DETERMINATION OF CREEP PARAMETERS OF FROZEN SOIL USING THE PRESSUREMETER TEST

by

Herbert Fensury

A thesis
presented to the University of Manitoba
in partial fulfillment of the
requirements for the degree of
Master of Science
in
the Department of Civil Engineering

Winnipeg, Manitoba

DETERMINATION OF CREEP PARAMETERS OF FROZEN SOIL USING THE PRESSUREMETER TEST

BY

HERBERT FENSURY

A thesis submitted to the Faculty of Graduate Studies of
the University of Manitoba in partial fulfillment of the requirements
of the degree of

MASTER OF SCIENCE

I hereby declare that I am the sole author of this thesis.

I authorize the University of Manitoba to lend this thesis to other institutions or individuals for the purpose of scholarly research.

Herbert Fensury

I further authorize the University of Manitoba to reproduce this thesis by photocopying or by other means, in total or in part, at the request of other institutions or individuals for the purpose of scholarly research.

Herbert Fensury

ABSTRACT

The objective of this laboratory study was to determine the long-term creep behaviour of frozen soil by means of an in-situ testing method, namely the pressuremeter test.

The investigation included: four multi-stage tests in frozen sand, five long-term single-stage creep tests in frozen sand and six standard pressuremeter tests in saturated unfrozen sand. Ladanyi's method (Ladanyi and Johnston, 1978) was used to evaluate the creep parameters of the frozen sand, and to predict its long-term behaviour.

Ladanyi's method led to predictions of strain which were higher than the actual strains in the frozen sand. A modified Ladanyi method was developed; and this new method gave better predictions than did Ladanyi's original method.

ACKNOWLEDGEMENTS

The author wishes to express his gratitude to the following people for their assistance during the preparation of this thesis:

Dr. D.H. Shields, the author's supervisor who offered guidance, enthusiasm and patience during the preparation of this thesis.

Dr. L. Domaschuk who offered assistance and participated in fruitful discussions during the early stages of the work.

Dr. C.-S. Man who assisted with the theoretical aspects of the thesis.

Dr. J. Graham for his encouragement and helpful suggestions.

Mr. E. Lemke, Mr. N. Piamsalee, Mr. M. Lemieux, Mr. J. Clark, Mr. S. Meyerhoff and Mr. B. Turnbull, technical staff of the Department of Civil Engineering, for their assistance during the laboratory investigations.

Mr. R.M. Kenyon who gave constant help and moral support during the preparation of this thesis.

Mr. B. Kjartanson and Mr. Q.X. Sun for their helpful discussions.

Miss M. Buller for her contribution to the computer programming.

Financial assistance in the form of support from NSERC grant #311-2720-12 is also acknowledged.

The author wishes to thank his brothers and sisters for their continuous support and encouragement which made the completion of this thesis possible.

Last but not least, the author wishes to thank his fiancee, Tammy Dahl, who has been a constant source of inspiration and support.

CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter I

INTRODUCTION

1.1 GENERAL

Over the last decade the petroleum industry and the Canadian government have directed their attention to the development of offshore oil and gas reserves. Major projects are situated in the Beaufort Sea, where artificial islands or atolls will be built on the seabed in shallow water (not more than 30 metres deep) for production purposes.

Much of the seabed of the Beaufort Sea is made up of warm ice-rich permafrost with temperatures ranging from 0°C to -5°C (Yong, 1983). It is anticipated that the permafrost will deform with time when it is subjected to loading. One of the major engineering concerns is to estimate the magnitude of settlement that will occur during the operations of the islands and atolls. These operations will continue for a long period of time, since the islands will be designed for a service life of from 20 to 25 years. In order to properly assess the probable settlement with time, a method has to be developed to determine the long-term creep behaviour of warm permafrost.

One method of measuring creep behaviour is to obtain core samples and carry out triaxial tests on the samples either on-board the drill ship or in an on-land laboratory. This laboratory method is known to cause mechanical and thermal disturbances in the samples due to drilling and handling.

An in-situ method such as the pressuremeter test offers a number of advantages. However, the time available for an individual in-situ test is frequently limited to less than a few hours due to the high operational cost of the drill ship and the crew. Therefore, a medium-term test which takes a total of approximately 5 hours, has been developed in an attempt to evaluate the long-term behaviour of frozen soil. At the University of Manitoba, pressuremeter tests have been carried out on frozen sand as part of a larger on-going project to study the behaviour of permafrost of the type that exists in the Beaufort Sea. The studies being undertaken include long-term triaxial tests; measurements of the properties of frozen soil such as salinity and unfrozen water content; and, most recently, pressuremeter tests and model pile tests on poly-crystalline ice.

1.2 SCOPE OF STUDY

A literature review revealed that few studies have been done on frozen soil with a pressuremeter, and most of these pressuremeter studies were accomplished by Dr. Branko Ladanyi. In 1973 Ladanyi and Johnston published a paper which describes the method for obtaining creep parameters of frozen soil by means of a pressuremeter test. This method will be referred to as Ladanyi's method. Following the above paper are: Ladanyi and Johnston (1978) and Ladanyi and Eckardt (1983). However, to the author's knowledge there has not been any publication that directly shows how well the method predicts the long-term behaviour of a frozen soil.

In this present study, Ladanyi's method has been used to determine the creep parameters of four laboratory-prepared frozen sand samples. The samples were prepared in such way that their properties should resemble the properties of field permafrost.

Chapter 2 presents a review of the available literature on frozen soil, concentrating on Ladanyi's method for predicting the long-term creep behaviour of frozen soil.

In Chapter 3, the testing program, the method of sample preparation, and a description of the test equipment and test procedure are presented.

In Chapter 4 all the test results from the experiment are given.

