HYDRAULIC DESIGN, OPERATION AND CLOGGING OF LEACHATE INJECTION PIPES IN BIOREACTOR LANDFILLS

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HYDRAULIC DESIGN, OPERATION AND CLOGGING OF LEACHATE INJECTION PIPES IN BIOREACTOR LANDFILLS

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A Thesis/Practicum submitted to the Faculty of Graduate Studies of The University of Manitoba in partial fulfillment of the requirement of the degree

OF

Master of Science

Jan Lozecznik Szyszeja
"Life teach us how to live"

ABSTRACT

Hydraulic design and operation of leachate injection pipes in bioreactor landfills were analyzed in this study. A conceptual framework that links the physical properties and hydraulic performance of the injection pipe with the overall design of the injection system was presented. A sensitivity analysis was completed for various literature reported pipe design and operation characteristics, showing that pipe diameter, perforation spacing and shape, pipe material, inlet flow rate and hydraulic head influence the perforation discharge along the pipe length. The sensitivity analysis suggested that long perforated pipes require high inlet flow rate and hydraulic head, resulting in high differences in perforation discharge between first and last perforation along the length of the pipe. This suggests that considerations should be given to design shorter length perforated pipes to overcome any pipe hydraulic limitations to uniformly discharge liquid along the length of the pipe.

Field studies of pipes used in leachate injection and collection systems have showed that leachate transmission pipes can clog with biological, chemical and soil materials over time. Clogging can impact the operating performance and service life of the injection system. Full-scale pipes were permeated leachate to provide insights into biological, chemical, and physical clogging mechanisms involved in clogging of leachate injection pipes under pressurized conditions. Two pipe external diameters (0.05 and 0.1 m) and three different average flow rates (0.25, 0.55 and 1.2 L/s) were tested. COD leachate concentrations and pH values between influent and effluent of the pipes did not change considerably during this laboratory study, indicating that not significant removal of organic acid occurred within the pipes. Calcium was removed, ranging from 25 to 50%

within the pipes, which resulted in an increase in inorganic clog accumulation within the pipes. High influent leachate pH values of 8.3 to 9.4 where measured, with higher pH occurring as flow rate within the pipe increased. Clog material accumulated on the inner surface of the pipes was physically and chemically analyzed and was mainly comprised of organic and inorganic material. Magnesium, calcium and carbonate where the main inorganic clog constituents with hydromagnesite ($Mg_5(CO_3)_4(OH)_2 4H_2O$) present as the sole phase mineral. More clog material, about 2 to 4.5 times, was accumulated within the small pipe diameter (0.05 m) for similar mass loads and flow rates compared to the larger pipe diameter (0.10 m), indicating that surface area has a direct effect on clog accumulation within the pipes. The experimental results showed that pipe physical characteristics and the hydraulic operation have a direct impact on changes in leachate composition and clog development within leachate injection pipes.

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CHAPTER 1: INTRODUCTION

1.1 PROBLEM DEFINITION

Modern landfills are constructed with large amounts of engineered infrastructure integrated in the design to safeguard the environment. An emerging landfill management strategy, called leachate recirculation, has received considerable attention as an economical means to increase refuse moisture content, thereby accelerate waste degradation and reduce the contaminating lifespan of a landfill (Reinhart *et al.*, 1997). Leachate recirculation involves collecting the leachate at the base of the landfill and injecting it back into the waste. Landfills that aim to enhance waste degradation are termed bioreactor landfills.

There are various methods of leachate recirculation, such as: surface spraying or irrigation, infiltration ponds, vertical injection wells, and horizontal injection trenches. A horizontal injection trench (HIT) is comprised of a perforated pipe surrounded by granular material of high permeability and positioned at various depths within the refuse. HIT have the capabilities of recirculating large quantities of leachate without interfering with waste placement operation compared to other recirculation strategies. Despite these advantages, there has been limited well characterized, long-term, field performance studies of HIT used in bioreactor landfills (Townsend 1995, Reinhart *et al.* 1997, Warzinski *et al.* 2000, and Yazdani 2002). To achieve optimum benefits of a bioreactor landfill, the method of leachate recirculation should uniformly wet the refuse; however, current HIT design methodologies (Townsend 1995, Al-Yousfi and Pohland 1998, and

Maier 1998) do not consider the hydraulic design of the perforated pipe to convey leachate along the trench length in the landfill.

Field studies of landfills around the world have indicated that the pipes used to transmit leachate in leachate collection systems (see Rowe and VanGulck 2004 for summary) or injection systems (Turk et al., 1997, Manning 2000, Maliva et al., 2000, Yazdani 2002, Bouchez *et al.,* 2003) can experience significant amounts of clogging due to the development of microbial slimes, precipitation of inorganic materials, and straining/filtration of suspended solids. From conclusions drawn from studies of clogging in porous media and filters used in leachate collection systems (VanGulck and Rowe 2004), it is likely that clogging in the perforated pipe within HIT is dependent on the leachate composition and the hydraulic design and operation of the recirculation system (inlet flow rate, inlet hydraulic head, pipe material, diameter and length, and perforation shape and spacing). Clog accumulation within the perforated pipe of a HIT can potentially impair the design hydraulic performance by reducing pipe diameter and perforation openings, and increasing pipe roughness. A change in the hydraulic performance can potentially affect the uniform infiltration of leachate into the refuse and therefore uniform waste degradation. Leachate recirculation systems are expected to perform until the organic fraction of the refuse is decomposed or leachate contaminant concentrations are reduced to desired level.

1.2 SCOPE OF THE THESIS

This study is undertaken to address two critical design and operation considerations of HIT in bioreactor landfills. The first consideration involves theoretical analysis of fluid flow in a perforated pipe to assess the influence of hydraulic design and operation of the

HIT to achieve uniform wetting of the refuse. The second consideration involves characterizing the mechanisms responsible for clogging in leachate transmission pipes through well-controlled laboratory experiments. The specific objectives of the research undertaken are to:

- Develop a conceptual framework that can be used in design of HIT considering the physical properties and hydraulic performance of the perforated pipe based on leachate availability and landfill dimension, combined with the hydraulic operation of the trench and pump operation.
- Investigate capabilities (or limitations) of current HIT design and operation through a sensitivity study of fluid flow through a perforated pipe to assess the importance of perforated pipe design to achieve uniform waste wetting.
- Investigate the influence of pipe diameter and flow rate on the changes (if any) in leachate composition as it is transmitted through pressurized pipe in the laboratory.
- Evaluate the composition and physical properties of any clog material that developed within the laboratory pipes.

1.3 THESIS OUTLINE

Chapter 2 reviews current leachate injection methodologies in bioreactor landfills and the mechanisms of clogging that occurs in leachate collection system porous media that could also occur in leachate transmission pipes. Chapter 3 describes the conceptual framework for HIT design and operation and describes the results of the theoretical analysis of fluid flow in a perforated pipe. Chapter 4 describes the results from laboratory pipes permeated with leachate that monitor any changes in leachate composition with time and the composition of any clog material accumulated within the pipe. Chapter 5 presents the conclusions and recommendations for future work.

CHAPTER 2: LITERATURE REVIEW

2.1 INTRODUCTION

Landfilling is one of the most common methods used around the world to dispose municipal and industrial wastes. Modern landfills commonly incorporate an engineered barrier system underneath of the waste that may include a liner(s) in combination with a leachate collection system to reduce contaminant migration into any subsurface aquifers (Rowe 2004). Above the refuse pile a cover system, comprised of soil or geosynthetic, is used to control liquid infiltration into the refuse and gas release into the atmosphere. When water comes into contact with refuse, it picks up the constituents of the waste and is called leachate. Leachate is formed largely due the net infiltration through the landfill cover and from degradation of the refuse itself. Refuse degradation occurs through sequences of biological, chemical and physical processes (Parkin and Owen 1986, Kjeldsen *et al.* 2002) which generate biogas that is mainly composed of carbon dioxide and methane gas.

In recent years, management of landfills as controlled reactor systems, called bioreactor, have incorporated large amount of engineered infrastructure to safeguard the environment. Some bioreactors employ leachate recirculation to increase waste moisture and biological activity within the refuse in attempts to enhance gas production, accelerate waste stabilization rates, store and treat leachate within the landfill, and reduce the contaminating lifespan of the landfill (Reinhart and Townsend 1997).

Leachate recirculation involves the collection of leachate at the base of the landfill, storage in a sump or lagoon, and injecting it back into the refuse. Recirculation techniques may be classified as either surface or subsurface applications. Methods of surface applications include surface spraying and surface ponds, while subsurface applications include vertical injection wells and horizontal injection trenches (each will be discussed in detail below). Pipes are commonly used to transmit leachate from the landfill to the sump or lagoon and sometimes to the final discharge location.

Field studies of leachate collection and injection systems have shown that leachate transmission pipes can accumulate biological, chemical, and soil materials within the pipe that can clog the pipe and perforations (Brune *et al.,* 1991, Turk *et al.,* 1997, Fleming *et al.,* 1999, Manning *et al.,* 2000, Maliva *et al.,* 2000, Yazdani 2002, and Bouchez *et al.,* 2003). Clogging can impair the hydraulic performance of the transmission pipe to convey leachate, and in some cases, deteriorate the function of this engineered system. However, the rate of clog development in leachate transmission pipes for various hydraulic designs is unknown, and therefore the service life of this engineered system is unknown. VanGulck and Rowe (2004a) hypothesized that the clogging process in drainage stone used in leachate collection systems also occurs in leachate transmission pipes.

The first objective of this chapter is to review current methods of leachate injection in bioreactor landfills. The second objective is to review the mechanisms of clogging that occurs in leachate collection system porous media that could also occur in leachate transmission pipes.

2.2 LEACHATE RECIRCULATION TECHNIQUES

The following section presents current methodologies of leachate recirculation and some of the main advantages and disadvantages of each method for use in bioreactor landfills.

2.2.1 Surface spraying

Surface spraying has been used in some countries where high rainfall associated with high infiltration into the refuse leads to the production of large volumes of dilute leachate or where discharge of leachate to sewer pipelines is unavailable and off site leachate disposal is costly (Gray *et al.* 2004). The various methods employed to spray leachate include rain guns, sprinklers, spray nozzles, and tanker trucks. Surface spraying is a flexible method that depends on the leachate availability and can accommodate a wide range of loading rates and location of application (Gray *et al.* 2004). Surface spraying is also used to reduce leachate volume through evaporation (Reinhart and Townsend 1997). Disadvantages of surface spraying include the potential for increased odors, aerosol dispersion endangering workers environment, clogging of the application devices, stormwater contamination, formation of hard pan deposits which limit infiltration, and incompatibility to continue recirculation after final cover has been constructed (McCreanor 1998).

2.2.2 Surface Pond

A surface pond consists of removing an upper waste lift at the landfill and filling the depression with leachate (Reinhart and Townsend 1997). The leachate in the pond has the potential to infiltrate into the refuse. As required, the pond is filled with leachate to continue the infiltration. Surface ponds can be used as an extra leachate storage facility and to promote evaporation of leachate (Miller *et al.* 1993 and Watson 1993). Disadvantages of surface ponds include a limited recharge area, may not be compatible with northern climates, floating refuse, and are not compatible with final landfill cover (Reinhart and Townsend 1997, McCreanor 1998).

2.2.3 Vertical Injection wells

Vertical injection wells consist of large or small perforated or slotted pipes installed vertically within waste lifts at various horizontal spacings to achieve a uniform spread of leachate within the waste (Al Yousfi 1992). Leachate is injected into the well for a set period of time from tanker trucks, hoses or stationary pipes to infiltrate into the surrounding refuse. Vertical wells are capable of injecting a large amount of leachate, additionally, they are easy to construct, have low material cost and are compatible with the landfill closure. However, an individual well has a limited zone of influence to increase refuse moisture content, is susceptible to seepage out of the landfill surface and side slopes, and can fail if landfill subsidence is large (McCreanor 1998). Additionally, clogging within the well casing, screen, and filter pack may impair recirculation performance and the system.

2.2.4 Horizontal Injection Trenches

Horizontal injection trenches commonly involve placement of a high permeability drainage material, containing a perforated pipe, within a trench that is positioned at various horizontal and vertical spacings within the waste cell. The perforated pipe conveys leachate from the landfill surface into the landfill and discharges the liquid into the refuse via the trench. The leachate permeates through the granular material within the trench and enters into the waste. This system may operate under gravity or pressurized conditions depending of the landfill liquid management strategy and design. Advantages of this system include: low material costs, large volume of leachate can be recirculated, system does not interfere with landfill operation, and is compatible with landfill closure (Reinhart and Townsend 1997, McCreanor 1998). Nevertheless, these systems are inaccessible for remediation, susceptible to surface and side slopes leachate seeps, the system can fail due to landfill subsidence, and clogging can occur within the perforated pipe and backfill material that can impair the recirculation performance.

2.3 HORIZONTAL INJECTION TRENCH

Reinhart and Townsend (1997) summarized pilot and full scale bioreactor experiences in Germany, Australia, and USA. With respect to leachate injection systems, the focus of the summary by these authors was focused on volume balance between leachate produced and leachate injection. Little documentation was provided to account for the hydraulic design of horizontal injection trenches. Horizontal injection trench (HIT) operation and design methodologies are described in detail in this section to demonstrate the hydraulic interrelations within the HIT components and the importance of perforated pipe hydraulic considerations in HIT performance.

2.3.1 Horizontal injection trenches operation

HIT are employed to deliver a specific amount of volume of liquid into the landfill. Depending on the nature of the refuse, compaction and the cover material used, waste placed within the cell will have an as placed moisture content. Liquid is added to the waste through the HIT to increase the refuse moisture content of the waste to or above field capacity to enhance refuse degradation (Reinhart and Townsend 1997). A pump and pipe network is used to convey leachate from the sump or tank to the trench location at a specified flow rate and hydraulic head. Commonly, the pipe network consists of a main header line and a series of horizontal distribution pipes that connect the main header to the perforated pipe in the trench, as shown in Figure 2.1. As liquid is conveyed along the perforated pipe, leachate is discharged from the perforations into the trench. The discharged fluid permeates into the refuse via the backfill material. If the trench fills with leachate and injection continues, the system becomes pressurized. The drainage of liquid into the waste is directly related to the liquid level in the trench, the unsaturated/saturated waste hydraulic conductivity of refuse, and the perforated pipe design and operation.

2.3.2 Horizontal injection trenches current design methodologies

A set of design methodologies for HIT were presented by Townsend (1995) and Al-Yousfi and Pohland (1998) which provide a conceptual and mathematical approach to select HIT horizontal spacing within the landfill. Townsend (1995) method hypothesizes horizontal injection lines as a horizontal injection well within the landfill. The method assumes a predefined shape of the saturation area (i.e. zone of influence) around the perforated pipe. The extent or distance of saturated area around the trench is a function of the pressure of fluid leaving the perforated pipe and hydraulic conductivity of the refuse. Steady state fluid flow conditions, constant fluid pressure leaving the pipe, and a constant refuse hydraulic conductivity are assumed. The analytical equation provides an estimate of the vertical and horizontal extents for the saturated zone of refuse around a HIT.

Al-Yousfi and Pohland (1998) developed an analytical solution to assess horizontal spacing of horizontal injection perforated pipes embedded within refuse (i.e., no trench or backfill material). This method provides a maximum space between two adjacent perforated pipes in the horizontal plane based on waste properties, overlapping of wetting refuse and head mound by leachate release through pipe perforations on the waste. The method applies Darcy's law for flow in transversal and horizontal axis, and assumes that the horizontal and vertical hydraulic conductivities within the waste are approximately equal and waste is completely saturated. This method generates a set of equations that describe the head mound on the waste supplied by two perforated pipes as a parabolic equation. This method suggests that liquid is pumped through two consecutive perforated pipes at certain hydraulic head and it is released from the pipe perforations equally spaced (L_i) at certain head mound (h_1), implying that hydraulic head along the length of the pipe is constant. This head mound into the waste has a parabola shape between the two perforated pipes constant and equally spaced (x_i) along the length of the pipelines, as shown schematically in Figure 2.2.

Although, Townsend (1995) and Al-Yousfi and Pohland (1998) provided conceptual and mathematical approaches to assess the hydraulic performance of horizontal injection systems, they do not consider the hydraulic head losses within the pipe, spatial rate of perforation discharge, or the hydraulic interactions between fluid flow in the perforated pipe and the trench, or interactions between fluid flow within the trench and into the refuse. Thus, hydraulics of fluid flow within the perforated pipe and the influence of pipe design and operation on injection system performance are not considered in current design methods. With specific reference to the methods described above, consideration is not given to the fact that a pipe may not have a constant hydraulic head or perforation discharge along the length of the line. This will impact the infiltration of liquid into refuse via the trench.

2.4 CLOGGING IN LEACHATE TRANSMISSION PIPES

Laboratory and field studies have demonstrated that drainage material from leachate collection system (LCS) can experience significant amount of clogging due to development of microbial slimes, precipitation of inorganic materials, and straining/filtration of suspended solids (Brune *et al.* 1991, Armstrong 1998, Rowe *et al.* , 2000a,b, 2004, 1998a,b, Fleming *et al.*, 1999, 2004 , Cooke *et al.,* 1999, 2001, 2005, McIsaac *et al.,* 2000, 2005, VanGulck *et al.,* 2003, 2004a,b). Clog accumulation within the drainage material decreases the porosity and hydraulic conductivity of the porous media and can impair the drainage of leachate towards the collection pipes, resulting in the development of a leachate mound on the liner. The service life of the collection system is reached when it can not maintain the leachate mound acting on the liner to a value below the design value (typically 0.3 m).

2.4.1 Theoretical development of clogging in leachate collection system

Microorganisms are ubiquitous in refuse and are transported by leachate percolation through the refuse into the collection system where they can attach to the surface of the drainage stone and grow as biofilm. Leachate that passes through this biofilm provides organics, nutrients and environmental conditions conducive for microbial growth. Volatile fatty acids (VFA) represent an important component of dissolve organic matter in landfill leachate that can be consumed within the biofilm. Biofilm growth is largely a result of microorganisms carrying out acetogenesis of propionate and butyrate and the methanogenesis of acetate in anaerobic biofilms. In anaerobic conditions, by-products of microbial fermentation (H_2O and CO_2) leads to the generation of carbonic acid (H_2CO_3). H_2CO_3 can dissociate to carbonate which may combined with metals like calcium, which is commonly supersaturated in leachate, to precipitate minerals like calcium carbonate ($CaCO_3$). Consumption of VFAs (a strong acid) to produce carbonic acid (a week acid) results in an increase in leachate pH. Thus, VFA destruction results in an increase in carbonate content in the leachate and the increase in leachate pH, both of which may induce the precipitation of carbonate based minerals (VanGulck *et al.* 2003, 2004a,b). A conceptual model was developed to capture the primary mechanisms of clogging within the granular material of a leachate collection system and to predict the service life of these systems, called BIOCLOG (Cooke 1997, Cooke *et al.* 1999, 2001, 2005). Some of the main mechanisms incorporated in BIOCLOG are explained as follows.

2.4.2 Conceptual development of clogging in leachate collection system

Conceptually, clogging occurs due to the build up of a biofilm or active film layer and an inorganic or inactive film layer on the surface of the drainage stone, as shown schematically in Figure 2.3. The active film consists of a biofilm layer where the majority of VFAs are consumed by acid degraders. The changes in leachate composition and the fluid flow characteristics through the drainage stone may control the rate of VFA consumption, the attachment/detachment of suspended or attached microorganisms and therefore net growth from this layer. The inactive film contains precipitated metals and the net attachment of fixed suspends solids from the leachate onto the drainage stone. The change in fluid flow through the porous media as clogging occurs may affect the attachment/detachment of inorganic particles (Cooke *et al.* 1999, 2001, 2005).

2.4.3 Clogging observation in leachate transmission pipes

Landfills pipes employed in collection and recirculation systems can clog with biological, chemical and soil materials over time (Brune *et al.*, 1991, Turk *et al.*, 1997, Fleming *et al.*, 1999, Manning *et al.*, 2000, Maliva *et al.*, 2000, Yazdani 2002, and Bouchez *et al.*, 2003). However, clogging is not considered in current design methodologies for horizontal injection trenches (Townsend 1995 and Al-Yousfi and Pohland 1998). Clog accumulation within the perforated pipe of a HIT may develop to a point where the injection system can no longer effectively transmit leachate back to the landfill, thus reaching the service life the system. The rate and mechanisms of clog development in leachate injection pipes is currently unknown for different pipe physical characteristics and hydraulic operation adopted; hence the service life of this system is unknown.

2.5 CONCLUSIONS

Horizontal injection trenches offer performance and design advantages compared to other methods of leachate injection in bioreactor landfills to increase refuse moisture content. Design methods presented by Townsend (1995) and Al-Yousfi and Pohland (1998) can be used to assess required HIT spacing within the waste cell to uniformly wet the waste. However, both methods of analysis do not consider: hydraulics of fluid flow within the perforated pipe, influence of pipe design and operation on injection system performance, and spatial variation in perforation discharge along the length of the line. Additionally, optimum HIT design requires consideration of the movement of fluid within the injection pipe, trench backfill material, and surrounding refuse.

Clogging of the drainage material used in leachate collection systems is mainly due to the accumulation of volatile and inorganic solids within the porous media. The accumulation of volatile solids is the net effect of growth and decay of attached microorganisms (biofilm), attachment of suspended microorganisms from the leachate onto the drainage stone, and biofilm detachment. The accumulation of inorganic solids is a result of mineral precipitation (a function of VFA fermentation from attached and suspended microorganisms), attachment of suspended inorganic particles from the leachate onto the drainage stone, and detachment from the drainage stone into the leachate. As the volatile and inorganic films increase in thickness, the porous media and hydraulic conductivity decreases. The process that contributes to clogging within the drainage stone of a collection systems are hypothesized to occur within leachate transmission pipes. Clogging has been observed in leachate transmission pipe. However, the mechanisms and processes that contributed to clogging in pipes and impact on HIT design has not yet been considered. Well controlled laboratory experiments are required to determine the influence of pipe hydraulic design and operation on leachate treatment as it is transmitted through the pipes and to gain insights into the mechanisms involved in clog development within HIT pipes.

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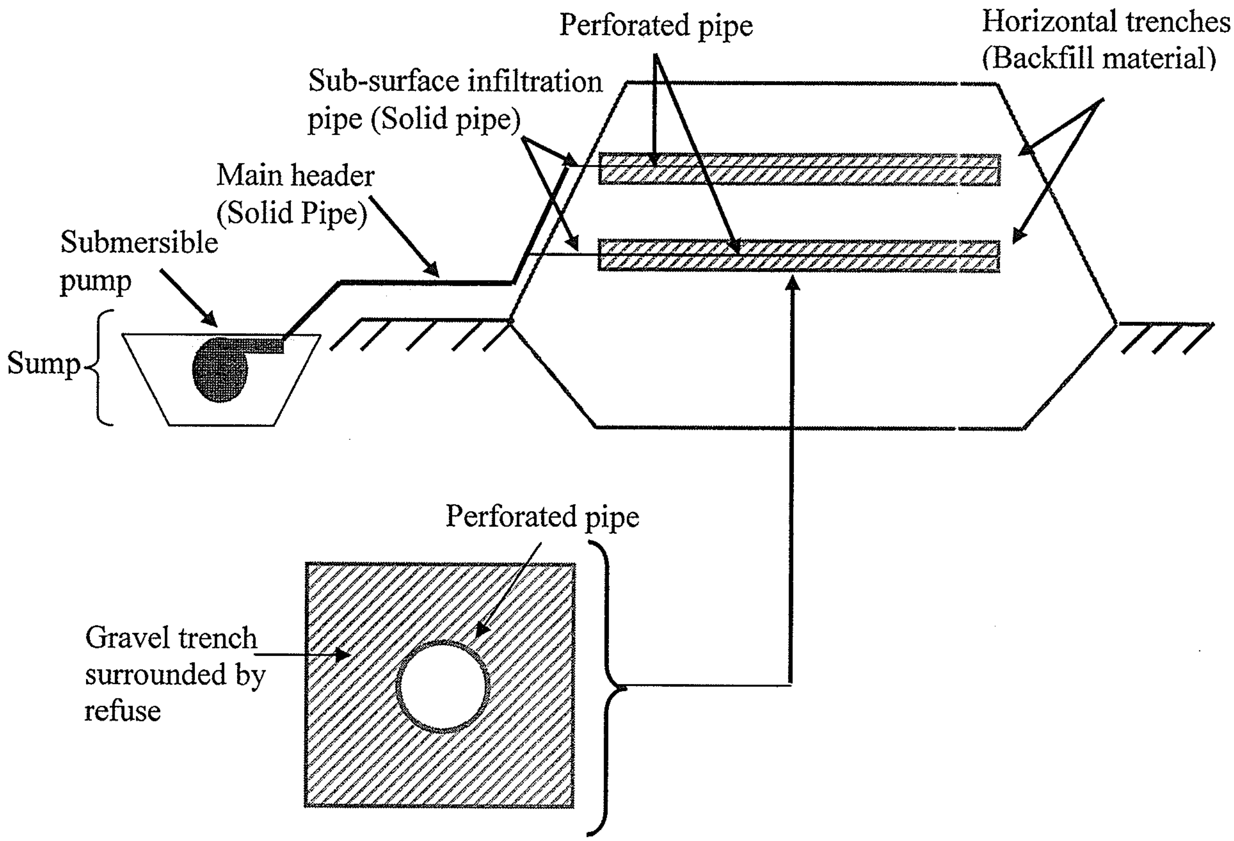

Figure 2.1 Schematic representation of horizontal injection trenches in a bioreactor landfill. (Not to scale).

