  $v$  of  $\underline{5.3 \times 10^{-11} \text{ m/s}}$

If however, the surface area of the clay is taken to be that measured as the specific surface area the results obtained change considerably.

Where  $S = 60 \text{ m}^2/\text{g}$  ( $60000 \text{ m}^2/\text{kg}$ )

$$S_T = 1.16 \times 10^8 \text{ m}^2$$

$$r_p = .336 / (1.16 \times 10^8 (.664)) = 4.36 \times 10^{-9} \text{ m}$$

$$v' = 1223.6 \times 1930 \times (4.36 \times 10^{-9})^2 = 1.03 \times 10^{-11} \text{ m/s}$$

$$v = .336 \times 1.03 \times 10^{-11} \text{ m/s} = 3.5 \times 10^{-12} \text{ m/s,}$$

$$\text{The k actually measured was} = 5.3 \times 10^{-11} \text{ m/s}$$

Where S = 45 m<sup>2</sup>/g (45000 m<sup>2</sup>/kg)

$$S_T = 8.69 \times 10^7 \text{ m}^2$$

$$r_p = .336 / (8.69 \times 10^7 (.664)) = 5.8 \times 10^{-9} \text{ m}$$

$$v' = 1223.6 \times 1930 \times (5.8 \times 10^{-9})^2 = 7.94 \times 10^{-11} \text{ m/s}$$

$$v = .336 \times 7.96 \times 10^{-11} \text{ m/s} = 2.7 \times 10^{-11} \text{ m/s}$$

$$\text{The k actually measured was} = 5.3 \times 10^{-11} \text{ m/s}$$

#### Sample Solution of Poiseuille Equation for a Bentonite Clay Specimen.

$$\text{BARCG05E } \gamma = 1150 \text{ kg/m}^3, n = 0.595$$

$$\text{Given average particle diameter} = 4 \times 10^{-6} \text{ m then } r = 2 \times 10^{-6} \text{ m.}$$

$$\text{Individual Particle Volume} = 3.35 \times 10^{-17} \text{ m}^3 \quad \text{Particle Surface Area} = 5.03 \times 10^{-11} \text{ m}^2$$

$$\text{Particle Mass} = 3.35 \times 10^{-17} \times 2840 = 9.51 \times 10^{-14} \text{ kg}$$

$$\# \text{ Particles} = 1150 / 9.51 \times 10^{-14} = 1.21 \times 10^{16} \quad \text{Total Surface Area} = 6.09 \times 10^5 \text{ m}^2$$

However, as with the illitic clay, the difference between the calculated surface area and that measured is considerable. For a bentonite the specific surface area is approximately 750 m<sup>2</sup>/g (7.5 x 10<sup>5</sup> m<sup>2</sup>/kg) or 8.63 x 10<sup>8</sup> m<sup>2</sup>/m<sup>3</sup> of specimen.

Using the calculated surface area,

$$r_p = n / (S_T(1-n)) \quad r_p = .595 / (6.09 \times 10^5 (.405)) = 2.41 \times 10^{-6} \text{ m}$$

$$v' = 1223.6 \times 1150 \times (2.41 \times 10^{-6})^2 = 8.17 \times 10^{-6} \text{ m/s}$$

$$v = 0.336 \times 1.79 \times 10^{-5} = 4.86 \times 10^{-6} \text{ m/s}$$

This compares to a measured v of 7.9 x 10<sup>-13</sup> m/s

If however, the surface area of the clay is taken to be that measured as the specific surface area the results obtained change considerably.