Chapter 5 describes step by step the procedure used to perform Ladanyi's method of determining creep parameters with the pressuremeter. The creep parameters which were obtained using this method were then used to predict the long-term creep strain of the frozen sand. Long-term constant stress pressuremeter tests were carried out so that a comparison could be made between predicted and actual behaviour. The Ladanyi method was found to overpredict the long-term strain of frozen sand, and so a modified method, which will be referred to as the Modified Ladanyi method, was developed in an attempt to improve the predictions of the long-term behaviour of frozen sand. This latter method shows some promise.

Chapter 6 presents discussions on both the Ladanyi and Modified Ladanyi methods. Conclusions from this study and recommendations for future studies are presented in Chapter 7.

Chapter II

THEORY OF FROZEN SOIL AS APPLIED TO THE PRESSUREMETER TEST

2.1 INTRODUCTION

The Menard pressuremeter has been used for more than a decade for testing frozen soil. Most of the related literature that was found involved Dr. Branko Ladanyi, beginning with the paper by Ladanyi and Johnston in 1973. Field pressuremeter tests in sea ice covers and ice-rich permafrost are among the subjects covered in the papers published by Ladanyi. It was not until 1981, in a report by Eckardt, that the use of the pressuremeter test to evaluate frozen sand properties under controlled laboratory conditions was documented.

Subsequently, another type of borehole dilatometer, known as the CSM (Colorado School of Mines) cell, was used by Ladanyi for determining the creep parameters of ice, frozen soils and rock salt. The test is called the borehole relaxation test in which the strain is controlled while the variation in stress is observed.

Here at the University of Manitoba, the OYO ELASTMETER 100 pressuremeter (model 4149, OYO Corporation, Japan) is used for testing frozen sands under controlled laboratory conditions. The OYO pressuremeter differs from a Menard pressuremeter in that 1) the OYO pressuremeter utilizes an electro-mechanical device to measure the radial expansion of the probe, 2) the OYO pressuremeter can use either gas or fluid to expand the probe, and 3) the OYO pressuremeter is a single cell device, that is to say it has no guard cells.

2.2 PRESSUREMETER METHOD IN FROZEN SOIL

The method for determining the creep parameters of frozen soil that will be discussed below follows the method proposed by Ladanyi and Johnston (1973, 1978) and Ladanyi (1983).

Hult (1966) proposed two practical methods for generalizing experimental creep information. The first method is applicable to long-term tests in which the steady state creep strains are relatively large in comparison to the instantaneous and primary creep strains. This method consists of linearizing the creep curves and considering the total strain at any time as being the sum of the pseudo-instantaneous and the steady state creep strain. However, experiments have shown that frozen soils show non-linear viscoelastic behaviour to such a degree that linear approximations cannot be adopted for most practical problems.

The second method, applicable to relatively short-term creep tests, considers creep deformation to be mostly primary creep and attempts to extrapolate short-term measurements to longer times using a convenient creep curve fitting method. According to Hult, there are two techniques for solving this second method. The first technique employs a time-hardening creep law in which time is considered to be the cause of the hardening. Time hardening creep laws have been used in calculations for various design problems because of their mathematical simplicity. However, the use of a time-hardening law is not advisable in cases where there are large stress redistributions. In frozen sand particularly, stress redistribution has been found to be quite significant (Ladanyi and Eckardt, 1983). The second technique uses a strain-hardening creep law. According to the second technique the pressuremeter data can be generalized using the solution to the problem of stationary creep under the internal pressure in a cylindrical cavity of infinite length located in an infinite medium.

The total strain attained on an ice-rich frozen soil, after a given time, under a constant stress, was given by (Hult, 1966)

$$\varepsilon = \varepsilon^{(i)} + \varepsilon^{(c)} \tag{1}$$

where $\varepsilon^{(i)}$ is the instantaneous portion of the total strain and $\varepsilon^{(c)}$ is the time dependent creep strain.

2.2.1 Solution to Creep Strain of Frozen Soil

The solution based on a strain-hardening creep law corresponds to a constant stress relation

$$\varepsilon^{(c)} = K\ \sigma^{a}\ t^{b} \tag{2}$$

where K, a and b = temperature dependent material constants

σ = stress

t = time.

Eq. 2 can be rewritten in more general form in a multiaxial state of stress:

$$\varepsilon_e^{(c)} = \left(\frac{\dot{\varepsilon}_c}{b}\right)^{b} \left(\frac{\sigma_e}{\sigma_c}\right)^{n} t^{b} \tag{3}$$

where $\varepsilon_e^{(c)}$ and σ_e are the equivalent creep strain and the equivalent stress, respectively, expressed in the following forms:

$$\varepsilon_e^{2} = \frac{2}{9}\{(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\} \tag{4}$$

$$\sigma_e^{2} = \frac{1}{2}\{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\} \tag{5}$$

σ_c is the reference stress at an arbitrary selected strain rate, $\dot{\varepsilon}_c$; and b and n are creep exponents. In frozen soil, $\dot{\varepsilon}_c$ is taken to be 10^{-5} min^{-1}.

To solve this problem, a transformed time unit τ is introduced to Eq. 3:

$$\tau = t^b \tag{6}$$

which allows Eq. 3 to be transformed into an ordinary power law:

$$d\varepsilon_e^{(c)}/d\tau = K\,\sigma_e^{\,n} \tag{7}$$

where $K = \left(\frac{\dot{\varepsilon}_c}{b}\right)^b \left(\frac{1}{\sigma_c}\right)^n$ (8)

For the problem of creep expansion of a cylindrical cavity under plane-strain conditions, the solution to Eq. 7 can be obtained by analogy with the corresponding solution in nonlinear elasticity. Complete solutions to this particular problem are described in Odquist (1966).