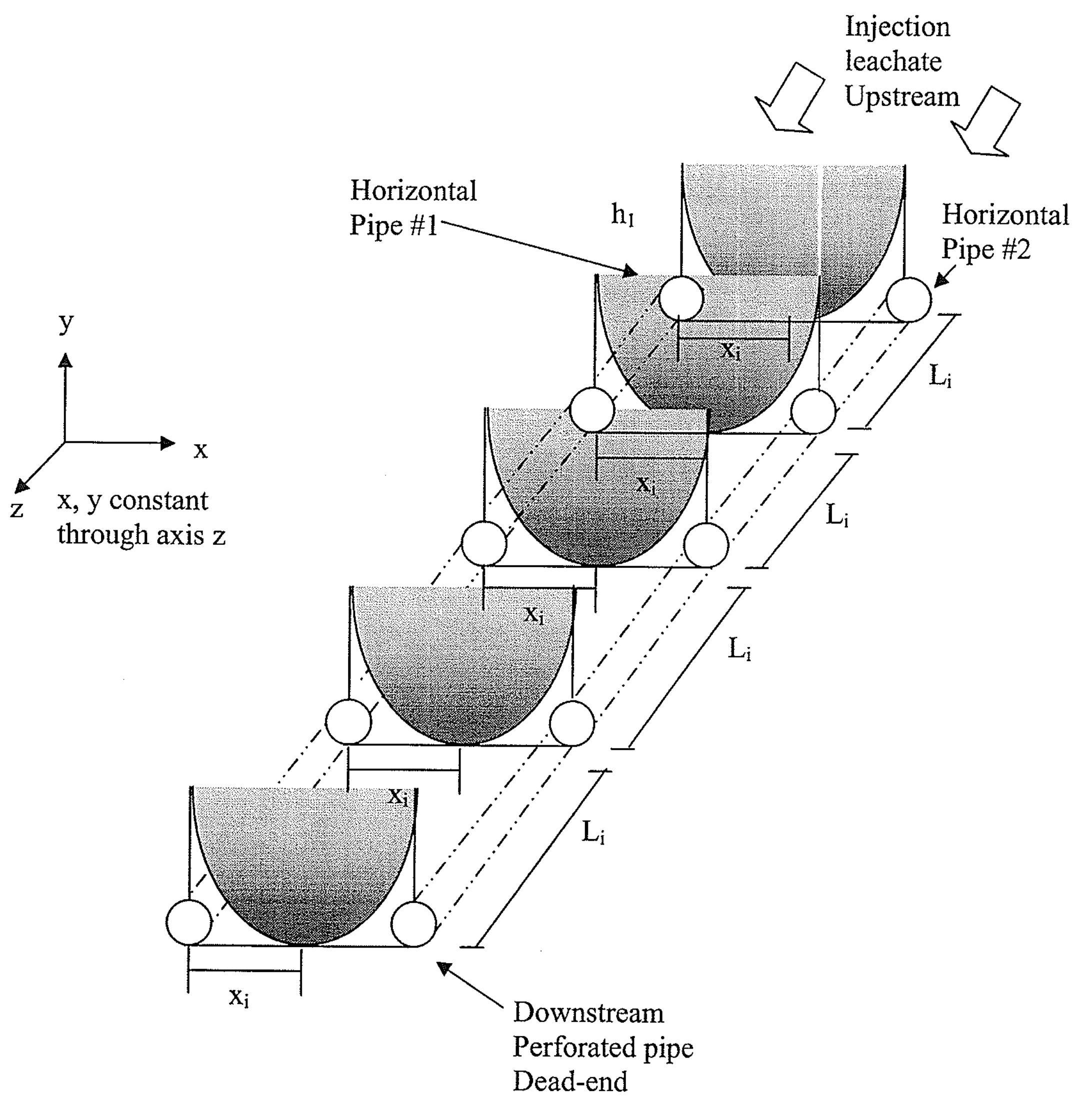

Figure 2.2 Schematic representation of pipe hydraulics conditions assumed by Al-Yousfi and Pohland (1998)

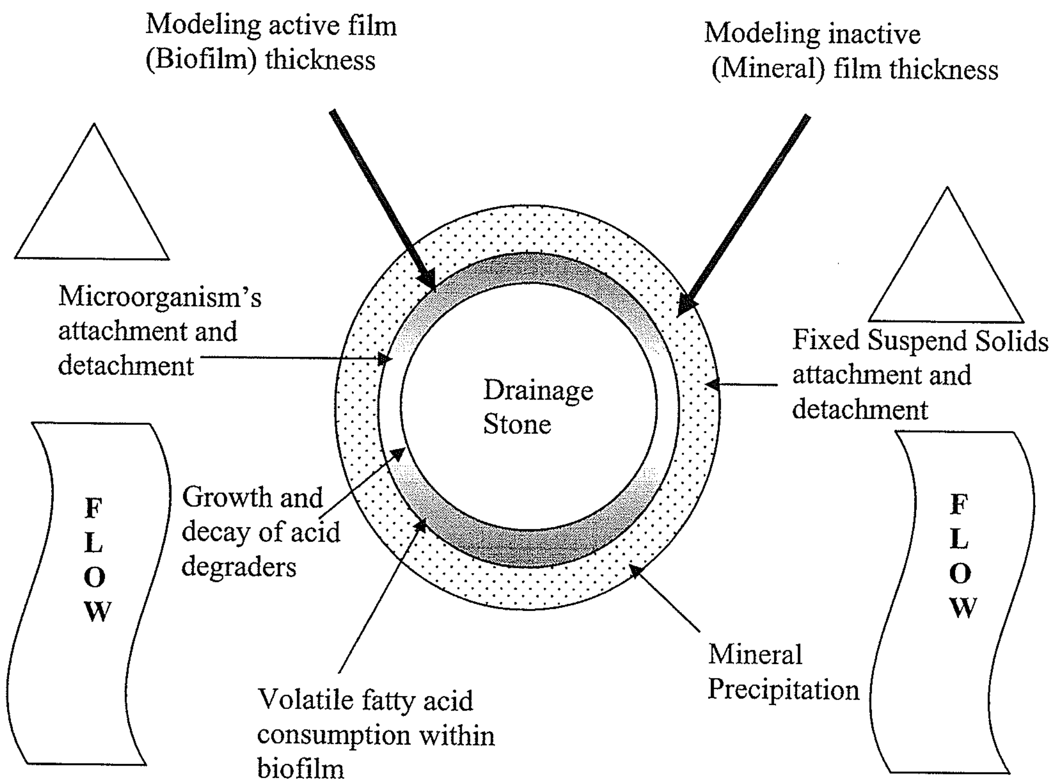

Figure 2.3 Conceptual representation of the mechanisms responsible for clogging within leachate collection system (Cooke *et al.* 1999, 2001, 2005).

CHAPTER 3: PIPE HYDRAULIC DESIGN CONSIDERATIONS FOR LIQUID INJECTION SYSTEMS IN BIOREACTOR LANDFILLS

3.1 INTRODUCTION

Liquid injection systems in bioreactor landfills are used to increase refuse moisture content in attempts to promote waste degradation, enhance waste settlement, and increase gas production (Pohland 1975, Reinhart and Townsend 1997). The various methods to inject leachate into the refuse include: surface spraying or irrigation, infiltration ponds, vertical injection wells, and horizontal injection trenches. Commonly, leachate is collected from a leachate collection system located at the base of the landfill and transmitted through a pipe network to the injection location within or at the surface of the landfill. Compared to other methods of liquid injection, horizontal injection trenches (HIT) have the advantage of recirculating large quantities of leachate with limited interference with landfilling operations (Reinhart and Townsend 1997). Horizontal injection systems commonly involve placement of a high permeability drainage material, containing a perforated pipe, within a trench that is positioned at various horizontal and vertical spacings within the waste cell. The perforated pipe conveys liquid (leachate or water) from the landfill surface into the landfill and discharges the liquid into the refuse via the trench. The inlet flow rate and hydraulic head and physical characteristics of the perforated pipe, as well as, the trench and refuse hydraulic properties, influence the volume of refuse that will experience an increase in moisture content (Al-Yousfi 1992).

Key to homogeneous moisture content and waste degradation within the landfill is a uniform wetting of the refuse. To achieve this, HIT in bioreactor landfills need an appropriate horizontal and vertical spacing and hydraulic operation. Townsend (1995) reported a method to design HIT spacing within a waste cell. The analysis assumes the shape of the saturated waste area around the trench, steady state conditions, and a spatially constant refuse hydraulic conductivity. The zone of influence, or the size of the presumed shape, is dependent on the pressure of fluid at the pipe which is assumed to be constant. Al-Yousfi and Pohland (1998) developed a set of mathematical equations to assess HIT spacing based on a constant hydraulic conductivity refuse, a constant pressure at the pipe, and a presumed shape for the zone of influence of fluid saturation horizontally from an injection pipe. The design methodologies by Townsend (1995) and Al-Yousfi and Pohland (1998) provided conceptual and mathematical approach to select HIT spacing within the landfill; however they do not consider the spatial and temporal changes in perforation discharge or hydraulic head at the pipe-waste or pipe-trench interface. Thus, hydraulics of fluid flow within the perforated pipe and the influence of pipe design and operation on injection system performance were not considered.

Reinhart and Townsend (1997) and Townsend and Miller (1998) have provided summaries of injection system design and operating characteristics used at various bioreactor landfills. However, the differences and wide ranges of the physical and operating characteristics of the perforated pipe raise question to whether some of these systems are capable of conveying leachate along the length of the line and therefore uniform wet the refuse.. Appropriated pipe diameter and length; perforation shape, diameter, and spacing; delivery hydraulic head and flow rate are critical to achieve a uniform discharge of liquid along the length of the perforated pipe.

The first objective of this chapter is to present a conceptual framework that can be used in design of HIT that links the physical properties and hydraulic performance of the injection pipe with the design of the trench and refuse properties. Using literature reported design and operating characteristics of HIT along with theoretical considerations for fluid flow in a perforated pipe, the second objective of this study is to demonstrate the importance of perforated pipe design parameters to achieve uniform waste wetting.

3.2 LIQUID INJECTION SYSTEMS

During liquid injection, liquid enters into the backfill material and drains into the surrounding refuse. If the liquid injection rate is higher than drainage rate into the refuse, the fluid pressure within the granular backfill will pressurize. The rate of liquid drainage into the refuse and pressure development within the trench is partially controlled by the hydraulic properties of the refuse and physical dimensions of the trench (see Novy *et al.*, 2005). The rate of liquid injection is a function of the perforated pipe characteristics, inlet flow rate and inlet hydraulic head. However, the development of pressure within the granular material during injection induces a back-pressure on the perforation, causing a reduction in the rate of liquid injection as back-pressure increases (see Novy *et al.*, 2005). Consideration should be given to the hydraulic interactions between movement of liquid in the trench, refuse, and perforated pipe during the design of HIT.

To obtain a uniform wetting of the refuse, the perforated pipe should also be designed to convey and deliver a uniform discharge of liquid along the entire length of the line. Critical to obtain a uniform perforation discharge along the line is an appropriate selection of pipe diameter, perforation size and spacing, as well as, the inlet flow rate and hydraulic head. Since it is impossible to achieve the same perforation discharge for the first and last perforation in a line, a constraint on the allowable percent difference in discharge (α) between the first and last perforation is required in design, as follows:

$$\alpha = \frac{q_1}{q_n} \times 100 \qquad [1]$$

Where q_1 = first perforation discharge [L^3/T]

q_n = last perforation discharge [L^3/T]

For a uniform perforation discharge, the increase in fluid pressure at the trench boundaries will be reasonably uniform along the trench length resulting in a consistent rate of leachate entering into the refuse along the length of the trench (Figure 3.1). If the difference in perforation discharge between the first and last perforation is large, it may result in a non-uniformly filling of the trench along the length of the line (schematically depicted in Figure 3.1), resulting in a non-uniform rate of liquid injection into the refuse along the length of the trench. The pipe design and operation characteristics are also critical to assess the zone of influence of liquid infiltration in the refuse around the HIT and therefore the selection of appropriate the horizontal and vertical spacings of HIT within the waste cell.

3.2.1 Design Objectives

Hydraulic design of HIT requires consideration given to capital and operating cost, liquid availability, pump operation, pipe hydraulics, and movement of fluid inside of the trench and into the surrounding refuse. A summary of HIT design and operation characteristics were consolidated from literature and personal communications and provided in Table 3.1. The common physical and hydraulic properties adopted for the perforated pipe include:

- High Density Polyethylene (HDPE) is the most common pipe material
- HIT lengths range between 30 to 300m (98 to 984 ft).
- Pipe external diameter range between 0.032 and 0.15 m ($1^{1/2}$" and 6")
- Inlet pipe flow rate range 0.0002 to 0.0083 m^3/s (0.007 to 0.29 ft^3/s)
- Inlet hydraulic head range 3.6 to 60 m (5 to 88 psi)
- Pipe perforations typically circular shape with diameters ranging between 0.0024 to 0.015 m (about <1/16" to 9/16") and spaced from 0.5 to 6 m (1.64 to 19.7 ft).

The range and paucity in select design values raises the question of what is an appropriate design for the perforated pipe to ensure uniform waste wetting in a HIT. To address this question, Figure 3.2 depicts a conceptual framework that identifies key variables and constraints important to hydraulically design HIT. First step is to estimate the volume of leachate available for volume balance purposes. Following this, the physical characteristics of the perforated pipe within the HIT need to be selected; specifically, this includes: pipe material, length and internal diameter, along with perforation size, spacing and shape. Selection of the pipe physical properties requires consideration of the hydraulic operation and performance of the pipe. For a given perforated pipe characteristic, there will be a unique combination of inlet flow rate and hydraulic head required to deliver liquid to the end of the line, while maintaining a reasonable difference in discharge between the first and last perforation. If the deduced inlet flow rate and hydraulic head, as well as, the difference in perforation discharge along the pipe are outside a practically achievable range, the physical pipe characteristics must be reevaluated.

The hydraulic performance of the perforated pipe, the design of the trench, and the hydraulic properties of the refuse will influence operation of the HIT and the zone of wetting of refuse around the HIT. Among other things, trench design involves selection of the physical dimensions, backfill material characteristics (e.g., hydraulic conductivity, porosity), and placement of pipe within the trench.

The next step involves whether to select a liquid injection time to pressurize or not to pressurize the trench. A non pressurized trench has the advantage of a small perforation backpressure and therefore small reduction in perforation discharge during trench filling. However, a non-pressurized trench may have limited wetting area of refuse outside the trench. A pressurized trench could result in a larger wetting area of refuse; however, a large perforation backpressure may develop and result in a significant reduction in perforation discharge. The reduction in perforation discharge requires consideration in liquid volume balance calculations.

During liquid injection, a zone of wetting around the HIT will develop. Within practical reason, the horizontal and vertical spacings of the HIT within the waste cell should be selected to uniformly wet the waste. If the amount of trenches required is considerable, or if the desired liquid volume balance is not achievable, it may be necessary to augment the design of the HIT to achieve an improved zone of wetting that require less amount of trenches within the landfill.

After the HIT physical dimensions and hydraulic operation are selected, a pump that can achieve the required delivery flow rate and hydraulic head to all the trenches requires selection. If the required pump specifications are not available, an alternative HIT design or leachate delivery design to the HIT may be required. Finally, the specification for pump operation cycle on/off time is required. During pumping, if the injection rate of liquid is higher than the drainage rate into refuse, the liquid level in the trench will rise and may pressurize the HIT. After pumping, the liquid in the trench will drain into the surrounding refuse. The selection of cycle of time for effective refuse saturation and HIT operation requires consideration of liquid movement from the pipe into the surrounding refuse (see Novy *et al.*, 2005 for details). The design of the perforated pipe is considered in detail in the next section.

3.3 METHODOLOGICAL HYDRAULIC DESIGN

For a given perforated pipe physical characteristic, the Bernoulli equation can be applied to assess the perforation discharge along the length of a pressurized pipe. The procedure involves balancing water and energy within the perforated pipe to deduce the required inlet hydraulic head and flow rate to achieve uniform perforation discharge along the pipe. Energy losses acting along the pipe length include: friction loss, changes in fluid velocity in response to perforation discharge, and minor head losses caused by pipe welds and perforations. The following is a summary of equations that can be used to deduce inlet hydraulic head and flow rate, as well as, perforation discharge along the length of a perforated pipe with the following assumptions: equally spaced perforations with circular shape, friction head loss and velocity head loss along the length of the pipe are considered, minor head loss due to perforations and welds were considered minimal and ignored, constant pipe diameter and material type, perforation backpressure was assumed to be negligible, and the pipe remains pressurized along the entire length of the line.

The method of analysis requires specifying the velocity at the end of the pipe and deducing the hydraulic head towards the inlet by accounting for energy losses along the pipe length using the set of equations provided below (described in Roberson *et al.*, 1988). Figure 3.3 depicts a schematic of a perforated pipe with some of the hydraulic variables and notation used in the following method of analysis. Assuming steady state conditions, the velocity of fluid in the pipe after the last perforation will zero if the end of the pipe is sealed. For a pipe with n number of circular perforations where n is the last perforation, the perforation discharge (q_n) is calculated through

$$q_n = K_n a_n \sqrt{2gE_n} \qquad [2]$$

where $K_n = 0.675\sqrt{1-\frac{V_n^2}{2gE_n}}$ = flow coefficient at the n perforation [3]

a_n = area of perforation [L^2]

E_n = hydraulic head in the pipe before perforation n [L]

The velocity before the last perforation (V_n), starting from end of the pipe (n-1) and stepping forward towards beginning of the pipe can therefore be calculated through

$$V_n = V_{n-1} + \Delta V \qquad [4]$$

where V_n = velocity in the pipe before perforation n [L/T]

V_{n-1} = velocity at the end of the pipe = 0 [L/T]

ΔV =difference in pipe velocity due to volume loss in the perforation n [L/T]

The difference in pipe velocity due to fluid discharged from perforation n, is represented by

$$\Delta V = \frac{q_n}{(\pi D^2 / 4)} \qquad [5]$$

where q_n = perforation discharge at perforation n [L^3/T]

D = internal diameter of the perforated pipe [L]

Using the deduced velocity before the perforation (V_n), the frictional head loss occurring within pipe between perforation n and n+1 can be calculated. Knowing the energy at perforation n (E_n), the energy loss due to fluid loss from perforation n, and the energy loss due to friction between perforation n and n+1, the energy at perforation n+1 can be deduced as follows:

$$E_{n+1} = E_n + f_n \left(\frac{l}{D}\right)\left(\frac{V_n^2}{2g}\right) + include\, head\, loss\, due\, to\, fluid\, loss \qquad [6]$$

where E_n = hydraulic head at the end of the pipe [L]

f_n = friction factor in the pipe before perforation n-1 [-]

l = perforation spacing [L]

g = gravitational acceleration [L/T^2]

The friction factor, in SI units, can be deduced through

$$f_n = \frac{0.25}{\left[\log\left(\frac{k_s}{3.7D} + \frac{5.74}{\mathrm{Re}_n^{\ 0.9}}\right)\right]^2} \qquad [7]$$

where k_s = rugosity of the pipe [L]

$\mathrm{Re}_n = V_n \dfrac{D}{\nu}$ = Reynolds number in the pipe before perforation n-1 [8]

ν = kinematic viscosity of the fluid [L^2/T]

For a given end of pipe hydraulic head, the perforation discharge and energy losses are deduced successively from the end to the inlet of the pipe using equations [1] through [7]. An iterative process is required to deduce the inlet hydraulic head for a specified inlet flow rate, or alternatively, to deduce the inlet flow rate for a specified inlet hydraulic head. An initial guess for the hydraulic head at the end of the pipe is used to calculate an inlet hydraulic head and flow rate. For the case of a specified inlet hydraulic head, if the calculated inlet hydraulic head using the initial guess is not equal to the specified value, a different guess for end of pipe hydraulic head is required until convergence between calculated and specified value is achieved. Once convergence is achieved, the percentage difference in discharge between the first and last perforation are compared with the specified (α) required to obtain uniform perforation discharge. If the calculated difference in perforation discharge is greater than the specified value, the pipe characteristics require modifications to achieve this final design constraint.

3.4 HYDRAULIC PERFORMANCE CALCULATIONS

There is an intimate relationship between the inlet flow rate and hydraulic head of the perforated pipe and the perforation discharge along the length of the line. The result of a sensitivity study to assess the influence of pipe length, internal pipe diameter, perforation diameter, and perforation spacing on the required inlet flow rate, delivery head, and percent difference in perforation discharge using literature reported values (see Table 3.1) are described in this section. The range of parameter values used in the sensitivity analysis includes:

- Pipe length of 30 m, 100 m, and 300 m
- Internal pipe diameter of 0.0392 m and 0.0816 m, which corresponds to an SDR 11 pipe with outer pipe diameter of 0.0508 m and 0.1016 m, respectively
- Perforation diameter of 0.005 m, 0.01 m, and 0.02 m
- Perforation spacing of 0.5 m, 1 m, 2 m, and 4 m

A general analysis from the sensitivity analysis study performed suggests that short pipes (30 m) with large pipe diameter (0.1 m), requires less inlet hydraulic head and has a lower percent difference between the first and last perforation, than the same length pipe with smaller pipe diameter (0.05m) for the same perforation sizes and spacing, as shown in Figure 3.4 and 3.4. On the other hand, long pipes (300m) require a combination of high flow rates (0.005 and 0.01 m^3/s), long perforation spacing (4m), and small pipe perforations (0.005m) to satisfy pressurized conditions along the entire length of the pipe. However, long pipes that achieve pressurized conditions along the line typically have high percentage difference in discharge between first and last perforations, as shown in Figures 3.4.

Table 3.2 and 3.3 include the results of the sensitivity analysis for the 0.0508 m and 0.1016 m external diameter pipes, respectively. Only conditions that satisfied fluid being discharged from the last perforation within a pressurized pipe are provided. Select results are also provided in Figure 3.4 and 3.5 and discussed below. Each combination of parameter values analyzed resulted in a unique inlet hydraulic head and perforation discharge for the specified inlet flow rate.