Where S = 750 m<sup>2</sup>/g

$$S_T = 8.63 \times 10^8 \text{ m}^2$$

$$r_p = .595 / (8.63 \times 10^8 (0.405)) = 1.7 \times 10^{-9} \text{ m}$$

$$v' = 1223.6 \times 1150 \times (1.7 \times 10^{-9})^2 = 4.07 \times 10^{-12} \text{ m/s}$$

$$v = .595 \times 4.07 \times 10^{-12} \text{ m/s} = 2.42 \times 10^{-12} \text{ m/s}$$

$$\text{The measured k for this specimen was } 7.9 \times 10^{-13} \text{ m/s}$$

## Appendix C2: The Kozeny-Carman Equation For Flow Through A Soil

From the Poiseuille equation a number of modifications have been made to try and make the equation produce results which are more representative of the flow which occurs through a porous medium. The development of this equation is taken from Yong and Warkentin (1975).

From the Poiseuille equation

$$v' = \gamma r_p^2 \Delta\Psi / (8\eta\Delta L) \quad (C-3)$$

parameters which account for factors such as pore shape ( $C_s$ ) and the tortuosity of the flow path ( $T$ ) were introduced to the Poiseuille equation.

$$v' = C_s \gamma r_p^2 \Delta\Psi / (\eta\Delta L) \quad (C-4)$$

and since  $v' = v/n$  it is possible to simplify the equation.

$$v' = v \Delta L_e / n \Delta L = v T / n \quad (C-5)$$

$$v = v'n / T \quad (C-6)$$

where,

$$r_p = n / (S_T(1-n)) \quad (C-7)$$

and substituting from C-5, C-6 and C-7

$$v = nv' / T = n^3 C_s \gamma \Delta\Psi / S_T^2(1-n)^2 T \eta \Delta L \quad (C-8)$$

using the effective flow path  $\Delta L_e$  instead of  $\Delta L$  to describe the potential gradient

$$v = nv' / T = n^3 C_s \gamma \Delta\Psi / S_T^2(1-n)^2 T \eta \Delta L_e \quad (C-9)$$

$$v = n^3 C_s \gamma \Delta\Psi / S_T^2(1-n)^2 T^2 \eta \Delta L \quad (C-10)$$

Since  $v=ki$ , and  $\Delta\Psi/\Delta L = i = \Delta h/\Delta x$

$$k = C_s \gamma n^3 / (\eta T^2 S_T^2 (1-n)^2) \quad (C-11)$$

As with the Poiseuille equation, a number of these parameters can be assumed to be constants.

These constants include;

$$C_s = 0.4, \quad \eta = 0.0101 \text{ Poise } (0.00101 \text{ kg m}^{-1} \text{ s}^{-1}) \quad T = f/2.$$

equation C-11 can then be simplified to:

$$k = 200 \gamma n^3 / (S_T^2(1-n)^2)$$

## SAMPLE SOLUTIONS OF KOZENY-CARMAN EQUATION

### Sample Solution of Kozeny-Carman Equation for a Quartz Sand Specimen.

Quartz Sand Specimen, 70-140 Frac Sand:  $\gamma = 1760 \text{ kg/m}^3$ ,  $S_T = 3.96 \times 10^4 \text{ m}^2$   
 $n = 0.336$

$$k = 200 \times 1760 \times (.336)^3 / ((3.96 \times 10^4)^2 (0.664)^2) \\ = \underline{1.93 \times 10^{-5} \text{ m/s}}$$

The actual k measured for this specimen was  $2.0 \times 10^{-5} \text{ m/s}$

### Sample Solution of Kozeny-Carman Equation for an Illitic Clay Specimen.

Specimen, LHI02B  $\gamma = 1930 \text{ kg/m}^3$ ,  $S = 6.0 \times 10^7 \text{ m}^2/\text{Mg}$  ( $S_T = 1.16 \times 10^8$ ),  $n = 0.336$

$$k = 200 \times 1930 \times (.336)^3 / ((1.16 \times 10^8)^2 (0.664)^2) \\ = \underline{2.47 \times 10^{-12} \text{ m/s}}$$