To process pressuremeter creep information, the only relationship needed from the solution is the one relating the creep cavity expansion rate with the applied internal pressure (Odquist, 1966 and Ladanyi and Johnston, 1978):

$$dr/d\tau = \left(\frac{\sqrt{3}}{2}\right)^{n+1} K\,r \left\{\frac{2(p_i - p_o)}{n}\right\}^n \tag{9}$$

where r = current radius of the cavity

p_i = constant applied internal pressure

p_o = radial pressure acting at infinity.

In this study, where the tests were run in frozen sand which was prepared in a thin-walled tank, p_o is negligible and is assumed to be zero.

Eq. 9 can be rewritten as:

$$dr/r = F\, d\tau \tag{10}$$

$$\text{where } F = \left(\frac{\sqrt{3}}{2}\right)^{n+1} \left(\frac{\dot{\varepsilon}_c}{b}\right)^{b} \left\{\frac{2(p_i - p_o)}{n\, \sigma_c}\right\}^{n} \tag{11}$$

For a finite time interval at a constant stress, Eq. 10 can be integrated to give:

$$\ln r = F\, \tau + C \tag{12}$$

Using $r = r_i$ at $\tau = 0$, i.e. at the beginning of the considered i^{th} loading stage, the integration constant C can be eliminated and Eq. 12 becomes:

$$\ln(r/r_i) = F\, t^{b} \tag{13}$$

This can also be written:

$$(r/r_i) = \exp.(F\, t^{b}) \tag{14}$$

where r_i is the radius of the cavity at time $t = 0$, i.e. at the start of a given constant pressure creep stage, and r is the cavity radius at time t after the step increase to the pressure $(p_i - p_o)$ in the i^{th} stage of loading. For clarification refer to Figure 1, which illustrates the mechanics of a multi-stage creep test.

The semi-graphical procedure described by Hult for primary creep can be used to determine the creep parameters b, n, and σ_c. Taking an ordinary logarithm of Eq. 13 then

$$\log[\ln(r/r_i)] = \log F + b \log t \tag{15}$$

When $\ln(r/r_i)$ is plotted against time in a log-log plot, according to Eq. 15 the pressuremeter creep curves should linearize and the slope of the straight line portions is equal to b or, as shown in Figure 2, $b = B/A$. From Figure 2 the intercept at unit time (say, 1 minute) of any creep line (each of different value of pressure $(p_i - p_o)$), is then equal to F.

In order to determine the parameters n and σ_c, Eq. 11 can be rewritten as:

$$\log F = \log M - n \log \sigma_c + n \log(p_i - p_o) \tag{16}$$

$$\text{where } M = \left(\frac{\sqrt{3}}{2}\right)^{n+1} \left(\frac{\dot{\varepsilon}_c}{b}\right)^{b} \left(\frac{2}{n}\right)^{n} \tag{17}$$

According to Eq. 16, plotting F against $(p_i - p_o)$ in a log-log plot will give a straight line with the slope equal