For the same flow rate and otherwise similar physical pipe characteristics:

- Larger pipe diameters (0.1016 m) compared to smaller pipe diameters (0.0506 m) require a lower inlet hydraulic head (see Figures 3.4 and 3.5). For the same flow rate, larger pipe diameters have a lower fluid velocity and therefore lower friction losses compared to smaller pipe diameters.
- Long pipes (L = 300m) compared to short pipes (L = 30 m) require a higher inlet hydraulic head to discharge liquid along the length of the pipe, see Figure 3.5. Friction loss is proportional of the pipe length, thus a long pipe would require a higher inlet hydraulic head to maintain pressurized conditions along the length of the line compared to a shorter pipe, for the same flow rate. Additionally, longer pipes have a greater number of perforations than a short pipe; thus, for all other conditions being equal, there would be more fluid volume loss in a long pipe than a short pipe. The greater the fluid volume loss, the larger the inlet hydraulic head to ensure pressurized conditions along the length of the pipe.
- Smaller diameter perforations (0.005 m) resulted in lower perforation discharge compared to large diameter perforations (0.02 m) , as shown in Tables 3.2 and 3.3, since perforation discharge is directly proportional to perforation area (see Equation 2).
- Shorter the perforation spacing, the greater the fluid volume loss within the pipe, which requires a larger inlet flow rate compared to longer perforation spacing to maintain pressurized pipe (see Figures 3.4 and 3.5).
- Generally, for cases when a pressurized pipe is maintained, the higher the inlet hydraulic head, the greater the perforation discharge along the pipe, and therefore a larger percent difference in perforation discharge between the first and last

perforation. As shown in Equation 2, perforation discharge is proportional to hydraulic head at the perforation location. Thus, a pipe with a high inlet hydraulic head has the potential for higher perforation discharge compared to a lower inlet hydraulic head. However, the higher the inlet hydraulic head, the larger the flow rate and head losses in the pipe compared to a lower inlet hydraulic head, resulting in reduced hydraulic head and therefore reduced perforation discharge near the end of the pipe.

3.4.1 Additional Design Considerations

In addition to the hydraulic analysis of perforated pipe, some additional design and operation considerations include:

- Material and installation cost.
- Operation cost for the adopted cycle time.
- Volume balance between fluid available and that required for injection.
- Adequate pipe structural integrity to withstand the applied loads (see Brachman *et al.,* 2000).
- Roughness of the pipe material must be considered in deducing required inlet flow rate, inlet delivery head, and perforation discharge.
- Development of back pressure at pipe perforations should be considered when selecting HIT spacing and pump capacity (see Novy *et al.,* 2005).
- Biological, physical and chemical clogging within the HIT (pipe and backfill material) can occur and impact the long-term hydraulic performance, operation,

and service life of the system (see Rowe and VanGulck 2005 for review of clogging literature and implications in landfills).

3.5 DESIGN EXAMPLE

Using the method of hydraulic analysis described above, the impact of pipe design and operation on HIT hydraulic performance for a hypothetical landfill is used in a design example. The analysis does not consider the influence of clogging within the pipe or the influence of perforation backpressure on influencing hydraulic performance. For the design example, a 10 ha area for leachate recirculation, 10 m^3/ha/d leachate production rate, and therefore 100 m^3/day of leachate produced, with 17 injection lines was assumed. These design values are within the range of bioreactor characteristics reported by Reinhart (1996a) and summarized in Table 3.4. For the purpose of the design example, it was assumed that 50% of the leachate produced (50 m^3/day) would be injected into the landfill, two injection lines would operate per day (25 m^3/day per line) for duration of 2 hours per day (12.5 m^3/hour per line or 0.0035 m^3/s per line). The selection of HIT operation characteristics and spacing requires consideration of liquid movement into the refuse to increase the moisture content to desired levels to enhance waste degradation, gas generation, or leachate treatment.

After deducing the required flow rate at the inlet of a single injection line based on fluid volume balance calculations, the inlet hydraulic head required to maintain pressurized pipe for various potential pipe characteristics can be deduced using the method of analysis described in section 3.3. Table 3.5 provides the five candidates pipe characteristics that will be considered in the HIT design. The pipe characteristics selected are within the literature reported range (see Table 3.1). For each candidate pipe, the inlet hydraulic head and difference in perforation discharge along the length of the line were deduced for a range of specified inlet flow rates (see Figures 3.6). Figure 3.6 only depicts cases for a fully pressurized pipe, thus, it can be readily observed that only cases one, three, and five satisfy the pressurized pipe constraint. For cases one, three, and five, the hydraulic head required to deliver the specified flow rate is within the literature reported values (see Table 3.1) and therefore likely achievable for a typical leachate pump. The percent difference in perforation discharge was deduced for these three cases to assess if a uniform discharge of liquid along the line can be achieved. Figure 3.6 shows that the percent difference in perforation discharge is about 69%, 18%, and 13% for case one, three, and five, respectively. It is possible to conclude that case one would not likely result in a uniform perforation discharge and therefore wetting of the refuse along the line. If an acceptable percent difference in perforation discharge is 20%, then cases three and five would be acceptable hydraulic designs. By assessing a wider range of inlet flow rates and hydraulic head for each case, the range of potentially suitable inlet flow rate and hydraulic head are obtained to assess the flexibility of the pipe design. Thus, if the leachate management strategy was to increase the amount of liquid injected, case five would have a percent difference in perforation discharge just exceeding the 20% acceptable criterion. After selecting the perforated pipe physical characteristics and its hydraulic operation, the hydraulic head used to select the required pump has to include the distance and the difference in elevation from the sump or tank where the pump is located to the pipe inlet placed within the trenches.

3.6 CONCLUSIONS

A conceptual framework was presented that links the hydraulic and physical interrelation between liquid availability, landfill characteristics, and HIT design and performance. HIT may have to perform from decades to centuries depending on its design intent of stabilizing the refuse or reducing leachate concentrations to desired levels. The conceptual framework is applicable for the early period of injection performance or short term operation. For long term operation, the design and operation of the HIT should consider the impact of biological, chemical and physical clogging within the pipe, trench and surrounding waste. Clogging may deteriorate the performance of the system from the initial design.

A wide range of reported hydraulic design and operation characteristics of HIT have been used in bioreactor landfills. A sensitivity study was completed to assess the influence of perforated pipe physical characteristics on hydraulic performance of the HIT. Critical to achieve uniform wetting of the refuse is a relatively uniform perforation discharge along the length of the HIT. A uniform discharge of liquid along the HIT will increase the potential for uniform wetting of the refuse and therefore waste degradation in bioreactor landfills. Results from the sensitivity study suggests that the range of literature reported HIT design and operating characteristics do not achieve uniform perforation discharge along the line, thus, highlighting the necessity to design HIT with consideration given to pipe hydraulics. For future design recommendations, physical design variables of the perforated pipe, including: internal diameter, pipe length, perforation shape and spacing, and pipe roughness need to be considered to calculate the inlet flow rate and hydraulic head required to achieve a uniform discharge of fluid along the length of the HIT.

The sensitivity analyses also suggest that long perforated pipes in HIT require high inlet flow rate and hydraulic head and generally result in a large percent difference in perforation discharge along the line compared to short pipe. Consideration should be given to design shorter length perforated pipes to overcome any hydraulic limitations.

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Table 3.1 Summary of literature reported injection system design parameters

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Yolo County Landfill, California, US (Northeast Anaerobic Cell)	Injection Pipes	HDPE	0.0318	90	0.0024	6	na	na	a
Yolo County Landfill, California, US (West Side Cell)	Injection lines	HDPE	0.0318	100	0.0024-0.003175	6	na	na	a
Lemons Landfill, Missouri, US	Vertical Injection wells	Pres cast perforated pipe	1.2	24 Max	na	na	na	0.0058	b
FCR Landfill, Buffalo, Minnesota, US	Horizontal trench	HDPE	0.15	180	na	na	na	na	c
Superior Emerald Park, Landfill, Muskego, Wisconsin, US	Horizontal trench	HDPE	0.15	180-270	na	na	na	na	c

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Central Facility Landfill, Worcester County,MD, US.	Vertical Injection wells	Pres cast perforated pipe	1.2	24 Max	na	na	na	na	b
County Farm Landfill, Kootenai County, Idaho, US	Horizontal trench	HDPE	0.0762	120	na	na	20.7	0.0022	d
Coastal Regional Solid Waste Management Authority Landfill, Craven County, North Carolina, US	Iron Probes	Steel Manifold and flexible hoses	0.0019-0.0032	1.5	0.0032-0.0064	na	30.36	0.0033-0.005	b
Pecan Row Landfill, Lowndes County, Georgia, US	Horizontal trench	Corrugated	0.15	30	na	na	na	0.0083	b

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Mill Seat Landfill, Monroe County, New York, US	Pressurized pipe loop	HDPE	0.1	na	na	na	na	0.0002-0.0012	b
Mill Seat Landfill, Monroe County, New York, US	Horizontal trench	HDPE	0.1	na	na	na	na	0.0002-0.0012	b
Mill Seat Landfill, Monroe County, New York, US	Horizontal trench	HDPE	0.1	na	na	na	na	0.0002-0.0012	b
Mill Seat Landfill, Monroe County, New York, US	Horizontal trench	No Pipe	na	na	na	na	na	0.0002-0.0012	b
King George County Landfill, Virginia, US	Horizontal trench	HDPE	0.15	na	na	na	na	0.00048	e

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Maplewood Recycling and Waste Disposal Facility, Virginia, US	Horizontal trench	HDPE	0.15	na	na	na	na	0.00097	e
Sainte-Sophie Landfill, Sainte-Sophie, Quebec, Canada	Horizontal trench	HDPE	0.15	300	na	na	na	na	f
DSWA Southern SWM Center, Jones Crossroads, Delaware, US	Injection Lines	HDPE	0.15	120-240	0.0127	0.1524	12-36	na	g
Buncombe County LF, Alexander, North Carolina, US	Injection Lines	HDPE	0.15	60-90	0.0127	3.048	12-60	na	g
Onyx Orchard Hills LF Junction Illinois, US	Injection Lines	PVC/HDPE	0.15	100-300	0.0127-0.015	0.0762	na	0.0019-0.0032	h

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Onyx Zion Landfill, Zion, Illinois, US	Injection Lines	PVC/HDPE	0.15	100-300	0.0048	1.5	na	0.0019-0.0032	h
Onyx Valley View. Decatur, Illinois, US	Injection Lines	PVC/HDPE	0.15	100-300	0.0064	0.6	na	0.0019-0.0032	h
Townsend and Miller 1998, Pilot project *	Horizontal trench	PVC	0.08	198	0.0064	0.6	15	0.0049	i
Townsend and Miller 1998, Pilot project *	Horizontal trench	PVC	0.08	198	0.0064	0.6	15	0.0049	i
Townsend and Miller 1998, Pilot project **	Horizontal trench	PVC	0.08	238	0.0095	0.6	7.8	0.0045	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	165	0.0095	0.6	4.8	0.0054	i

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	165	0.0095	0.6	13.6	0.0049	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	159	0.0095	0.6	7.2	0.0054	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	165	0.0095	0.6	3.6	0.005	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	110	0.0095	0.6	13	0.005	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	159	0.0095	0.6	7.6	0.0049	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	165	0.0095	0.6	4.6	0.0046	i

LANDFILL	Method of Recirculation	Pipe Material	Pipe Diameter [m]	Average Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Pressure in Pipe [m]	Pipe Flow Rate [m3/s]	Reference
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	110	0.0095	0.6	14.9	0.0046	i
Townsend and Miller 1998, Pilot project ***	Horizontal trench	PVC	0.08	159	0.0095	0.6	8.7	0.0044	i
Plantation Oaks project, Sibley, Mississippi, US	Injection Line	HDPE	0.1	60-180	0.0127	na	na	varies site	j

[a] Reported by Al-Yousfi (1993); [b] Reported by Reinhart and Townsend (1997); [c] Reported by Warzinski *et al.*(2000);
[d] Reported by Miller *et al.* (1997); [e] Reported by GeoSyntec Consultants (2000); [f] Reported by Simard *et al.* (2003);
[g] Christopher Gabel (personal communication, June 30, 2005); [h] Randy Frank (personal communication, August 5, 2005),
[i] Reported Townsend *et al.* (1998). * One hole per 1.5m average. ** One hole every 0.6m.*** Two holes every 1.5m average
[j] Jeff Harris (personal communication, June 28, 2005); na: not available

Table 3.2 Summary of senstivity analysis of pipe hydraulic characteristics for 0.0508[m] external pipe diameter (HDPE SDR 11) .

Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Flow Rate [m^3/s]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge x 10^{-5} [m^3/s]	Change in Perforation Discharge [%]
30	0.005	4	0.0005	0.91	6	5	11.02
30	0.005	2	0.001	1.21	6	5	22.38
30	0.005	4	0.001	1.57	6	5	26.7
30	0.005	1	0.005	10.57	18	5	72.01
30	0.005	2	0.005	14.03	21	6	72.7
30	0.005	4	0.005	18.74	23	7	67.09
30	0.005	0.5	0.01	26.45	28	5	82.13
30	0.005	1	0.01	37.74	34	6	83.32
30	0.005	2	0.01	49.52	40	8	80.38
30	0.01	2	0.01	24.68	108	21	80.44
30	0.005	4	0.01	65.33	42	12	72
30	0.01	4	0.01	43.73	129	32	75.25
100	0.005	4	0.005	25.09	29	5	81.65
100	0.005	2	0.01	60.48	44	5	88.64
100	0.005	4	0.01	91.12	55	6	88.2

Table 3.3 Summary of sensitivity analysis of pipe hydraulic characteristics for 0.1016 [m] external pipe diameter (HDPE SDR 11).

Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Flow Rate [m^3/s]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge x 10^{-5} [m^3/s]	Change in Perforation Discharge [%]
30	0.005	4	0.0005	0.71	5	5	0.32
30	0.005	2	0.001	0.73	5	5	1.15
30	0.005	4	0.001	0.74	5	5	1.49
30	0.005	0.5	0.005	1.08	6	5	17.20
30	0.005	1	0.005	1.20	6	5	21.52
30	0.005	2	0.005	1.28	7	5	23.34
30	0.01	2	0.005	1.06	24	20	16.40
30	0.005	4	0.005	1.35	6	5	21.88
30	0.01	4	0.005	1.24	25	20	18.77
30	0.005	0.5	0.01	2.33	9	5	42.22
30	0.005	1	0.01	2.64	9	5	44.56
30	0.01	1	0.01	1.86	30	20	34.84
30	0.005	2	0.01	2.80	10	5	45.88
30	0.01	2	0.01	2.27	34	20	40.56
30	0.005	4	0.01	3.01	9	5	42.32
30	0.01	4	0.01	2.74	35	21	40.17
30	0.02	4	0.01	2.04	117	80	31.60
100	0.005	2	0.005	1.83	8	5	36.82
100	0.005	4	0.005	2.21	9	5	42.03
100	0.005	1	0.01	3.88	11	5	55.74

Pipe Length [m]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Flow Rate [m^3/s]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x\ 10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
100	0.005	2	0.01	5.24	13	5	61.93
100	0.005	4	0.01	6.34	15	5	64.08
100	0.01	4	0.01	3.78	45	20	55.20
300	0.005	4	0.005	2.74	10	5	48.77
300	0.005	4	0.01	9.08	18	5	71.56

Table 3.4 Leachate availability and injected from full scale landfill water balance data (with exception of percentage recirculation, values reported are based on current operation area modified from Reinhart 1997)

Landfill site	Leachate Production $[m^3ha^{-1}/d]$	Leachate Recirculation $[m^3ha^{-1}/d]$	Percentage Recirculation [%]	Landfilling Active Area [ha]	Leachate Availability $[m^3/d]$
Alachua County	7.8	4.3	55.1	11	85.8
Worcester County	2.6	2.1	80.8	6.9	17.9
Winfield County	19	13.8	72.6	2.8	53.2
Pecan Row	2.7	1.1	40.7	4.5	12.5
Lower Mt	14.6	9.5	65.1	0.45	6.57
Washington Valley	16.6	11.7	70.5	5.7	94.6
CRSWMA					

*A total of 17 injection lines are installed within a waste cell

Table 3.5 Injection pipe characteristics

Case	Pipe Length [m]	Pipe internal diameter [m]	Perforation diameter [m]	#perforations per spacing [m]	Perforation spacing [m]
1	50	0.0392	0.005	1	2
2	50	0.0392	0.01	1	4
3	50	0.0816	0.005	1	2
4	50	0.0816	0.01	1	2
5	50	0.0816	0.01	1	4

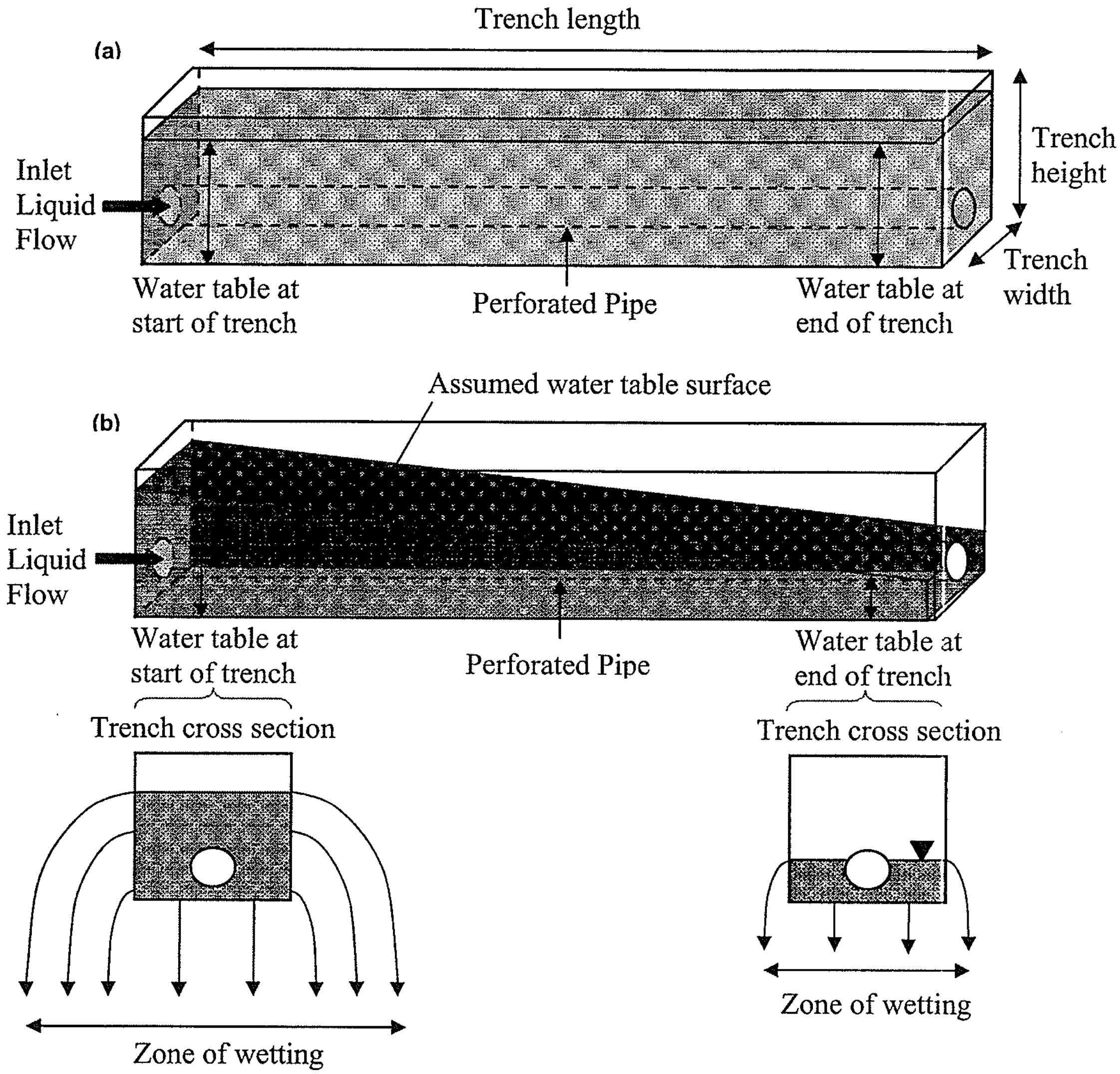

Figure 3.1 Schematic representation of injection trench and zone of wetting within the waste for (a) uniform discharge of leachate from the pipe perforations and (b) non-uniform discharge of leachate from the pipe perforations.

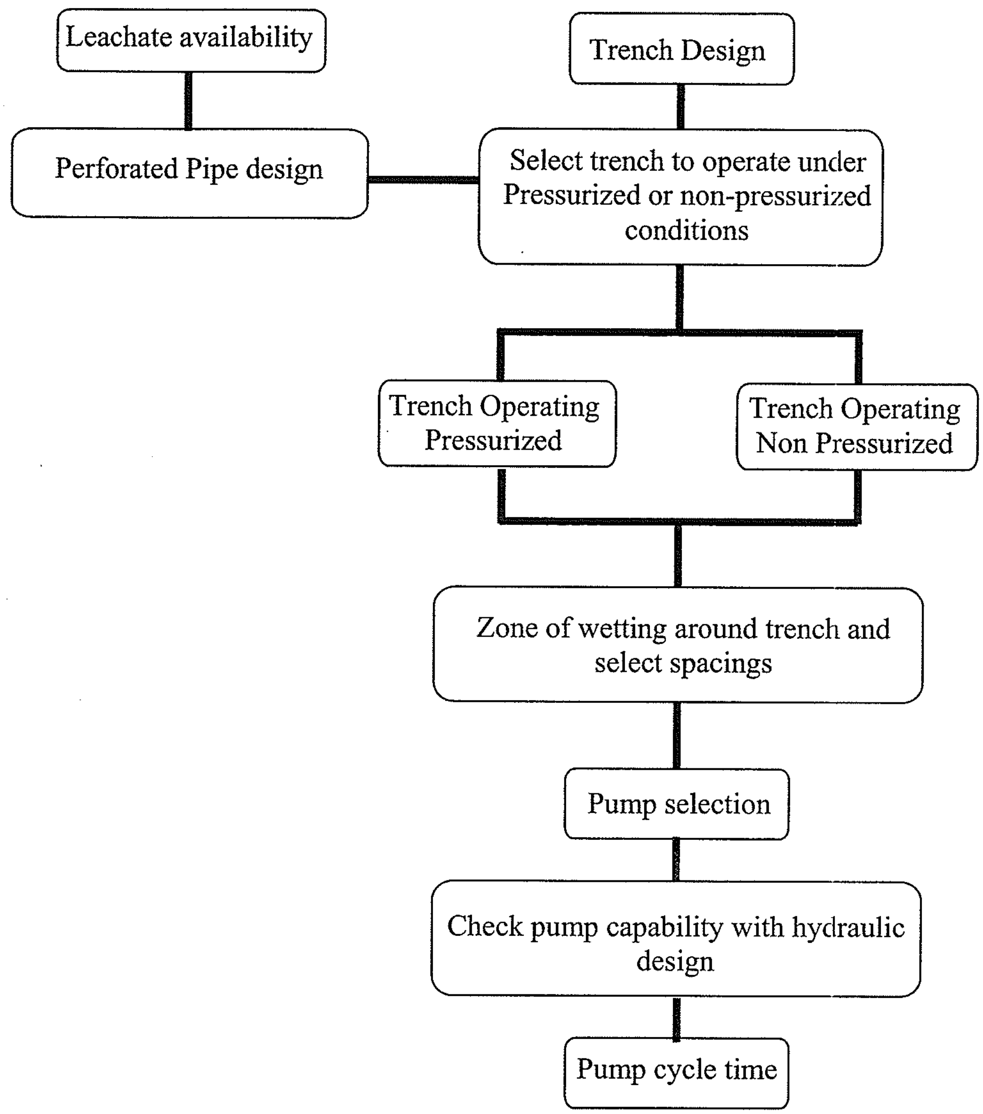

Figure 3.2 Conceptual framework criteria based on a flowchart to design horizontal injection trenches systems in bioreactor landfills.