The actual k measured for this specimen was  $5.3 \times 10^{-11} \text{ m/s}$

### Sample Solution of Kozeny-Carman Equation for a Bentonite Clay Specimen.

BARCG05E  $\gamma = 1150 \text{ kg/m}^3$ ,  $S = 7.5 \times 10^8 \text{ m}^2/\text{Mg}$  ( $S_T = 8.63 \times 10^8 \text{ m}^2$ ),  $n = 0.595$

$$k = 200 \times 1150 \times (0.595)^3 / ((8.63 \times 10^8)^2 (0.405)^2) \\ = \underline{3.97 \times 10^{-13} \text{ m/s}}$$

The actual k measured for this specimen was  $7.9 \times 10^{-13} \text{ m/s}$

## **APPENDIX D: SUMMARY OF LITERATURE DATA USED**

# APPENDIX D: SUMMARY OF LITERATURE DATA USED

| Data Origin           | % Clay | Dry Density | Clay Density | Porosity | Testing Gradient | k m/s   | Specific Product | Permeant |
|-----------------------|--------|-------------|--------------|----------|------------------|---------|------------------|----------|
| Wood 1982             | 100    | 1.7         | 1.7          | 0.401    | NR               | 3.0E-14 | Baroid           | DDW      |
| Wood 1982             | 50     | 1.71        | 1.26         | 0.378    | NR               | 2.0E-13 | Baroid           | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 10000            | 2.2E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 5000             | 2.0E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 2000             | 1.9E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 1000             | 1.3E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 10000            | 2.3E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.42        | 1.42         | 0.500    | 10000            | 1.2E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.69        | 1.69         | 0.405    | 10000            | 2.0E-14 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 5000             | 2.0E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.42        | 1.42         | 0.500    | 5000             | 1.0E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.3         | 1.3          | 0.542    | 2000             | 1.9E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.42        | 1.42         | 0.500    | 2000             | 9.0E-14 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.69        | 1.69         | 0.405    | 2000             | 2.0E-14 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 2000             | 3.6E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 2000             | 6.0E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 1000             | 1.5E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 1000             | 6.0E-14 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 1000             | 3.4E-13 | MX-80            | DDW      |
| Pusch 1980b           | 100    | 1.34        | 1.34         | 0.528    | 1000             | 5.0E-13 | MX-80            | DDW      |
| Pusch 1980a           | 100    | 1.1         | 1.1          | 0.613    |                  | 1.0E-12 | MX-80            | DDW      |
| Pusch 1980a           | 100    | 1.22        | 1.22         | 0.570    |                  | 5.0E-13 | MX-80            | DDW      |
| Pusch 1980a           | 100    | 1.39        | 1.39         | 0.511    |                  | 1.5E-13 | MX-80            | DDW      |
| Pusch 1980a           | 100    | 1.55        | 1.55         | 0.454    |                  | 8.0E-14 | MX-80            | DDW      |
| Pusch 1980a           | 100    | 1.7         | 1.7          | 0.401    |                  | 2.0E-14 | MX-80            | DDW      |
| Borgesson et al. 1988 | 100    | 1.7         | 1.7          | 0.401    |                  | 3.0E-14 | MX-80            |          |
| Borgesson et al. 1988 | 100    | 1.39        | 1.39         | 0.511    |                  | 1.9E-13 | MX-80            |          |
| Borgesson et al. 1988 | 100    | 1.09        | 1.09         | 0.616    |                  | 2.0E-12 | MX-80            |          |
| Borgesson et al. 1988 | 100    | 0.89        | 0.89         | 0.687    |                  | 6.0E-12 | MX-80            |          |
| Borgesson et al. 1988 | 100    | 0.49        | 0.49         | 0.827    |                  | 3.8E-11 | MX-80            |          |
| Bucher et al., 1986   | 100    | 1.1         | 1.1          | 0.613    |                  | 4.0E-11 | MX-80            | DDW      |
| Bucher et al., 1986   | 100    | 1.4         | 1.4          | 0.507    |                  | 1.0E-13 | MX-80            | DDW      |
| Bucher et al., 1986   | 100    | 1.45        | 1.45         | 0.489    |                  | 1.0E-13 | MX-80            | DDW      |
| Bucher et al., 1986   | 100    | 1.6         | 1.6          | 0.437    |                  | 1.0E-13 | MX-80            | DDW      |
| Bucher et al., 1986   | 100    | 1.7         | 1.7          | 0.401    |                  | 1.0E-13 | MX-80            | DDW      |