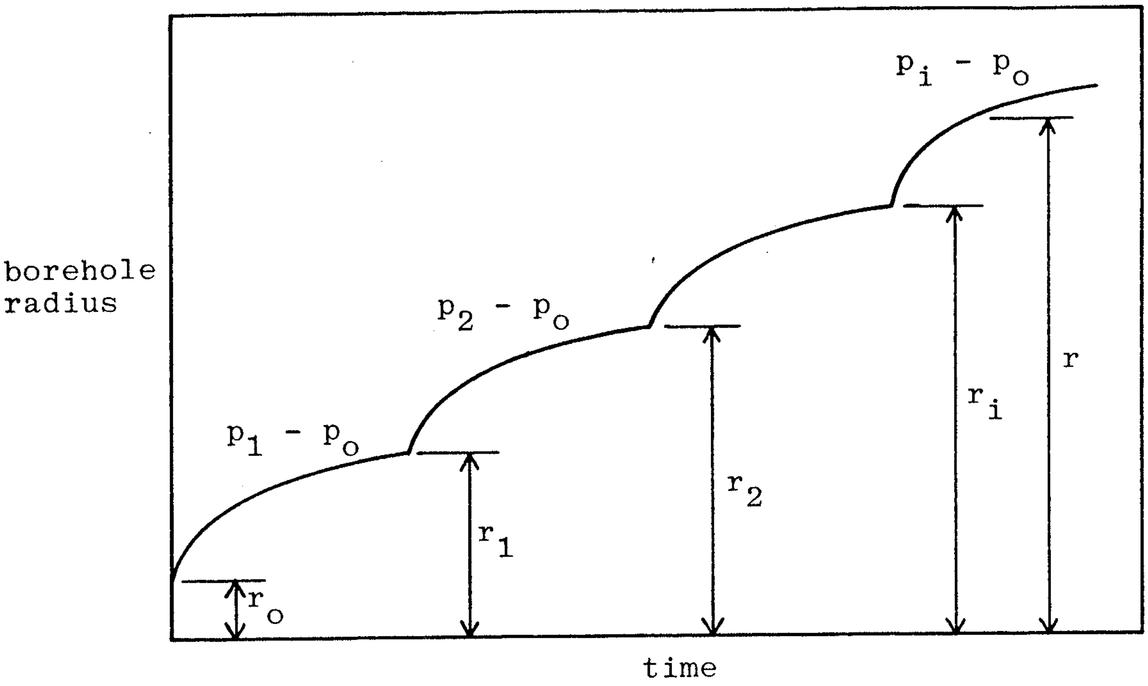


Figure 1: Mechanics of a Multi-Stage pressuremeter Test

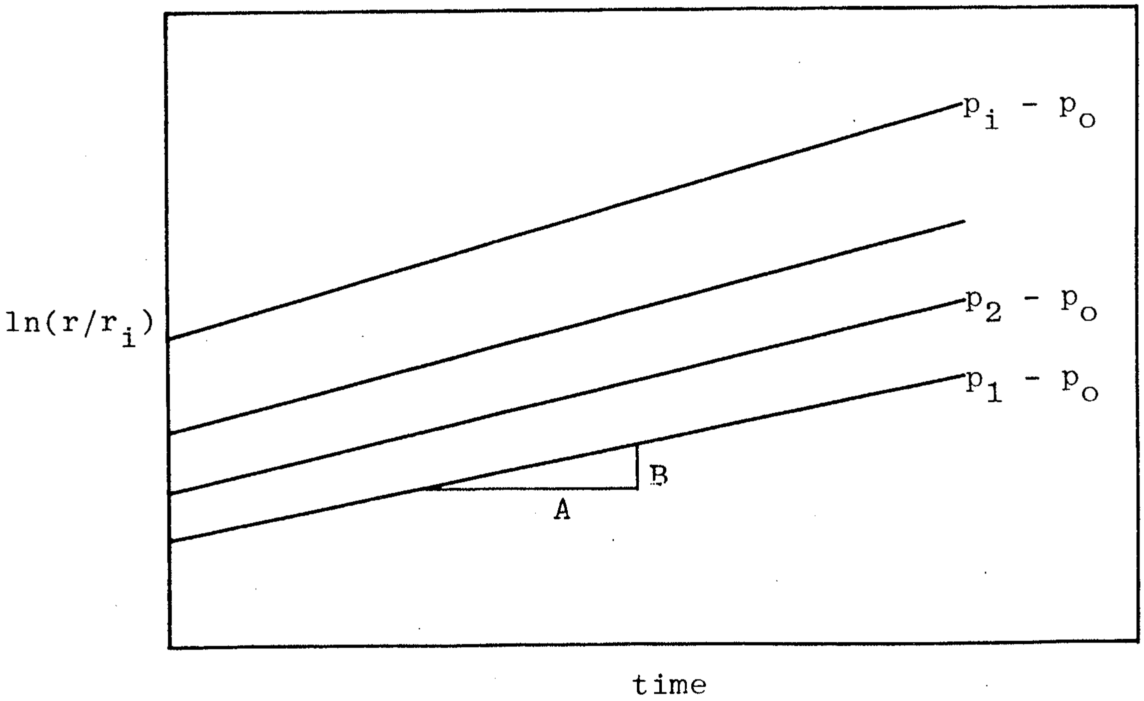


Figure 2: Determination of b and F (log-log plot)

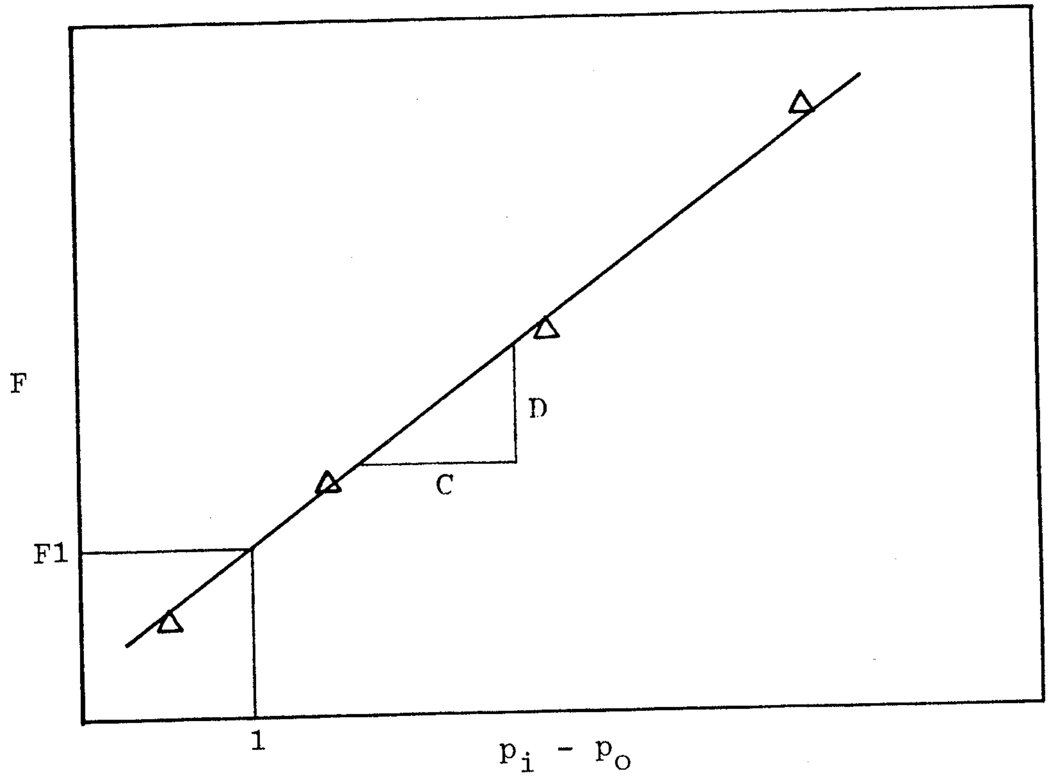


Figure 3: Determination of n (log-log plot)

to n as shown in Figure 3. From Figure 3, $n = D/C$ and its intercept at a unit value of pressure $(p_i - p_o)$ (say, 1 MPa) is according, to Eq. 16, equal to

$$Fl = M/(\sigma_c)^n \tag{18}$$

Knowing b, n, the value M calculated from Eq. 17, and an arbitrary selected value of $\dot{\varepsilon}_c$, the value of σ_c is:

$$\sigma_c = (M/Fl)^{1/n} \tag{19}$$

Substituting the values of b, n, and σ_c into Eq. 3 gives the general creep equation of the frozen soil. The equation can be used for extrapolating the pressuremeter creep information to longer time intervals.

2.2.2 Solution to Creep Strength of Frozen Soil

In association with a failure strain, an equation can be developed to predict the long-term strength of a frozen soil.