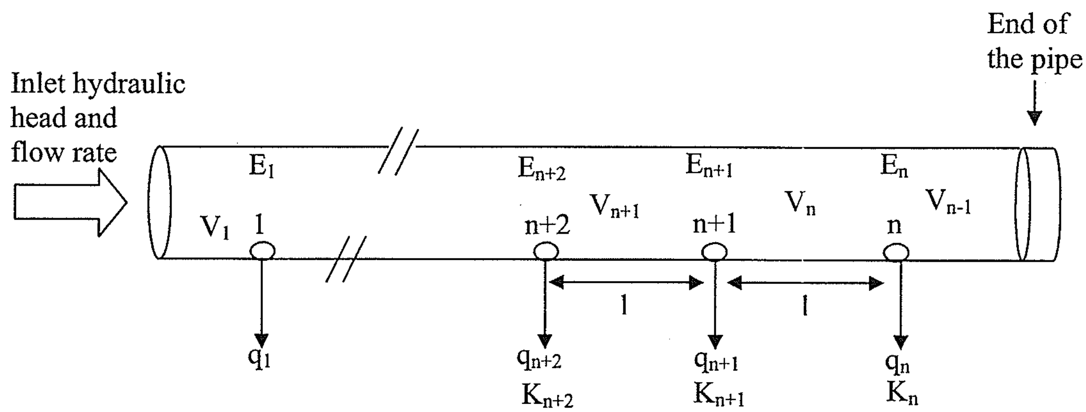

Figure 3.3 Schematic representation of the perforated pipe showing the hydraulic variables involved in the method proposed base on Bernoulli's formula for a perforated pressurized pipe. Not to scale

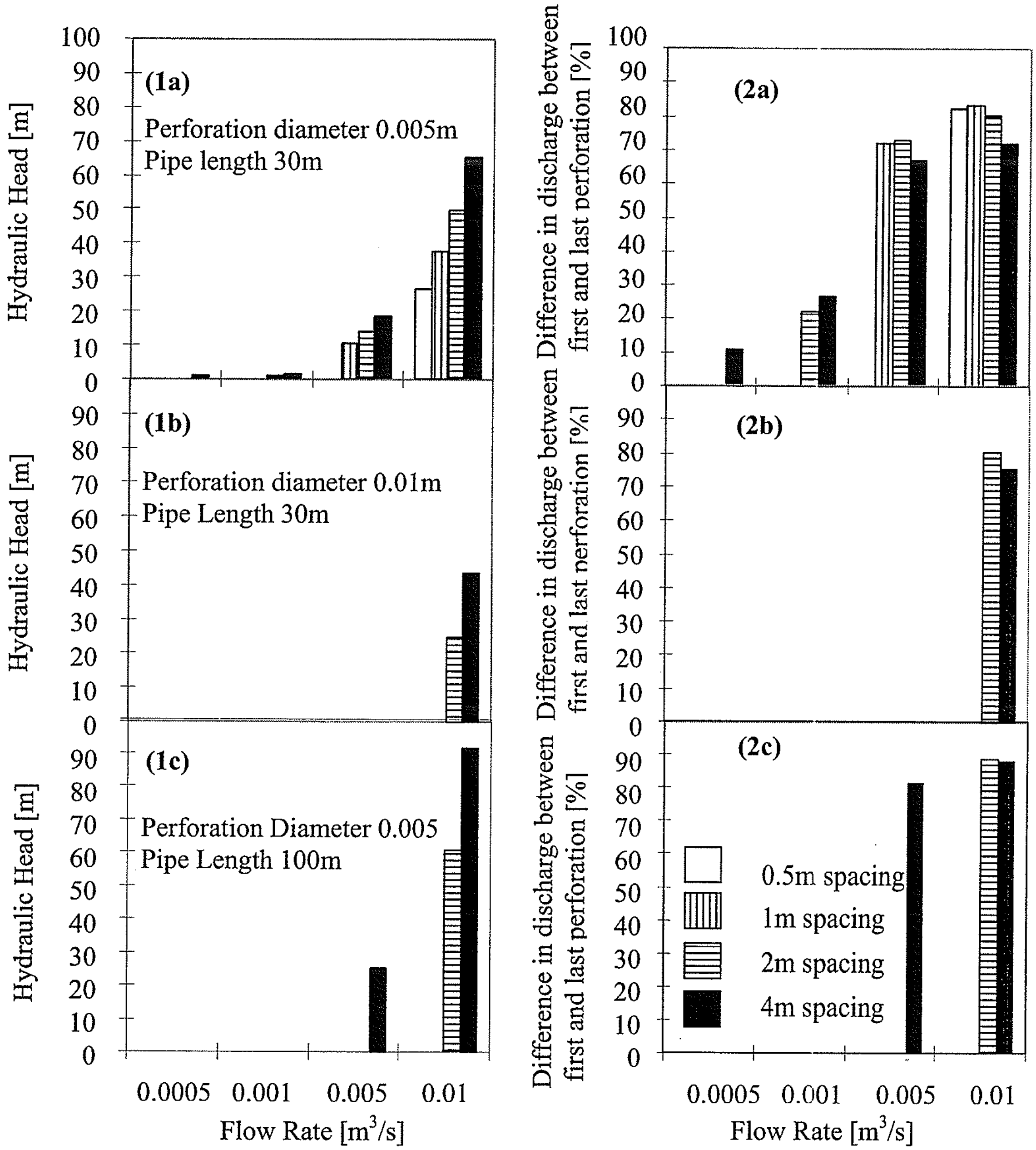

Figure 3.4 (1) Variation in inlet flow rate versus hydraulic head required to convey leachate along the length of a pressurized pipe and (2) Variation in inlet flow rate versus difference in perforation percentage discharge between first and last perforation for a 0.0506 m external diameter pipe (HDPE SDR 11).

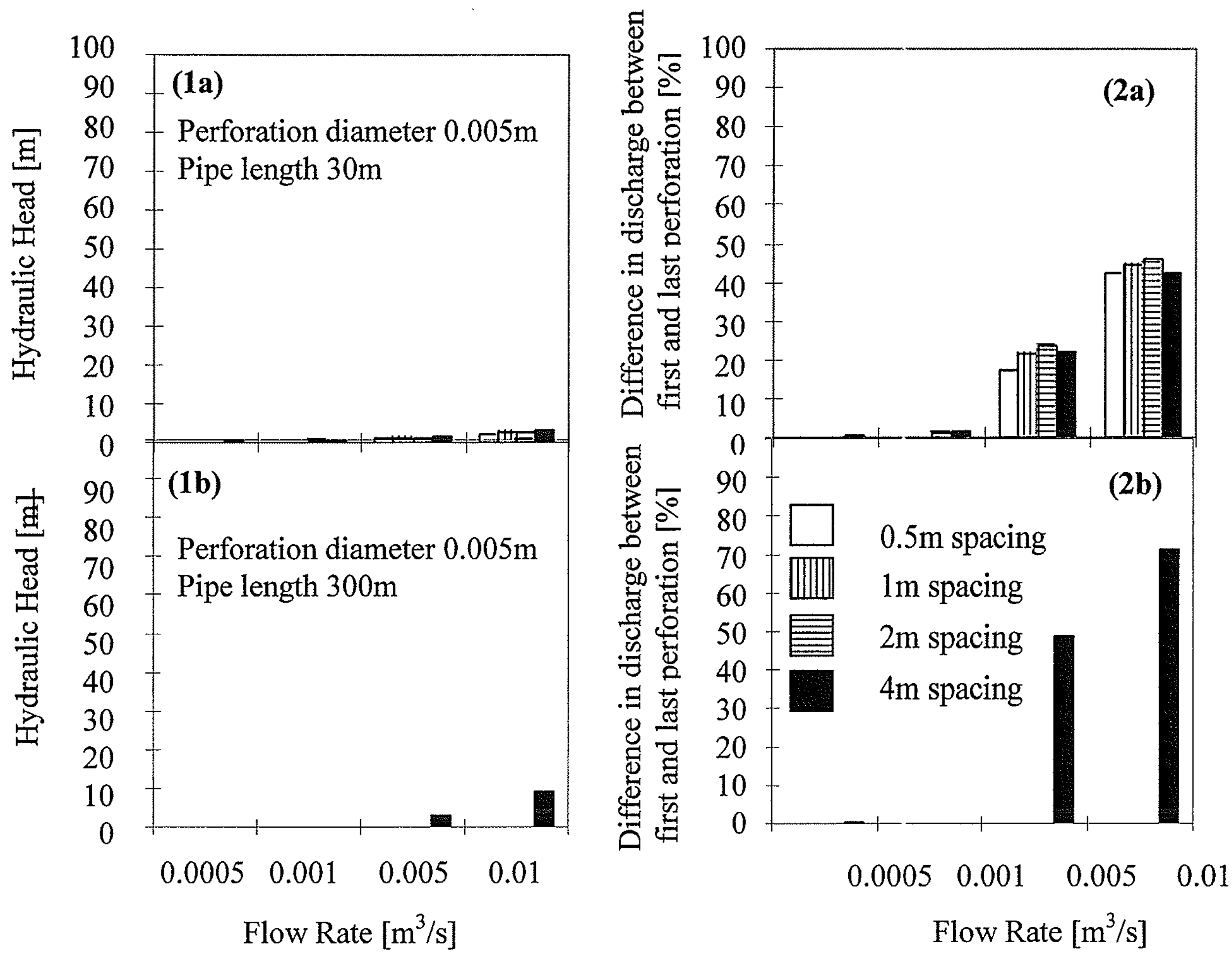

Figure 3.5 (1) Variation in inlet flow rate versus hydraulic head required to convey leachate along the length of a pressurized pipe and (2) Variation in inlet flow rate versus difference in perforation percentage discharge between first and last perforation for a 0.1016 m external diameter pipe (HDPE SDR 11).

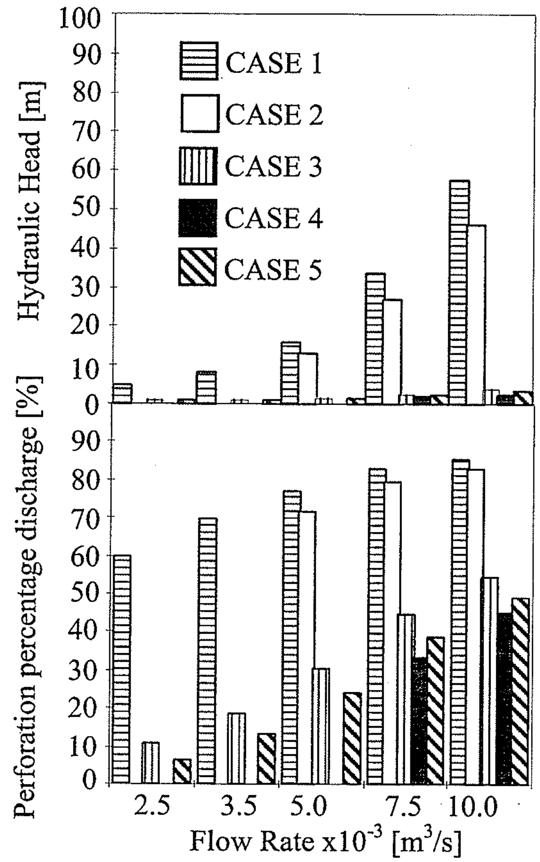

Figure 3.6 Variation in inlet flow rate versus hydraulic head (1) and variation in inlet flow rate versus difference in perforation discharge between first and last perforation (2), required to convey leachate along the length of the pressurized pipe, for the perforated pipe for cases shown in Table 3.5

CHAPTER 4: FULL-SCALE LABORATORY STUDY INTO CLOGGING OF PIPES PERMEATED WITH LANDFILL LEACHATE

4.1 INTRODUCTION

Leachate recirculation in bioreactor landfills is a landfill management alternative that has been employed to enhance biological degradation of the refuse, biogas production, and waste settlement, while reducing off-site leachate treatment. Recirculation involves collection of leachate at the base of the landfill and injection of leachate into the waste cell. The liquid then percolates through the refuse to be collected at by the collection system. One method of leachate injection involves placement of horizontal injection trenches (HIT), which contains a perforated pipe surrounded by high permeability material, positioned at a regular horizontal and vertical spacing within the landfill (Reinhart *et al.*, 1997). Field studies of pipes used in leachate collection and injection systems have showed that leachate transmission pipes can experience significant amount of clogging due to the development of microbial slimes, precipitation of inorganic material, and straining/filtration of suspend solids (Brune *et al.,* 1991, Turk *et al.,* 1997, Fleming *et al.,* 1999, Manning *et al.,* 2000, Maliva *et al.,* 2000, Yazdani 2002, and Bouchez *et al.,* 2003).

The impact of clog development on injection pipe walls and perforations is not considered in literature reported design methodologies for leachate injection systems (Townsend 1995, Al-Yousfi and Pohland 1998). Clog accumulation within leachate injection pipes can deteriorate the hydraulic performance from the design value and potentially result in a non-uniform infiltration of leachate into the refuse, thereby, impacting waste degradation and the benefits of leachate recirculation. Clog accumulation within injection pipes may develop to the point where the injection system can no longer effectively transmit leachate, thus reaching its service life. However, the rate of clog development in leachate transmission pipes for various hydraulic designs is unknown, and therefore the service life of this engineered system is unknown.

The objectives of this study are to measure the changes (if any) in leachate composition as leachate is permeated through full-scale transmission pipe in a well controlled laboratory experiment. Additionally, the influence of flow rate and pipe diameter on changes in leachate composition within the pipe will be assessed to gain insight into the mechanisms involved in clog development for different physical configurations and hydraulic operations of the pipe. Finally, the chemical and physical characteristics of the clog material accumulated within the pipe will be measured.

4.2 METHODOLOGY

Four HDPE pipes (SDR 11) of length 1.2 m were permeated with leachate under pressurized conditions. HDPE is a common material used for pipes used in liquid injection systems (Chapter 3). Leachate was collected on a monthly basis from the Brady Road landfill in Winnipeg, Canada, stored in 25 L carboys and transported to the laboratory. The leachate was obtained from randomly different wells at this municipal solid waste landfill and therefore the composition of the leachate is representative of leachate generated from waste that is between about 5 to 15 years in age. Part of the total volume of leachate collected was equilibrated to laboratory temperatures and replaced the leachate circulating through the laboratory pipes. The remaining volume of leachate was stored at 4°C to limit biological processes from occurring within the carboys. After about two to three weeks of leachate circulation in the laboratory pipes, the stored leachate was equilibrated to laboratory temperatures and replaced the leachate circulating through the laboratory pipes. The process of replenishing the source leachate was repeated several times over the duration of the experiment to maintain dissolved and suspended solids in the source leachate.

Two of the four laboratory pipes had external diameter of 0.05 m and internal diameter of 0.04 (call series 1), the other two pipes had an external diameter of 0.1 m and internal diameter of 0.08 (call series 2). Each series of pipes were connected to a reservoir via a manifold to deliver leachate to the pipes and to maintain a constant inlet pressure of leachate (see Figure 4.1 for schematic). The effluent end of each pipe was equipped with a ball-valve to assist in controlling the flow rate through the pipe. Discharge from the pipe entered into a storage reservoir, which was then connected to a recirculation pump, to convey leachate back into the upstream reservoir. For all practical purposes, each pipe in each series were constructed and operated nominally identical. All connections into the pipe were sealed and were maintained under anaerobic conditions.

To assess the effects of different hydraulic retention time (HRT) on changes in leachate composition within the pipe, three different flow rates were applied to each series over the duration of the study. These flow rates were classified as low, medium and high, where the HRT produced were high, medium and low and denoted as HRT_L, HRT_M and HRT_H, respectively. Flow rates utilized were selected based on reported field studies of injection rates used in HIT of 370 to 620 L/d/m of trench (Miller *et al.,* 1993). Typical trench lengths have been reported to range between 30 to 200 m (Miller *et al.*

(1997), Reinhart and Townsend (1997), Townsend *et al.* (1998), GeoSyntec Consultants (2000), Yazdani *et al.* 2003). Thus, for a 30 m long trench the range of injection rate is 0.13 to 0.21 L/s, and for a 200 m long trench the range of injection rate is 0.86 to 1.44 L/s. With consideration given to flow rate anticipated in HIT, the following flow rates were applied over the following periods of time: no flow for the first 7 days, 0.5 to 0.6 L/s between day 7 to 73, 0.2 to 0.3 L/s between day 73 to 112, and 1 to 1.4 L/s between day 112 to 144. Each flow rate will give rise to a different hydraulic retention time (HRT) for each pipe series due to differences in internal volume for pipe series 1 compared to 2. The HRT for pipe series 1 were 2.41-2.89 s, 1.03-1.45 s, 4.83-7.24 s and for pipe series 2 were 10.46-12.55 s, 4.48-6.28 s, and 20.92-31.38 s in HRT_M, HRT_H and HRT_L, respectively. The pipes operated with no flow control for the first seven days in attempts to partially acclimate the pipe environment to leachate before flow was induced.

Each pipe was equipped with an influent leachate sample port 5 cm before the HDPE pipe within the PVC coupler that joined the HDPE pipe to the manifold and inlet reservoir (see Figure 4.1). An effluent leachate sample port was located 5 cm from the end of the 1.2 m long pipe. Leachate was collected for chemical analysis from these ports, instead of the upstream and downstream reservoirs to ensure measurement is representative of leachate entering and exiting the pipe. Additionally, each pipe contained two monometers located at 0.1 m from the influent and effluent ends of the pipe to measure pressure and to remove some of the gas generated within the pipe. The reservoirs, manifolds, pipes, and monometers were all sealed to maintain anaerobic conditions within the experiment.

The laboratory pipes were operated and maintained within an ambient temperature of 30 to 50°C (average of 40°C, stdv of 4.18 for 14 readings), to simulate potential field conditions. MSW landfills with different physical and operational characteristics have reported temperatures values ranging from about 30 to 50°C (Rowe *et al.* 2004, Southen and Rowe 2005). For bioreactor landfills, reported temperatures ranged from about 30 to 60°C (Yolo County Landfill, Yazdani 2003), 32 to 54°C (New River Regional Landfill, Reinhart *et al.* 2002), and 40 to 60°C (Columbia Country Baker Place Road Landfill and Atlanta Landfill, Hudgins and Harper 1999).

4.3 LEACHATE ANALYSIS

Field and laboratory studies focused on clogging in granular media permeated with landfill leachate that contains degradable organic acids, dissolved inorganic constituents, and suspended particles have showed that clog accumulation can develop within the pore spaces of the porous media due to the development of biofilm, mineral precipitation, and straining/filtration of suspended particles (VanGulck *et al.*, 2003). The processes that contribute to clogging in porous media of a leachate collection system has been hypothesized to be similar to that which occur in leachate transmission pipes (VanGulck and Rowe 2004). In field studies that examined clog material from leachate transmission pipes (Brune *et al.* 1991, Fleming *et al.,* 1999, Maliva *et al.,* 2000, Manning 2000), calcium and carbonate has been the main inorganic clog constituent.

With consideration given to the biological, chemical, and physical processes that contribute to clog development from previous studies, leachate was collected from the influent and effluent samples ports and tested on a weekly basis for the following characteristics: chemical oxygen demand (COD), dissolved calcium concentration (Ca^{+2}), pH, total suspended solids (TSS), volatile suspended solids (VSS), fixed suspend solids (FSS), temperature, electrical conductivity (eH), and suspended particle size distribution. COD and Ca^{2+} concentrations were measured weekly in duplicates, other water quality parameters were single measurement for each leachate sample. To obtain leachate composition within the pipe at a discrete position, about 100 to 150 mL (4 to 7% and 1 to 2% of total pipe volume in series one and two, respectively) of leachate was removed from each sample port. COD was measured using HATCH™ COD reactor with HATCH™ COD reagents that heated the reagent and leachate at 150°C for 4 hours, and then analyzed with the HATCH™ DR/2500 Spectrophotometer. Ca^{+2} concentrations were obtained using EDTA Titrimetric method (3500-Ca D, Standard Methods 1992). The pH was measured using an Accumet® portable pH meter AP61 (Fisher Scientific) that was equipped with the appropriate electrical probe. Total suspended solids (TSS) and fixed suspended solids (FSS) were tested using a gravimetric measurement of the residue retained on a 0.45 μm glass fiber filter dried at 105°C and 550°C, respectively (2540 Solids D and E, Standard Methods 1992). Volatile suspended solids (VSS) concentrations were calculated as the difference between TSS and FSS concentrations. Temperature was measured using a 76MM IMM 14-997 Fisher® thermometer. Particles were counted using Laser Particle Counting System Supercount™ LPC PC-2200 and Spectrex LPC software. Electrical conductivity was measured with an Accumet Meter® pH meter 50.

4.4 CLOG COMPOSITION ANALYSIS

After about 20 weeks of operation, the pipes were cut open and clog material accumulated in the pipe was collected and tested for physical and chemical characteristics. Solids density was measured using a modified version of ASTM (D854) for calculating the specific gravity of soil solids. Inorganic and organic clog compositions were analyzed in a commercial laboratory using inductively coupled plasma mass spectrometry (ICPMS) for cation / metal analysis, LECO method for total organic carbon –distillation and two-part titration for inorganic carbon, and volatilization with hydrochloric and hydrofluoric acids for silicon.

Clog material was also analyzed with CAMBRIDGE Stereoscan 120 Scanning Electron Microscope (SEM), equipped with scanning control with EDAX Genesis 4000 software to obtain the X-ray Energy Dispersive Spectrum (EDS). The SEM and EDS analysis provided a qualitative elemental composition of the clog material. For the SEM and EDS analysis, clog samples were covered with a gold-palladium thin film deposited by an Edwards sputtering system Model S150B. The SEM was operated at 30 kV accelerating voltage and the secondary emission detector was used for imaging the samples. The EDS spectrums were captured using a Kevex detector and an electron beam of less than 2 microns in size.

Mineralogy of the clog material was measured by conducting X-Ray Diffraction dataset (XRD) using Cu radiation collected from 4 to 60 degrees 2-theta, using a step width of 0.05 degree and a dwell time of 1 sec/step, on a Philips PW1710 automated powder diffractometer. The diffractometer is configured with 1-degree divergence and anti-scatter slits and a 0.2 mm receiving slit and a curved graphite crystal, diffracted beam monochromatic. The observed data was checked against the Powder Diffraction File (PDF) database from the International Centre for Diffraction Data (ICDD) for any matching phases using the search-match capabilities of Material Data Inc.'s Jade 7+ XRD-pattern processing software.

Resin embedding and microtone sectioning were performed prior to light microscopy on clog material attached onto the pipe, to detect the presence of organic matter. JB-4© plus embedding kit, which contained glycol methacrylate, was used as a resin in the embedding solution (see Appendix E for embedding procedure). Microtome sections of embedded samples with thickness of 2 to 3 μm were collected and placed onto a drop of water on a glass slide, and dried at 60 °C in a slide warmer. The samples were flooded with a stain (Toluene Blue), rinsed and then dried in the slide warmer at 60 °C. The Image-pro plus software was used for image analysis of the glass slides, captured by an Olympus digital camera DP70 connected with a Nikon Y-FL microscope using 10X magnification and a stage micrometer was used to create reference calibrations for each magnification and light settings to calibrate all captured images.

4.5 LEACHATE COMPOSITION VARIATION THROUGH THE PIPES

The influent and effluent COD concentrations within the pipes did not change considerably with elapsed time, as shown in Figure 4.2; a maximum percentage of COD removal for pipe series 1 and 2 occurred during HRT_L in an amount of about 10 and 25%, respectively. 25 to 50% Ca^{+2} removal occurred within the pipes during each of the three retention times, as shown in Figure 4.3. The average influent leachate pH differed for each HRT with value of 8.3, 8.7, and 9.4 for HRT_L, HRT_M, HRT_H, respectively (as shown in Figure 4.4). The effluent was typically marginally higher than the influent pH. The difference in influent leachate characteristics between each series of pipe was not large and is largely a result of the circulated leachate being conveyed to a common sump.

Relatively high influent pH influent values (8.3 to 9.4) were measured in this study, which were about 0.5 to 2.5 pH units higher than the influent leachate characteristics reported in laboratory column studies of clogging in porous media (listed in Table 4.4). Additionally, these past studies reported effluent pH values approaching pH of 8.0 after the leachate permeated through a porous media. Rittman *et al.* (2003) reported that leachate pH increase observed in Cooke *et al.*, (2001) was a combined effect of 1) organic acid consumption (COD removal of about 35 to 55% during steady period), which destroyed volatile fatty acids (strong acids) to produce the carbonic acid (H_2CO_3, weak acid) as a by-product of microbial fermentation, and 2) degasification of $CO_{2(g)}$ from the liquid phase which reduces carbonate content.. Although COD influent and effluent variations in leachate concentrations were not significant within this study (maximum between 10 to 25%), degassing of the leachate was observed to escape the system from the gas lines connected to the pipes, sump, and influent tank. It is hypothesized that the pH values greater than 8.0 measured in this study is largely a result of degasification of CO_2 from the leachate. The higher flow rates through the pipes gave rise to higher leachate pH values, suggesting that increased turbulence and agitation of leachate within the system may impact the amount of degassing.