APPENDIX D (Continued): SUMMARY OF LITERATURE DATA USED

| Data Origin           | % Clay | Dry Density | Clay Density | Porosity | Testing Gradient | k m/s   | Specific Product | Permeant |
|-----------------------|--------|-------------|--------------|----------|------------------|---------|------------------|----------|
| Sandia N.L. 1982      | 100    | 1.04        | 1.04         | 0.634    |                  | 2.1E-13 | unknown          | DDW      |
| Sandia N.L. 1982      | 30     | 1.98        | 1.26         | 0.269    |                  | 2.2E-12 | unknown          | DDW      |
| Sandia N.L. 1982      | 100    | 1.57        | 1.57         | 0.447    |                  | 2.3E-13 | unknown          | DDW      |
| Sandia N.L. 1982      | 70     | 1.8         | 1.58         | 0.353    |                  | 1.0E-12 | unknown          | DDW      |
| Sandia N.L. 1982      | 100    | 1.6         | 1.6          | 0.437    |                  | 1.6E-13 | unknown          | DDW      |
| Sandia N.L. 1982      | 100    | 1.63        | 1.63         | 0.426    |                  | 3.2E-13 | unknown          | DDW      |
| Sandia N.L. 1982      | 100    | 1.73        | 1.73         | 0.391    |                  | 2.3E-13 | unknown          | DDW      |
| Sandia N.L. 1982      | 100    | 2           | 2            | 0.296    |                  | 4.0E-14 | unknown          | DDW      |
| Bucher & Speigl, 1986 | 100    | 1.8         | 1.8          | 0.366    |                  | 6.0E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.08        | 1.73         | 0.244    |                  | 5.1E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.13        | 1.77         | 0.225    |                  | 3.9E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.25        | 1.91         | 0.182    |                  | 3.4E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 75     | 2.1         | 1.96         | 0.247    |                  | 8.0E-15 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.05        | 2.05         | 0.278    | 209000           | 6.7E-15 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.13        | 2.13         | 0.250    | 156000           | 5.6E-15 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.12        | 2.12         | 0.254    | 162000           | 4.6E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.12        | 2.12         | 0.254    | 71800            | 3.3E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.12        | 2.12         | 0.254    | 21500            | 4.0E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.09        | 2.09         | 0.264    | 173000           | 6.4E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.22        | 1.91         | 0.193    | 166000           | 4.1E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.22        | 1.91         | 0.193    | 37800            | 3.5E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.22        | 1.91         | 0.193    | 22700            | 3.1E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 50     | 2.22        | 1.91         | 0.193    | 17000            | 2.9E-14 | MX-80            | DDW      |
| Westsik et al., 1982  | 100    | 2.1         | 2.1          | 0.261    | 10               | 2.3E-13 | MX-80            | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.2         | 0.2          | 0.930    | 12               | 7.0E-10 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.35        | 0.35         | 0.877    | 12               | 1.2E-10 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.35        | 0.35         | 0.877    | 12               | 1.3E-10 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.49        | 0.49         | 0.827    | 12               | 2.5E-11 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.48        | 0.48         | 0.831    | 12               | 3.7E-11 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.45        | 0.45         | 0.842    | 12               | 3.3E-11 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 0.44        | 0.44         | 0.845    | 12               | 3.5E-11 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 1.08        | 1.08         | 0.620    | 57               | 9.0E-13 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992  | 100    | 1.03        | 1.03         | 0.637    | 57               | 3.0E-12 | CETCO-CS         | DDW      |