If ε_{ef} denotes the equivalent failure strain and σ_{ef} the equivalent creep strength, then Eq. 3 becomes:

$$\sigma_{ef} = \sigma_c \; \varepsilon_{ef}{}^{1/n} \left(\frac{\dot{\varepsilon}_c \; t}{b}\right)^{-b/n} \tag{20}$$

To apply the above analysis in practice the data should satisfy two conditions:

1. creep curves should linearize in a log-log plot.
2. creep curves for different sustained pressures should be parallel to each other.

Note that the analysis neglects the instantaneous strains; therefore, all such strains must be added to the creep strains in processing experimental data. It has been demonstrated by Ladanyi and Eckardt (1983) that better results can be obtained if the instantaneous strains are separated from the creep strains.

Finally, if the tests are not performed in the field in a semi-infinite medium, but rather in thick cylinders of frozen soil, all the described procedures for determining the parameters from creep tests remain valid, provided σ_c in Eq. 19 is replaced by $m_c\sigma_c$, where

$$m_c = 1 - (a/b)^{2/n} \tag{21}$$

where a = inner radius of the cylinder
b = outside radius of the cylinder.

If the tests are performed under confining pressures then p_o used in the above formula will be equal to the applied confining pressures.

Chapter III

TESTING PROGRAM

3.1 INTRODUCTION

Because of the prohibitive cost of performing in-situ pressuremeter tests in seabottom permafrost for purely research purposes, a laboratory-simulated in-situ technique was used as an alternative. The seabottom permafrost in the Beaufort Sea is either ice-bonded or non ice-bonded mixtures of sand, silt or clay which can be more or less saline (Yong, 1983). It was realized that there would be considerable difficulty in making up identical samples of frozen soil if fine-grained soil were used or if a saline solution were used for the porewater. This is because the tests were to be carried out close to $0^{o}C$ and the degree of ice bonding could vary significantly. Since repeatibility and uniformity were all important at this stage of our work, in this study only medium grain sand and fresh water were used to prepare the test specimens.

A summary of all the pressuremeter tests in frozen sand and a description of each frozen sand specimen can be found in Table 1. Table 2 presents a description of all the tests in saturated unfrozen sand. (The last two columns giving the values of E_M and p_ℓ will be discussed in a later section).

TABLE 1

The Frozen Soil Test Program and Description of Specimens

Test	Type of test	Time interval	Pressure increment (MPa)	Pressure range (MPa)	Test temp. (^{o}C)	ρ bulk (kg/m^3)	ρ dry (kg/m^3)	Ice saturation (%)	Ice content (%)
PT102	Multi-stage	15 min.	0.5	0.36 - 6.25	-2.3	1840	1460	88.1	24.2
PT103	Multi-stage	45 min.	0.5	0.06 - 3.71	-1.9	1820	1460	87.4	24.5
PT201	Multi-stage	45 min.	0.5	0.75 - 3.91	-2.9	1790	1420	85.7	26.3
PT202A	Single-stage	10 days	-	1.0	-3.2	1830	1470	86.2	24.7
PT202B	Single-stage	22 days	-	2.0	-2.9	1830	1470	86.2	24.7
PT203	Single-stage	3 hours	-	4.2	-2.6	1810	1410	92.5	29.4
PT204	Single-stage	27 hours	-	3.0	-2.8	1830	1460	87.7	25.3
PT211	Multi-stage	45 min.	0.25	0.50 - 2.50	-2.7	1910	1530	95.8	25.6
PT212	Single-stage	22 days	-	2.0	-3.0	1880	1490	94.2	26.1

TABLE 2

The Unfrozen Soil Test Program and Test Results

Test	Pressure increment (kPa)	No. of increment	Test temp. ($^{\circ}$C)	ρ_{bulk}* (kg/m^3)	ρ_{dry}* (kg/m^3)	Water content* (%)	E_M (kPa)	p_ℓ (kPa)
PT205	21	10	18.5	1860	1470	30	490	40
PT206	35	12	18.5	2010	1660	21	4040	310
PT207	21	9	19.5	1860	1470	30	240	45
PT208	35	11	17.5	2010	1660	21	3120	300
PT209	21	9	18.5	1860	1470	30	450	45
PT210	35	10	18.5	2010	1660	21	4000	290

* from model test

3.2 TEST EQUIPMENT

A typical setup of the test equipment and the frozen sand specimen is shown in Figure 4.

All pressuremeter tests were carried out using an OYO ELASTMETER 100 pressuremeter. The instrument is a monocellular borehole extensometer which uses an electro-mechanical caliper to measure changes of borehole radius. The rubber membrane is capable of being expanded up to 25% of its initial radius. Nitrogen gas was used to inflate the rubber membrane.

Throughout the laboratory testing program two types of rubber membranes were used, depending on the pressure range of the test.

1. Hard membrane

   This membrane measures 540 mm in length, 14 mm in thickness and 70 mm in outside diameter when uninflated. The specified maximum pressure for this membrane is 20 MPa.

2. Soft membrane

   The rubber tube measures 390 mm in length, 4 mm in thickness and 70 mm in outside diameter before inflation. The specified maximum pressure for this membrane is 3 MPa.

Two types of containers, representing two different boundary conditions, were used in this study; the two types are described below.