FSS are the inorganic fraction (partially comprised of mineral precipitate and soil particles) and VSS are the volatile fraction (partially comprised of microorganism and organic mater) of TSS. Changes in influent and effluent FSS, VSS, and TSS within pipes may provide an indication of retention or production of suspended solids within the pipe. Retention of suspended solids may result in accumulation of clog material within the pipe. Production of suspended solids may be the result of detachment of clog material from the pipe wall into the leachate or generation of particles (e.g., due to mineral formation) as leachate passes through the pipe.

Under turbulent flow conditions, suspended particles entering the pipe could can settle out and accumulate on the inner pipe wall due to the following main mechanisms: gravitational, diffusional, electrostatic, and inertial forces (Friedlander and Johnstone, 1957). However, detachment or sloughing of clog material from the pipe wall into the passing liquid can also occur. Detachment of biofilm may be shear stress related (Rittmann and McCarty 2001) or dependent on the biofilm growth kinetics (Characklis and Marshall 1990) , while other clog material attached to biofilm may be eroded from pipe wall and will be partially dependent on the fluid shear stress. The net effect of mechanisms that may decrease or increase suspended particle concentration within the pipe is captured by deducing the removed TSS concentration. Even though TSS, FSS and VSS accumulation within the pipe series were measured for different HRT, there was not a clear indication of suspended solid concentration increase or decrease within the pipe for the various HRT, as shown in Table 4.1. Thus, the dominant mechanisms for suspended solid removal or production within the leachate as it permeates through the pipe are unknown since only net removal was calculated.

In addition to measuring the suspended solids concentration, an average particle diameter was calculated based on the number of each particle diameter divided by the total number of particles. The influent and effluent average particle size with elapsed time for each pipe series is provided in Figure 4.5. The average influent size of particles for HRT_M, HRT_L, HRT_H was 1.46, 2.16 and 2.59 [μm] for pipe series 1 and 1.36, 2.38 and 2.75 [μm] for pipe series 2, respectively. The difference in influent and effluent average particle size were similar for each HRT, although some variations did exist, the maximum difference was generally less than 7% over the duration of the experiment.

4.6 CLOGGING COMPOSITION

After 144 days of operation for pipe series 1 and 151 days of operation for pipe series 2, the pipes were disassembled to assess clog composition. In each pipe, clog material accumulated on the inner pipe wall, and visually there was more material accumulated on the bottom half of the pipe compared to the top half, as shown in Figure 4.6. Despite gas ports located within the pipes to remove accumulated gas, it is suspected that gas still accumulated near the crown of the pipe which would reduce contact of the pipe wall with leachate and therefore limiting clog accumulation in the top portion of the pipe. Total elemental analysis was performed on clog samples taken from each pipe series and summarized in Table 4.2 along with a summary of some additional clog properties. Water content on the clog material averaged about 41% and 56% for pipe series 1 and 2, respectively. The clog material contained a high proportion of Mg^{2+} and Ca^{2+} along with carbonate, suggesting that these metals may be bound to carbonate in solid form. On a dry mass basis, there was about 2 to 3 times greater mass of Mg^{2+} in the clog compared to Ca^{2+}. Mg^{2+} measured in pipe series 1 and 2 comprised about 16 to 20% and the percentage of carbonate per unit of dry mass within the pipe series 1 and 2 was about 43 to 49%, respectively.

X-ray diffraction analyses completed on clog material measured hydromagnesite ($Mg_5(CO_3)_4(OH)_2\ 4H_2O$) to be the dominant mineral constituent within the clog (see Appendix D for additional details). The molecular weight ratio of Mg^{2+}/CO_3^{2-} in pure hydromagnesite is theoretically 0.4, which compares well with the average value of 0.39 deduced from the clog analysis results. The high measured to theoretical Mg^{2+}/CO_3^{2-} ratio suggests that the majority of the carbonate was bound to magnesium, not calcium, and supports the X-ray diffraction analysis.

The main results of the elemental analysis of the clog material were compared with published compositions of clog accumulated within the pore space of granular material permeated with landfill leachate (see Table 4.3). Fleming *et al.* (1999) analyzed the incrustation material accumulated within the pore spaces of granular material permeated with leachate from laboratory experiments and from a Toronto, Canada landfill. The author's reported that calcium carbonate was the main component of the inorganic clog material. Maliva *et al.* (2000) analyzed clog material flushed out from a leachate collection pipe in a Florida Landfill that received incinerator ash and municipal solid waste and reported a low magnesium form of calcite was the main mineral formed. Manning *et al.* (2001) reported that leachate suspended solids and their sediment load from leachate obtained from Lancashire and West Midlands Landfills (UK) were mainly composed by calcite together with quartz and clay minerals. VanGulck and Rowe (2004a,b) reported calcite, and aragonite combined with some magnesian, to be the dominate mineral fraction in clog material formed in leachate collection pipes and within granular material permeated with leachate.

Rowe *et al.*, (2002) showed that the composition clog material is partially depended on the leachate characteristics. Comparing select leachate characteristics between this study and VanGulck and Rowe (2004a,b), there was about an order of magnitude lower calcium concentration and about 1 to 1.5 units higher pH; magnesium concentration in the leachate was not measured in each study to compare. The leachate composition differences between these studies was likely why VanGulck and Rowe (2004a,b) measured calcium bearing minerals and this study measured magnesium bearing mineral.

4.7 CLOGGING MORPHOLOGY

SEM photography of clog material attached near the inlet of pipe series 2 are provided in Figure 4.7, using magnifications of 20X , 50X, 200X, and 1000X. These images show a main presence of single crystals spread onto the pipe surface, accumulating on top of adjacent crystals to form rosettes structures with apparent jagged edges. Similar physical characteristics were identified by Li *et al.* (2003) for hydromagnesite synthesized in a laboratory study From the SEM and observations of the clog material (Figures 4.6 and 4.7), it can be concluded that the accumulation of clog material on the pipe wall will change wall roughness, or rugosity, of the pipe. A rougher pipe wall may give rise to larger friction loss within the pipe and may impact the hydraulic performance of the pipe compared to the original value.

Organic matter based on total volatile solids (TVS) within the clog material for each pipe series ranged between about 39 to 43% per unit of dry mass, suggesting that in addition to inorganic constituents there was a significant about of biomaterial within the clog. Resin embedding and light microscopy completed on three samples of clog from pipe series 2 showed that the organic matter (blue/purple stain) was present throughout the clog thickness (see Figure 4.8). Thus, it is hypothesized that a biofilm accumulated within the pipe and developed concurrently with mineral precipitation and the net retention of suspended particles. The porosity of the clog material was deduced within the polygons that overlie on the photographs in Figure 4.8 from the area of pores divided by the total area. The range in porosity of these three measurement locations ranged from 0.22 to 0.7. The voids within the clog could assist with the migration of organics and nutrients to depths within the clog that may assist with biofilm growth and additional mineral precipitation.

4.8 CLOGGING PHYSICAL CHARACTERICTICS

The clog material was removed from the pipe surface after about 5 months of operation. The clog wet mass, which consists of organic and inorganic materials, was about 0.74 to 1.49 g per cm of pipe, for pipe series 1, and 2.88 to 3.36 g per cm of pipe for pipe series 2 (Table 4.4). Pipes located closest to the influent end of the inlet constant head tank experienced more clogging than pipes located further away. Generally, pipes closest to the inlet end of the constant head tank had a higher concentration of leachate constituents than pipes further away due to treatment of leachate in the tank. While the differences in amount of material collected were 2 to 4.5 times greater for pipe series 2 than series 1, the average influent mass loading over the duration of the experiment (sum of Ca^{2+}, COD, and TSS concentration multiplied by the flow rate) into pipe series 1 (about 425 kg/day) was similar to that of pipe series 2 (about 410 kg/day). Thus, influent mass loading alone can not explain why more clog accumulated in pipe series 2 compared to pipe series 1. The other physical pipe characteristic that differs between each pipe series is the internal surface area that is about two times larger for pipe series 2 than 1, which is reasonably similar to the differences in mass of material accumulated between each pipe series. Thus, mass loading into the pipe (function of flow rate and leachate concentrations), in conjunction with pipe internal surface area (function of pipe diameter), both impact the accumulation of clog.

Assuming that the clog material uniformly developed over the entire internal surface area of the pipe, the thickness of the clog material was deduced based on the measured bulk density (described below) and wet clog mass. The clog thickness for pipe series 1 and 2 ranged from about 0.8 to 1.7 mm and about 1.3 to 2.0 mm, respectively (Table 4.4). Therefore, large pipe diameter (0.1 m) generated thicker clogging than smaller pipe diameter (0.05 m), however, the reduction in pipe diameter was about 2 to 4.2 % for the pipe series 1 compared to about 1.6 to 2.5% for the pipe series 2. The higher reduction in pipe cross-section area in the 0.05 m diameter pipe compared to the 0.1 m diameter pipe indicates that smaller pipe diameters require less mass of clog to reduce internal diameter for all other conditions being equal.

The bulk density and non-volatile solids density of the clog material were similar for pipe series 1 and 2 (see Table 4.4) with an average value of 1.53 [mg/m^3], and 2.45 [mg NVS/m^3], respectively. The measured clog density values were within the range reported by Rowe *et al.* (2002) and VanGulck and Rowe (2004a,b) for a mature clog of about 1.32 to 2.21 [mg/m^3] for bulk densities and about 1.64 to 3.03 for non-volatile solid densities despite the fact that this study permeated leachate through a pipe at a much higher flow rate than the past studies permeating leachate through a porous media. Additionally, the measured non-volatile clog density also compares well with the density of hydromagnesite of 2.25 g/cm^3 (Goto *et al.* 2003).

The average volatile density, calculated based on the method described in Rowe *et al.* (2002), was about 0.63 and 0.31 [mgVS/m^3] for pipe series 1 and 2, respectively. Volatile density values of clogging reported by Rowe *et al.* (2002) and VanGulck and Rowe (2004a,b) ranged from 0.037 to 0.193 [mg VS/cm^3]. An estimated error in the calculated volatile density of about 15 to 30% is an expected, since it was assumed that the entire internal surface area contained clog material, where in fact, part of the crest of the pipe visually did not contain clog material. Despite the overestimation in volatile density due to this assumption, the values deduced are larger than that reported by Rowe *et al.* (2002) and VanGulck and Rowe (2004a,b) and may be the result of differences in flow rates between the studies. This study operated with about 5 to 6 order of magnitude higher flow rate then the other mentioned studies, which would produce a greater shear stress acting on the biofilm (Rittmann and McCarty 2001).

4.9 CONCLUSIONS

Full scale pipes, with external diameter of about 0.5 and 0.1 m, were permeated with leachate to gain insight into the mechanisms responsible for clogging due to biological, chemical and physical processes. Changes in physical and chemical leachate characteristics under anaerobic conditions were measured in the leachate as it flowed through 1.2 m of pipe, obtaining leachate average temperatures from 45 to 48 °C, for each of the three average of flow rates (0.25 L/s, 0.55 L/s and 1.2 L/s) tested. COD removal was limited to about 10 and 25% within the all the pipes with the greatest removal occurred during the lowest flow rate (0.25 L/s). The pH of the influent leachate to the pipes increased in value from 8.3 to 9.4 as the average flow rate in the pipes increased from 0.25 to 1.2 L/s, respectively. Ca^{+2} was consistently removed in an amount of about 25 to 50%, within both pipes diameters for the three flow rates tested, suggesting that inorganic dissolved solids in the initially in leachate are precipitating and accumulating within the pipe. Measured changes in suspended solids concentration within the pipe did not reveal a consistent trend in removal or production during each flow rate or between each pipe diameter tested. The changes in leachate composition within the pipes indicated that biological, chemical and physical processes occurred within the pipes for each flow rate tested, and that these processes contribute to the development of clog material within the pipe.

The clog material accumulated on the inner surface of the pipes contained organic and inorganic materials and was comprised of biofilm, mineral precipitate, and retained suspended solids. Chemical and light microscopy analyses were performed on the clog material. The clog material was comprised of about 40% organic mater and it was present throughout the clog material. Magnesium, calcium, and carbonate where the main inorganic clog constituents with hydromagnesite ($Mg_5(CO_3)_4(OH)_2 4H_2O$) present as one mineral phase.

After five months of operation, the accumulation of clog material was greater within the larger diameter pipes (288 and 336 gr/m of pipe) compared to the small diameter pipes (74 and 149 gr/m of pipe), for conditions where there was similar flow rate, influent mass loading, and length of pipe. Thus, the larger the internal surface area of the pipe, for all other conditions being equal, the greater the accumulation of clog. Even though, a higher leachate treatment or greater clog accumulation occurred within the large diameter pipes, small diameter pipes experienced a greater reduction in cross-sectional area for flow.

This study has demonstrated that pipe physical characteristics and the hydraulic operation have a direct impact on changes in leachate composition and clog development within leachate transmission pipes. Clog development within a perforated pipe transmitting leachate will reduce the cross sectional area for fluid flow within the pipe and, likely, perforation opening, both of which will impact the HRT within the pipe. The service life of the transmission pipe will be reached when it can no longer effectively discharge leachate into the trench. Clog material accumulated within the pipe may also change the original pipe rugosity (wall friction), thereby impacting the perforation discharge and hydraulic head along the length of the pipe during injection. Thus, this may result in a non-uniform leachate injection into the refuse along the length of the line, thereby reducing the benefits of a uniform leachate recirculation within the landfill.

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Table 4.1 Summary of TSS, FSS, VSS, temperature, and pH average values for each pipe series and HRT.

Pipe Series	Parameter	Units	HRT_M	HRT_L	HRT_H
(1)	TSS_i	mg/L	77	71	102
	TSS_e	mg/L	96	70	82
	Normalized TSS	%	1.25	0.99	0.80
	FSS_i	mg/L	28	30	39
	FSS_e	mg/L	45	24	22
	Normalized FSS	%	1.61	0.80	0.56
	VSS_i	mg/L	50	45	62
	VSS_e	°C	56	46	60
	Normalized VSS	%	1.12	1.02	0.97
	T	°C	47.9	45.3	47.8
	pH		8.7	8.3	9.4
(2)	TSS_i	mg/L	83	72	90
	TSS_e	mg/L	78	81	84
	Normalized TSS	%	0.94	1.13	0.93
	FSS_i	mg/L	34	26	27
	FSS_e	mg/L	22	36	30
	Normalized FSS	%	0.65	1.38	1.11
	VSS_i	mg/L	56	46	63
	VSS_e	°C	60	45	54
	Normalized VSS	%	1.07	0.98	0.86
	T	°C	46.5	44.2	47.0
	pH		8.7	8.3	9.4

Note: Subscripts i and e indicate influent and effluent.

Table 4.2 Composition of clog material precipitated within each pipes permeated with leachate.

Parameter	Symbol	Unit	Pipe series (1)	Pipe series (2)	Pipe Series (1)	Pipe Series (2)
Water Content		%wet	32.52	49.96	55.08	57.47
Organic Matter		%dry	41.33	42.53	40.05	39.51
Carbonate as CO_3		%dry	43.2	48.84	47.76	47.16
Calcium		%dry	7.26	6.88	7.5	8.57
Aluminum	Al	$mg \cdot kg^{-1}$	114	81	140	173
Barium	Ba	$mg \cdot kg^{-1}$	165	158	168	172
Boron	B	$mg \cdot kg^{-1}$	48.5	49.8	62.5	66.6
Calcium	Ca	$mg \cdot kg^{-1}$	72600	68800	75000	85700
Cobalt	Co	$mg \cdot kg^{-1}$	1.17	1.06	1.56	1.87
Chromium	Cr	$mg \cdot kg^{-1}$	18.4	16.4	24.2	27
Copper	Cu	$mg \cdot kg^{-1}$	11.2	12	10.6	14
Iron	Fe	$mg \cdot kg^{-1}$	5380	4620	10400	11600
Lead	Pb	$mg \cdot kg^{-1}$	3.68	3.41	5.37	5.77
Magnesium	Mg	$mg \cdot kg^{-1}$	197000	191000	171000	168000
Manganese	Mn	$mg \cdot kg^{-1}$	127	117	150	189
Molybdenum	Mo	$mg \cdot kg^{-1}$	0.49	0.35	0.78	0.87
Nickel	Ni	$mg \cdot kg^{-1}$	3.6	3.5	4.6	5.4
Potassium	K	$mg \cdot kg^{-1}$	893	790	1280	1190
Silver	Ag	$mg \cdot kg^{-1}$	1<	1<	1<	1<
Sodium	Na	$mg \cdot kg^{-1}$	2020	1860	2780	2730
Strontium	Sr	$mg \cdot kg^{-1}$	1870	1800	1820	1970
Tin	Sn	$mg \cdot kg^{-1}$	10	10	12	13
Zinc	Zn	$mg \cdot kg^{-1}$	122	119	158	213
Ca/CO_3			0.17	0.14	0.16	0.18
Mg/CO_3			0.46	0.39	0.36	0.36

Table 4.3 Summary of clog composition that accumulated within porous media and pipes permeated with landfill leachate (values reported are in percentage except for $CaCO_3$ and Mg/CO_3).

	Ca	CO_3	Si	Mg	Fe	Ca/CO_3	Mg/CO_3
German Landfill Brune *et al* (1991)	21	34	16	1	8	0.62	0.03
KVL-Temperature*							
21 °C	30	47	2	<1	2	0.64	0.019
27 °C	25	50	3	1	4	0.48	0.018
Armstrong (1998)							
Toronto Landfill Fleming *et al.* (1999)	20	30	21	2	8	0.67	0.017
KVL-Mass loading series*							
0.51 $m^3/m^2/d$	24	50	3	1	4	0.48	0.017
1.02 $m^3/m^2/d$	27	58	3	1	4	0.47	0.02
2.04 $m^3/m^2/d$	27	49	3	<1	4	0.55	<0.02
Rowe *et al.* (2000a)							
KVL-Particle size series*							
4 mm	24	50	3	1	4	0.48	0.02
6 mm	27	58	3	1	4	0.47	0.02
15 mm	27	49	3	<1	4	0.55	<0.02
Rowe *et al.* (2000b)							
Synthetic Leachate*							
21 °C, 6 mm beads	36	51	-	<1	<1	0.71	<0.02
Rowe *et al.* (2001)							
Synthetic Leachate*							
21 °C, 6 mm beads	37	57	<1	<1	<1	0.66	<0.02
VanGulck and Rowe (2004a)							
KVL-Leachate*							
21 °C, 6 mm beads	29	50	2	1	3	0.58	<0.02
VanGulck and Rowe (2004b							
Pressurized pipe experiment (this study)*							
Pipe series 1 (1)	7.0	43.0	1.4	19.7	0.5	0.17	0.46
Pipe series 1 (2)	6.9	48.8	0.8	19.1	0.5	0.14	0.39
Pipe series 2 (1)	7.5	47.7	1.2	17.1	1.0	0.16	0.36
Pipe series 2 (2)	8.6	47.1	1.2	16.8	1.2	0.18	0.36

* Laboratory study

Table 4.4 Clog thickness and flux calculated for each pipe at different hydraulic retention times applied during the laboratory experiment.

Parameter	Unit	Pipe series 1		Pipe series 2	
		(1)	(2)	(1)	(2)
Wet mass collected	[g/cm of pipe]	0.74	1.49	2.88	3.36
Bulk density	[mg/m^3]	1.53	1.49	1.78	1.3
Volatile solid density	[mg VS/m^3]	0.85	0.42	0.32	0.29
Inorganic solid density	[mg NVS/m^3]	2.29	2.36	2.87	2.29
Clog thickness	[mm]	0.8	1.7	1.3	2.0

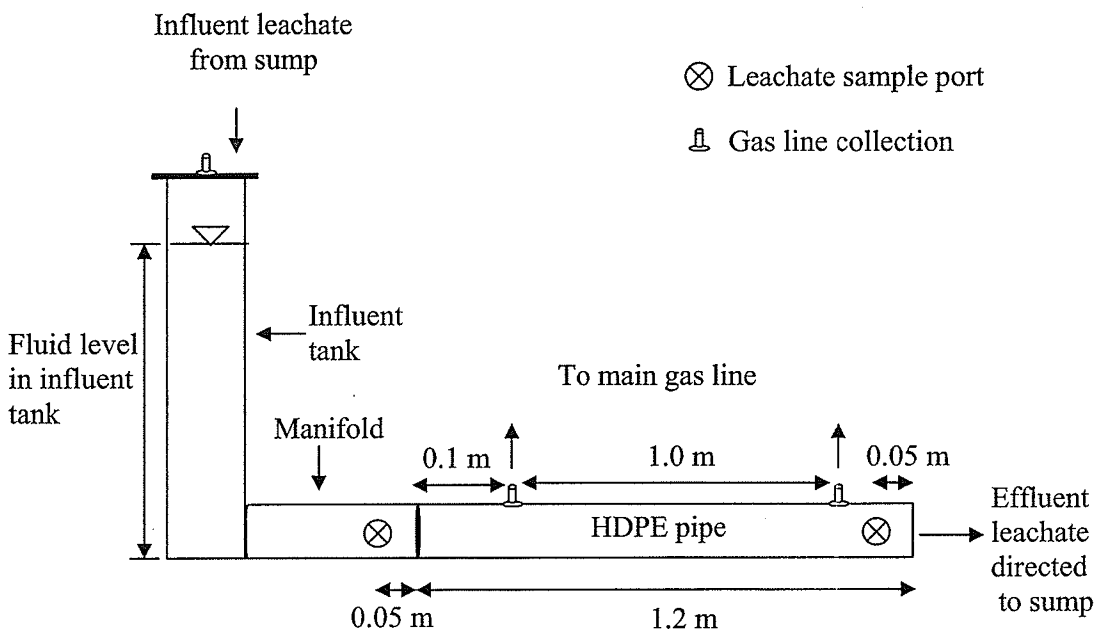


Figure 4.1 Schematic of laboratory pipe experiments (not to scale)

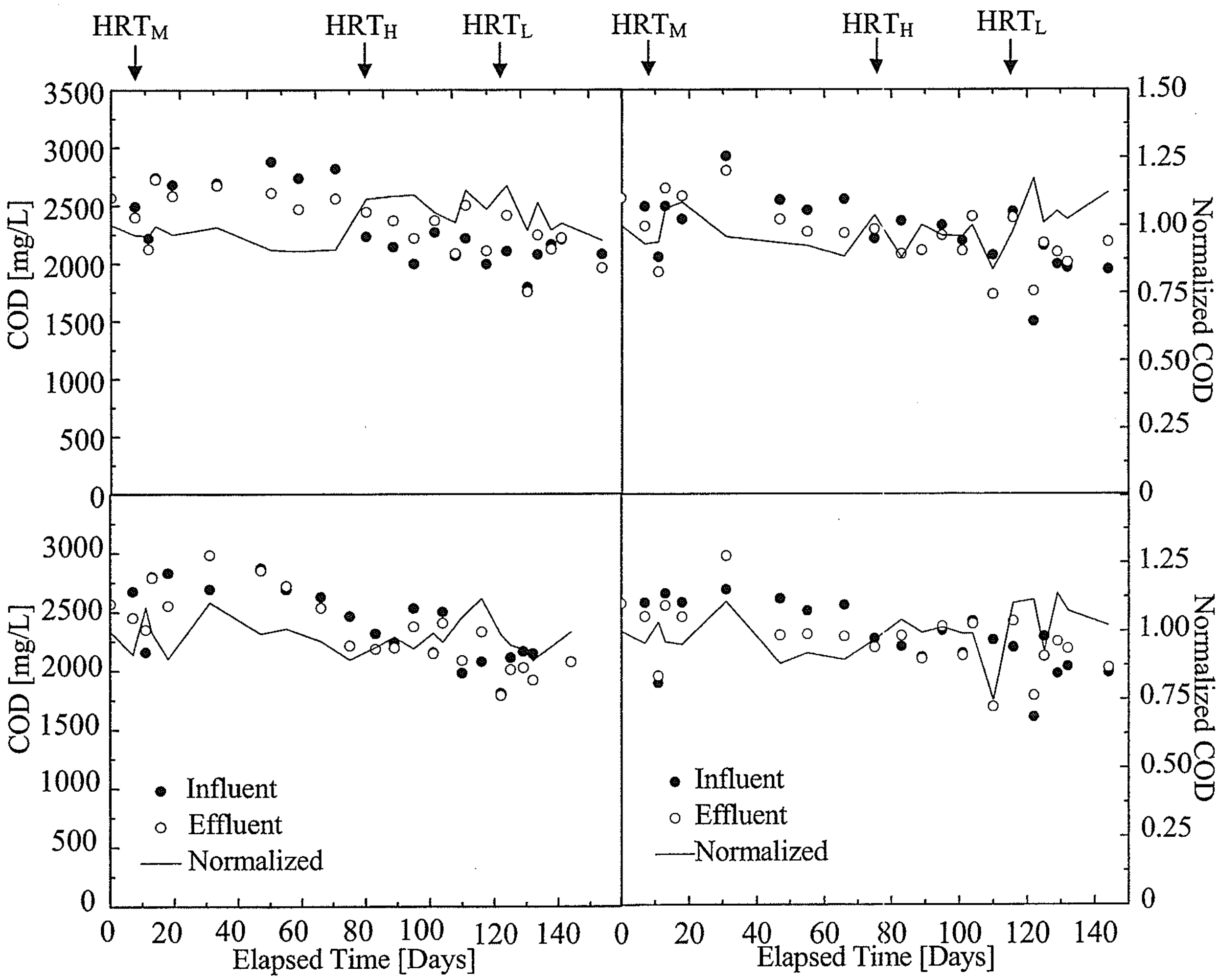


Figure 4.2 COD variation in pipe series 1 (a) Pipe 1 (b) Pipe 2, COD variation in pipe series 2 (c) Pipe 1 (d) Pipe 2 with elapsed time.