APPENDIX D (Continued): SUMMARY OF LITERATURE DATA USED

| Data Origin             | % Clay | Dry Density | Clay Density | Porosity | Testing Gradient | k m/s   | Specific Product | Permeant |
|-------------------------|--------|-------------|--------------|----------|------------------|---------|------------------|----------|
| Ouyang & Daemen 1992    | 100    | 0.81        | 0.81         | 0.715    | 77               | 2.2E-11 | CETCO-CS         | DDW      |
| Ouyang & Daemen 1992    | 100    | 1.05        | 1.05         | 0.630    | 50               | 1.1E-12 | CETCO-CS         | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.55        | 1.1          | 0.436    | 1124             | 1.3E-12 | BHB              | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.65        | 1.2          | 0.400    | 70               | 1.2E-12 | BHB              | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.68        | 1.23         | 0.389    | 70               | 1.1E-12 | BHB              | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.68        | 1.23         | 0.389    | 70               | 1.4E-12 | BHB              | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.68        | 1.23         | 0.389    | 282              | 7.5E-13 | BHB              | DDW      |
| Radhakrishna & Chan 198 | 50     | 1.8         | 1.36         | 0.345    | 832              | 3.7E-13 | BHB              | DDW      |
| Couture & Seitz, 1983   | 50     | 2           | 1.61         | 0.273    |                  | 9.0E-14 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 100    | 1.66        | 1.66         | 0.415    |                  | 6.0E-14 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 50     | 2.04        | 1.67         | 0.258    |                  | 6.0E-14 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 50     | 2.08        | 1.7          | 0.244    |                  | 4.5E-14 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 100    | 1.74        | 1.74         | 0.387    |                  | 3.0E-13 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 100    | 1.85        | 1.85         | 0.349    |                  | 3.0E-14 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 100    | 2.1         | 2.1          | 0.261    |                  | 7.0E-15 | WB-EG200         | DDW      |
| Couture & Seitz, 1983   | 100    | 2.15        | 2.15         | 0.243    |                  | 7.0E-15 | WB-EG200         | DDW      |
| Dixon & Miller, 1995    | 100    | 1.13        | 1.13         | 0.602    | 25-200           | 1.9E-12 | MI-Ash           | DDW      |
| Dixon & Miller, 1995    | 100    | 1.16        | 1.16         | 0.592    | 25-200           | 2.4E-12 | MI-Ash           | DDW      |
| Dixon & Miller, 1995    | 100    | 1.13        | 1.13         | 0.602    | 20-170           | 1.6E-12 | MI-CG            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.32        | 1.32         | 0.535    | 4-150            | 3.9E-12 | MI-CG            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.31        | 1.31         | 0.539    | 150-1250         | 3.9E-13 | MX-80            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.07        | 1.07         | 0.623    | 150-1500         | 1.0E-12 | CETCO-CS20       | DDW      |
| Dixon & Miller, 1995    | 100    | 1.25        | 1.25         | 0.560    | 150-1500         | 4.6E-13 | BC-ES            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.17        | 1.17         | 0.588    | 150-1500         | 1.6E-12 | BHB-404          | DDW      |
| Dixon & Miller, 1995    | 100    | 1.15        | 1.15         | 0.595    | 150-1500         | 1.2E-12 | MI-FJ            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.18        | 1.18         | 0.585    | 150-1500         | 1.6E-12 | MI-FS200         | DDW      |
| Dixon & Miller, 1995    | 100    | 1.22        | 1.22         | 0.570    | 150-1500         | 9.4E-13 | WB-UNTR          | DDW      |
| Dixon & Miller, 1995    | 100    | 1.12        | 1.12         | 0.606    |                  | 3.0E-13 | TMP-CS           | DDW      |
| Dixon & Miller, 1995    | 100    | 1.19        | 1.19         | 0.581    |                  | 1.7E-12 | RAPI             | DDW      |
| Dixon & Miller, 1995    | 100    | 1.34        | 1.34         | 0.528    |                  | 2.2E-12 | RSS              | DDW      |
| Dixon & Miller, 1995    | 100    | 1.31        | 1.31         | 0.539    |                  | 5.0E-13 | ACC-MX80         | DDW      |
| Dixon & Miller, 1995    | 100    | 1.07        | 1.07         | 0.623    | 150-1500         | 5.6E-12 | HK-AS            | DDW      |
| Dixon & Miller, 1995    | 100    | 1.2         | 1.2          | 0.577    | 150-1500         | 2.9E-12 | KM-KJ            | DDW      |
| Dixon, unpubl. data     | 100    | 0.82        | 0.82         | 0.711    | 400-5000         | 4.5E-12 | Sask             | DDW      |