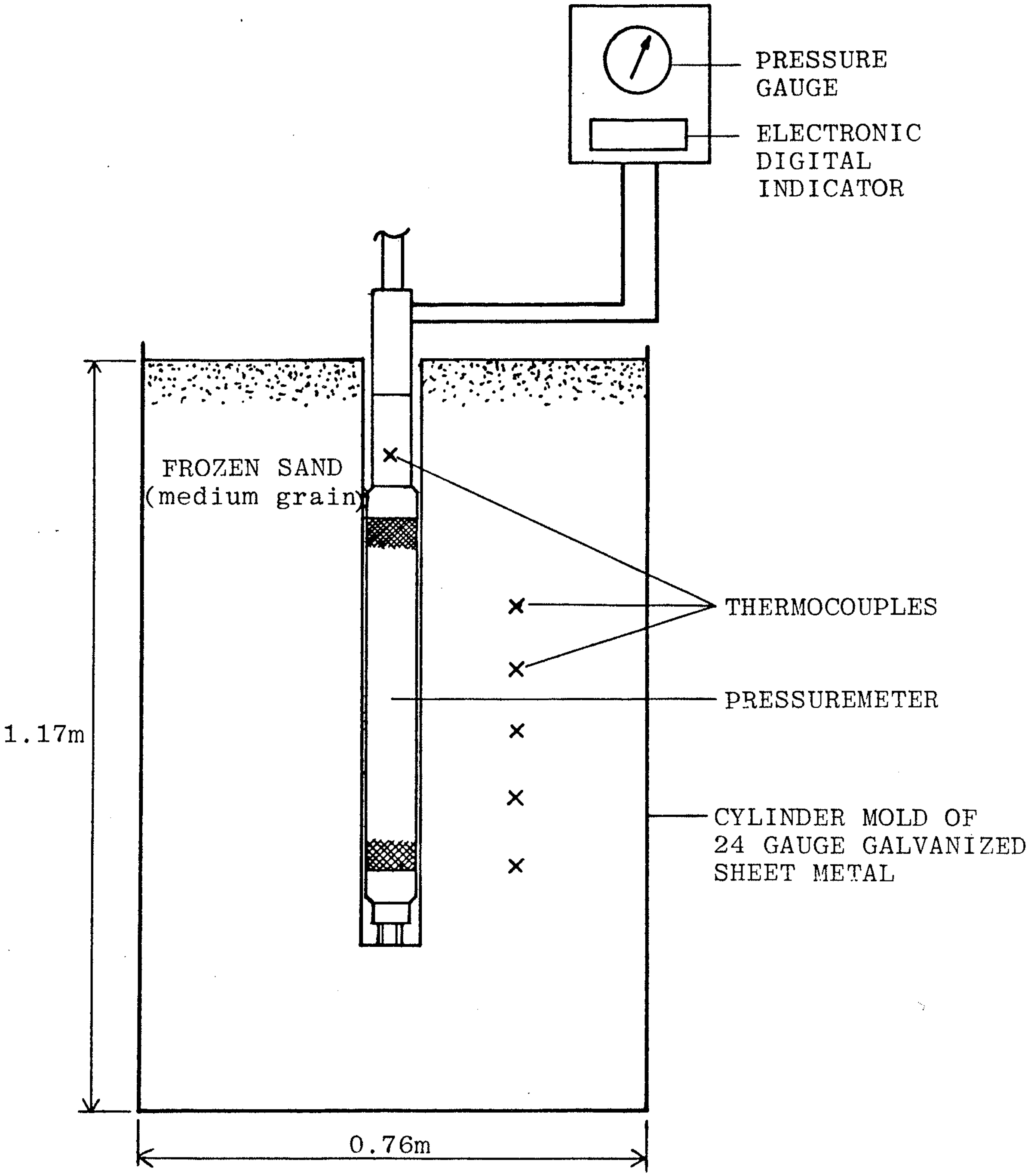


Figure 4: Typical Setup of Test Equipment and Frozen Sand Specimen

1. Thin tank (free boundary)

   The thin tank was made of 24 gauge galvanized sheet metal; it measures 760 mm in diameter and 1170 mm in height. A 250 mm joiner strip of flexible rubber, approximately 10 mm thick, was installed the length of the tank vertically to 1) accommodate the expansion of the sample due to freezing without damaging the tank and 2) to minimize the boundary constraint during testing.

2. Thick tank (rigid boundary)

   This rigid tank was made of a section of steel pipe measuring 1020 mm (40 inches) in height, 915 mm (36 inches) in diameter and 13 mm (1/2 inch) thick. The steel pipe was the same type as that used in the Alayaska Pipeline.

3.3 TEST MATERIAL

A uniform, quartz-dolomite-feldspar, medium grain sand was used in all the tests. This natural, light brown sand was obtained from the Bird's Hill pit in Manitoba. The maximum and minimum dry densities of the sand, obtained by the ASTM standard method, were 1650 and 1450 kg/m^3, respectively. A typical grain size distribution was about 94% by weight between 0.1 and 1.0 mm, with less than 4% below 0.1 mm and less than 1% above 2.0 mm. The coefficient of uniformity was about 2.0. A detailed description of the sand can be found in Appendix A.

3.4 SAMPLE PREPARATION

The preparation of a frozen sample includes: pouring the sand, freezing the specimen, and allowing the temperature to become uniform throughout the sample. A description of the preparation of the different series of pressuremeter tests will be presented below in chronological order.

3.4.1 Test Series 1

The sand pouring method used in Series 1 tests will be referred to as the dry pouring method. The procedure for the dry pouring method is described below.

Dry Pouring Method

The oven dried sand was run through a funnel at a constant rate while a constant height of fall of approximately 25 mm was maintained. The sand was saturated by tap water flowing continuously upwards from the bottom of the tank as the sand was poured. Five thermocouples were installed as the sand level rose at depths of 40, 50, 60, 70, and 80 cm from the bottom of the tank. The ends of the thermocouples were in 20 cm from the side of the tank.

An average dry density of 1540 kg/m^3 (ranged from 1520 to 1550) and water content of 24% (ranged from 23.5 to 24.9) were obtained using the dry pouring method. The densities and water contents prior to freezing were measured independently by carrying out three tests. The specimen for each test was specially prepared for this purpose, using the same pouring method (dry), in a container having a diameter of 200 mm and a height of 200 mm.