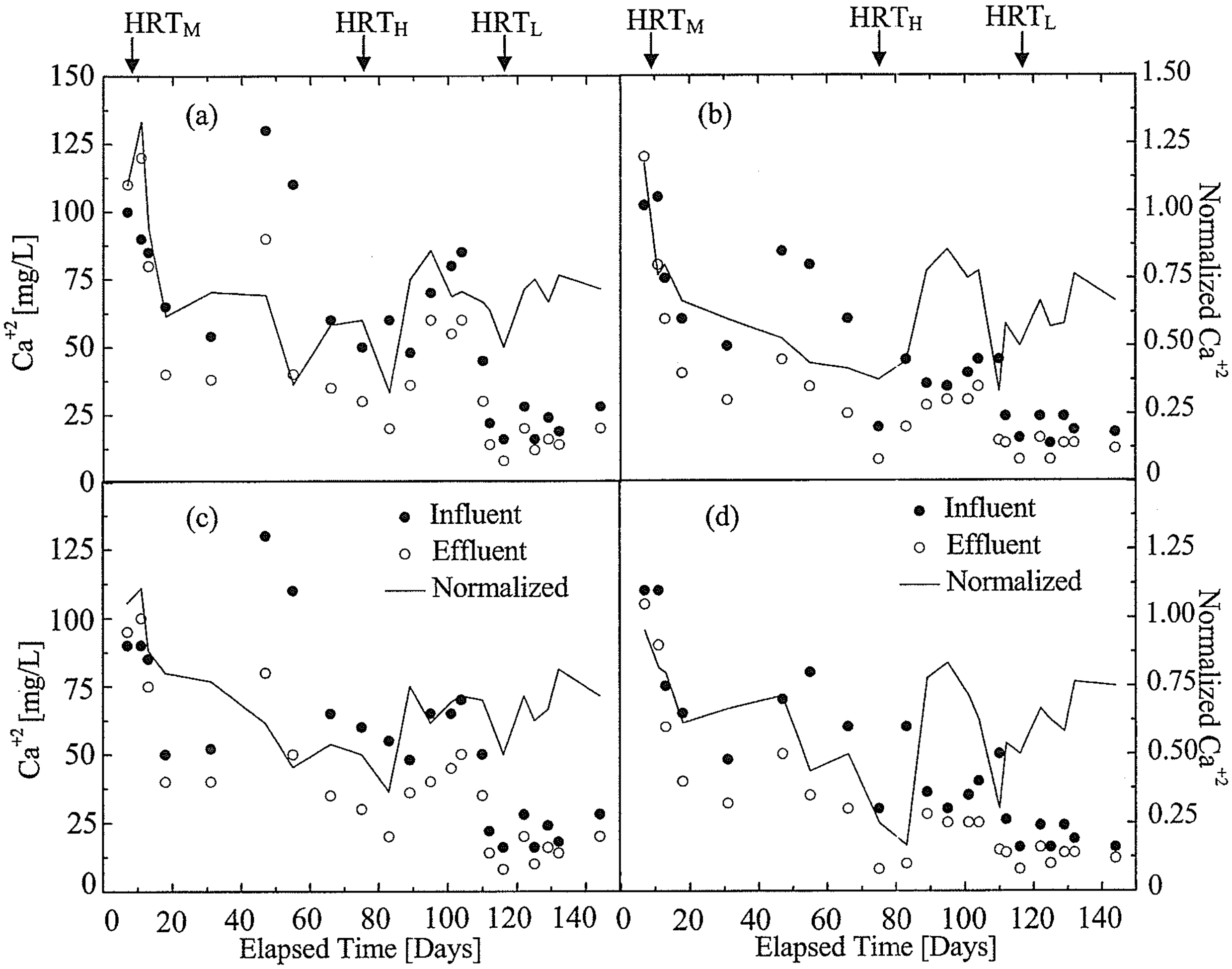


Figure 4.3 Ca^{+2} variation in pipe series 1 (a) Pipe 1 (b) Pipe 2, Ca^{+2} variation in pipe series 2 (c) Pipe 1 (d) Pipe 2 with elapsed time.

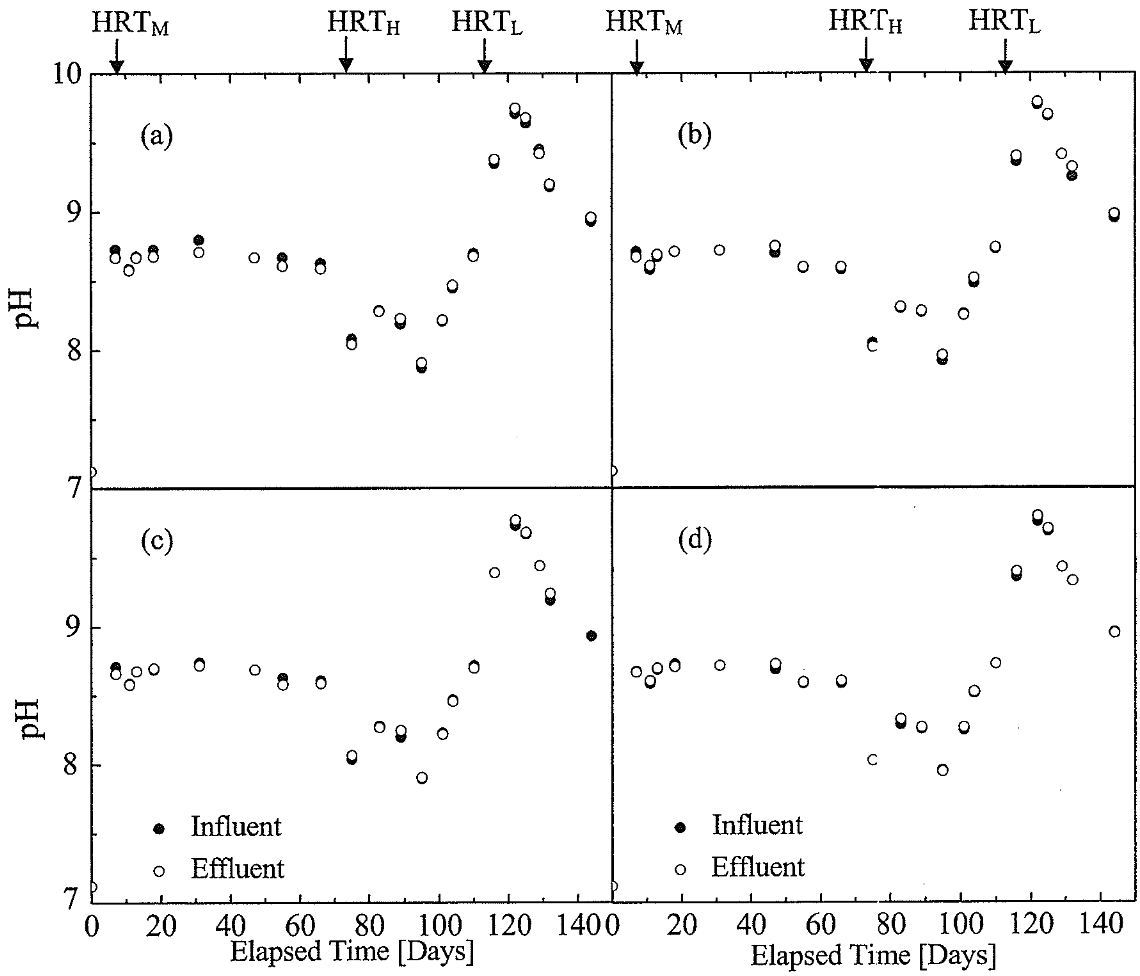


Figure 4.4 pH average variation in pipe series 1 (a) Pipe 1 (b) Pipe 2 and pipe series 2 (c) Pipe 1 (d) Pipe 2 with elapsed time.

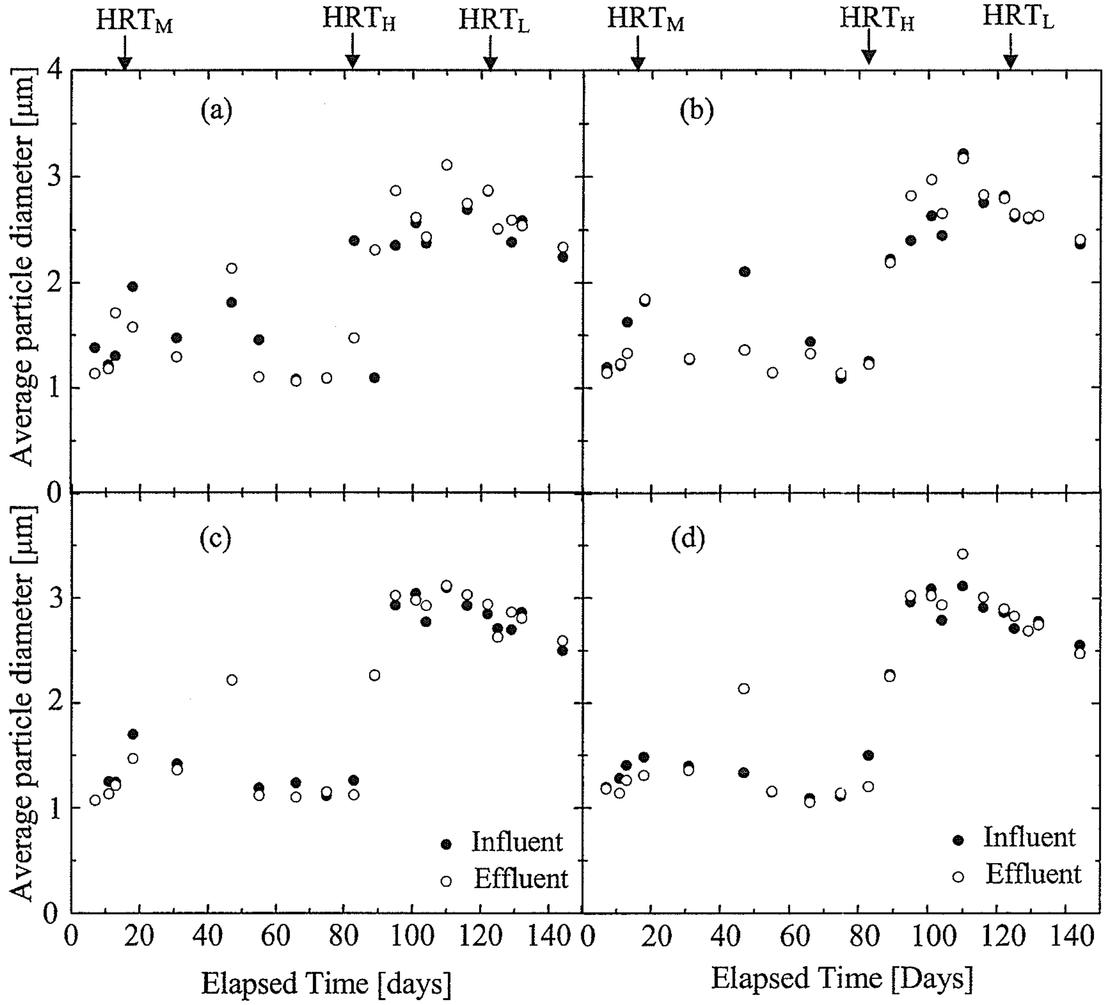


Figure 4.5 Average particle diameter in series 1 (a) Pipe 1, (b) Pipe 2 and pipe series 2 (c) Pipe 1 (d) Pipe 2 with elapsed time.

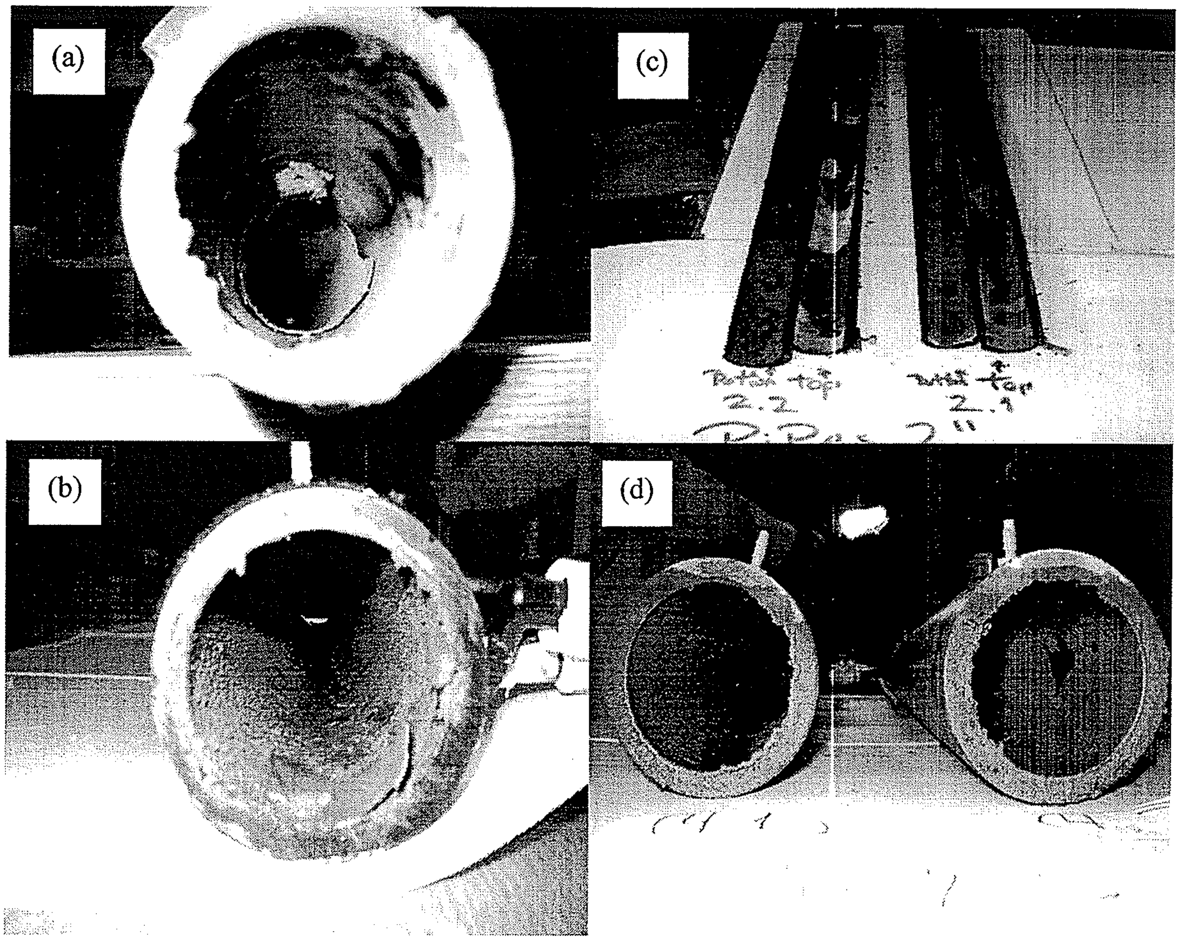


Figure 4.6 (a) Pipe series 1, pipe 1 (b) Pipe series 2, pipe 1, (c) Clog scale formation in pipe series 1, and (d) Clog scale formation in pipe series 2, after 5 months of operation.

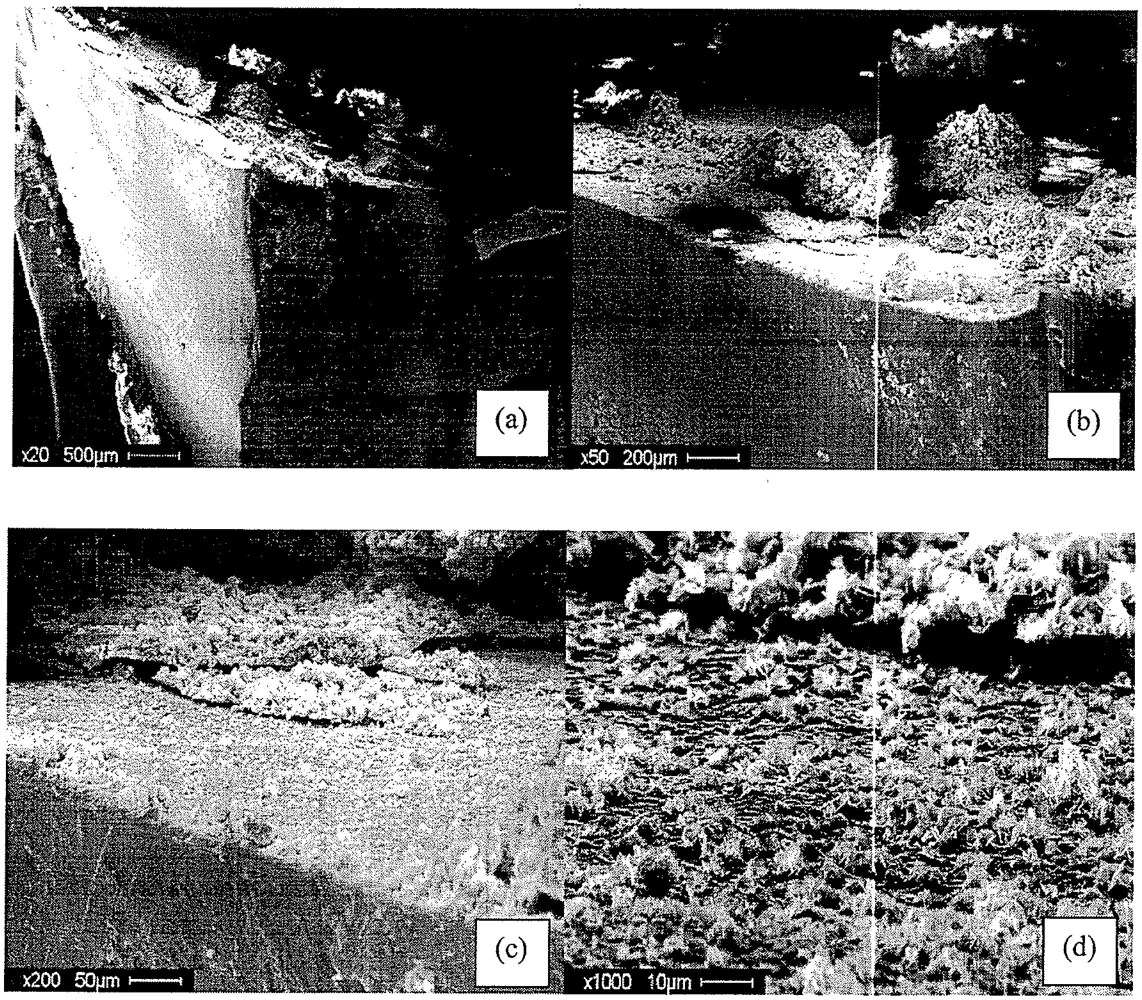


Figure 4.7 SEM photographs showing a sequence of a pipe from series 2 clogged. Magnifications of 20X, 50X, 200X and 1000X were performed.

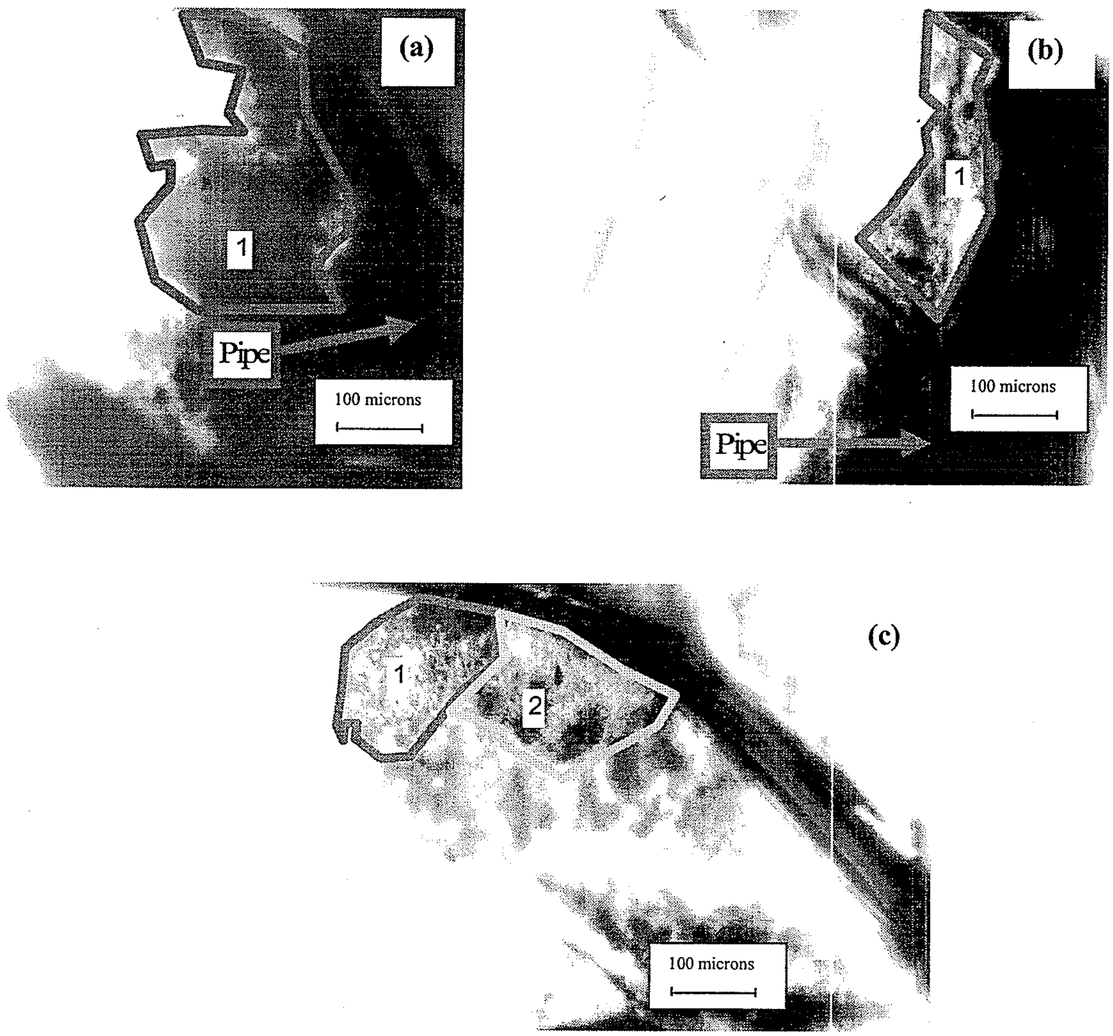


Figure 4.8 Clogging and pipe pictures (a, b and c) taken at 10X magnification. Segmented by a polygonal line (denoted with a [1] or [2] in the figure) are the areas (a) 0.1, (b) 0.1, (c) 0.1 and 0.2 μm^2 of clog material that had deduced porosity of 0.22, 0.5, 0.7, and 0.58 and thickness of 293, 171, 148, and 152 m perpendicular to the pipe, respectively..