APPENDIX D (Continued): SUMMARY OF LITERATURE DATA USED

| Data Origin         | % Clay | Dry Density | Clay Density | Porosity | Testing Gradient | k m/s   | Specific Product | Permeant |
|---------------------|--------|-------------|--------------|----------|------------------|---------|------------------|----------|
| Dixon, unpubl. data | 45     | 1.79        | 1.26         | 0.370    | 250-5000         | 7.7E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 0.5         | 0.5          | 0.824    | 350-5000         | 5.0E-12 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 0.71        | 0.71         | 0.750    | 200-5000         | 4.4E-12 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 1.2         | 1.2          | 0.577    | 800-4000         | 6.3E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 50     | 1.73        | 1.28         | 0.391    | 1020-8600        | 1.5E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 1.33        | 1.33         | 0.532    | 460              | 1.5E-12 | Sask             | DDW      |
| Dixon, unpubl. data | 25     | 1.92        | 1.05         | 0.324    | 680-34000        | 3.8E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 50     | 1.86        | 1.43         | 0.345    | 680-34000        | 1.2E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 1.14        | 1.14         | 0.599    | 750-1500         | 3.1E-12 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 1.18        | 1.18         | 0.585    | 850-5100         | 8.5E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 50     | 1.44        | 0.99         | 0.493    | 760-4560         | 5.0E-13 | Sask             | DDW      |
| Dixon, unpubl. data | 50     | 1.48        | 1.03         | 0.479    | 780-4700         | 2.4E-12 | Sask             | DDW      |
| Dixon, unpubl. data | 100    | 1.46        | 1.46         | 0.486    | 1600-16000       | 1.5E-13 | Sask             | SCSSS    |
| Dixon, unpubl. data | 50     | 1.64        | 1.15         | 0.423    | 1800             | 6.6E-13 | Sask             | SCSSS    |
| Dixon, unpubl. data | 50     | 1.71        | 1.26         | 0.398    | 1700-5500        | 7.0E-13 | Sask             | SCSSS    |
| Dixon, unpubl. data | 100    | 0.85        | 0.85         | 0.701    | 600-3500         | 5.8E-11 | Sask             | SCSSS    |
| Dixon, unpubl. data | 100    | 1.26        | 1.26         | 0.556    | 1600-8100        | 2.6E-12 | Sask             | SCSSS    |
| Dixon, unpubl. data | 50     | 1.58        | 1.13         | 0.444    | 1700             | 2.6E-11 | Sask             | SCSSS    |
| Dixon, unpubl. data | 50     | 1.3         | 0.87         | 0.542    | 1500             | 1.3E-11 | Sask             | SCSSS    |
| Dixon, unpubl. data | 50     | 1.67        | 1.21         | 0.412    | 1500-3000        | 7.2E-13 | Sask             | SCSSS    |
| Dixon, unpubl. data | 100    | 1.24        | 1.24         | 0.563    | 1700             | 6.0E-13 | Sask             | SCSSS    |
| Dixon, unpubl. data | 25     | 1.9         | 1.03         | 0.331    | 150-33300        | 6.3E-13 | Sask             | SCSSS    |