Freezing

After pouring was completed, the sides of the tank were insulated to promote one-dimensional freezing. The sample was frozen at a chamber temperature of -20^{o}C. The freezing process took about 7 days to complete, after which the chamber temperature was raised to the desired test level of -3^{o}C. It took approximately 7 days for the sample to reach equilibrium temperature. Details of the recorded temperatures in a typical specimen can be found in Appendix B.

This test series includes PT102, PT103, PT201, PT202A, PT202B, PT203 and PT204.

3.4.2 Test Series 2

According to Ladanyi, the creep strength of a frozen soil at infinite time is equal to the strength or limit pressure of the soil in an unfrozen state. This series of tests was carried out to determine the pressuremeter modulus and the limit pressure of the saturated sand when unfrozen and at two different densities (loose and dense). The sand was the same as was used in all the other series of tests. A wet pouring method was used when preparing the unfrozen sand for Series 2 tests. The procedure for the wet pouring method is described below.

Wet Pouring Method

Wet sand was used to fill a #4 sieve to a thickness of about 25 mm. The sieve which had the same diameter as the tank was then immersed in the water to cause the sand to fall into place. The bottom of the sieve was immersed no more than 25 mm and the height of the water was maintained about 100 mm above the sand surface at all times. The sieve filling and submergence process was repeated until the desired height of the sand sample was reached.

For all Series 2 tests, the sand was poured with the pressuremeter held in place in the tank to minimize disturbances that would have resulted from the insertion of the pressuremeter after the tank was full of sand (see Figure 5 for details).

A loose saturated sand with an average dry density of 1470 kg/m^3 and an average water content of 30% was produced using the wet pouring method. The densities and water contents were measured by placing 24 small containers over the surface of the sand and carrying out the next lift of sand placement in the normal way. These

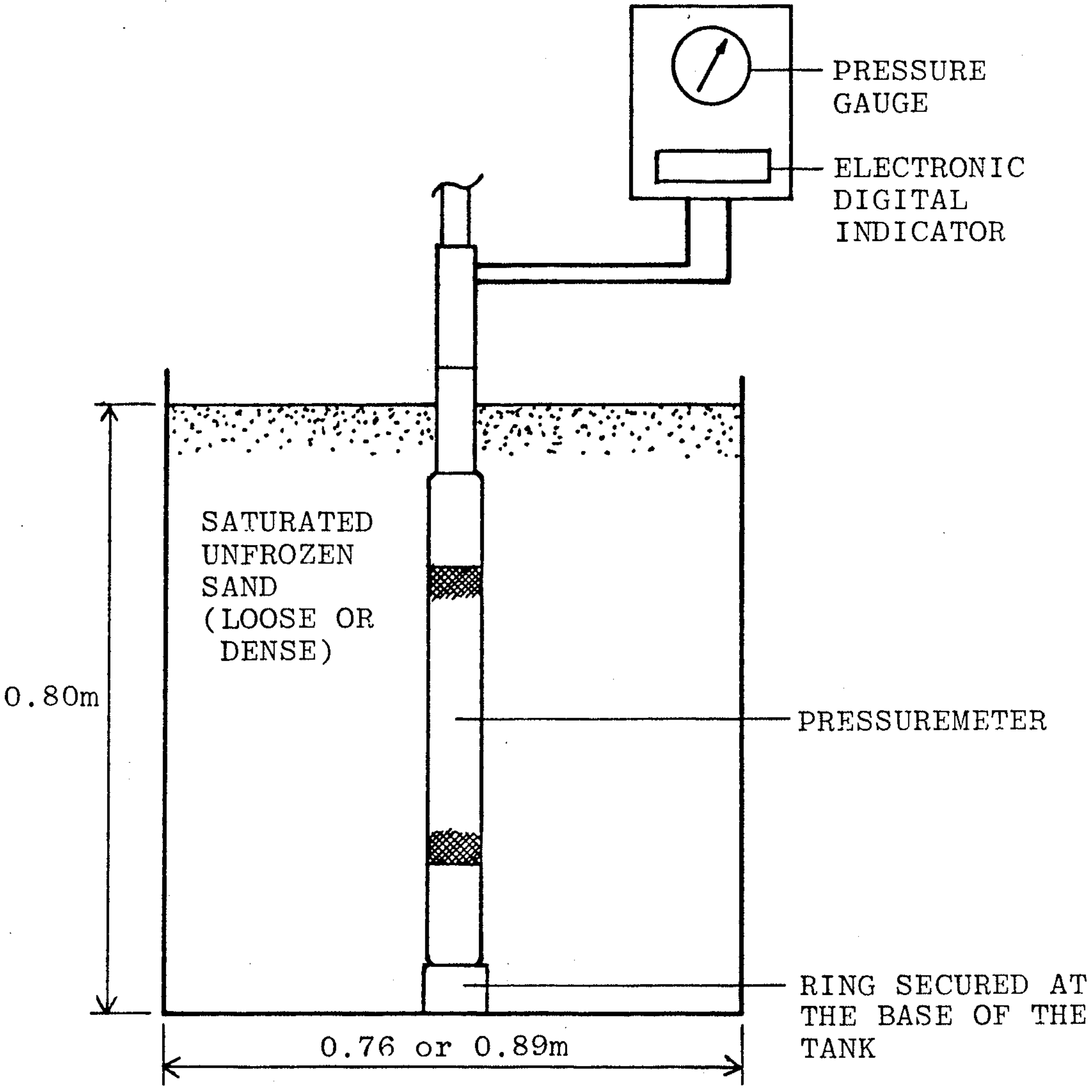


Figure 5: Typical Setup of Test in Unfrozen Sand

measurements were made in an independent specimen specially prepared for this purpose. Densities ranged from 1460 to 1490 kg/m^3, indicating conditions across the tank were relatively uniform.

The wet pouring method has advantages over the dry pouring method as listed below:

1. No oven-drying of sand is required; therefore, far less labour and time is required.
2. Drying the sand in the oven may cause the sand particles to break down more quickly.
3. The wet method is more representative of the natural sedimentation process in the field.