CHAPTER 5: CONCLUSIONS AND RECOMMENDATIONS

5.1 INTRODUCTION

The research conducted in this thesis theoretically considered implications of pipe hydraulics in the design and operation of a horizontal injection trench for use in bioreactor landfills, as well as, the select mechanisms responsible for clogging in pressurized pipes observed in a well controlled full-scale laboratory experiment. This chapter provides a summary and the conclusions of the work presented in this thesis and recommendations for future work.

5.2 SUMMARY AND CONCLUSIONS

A conceptual framework to design horizontal injection trenches (HIT) and a hydraulic design methodology, based on Bernoulli's equation for perforated pipes used in HIT, was presented. In addition to this, a laboratory experiment that involved permeated leachate under pressurized conditions through transmission pipes were operated to measured clog composition, and assess the influence of pipe diameter and flow rate on the changes in leachate composition changes within the pipe. The experiment was designed to represent real leachate injection conditions with pipe physical characteristics and flow rates used in practice.

Chapter 2 presented a review of leachate injection systems with emphasis on HIT and design methodologies. Also, it includes an overview of clogging mechanisms observed for porous media permeated with leachate. The mechanisms for clogging in a porous media were hypothesized to occur within leachate transmission pipes.

Chapter 3 provided a summary of HIT design and operational parameters from literature and reported pilot and full-scale bioreactor landfills. A methodological hydraulic design based on Bernoulli's equation that links perforated pipe physical and operational values to achieve uniform discharge of liquid along the length of the line was presented. A sensitivity analysis was conducted with the design and operational values of perforated pipes reported in practice. Many combinations of reported designs and operations did not achieve uniform discharge along the length of the line and therefore would likely not uniformly wet the refuse around the trench. Finally, a conceptual framework was presented that links HIT components, such as leachate availability, hydraulic performance of the perforated pipe, trench filling strategy, and pump cycle time, to uniform filling the trench and wet the surrounded refuse. A uniform waste wetting will likely maximize to the benefits of leachate recirculation by HIT.

Chapter 4 presented the results of the laboratory investigation into clogging of transmission pipes permeated with leachate with external diameters of 0.05 and 0.1 m. Calcium removal within the pipe series was practically similar for the three HRT (for flow rates 0.5 to 0.6 L/s, 0.2 to 0.3 L/s and 1 to 1.4 L/s) tested. COD and pH did not change considerably within the pipes, indicating that organic acid consumption was not large. High influent leachate pH values (8.3, 8.7 and 9.4) were measured for each HRT tested and the highest flow rate gave rise to the largest pH. The high influent leachate pH was likely associated with the hydraulic operation of the laboratory experiments, which permitted degasification of CO_2 from the pipelines, sump and tanks during leachate recycle to the pipes.

After about 5 months of operation, clog accumulated within the pipes as a circular layer covering the internal diameter of the pipes, with more material accumulated on the bottom half of the pipe than the top half. Less amount of clog accumulated on the top half due to gas accumulating in this part of the pipe and reduced the contact of the pipe surface with leachate. The clog material was comprised on organic (biofilm) and inorganic materials (hydromagnesite mineral). Volatile solids and carbonate comprised 40% and 45% of clog material, respectively, and account for most of the organic and inorganic clog. Even though mass loads into the pipes (function of flow rate and leachate composition) were practically similar for both pipe diameters, more clog material was accumulated within the larger diameter pipe and was likely a result of a larger interior surface area of a larger diameter pipe compared to a smaller diameter pipe of equal lengths.

5.3 PRACTICAL FINDINGS AND RECOMMENDATIONS

Physical design variables of the perforated pipe, including: internal diameter, pipe length, perforation shape and spacing, and pipe roughness need to be considered to calculate the inlet flow rate and hydraulic head required to achieve a uniform discharge along the length of the trench to achieve uniform waste degradation and its benefits. However, the methodological hydraulic design proposed for perforated pipes employed in horizontal leachate recirculation systems on Chapter 3, does not include clogging and the hydraulic consequences produced by its accumulation within pipe internal diameter and perforations. Further research is needed to predicting clog development within the pipe and perforations to assess the long term pipe performance after clogging occurs, and also the service life of this system.

Full scale pipes were permeated with leachate to gain insight into the mechanisms responsible for clogging due to biological, physical and chemical processes. The experimental results showed that high flow rates enhance leachate CO_2 degasification, increasing the pH and may enhance rate of clogging within the pipes. The magnesium and calcium concentration in leachate can impact the mineral composition of the clog material formed within the pipe. Hydromagnesite was formed in this study; however, previous study of clogging in porous media measured calcite to be the dominant mineral phase. Calcium and magnesium concentrations within the leachate should be measured together in future research in pipe clogging to quantify the individual or combined effect on the mineral formed within the clog material. The mineral type and structure can determine the efficiency of the cleaning strategy adopted to remove the clog from the pipes. Finally, the accumulation of clog material within the pipe internal surface may change the original rugosity of the pipe thereby affecting the friction factor of the pipe, and therefore the hydraulic efficiency of the injection system. Additional research is required to assess the decrease in hydraulic performance with clog accumulation.

For the same flow rate and leachate characteristics, small diameter pipes are more susceptible to internal diameter reduction than large diameter pipes for all other conditions being equal. Thus, pipe design and operation can impact the amount, and likely rate, of clog within leachate injection pipes. As clog accumulates, there will likely be a change in the pipe hydraulics and therefore performance of the injection system compared to the design value.

APPENDIX A SENSITIVITY ANALISYS RESULTS

Table A 1 Sensitivity matrix of parameters analyzed for 0.05 [m] external pipe diameter and pipe length 30 m using the mathematical method proposed.

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x\ 10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
0.5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	0.91	5.56	4.94	11.2
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
1	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	1.21	6.37	4.94	22.4
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	1.57	6.88	5.05	26.7
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate x10-3 [m3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge x10-5 [m3/s]	Last Perforation Discharge x 10-5 [m3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	10.57	18.27	5.12	72.0
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	14.03	21.29	5.81	72.7
	0.01	2	-	-		-
	0.02	2	-	-		-
	0.005	4	18.74	22.73	7.48	67.1
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
10	0.005	0.5	26.45	28.12	5.02	82.1
	0.01	0.5	-			-
	0.02	0.5	-			-
	0.005	1	37.74	34.35	5.73	83.3
	0.01	1	-			-
	0.02	1	-			-
	0.005	2	49.52	39.82	7.81	80.4
	0.01	2	24.68	108.00	21.12	80.4
	0.02	2	-			-
	0.005	4	65.33	42.24	11.83	72.0
	0.01	4	43.73	128.96	31.92	75.2
	0.02	4	-	-	-	-

Note: No data indicates that pipe does not satisfy pressurized conditions.

Table A.1 Sensitivity matrix of parameters analyzed for 0.1 [m] external pipe diameter and pipe length 30 m using the mathematical method proposed.

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x\ 10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
0.5	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	0.71	4.95	4.94	0.3
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
1	0.02	1	-	-	-	-
	0.005	2	0.73	4.99	4.94	1.2
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	0.74	5.02	4.94	1.5
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate x10^{-3} [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge x10^{-5} [m^3/s]	Last Perforation Discharge x 10^{-5} [m^3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	1.08	5.97	4.94	17.2
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	1.20	6.31	4.95	21.5
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	1.28	6.51	4.99	23.3
	0.01	2	1.06	23.68	19.79	16.4
	0.02	2	-	-	-	-
	0.005	4	1.35	6.48	5.06	21.9
	0.01	4	1.24	24.68	20.05	18.8
	0.02	4	-	-	-	-
10	0.005	0.5	2.33	8.59	4.96	42.2
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	2.64	9.05	5.02	44.6
	0.01	1	1.86	30.39	19.80	34.8
	0.02	1	-	-	-	-
	0.005	2	2.80	9.50	5.14	45.9
	0.01	2	2.27	33.90	20.15	40.6
	0.02	2	-	-	-	-
	0.005	4	3.01	9.34	5.38	42.3
	0.01	4	2.74	35.24	21.09	40.2
	0.02	4	2.04	117.12	80.11	31.6

Note: No data indicates that pipe does not satisfy pressurized conditions.

Table A.2 Sensitivity matrix of parameters analyzed for 0.0508[m] external pipe diameter and pipe length 100 m using the mathematical method proposed.

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge x 10^{-5} [m^3/s]	Change in Perforation Discharge [%]
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
0.5	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
1	0.02	1		-	-	
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate $\times 10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $\times 10^{-5}$ [m^3/s]	Last Perforation Discharge $\times 10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	25.090	28.89	5.30	81.6
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
10	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	60.48	44.31	5.03	88.6
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	91.12	54.95	6.49	88.2
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Note: No data indicates that pipe does not satisfy pressurized conditions.

Table A.3 Sensitivity matrix of parameters analyzed for 0.1 [m] external pipe diameter and pipe length 100 m using the mathematical method proposed.

Inlet Flow Rate	Perforation Diameter	Perforation Spacing	Inlet Hydraulic Head	First Perforation Discharge	Last Perforation Discharge	Change in Perforation Discharge
$x10^{-3}$ [m^3/s]	[m]	[m]	[m]	$x10^{-5}$ [m^3/s]	x 10^{-5} [m^3/s]	[%]
0.5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
1	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate x10^{-3} [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge x10^{-5} [m^3/s]	Last Perforation Discharge x 10^{-5} [m^3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	1.828	7.84	4.95	36.8
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	2.21	8.64	5.01	42.0
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
10	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	3.88	11.18	4.95	55.7
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	5.24	13.20	5.02	61.9
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	6.34	14.56	5.23	64.1
	0.01	4	3.78	44.49	19.93	55.2
	0.02	4	-	-	-	-

Note: No data indicates that pipe does not satisfy pressurized conditions.

Table A.4 Sensitivity matrix of parameters analyzed for 0.05 [m] external pipe diameter and pipe length 300 m using the mathematical method proposed.

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
0.5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
1	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
10	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Note: No data indicates that pipe does not satisfy pressurized conditions.

Table A.5 Sensitivity matrix of parameters analyzed for 0.1 [m] external pipe diameter and pipe length 300 m using the mathematical method proposed.

Inlet Flow Rate $x10^{-3}$ [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge $x10^{-5}$ [m^3/s]	Last Perforation Discharge $x10^{-5}$ [m^3/s]	Change in Perforation Discharge [%]
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
0.5	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
1	0.02	1		-	-	
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	-	-	-	-
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Inlet Flow Rate x10^{-3} [m^3/s]	Perforation Diameter [m]	Perforation Spacing [m]	Inlet Hydraulic Head [m]	First Perforation Discharge x10^{-5} [m^3/s]	Last Perforation Discharge x10^{-5} [m^3/s]	Change in Perforation Discharge [%]
5	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	2.74	9.64	4.94	48.8
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-
10	0.005	0.5	-	-	-	-
	0.01	0.5	-	-	-	-
	0.02	0.5	-	-	-	-
	0.005	1	-	-	-	-
	0.01	1	-	-	-	-
	0.02	1	-	-	-	-
	0.005	2	-	-	-	-
	0.01	2	-	-	-	-
	0.02	2	-	-	-	-
	0.005	4	9.08	17.50	4.98	71.6
	0.01	4	-	-	-	-
	0.02	4	-	-	-	-

Note: No data indicates that pipe does not satisfy pressurized conditions.

APPENDIX B LEACHATE DATA FOR PIPE SERIES 1 AND 2

Table B.1 COD average influent and effluent measurements for pipe series 1 and 2

Time	COD Influent [mg/L]		COD Effluent [mg/L]		COD Influent [mg/L]		COD Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	2568	2568	2568	2568	2568	2568	2568	2568
7	2492	2675	2400	2453	2496	2574	2326	2459
11	2216	2159	2123	2349	2060	1888	1932	1951
13	2739	2798	2726	2791	2498	2653	2653	2551
18	2679	2831	2582	2554	2385	2579	2587	2454
31	2695	2695	2673	2985	2927	2686	2804	2975
47	2879	2874	2609	2853	2550	2608	2383	2299
55	2735	2691	2469	2722	2460	2508	2275	2307
66	2815	2629	2559	2537	2558	2556	2265	2288
75	2232	2465	2445	2214	2219	2269	2301	2195
83	2141	2317	2369	2184	2369	2203	2087	2295
89	1996	2239	2217	2197	2115	2112	2118	2098
95	2267	2533	2369	2375	2333	2340	2245	2373
101	2067	2157	2084	2147	2200	2146	2113	2125
104	2217	2501	2501	2407	2407	2420	2409	2396
110	1993	1982	2108	2089	2074	2257	1736	1687
116	2106	2080	2414	2333	2449	2194	2397	2418
122	1792	1808	1753	1790	1505	1600	1767	1783
125	2076	2114	2246	2012	2161	2286	2181	2120
129	2165	2165	2122	2027	1997	1972	2101	2245
132	2206	2147	2219	1922	1970	2032	2014	2184
144	2079	2079	1959	2076	1953	1982	2190	2023

Table B.2 Ca^{+2} average influent and effluent measurements for pipe series 1 and 2

Time	Ca^{+2} Influent [mg/L]		Ca^{+2} Effluent [mg/L]		Ca^{+2} Influent [mg/L]		Ca^{+2} Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	-	-	-	-	-	-	-	-
7	100	90	110	95	102	110	120	105
11	90	90	120	100	105	110	80	90
13	85	85	80	75	75	75	60	60
18	65	50	40	40	60	65	40	40
31	54	52	38	40	50	48	30	32
47	130	130	90	80	85	70	45	50
55	110	110	40	50	80	80	35	35
66	60	65	35	35	60	60	25	30
75	50	60	30	30	20	30	8	8
83	60	55	20	20	45	60	20	10
89	48	48	36	36	36	36	28	28
95	70	65	60	40	35	30	30	25
101	80	65	55	45	40	35	30	25
104	85	70	60	50	45	40	35	25
110	45	50	30	35	45	50	15	15
112	22	22	14	14	24	26	14	14
116	16	16	8	8	16	16	8	8
122	28	28	20	20	24	24	16	16
125	16	16	12	10	14	16	8	10
129	24	24	16	16	24	24	14	14
132	19	18	14	14	19	19	14	14
144	28	28	20	20	18	16	12	12

Table B.3: pH influent and effluent measurements for pipe series 1 and 2

Time [days]	pH Influent [mg/L]		pH Effluent [mg/L]		pH Influent [mg/L]		pH Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	7.12	7.12	7.12	7.12	7.12	7.12	7.12	7.12
7	8.73	8.71	8.67	8.66	8.71	8.68	8.67	8.67
11	8.59	8.59	8.58	8.58	8.58	8.59	8.61	8.61
13	8.68	8.68	8.67	8.68	8.67	8.69	8.69	8.7
18	8.73	8.69	8.68	8.7	8.71	8.73	8.71	8.71
31	8.8	8.74	8.71	8.72	8.72	8.72	8.72	8.72
47	8.67	8.69	8.67	8.69	8.7	8.69	8.75	8.73
55	8.67	8.63	8.61	8.58	8.59	8.59	8.6	8.6
66	8.63	8.61	8.59	8.59	8.58	8.59	8.60	8.61
75	8.08	8.04	8.04	8.07	8.05	8.03	8.02	8.03
83	8.29	8.28	8.28	8.27	8.30	8.29	8.31	8.33
89	8.19	8.20	8.23	8.25	8.27	8.26	8.28	8.27
95	7.87	7.90	7.91	7.91	7.92	7.96	7.96	7.95
101	8.21	8.23	8.22	8.22	8.26	8.25	8.25	8.27
104	8.45	8.47	8.47	8.46	8.48	8.52	8.52	8.53
110	8.70	8.72	8.68	8.7	8.73	8.73	8.74	8.73
116	9.35	9.39	9.38	9.39	9.36	9.36	9.40	9.4
122	9.71	9.73	9.75	9.77	9.77	9.76	9.79	9.8
125	9.64	9.67	9.68	9.68	9.69	9.69	9.70	9.71
129	9.45	9.44	9.42	9.44	9.41	9.43	9.41	9.43
132	9.18	9.19	9.20	9.24	9.25	9.33	9.32	9.33
144	8.93	8.93	8.96	8.95	8.95	8.96	8.98	8.95

Table B.4 TSS influent and effluent measurements for pipe series 1 and 2

Time [days]	TSS Influent [mg/L]		TSS Effluent [mg/L]		TSS Influent [mg/L]		TSS Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	155	155	155	155	155	155	155	155
7	80	80	140	90	30	100	80	170
11	100	60	200	260	80	160	80	60
13	40	30	40	40	50	20	40	40
18	110	60	80	90	80	80	80	110
31	80	130	60	70	90	90	50	70
47	60	100	80	90	110	110	100	90
55	90	60	100	90	80	100	50	100
66	70	90	40	70	80	70	70	60
75	50	70	40	80	80	60	70	70
83	80	50	80	80	70	60	70	70
89	90	60	70	70	50	80	110	130
95	60	120	80	90	140	90	90	120
101	120	80	80	80	100	70	80	100
104	30	50	30	40	40	40	50	60
110	70	70	80	80	90	40	60	60
116	110	60	60	90	120	70	150	130
122	100	100	80	50	50	40	60	80
125	110	30	70	50	50	50	30	50
129	130	130	120	90	120	130	120	100
132	140	130	110	110	90	180	60	60
144	110	70	70	90	100	80	80	90

Table B.5 FSS influent and effluent measurements for pipe series 1 and 2

Time [days]	FSS Influent [mg/L]		FSS Effluent [mg/L]		FSS Influent [mg/L]		FSS Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	55	55	55	55	55	55	55	55
7	10	0	40	0	0	0	0	30
11	90	10	160	220	20	100	10	20
13	10	0	0	0	0	0	10	0
18	50	40	20	10	20	10	10	30
31	40	50	20	20	10	40	0	10
47	10	40	40	40	70	70	60	40
55	30	20	40	40	30	50	30	60
66	10	40	10	10	40	20	20	10
75	0	40	0	10	40	0	20	20
83	30	20	30	30	30	40	10	30
89	40	10	30	30	30	0	30	60
95	10	30	30	30	40	40	40	70
101	70	30	30	20	40	30	30	30
104	0	10	20	10	10	20	50	40
110	50	50	30	30	40	10	40	40
116	30	10	10	20	40	10	70	60
122	30	30	30	0	10	20	10	20
125	30	10	0	10	10	20	30	30
129	70	50	40	20	30	50	50	30
132	80	60	60	30	30	80	10	10
144	40	30	20	30	20	0	10	30

Table B.6 VSS influent and effluent measurements for pipe series 1 and series 2

Time [days]	VSS Influent [mg/L]		VSS Effluent [mg/L]		VSS Influent [mg/L]		VSS Effluent [mg/L]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	100	100	100	100	100	100	100	100
7	70	90	100	120	30	140	130	140
11	10	50	40	40	60	60	70	40
13	30	30	40	40	50	20	30	40
18	60	20	60	80	60	70	70	80
31	40	80	40	50	80	50	50	60
47	50	60	40	50	40	40	40	50
55	60	40	60	50	50	50	20	40
66	60	50	30	60	40	50	50	50
75	50	30	40	70	40	60	50	50
83	50	30	50	50	40	20	60	40
89	50	50	40	40	20	80	80	70
95	50	90	50	60	100	50	50	50
101	50	50	50	60	60	40	50	70
104	50	40	10	30	30	20	0	20
110	20	20	50	50	50	30	20	20
116	80	50	50	70	80	60	80	70
122	70	70	50	50	40	20	50	60
125	80	20	70	40	40	30	0	20
129	60	80	80	70	90	80	70	70
132	60	70	50	80	60	100	50	50
144	70	40	50	60	80	80	70	60

Table B.7 Average particle sizes influent and effluent measurements for pipe series 1 and series 2

Time [days]	Particles Influent [μm]		Particles Effluent [μm]		Particles Influent [μm]		Particles Effluent [μm]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	-	-	-	-	-	-	-	-
7	1.38	1.19	1.14	1.13	1.07	1.20	1.08	1.19
11	1.22	1.20	1.18	1.22	1.25	1.29	1.14	1.15
13	1.30	1.62	1.71	1.32	1.25	1.41	1.22	1.27
18	1.96	1.82	1.58	1.84	1.70	1.49	1.47	1.31
31	1.47	1.26	1.30	1.27	1.42	1.40	1.36	1.36
47	1.81	2.10	2.14	1.35	2.22	1.34	2.22	2.14
55	1.46	1.13	1.11	1.14	1.19	1.16	1.12	1.16
66	1.08	1.43	1.06	1.32	1.24	1.10	1.10	1.06
75	1.09	1.08	1.09	1.13	1.12	1.11	1.15	1.15
83	2.39	1.25	1.47	1.22	1.26	1.50	1.13	1.21
89	1.10	2.22	2.31	2.18	2.26	2.28	2.26	2.25
95	2.35	2.39	2.87	2.82	2.93	2.97	3.02	3.03
101	2.56	2.63	2.62	2.97	3.04	3.09	2.98	3.02
104	2.37	2.44	2.43	2.65	2.77	2.79	2.93	2.94
110	3.11	3.21	3.11	3.17	3.10	3.12	3.12	3.42
116	2.69	2.75	2.75	2.83	2.93	2.91	3.03	3.01
122	2.86	2.81	2.87	2.79	2.85	2.87	2.94	2.90
125	2.50	2.62	2.51	2.65	2.71	2.71	2.63	2.83
129	2.38	2.60	2.59	2.61	2.70	2.69	2.87	2.69
132	2.58	2.63	2.54	2.63	2.86	2.78	2.81	2.75
144	2.24	2.36	2.34	2.40	2.50	2.55	2.59	2.47

Table B.8 eH influent and effluent measurements for pipe series 1 and series 2

Time [days]	eH Influent [mV]		eH Effluent [mV]		eH Influent [mV]		eH Effluent [mV]	
	Pipe series 1		Pipe Series 1		Pipe series 2		Pipe Series 2	
	(1)	(2)	(1)	(2)	(1)	(2)	(1)	(2)
0	8.5	8.5	8.5	8.5	8.5	8.5	8.5	8.5
7	95	95	96	96	97	96	97	96
11	75	73	72	72	74	73	79	79
13	75	73	69	70	71	71	72	72
18	24	29	24	22	17	19	14	16
31	31	32	31	30	37	30	27	25
47	85	83	82	83	80	84	82	86
55	72	70	64	65	58	59	59	63
66	80	75	74	72	68	64	54	55
75	106	99	103	101	86	87	91	79
83	103	89	83	81	79	78	76	76
89	9	2	7	11	5	10	13	18
95	87	76	73	95	76	72	72	63
101	87	74	70	68	67	60	57	56
104	42	41	45	45	47	46	50	47
110	65	52	50	50	54	56	50	41
116	30	10	14	8	5	3	6	0
122	13	17	11	10	11	6	4	3
125	-5	-2	0	2	4	13	22	38
129	-24	-19	-15	-15	-8	-4	1	2
132	28	10	11	12	15	3	4	2
144	39	37	26	22	20	15	12	17

APPENDIX C CLOG MATERIAL DENSITIES FOR PIPE SERIES 1 AND 2

Table C.1 Pipe series 1(1) clog material density data

Bulk Density Data	Pipe series 1 (1)			
	Influent		Effluent	
Temperature °C	23.80	23.60	23.40	23.40
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	33.07	26.95	29.63	30.91
Mass tare + soil [gr]	35.36	28.31	30.18	33.62
Mass flask [gr]	119.63	116.37	120.34	119.31
Mass flask + Water [gr]	616.70	613.54	617.65	616.45
Mass flask + Water + Soil [gr]	617.94	614.86	618.16	617.40
Mass of water [gr]	1.06	0.04	0.04	1.76
Temperature [°C]	23.80	23.60	23.40	23.40
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	0.99	0.99
Water density (t=T°C) [g/cm^3]	1.00	1.00	0.99	0.99
Soil volume [cm^3]	1.06	0.04	0.04	1.77
Bulk density (t=T°C) [g/cm^3]	-	-	-	1.53

Dry Density Data	Pipe series 1 (1)			
	Influent		Effluent	
Temperature °C	18.80	18.80	19.40	19.20
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	33.07	30.91	29.63	33.25
Mass tare + soil [gr]	33.97	31.55	30.00	34.17
Mass flask [gr]	119.63	116.35	120.32	119.29
Mass flask + Water [gr]	617.68	614.10	618.01	617.07
Mass flask + Water + Soil [gr]	618.13	614.48	618.09	617.56
Mass of water [gr]	0.45	0.26	0.29	0.43
Temperature [°C]	18.80	18.80	19.40	19.20
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.46	0.26	0.29	0.43
Dry density (t=T°C) [g/cm^3]	1.99	-	-	2.15

Ash Density Data	Pipe series 1 (1)			
	Influent		Effluent	
Temperature °C	19.20	19.20	19.20	19.20
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	33.07	30.91	29.63	33.25
Mass tare + soil [gr]	33.72	32.00	29.76	33.86
Mass flask [gr]	119.60	116.34	120.30	119.26
Mass flask + Water [gr]	617.47	614.34	618.15	617.20
Mass flask + Water + Soil [gr]	618.02	614.95	618.16	617.34
Mass of water [gr]	0.11	0.47	0.12	0.47
Temperature [°C]	19.20	19.20	19.20	19.20
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.11	0.47	0.12	0.47
Ash density (t=T°C) [g/cm^3]	-	2.29	-	-

Table C.2 Pipe series 1(2) clog material density data

Bulk Density Data	Pipe series 1 (2)			
	Influent		Effluent	
Temperature °C	23.60	23.40	23.50	23.60
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	33.25	24.77	22.98	31.08
Mass tare + soil [gr]	36.73	26.73	25.41	36.67
Mass flask [gr]	116.05	116.16	116.60	117.07
Mass flask + Water [gr]	613.25	613.25	613.64	614.25
Mass flask + Water + Soil [gr]	614.22	613.90	614.76	615.41
Mass of water [gr]	2.51	1.31	1.31	4.42
Temperature [°C]	23.60	23.40	23.50	23.60
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	0.99	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	0.99	1.00	1.00
Soil volume [cm^3]	2.52	1.32	1.31	4.43
Bulk density (t=T°C) [g/cm^3]	1.38	1.48	1.85	1.26

Dry Density Data	Pipe series 1 (2)			
	Influent		Effluent	
Temperature °C	18.8	18.8	19.20	19.40
Time under vacuum [min]	1440	1440	1440.0	1440.0
Mass tare [gr]	26.9552	31.0876	24.77	22.98
Mass tare + soil [gr]	27.1995	32.3586	25.84	24.35
Mass flask [gr]	116.05	116.15	116.60	117.07
Mass flask + Water [gr]	614.11	613.85	614.35	615.40
Mass flask + Water + Soil [gr]	614.28	613.88	614.71	616.51
Mass of water [gr]	0.0743	1.241	0.71	0.26
Temperature [°C]	18.8	18.8	19.20	19.40
Water density (t=20°C) [g/cm3]	0.99823	0.99823	1.00	1.00
Temp. correction coefficient (α)	1.00024	1.00024	1.00	1.00
Water density (t=T°C) [g/cm^3]	0.99847	0.99847	1.00	1.00
Soil volume [cm^3]	0.074414	1.242902	0.71	0.26
Dry density (t=T°C) [g/cm^3]	-	-	1.50	-

Ash Density Data	Pipe series 1 (2)			
	Influent		Effluent	
Temperature °C	19.20	19.20	19.20	19.20
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	26.96	31.09	24.77	22.98
Mass tare + soil [gr]	27.99	32.39	25.61	24.47
Mass flask [gr]	116.03	116.13	116.58	117.04
Mass flask + Water [gr]	613.93	613.87	614.44	614.91
Mass flask + Water + Soil [gr]	614.44	614.72	614.88	615.80
Mass of water [gr]	0.53	0.46	0.40	0.60
Temperature [°C]	19.20	19.20	19.20	19.20
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.53	0.46	0.40	0.60
Ash density (t=T°C) [g/cm^3]	1.97	2.86	2.10	2.49

Table C.3 Pipe series 2(1) clog material density data

Bulk Density Data	Pipe series 2 (1)			
	Influent		Effluent	
Temperature °C	16.40	16.40	16.40	16.40
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	33.07	30.90	29.62	33.24
Mass tare + soil [gr]	37.20	32.56	34.01	34.93
Mass flask [gr]	119.63	116.57	120.30	119.28
Mass flask + Water [gr]	617.48	614.59	614.07	613.99
Mass flask + Water + Soil [gr]	619.33	615.54	615.78	614.77
Mass of water [gr]	2.28	0.71	2.68	0.91
Temperature [°C]	16.40	16.40	16.40	16.40
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.01	1.01	1.01	1.01
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	2.27	0.71	2.67	0.91
Bulk density (t=T°C) [g/cm^3]	1.82	-	1.65	1.87

Dry Density Data	Pipe series 2 (1)			
	Influent		Effluent	
Temperature °C	19.80	19.80	20.00	20.00
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	16.25	17.61	16.82	17.36
Mass tare + soil [gr]	17.98	18.35	18.02	18.34
Mass flask [gr]	119.63	116.32	120.30	119.28
Mass flask + Water [gr]	617.29	614.14	618.22	617.05
Mass flask + Water + Soil [gr]	618.53	614.67	618.79	617.26
Mass of water [gr]	0.49	0.21	0.63	0.77
Temperature [°C]	19.80	19.80	20.00	20.00
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.49	0.21	0.63	0.77
Dry density (t=T°C) [g/cm^3]	-	-	1.90	-

Ash Density Data	Pipe series 2 (1)			
	Influent		Effluent	
Temperature °C	12.90	13.30	9.80	9.80
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	16.75	16.74	18.04	17.75
Mass tare + soil [gr]	18.06	17.66	19.16	18.60
Mass flask [gr]	119.61	116.39	120.33	119.29
Mass flask + Water [gr]	617.76	614.90	618.67	617.60
Mass flask + Water + Soil [gr]	618.69	615.50	619.53	618.42
Mass of water [gr]	0.38	0.32	0.26	0.03
Temperature [°C]	12.90	13.30	9.80	9.80
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.38	0.32	0.26	0.03
Ash density (t=T°C) [g/cm^3]	-	2.87	-	-

Table C.4 Pipe series 2(2) clog material density data

Bulk Density Data	Pipe series 2 (2)			
	Influent		Effluent	
Temperature °C	16.70	16.80	16.80	16.80
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	27.15	31.23	25.41	23.17
Mass tare + soil [gr]	33.31	34.70	30.22	26.39
Mass flask [gr]	116.05	116.12	116.32	117.06
Mass flask + Water [gr]	618.56	617.14	614.51	615.27
Mass flask + Water + Soil [gr]	618.84	618.65	615.25	615.73
Mass of water [gr]	5.88	1.96	4.07	2.76
Temperature [°C]	16.70	16.80	16.80	16.80
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.01	1.01	1.01	1.01
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	5.86	1.95	4.05	2.75
Bulk density (t=T°C) [g/cm^3]	1.05	1.78	1.19	1.17

Dry Density Data	Pipe series 2 (2)			
	Influent		Effluent	
Temperature °C	19.60	19.60	20.00	20.00
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	17.14	16.97	17.54	15.40
Mass tare + soil [gr]	19.68	17.93	20.52	17.14
Mass flask [gr]	116.05	116.12	116.57	117.06
Mass flask + Water [gr]	614.48	613.96	614.97	615.07
Mass flask + Water + Soil [gr]	615.34	614.38	616.26	615.69
Mass of water [gr]	1.68	0.54	1.69	1.12
Temperature [°C]	19.60	19.60	20.00	20.00
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	1.68	0.54	1.69	1.12
Dry density (t=T°C) [g/cm^3]	1.51	1.77	1.76	1.55

Ash Density Data	Pipe series 2 (2)			
	Influent		Effluent	
Temperature °C	13.00	13.20	10.00	10.00
Time under vacuum [min]	1440	1440	1440	1440
Mass tare [gr]	17.71	17.66	19.18	17.56
Mass tare + soil [gr]	18.93	18.81	21.27	18.47
Mass flask [gr]	116.03	116.16	116.59	117.07
Mass flask + Water [gr]	614.33	614.54	615.65	615.91
Mass flask + Water + Soil [gr]	615.31	615.44	617.11	616.10
Mass of water [gr]	0.24	0.25	0.63	0.72
Temperature [°C]	13.00	13.20	10.00	10.00
Water density (t=20°C) [g/cm3]	1.00	1.00	1.00	1.00
Temp. correction coefficient (α)	1.00	1.00	1.00	1.00
Water density (t=T°C) [g/cm^3]	1.00	1.00	1.00	1.00
Soil volume [cm^3]	0.24	0.25	0.63	0.72
Ash density (t=T°C) [g/cm^3]	-	-	3.32	1.26

APPENDIX D XRD ANALYSIS FOR PIPE SERIES 1 AND 2

Figure D.1 XRD analysis for pipe series 1(1) for clog sample

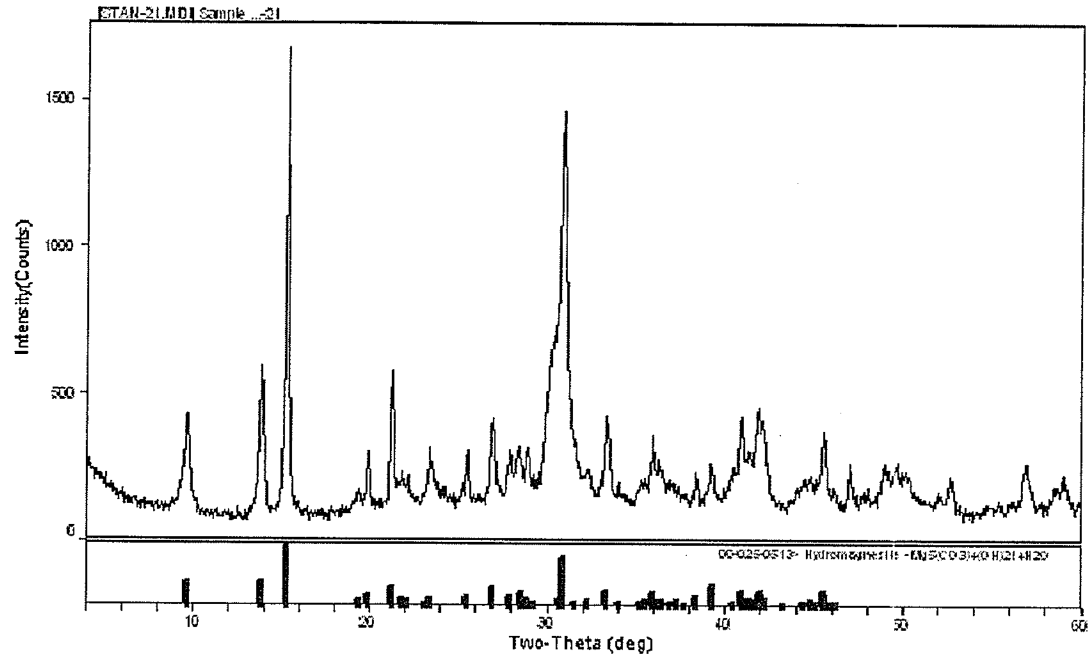


Figure D.2 XRD analysis for pipe series 1(2) for clog sample

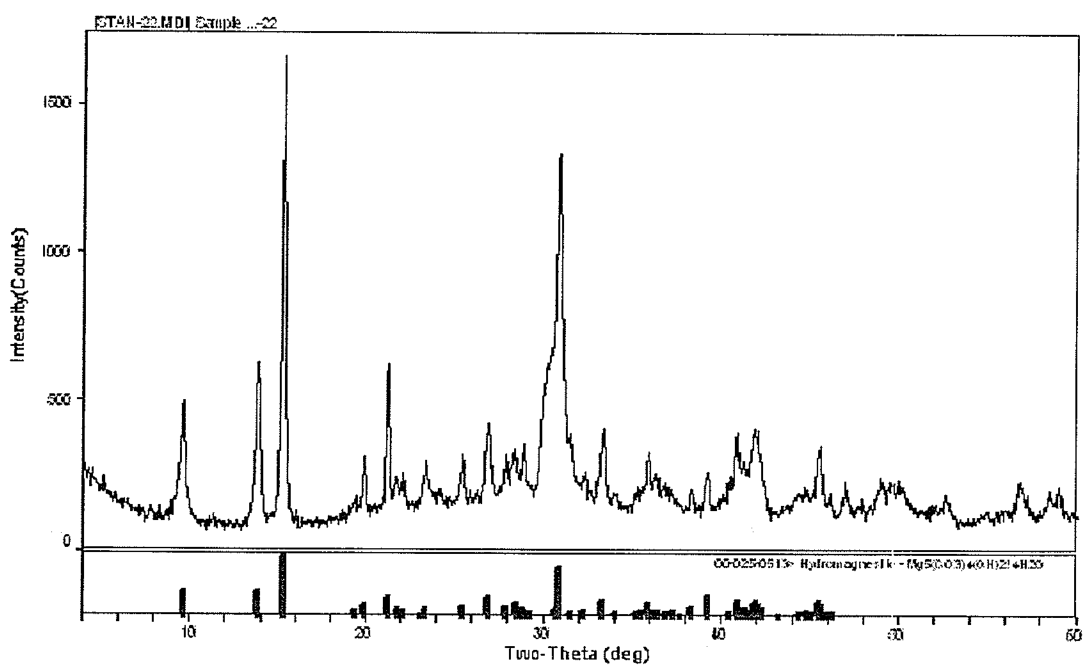


Figure D.3 XRD analysis for pipe series 2(1) for clog sample

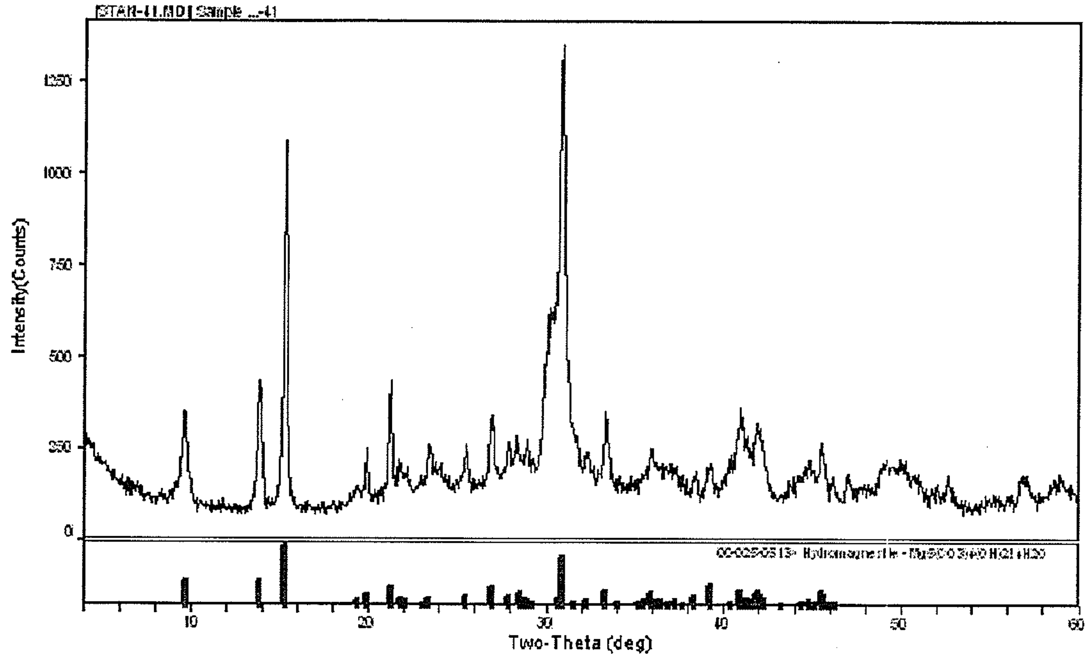
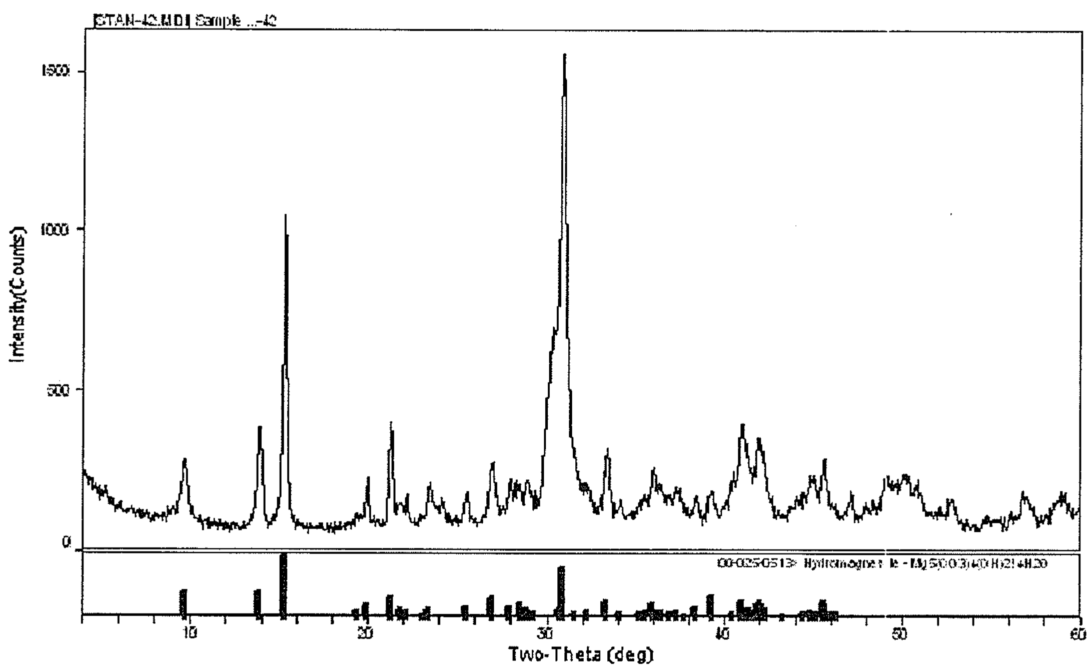


Figure D.4 XRD analysis for pipe series 2(2) for clog sample



APPENDIX E EMBEDDING PROCEDURE

JB-4™ Plus Embedding Kit.

#049-12

Introduction:

This new water-soluble plastic resin kit is intended for use in the preparation of embedded samples used for high resolution light microscopy evaluation. This kit produces water-white, clear casts in 1-2 hours or less at room temperature. It yields sections down to 0.5 µ with excellent morphologic structural preservation. Our JB-4™ Plus embedding kit provides brilliant staining, eliminates hazardous dehydration solvents and is excellent with hard and difficult specimens.

Fixation:

Tissue can be fixed with routine light microscopy fixatives. Best results are obtained with neutral buffered Formalins, Bouins, Polylem, Glutaraldehyde*, or Glutaraldehyde/Formaldehyde formulations.

Dehydration:

Dehydrate samples through a graded series of ethanols 70% - 95%.

Because the JB-4™ Plus resin is water-soluble, complete dehydration through 100% ethanol is not necessary, although recommended especially for large or dense tissue. Clearing agents such as xylene or chloroform are unnecessary. Fixation, dehydration and infiltration can be accomplished manually or automated with the use of a regular tissue processor used for paraffin processing. Processing through cold (4°C) fixative, buffer rinse and infiltration resin can be used for optimal enzyme and antigen retention and preservation. This procedure uses the infiltration resin as the dehydrating agent replacing the alcohol series. No alcohol dehydration is needed, but recommended for large, bloody, or fatty tissue.

Infiltration:

Prepare the infiltration resin as follows: 100 ml of JB-4™ Plus Solution A and 1 gram of JB-4™ Plus Catalyst powder. Stir until dissolved, avoid bubble formation. This infiltration solution may be stored for 5 to 6 weeks at 4°C in a dark bottle.

The percentage of catalyst added to Solution A should be decreased to 0.5% - 0.7% when using large quantities for automatic processor units. This aids in solution preservation and minimizes heat sensitivity under processor conditions. Infiltration time ranges from 2 hours to several days depending on size and tissue density. The tissue appears translucent and usually sinks to the bottom of the container. *These solutions should always be kept cold.*

Embedding:

Have embedding molds*, labels, ice bath, gloves*, instruments and cold fresh catalyzed Solution A ready before proceeding.

Prepare the embedding resin as follows: 15 ml of fresh infiltration solution and 1 ml of JB-4™ Plus Solution B. Stir well and place into an ice bath while embedding to retard premature polymerization. *Anaerobic conditions are needed for polymerization.* Molds* or BEEM** capsules must be filled and covered or capped tightly, using GMA block holders. Polymerization is complete at room temperature in 1-2 hours. NOTE: Polymerization proceeds more rapidly in larger batches, remove the specimen cast from the mold and carefully wipe off any unpolymerized resin solution.

Sectioning:
Optimal sectioning is performed with a microtome designed for plastic embedments. 0.5µ - 3µ sections are cut with a dry glass knife, collected with forceps and transferred onto a room-temperature water bath surface, releasing sections before they touch the water. Sections are collected on pre-cleaned glass slides and air-dried before staining. Sections can also be dried at 60°C.

Staining:
Dry sections are stained directly without xylene or alcohol pre-treatment. Longer staining times or higher stain concentration may be necessary for thin sections. Alcohol or water rinses may be necessary after staining but the last step in the process should be water. Tissue-Tack* may be used to affix tissue to the slide during lengthy procedures. Slides are mounted while still moist with Plastic Mount* or are dried & mounted with Poly-Mount*.

Storage & Handling:
CAUTION: Impervious gloves and good laboratory handling procedures are to be employed when working with JB-4™ Plus Kit parts. Care should be taken to avoid skin contact and inhalation of vapors. In case of skin contact, and after removing gloves, immediately and thoroughly wash with soap and water. Work should be conducted in a well-ventilated area. Use of disposable utensils and tools is recommended. The full chemical, physical and toxicological properties of this kit are not known. Some people report skin sensitivities to methacrylates. If there is any noticeable irritation, use of JB-4™ Plus embedding medium should be stopped. All components may cause irritation. Solution B may be toxic if ingested.

JB-4™ Plus Catalyst:
The JB-4™ Plus catalyst is an organic peroxide and should be kept cool and tightly sealed to avoid drying out. Avoid grinding or contact with flammable or reducing agents. The catalyst decomposes as it ages, therefore, aged catalyst may require a greater amount, a longer time, or more heat to achieve the same results as fresh catalyst.
Solution A:
Solution A is best stored in a dark bottle at 4°C. Under these conditions it is stable for 9-12 months. Catalyzed Solution A may be kept in the dark and the cold for about five weeks. When catalyzed Solution A is left at room temperature, the catalyst will decompose.
Solution B:
Room temperature storage is recommended. Do not refrigerate. Shake before using. *Cool temperatures may cause precipitate to form. Warm gently to dissolve.*

Disposal:
The catalyst may be destroyed by adding it in small portions to cold 10% sodium hydroxide solution. Use at least 4 times as much solution as the weight of the catalyst. Do not allow material to settle or form lumps.

Dispose of this solution and Solution A and B along with other hazardous wastes in accordance with municipal,provincial and federal regulations.

Wastes of catalyzed Solution A may be disposed by polymerization. Using disposable containers, carefully mix in the volumes described on the first page. Polymer may be landfilled. Observe federal,provincial and municipal regulations.

*   Available from CANEMCO INC..
**   BEEM is a registered Trademark of Better Equipment for Electron Microscopy, Inc.
       JB-4 is a registered trademark of Polysciences, Inc.