After each test in the unfrozen loose sand, the pressuremeter was deflated and the specimen was densified for the test in unfrozen dense sand. Densification was carried out with a concrete vibrator operating at a frequency of 60 Hz. The probe of the vibrator was submerged in the sand/water mixture and the sand was vibrated in layers 200 mm thick working from the bottom upwards. The probe was positioned at 12 well spaced locations in each layer and vibrated for 1 minute duration at each location.

An average dry density of 1660 kg/m^3 and water content of 21% were obtained for the vibrator densified specimens. The densities and water contents were measured independently by carrying out two tests. The sample for each test was prepared in a container (200 mm in diameter and 200 mm im height) using the same method for preparing the actual dense sand specimen. The variation in the results of the two tests was less than 1%.

The Series 2 tests in loose sand include PT205, PT207 and PT209. The Series 2 tests in dense sand consist of PT206, PT208 and PT210.

3.4.3 Test Series 3

This test series involves pressuremeter tests in frozen samples using a procedure which was similar to test Series 1, except that the wet pouring method was employed in preparing the samples instead of the dry pouring method. After pouring was completed, a rod with thermocouples attached at depths of 0, 15, 30, 45, 60, 75 and 100 cm from the bottom, was inserted completely into the sample. A total of 48 m of heat-tape was wrapped around the tank in a spiral fashion, to be turned on only when needed to prevent freezing from the sides of the specimen. The sides of the tank were then wrapped with a thin layer of fibreglass insulation and the top of the tank was covered with a styrofoam board. With this setup, one-dimensional freezing from the bottom upwards was assured; this was confirmed by the temperature measurements taken during freezing at the chamber temperature of -20°C (see Appendix B). After freezing was completed, the sample was allowed to come to temperature equilibrium at -3°C.

The Series 3 tests consist of PT211 and PT212.

3.5 TEST PROCEDURE

The main objectives of this study are 1) to verify Ladanyi's method (Ladanyi and Johnston, 1978, as presented in Chapter 2) of characterizing the creep parameters of a frozen soil, as well as 2) to develop an efficient procedure for running a pressuremeter test in a frozen soil. Three types of tests were carried out in order to produce a sufficient number of results for the analysis of Ladanyi's method.

Checking (for gas leaks, electronic drift, etc.) and calibrating (for membrane resistance and thickness changes) the equipment were performed at the test temperature prior to the test itself. A detailed description for calibrating the equipment has been reported by Ohya (1982) and Ohya and Morita (1982). A typical checking and calibration of the pressuremeter prior to a test in frozen sand specimen can be found in Appendix C.

3.5.1 Tests in Frozen Sand

Prior to running a pressuremeter test in a frozen sand specimen, a borehole had to be drilled with minimal mechanical and thermal disturbances to the specimen. A modified CRREL-type, hollow core barrel was used to auger a hole down the centre of the frozen sand. Continuous samples of core were retrieved for determination of density, void ratio, ice content and ice saturation. The core barrel was powered by an electric drill and rotated at approximately 60 revolutions per minute. During drilling, the cuttings returned to the surface remained as frozen sand and ice crystals, indicating minimal thermal disturbance. A relatively smooth-walled (i.e. no visible grooves and gouges), 39 to 39.5 mm radius cylindrical cavity was produced using the 38.1 mm radius cutting head, signifying little mechanical disturbance.

Two types of tests were carried out in the frozen sand and they are described below.

3.5.1.1 Multi-Stage Creep Tests

During this test, the pressuremeter applied a given constant pressure to the cavity of the frozen sand. The pressure was held constant for a given length of time during which the readings of the radial expansion of the pressuremeter probe were taken. At the end of the specified time interval, the pressure was increased to another level and held constant while the readings of the radial expansion of the probe were once again recorded. The test was run until the maximum permissible radius of the probe i.e. 47.5 mm was reached.

3.5.1.2 Single-Stage Creep Tests

In this test only one specified pressure was applied to the cavity of the frozen sand. The pressure was held constant until the maximum permissible radius of the probe was reached. Readings on the radial expansion of the probe were taken during that period of time. An exception was made with test PT202A, which was a single-stage creep test at pressure p = 1.0 MPa. This test was terminated after ten days, although the maximum permissible radius was not reached, simply because probe movements were so small. Test PT202B was carried out raising the pressure to a constant p = 2.0 MPa on the same sample.

3.5.2 Tests in Unfrozen Sand

Pressuremeter tests were also carried out in saturated unfrozen sand. Only one type of test i.e. a standard incremental pressuremeter test, was performed in these samples. The test procedure will be described below.

3.5.2.1 Standard Pressuremeter Tests

The standard test was run by applying 8 to 14 equal pressure increments to the pressuremeter probe with the aim of reaching the limit pressure when the volume of the cavity was doubled, that is to say when the radius of the cavity was increased by 41%. Readings were taken at 15, 30 and 60 seconds while each pressure level was held constant; the pressure was increased to the next pressure level immediately after the 60 second reading was taken.

A detailed description for running a standard pressuremeter test can be found in the text by Baquelin et al. (1978).

Chapter IV

RESULTS FROM EXPERIMENTS

The results from the different series of pressuremeter tests will be presented in the following sections:

4.1 MULTI-STAGE CREEP TESTS

Figures 6, 7, 8 and 9 show the creep information, plotted as circumferential strain versus time at each pressure level, for tests PT102, PT103, PT201 and PT211, respectively.

PT103 and PT201 are identical tests in that each had 0.5 MPa pressure increments at 45 minute time intervals. The magnitude of the strains at the same pressure show good agreement between the two tests, indicating that tests are reproducible. The reproducibility of results is confirmed by the fact that the creep parameters from the tests are similar; this will be discussed later.

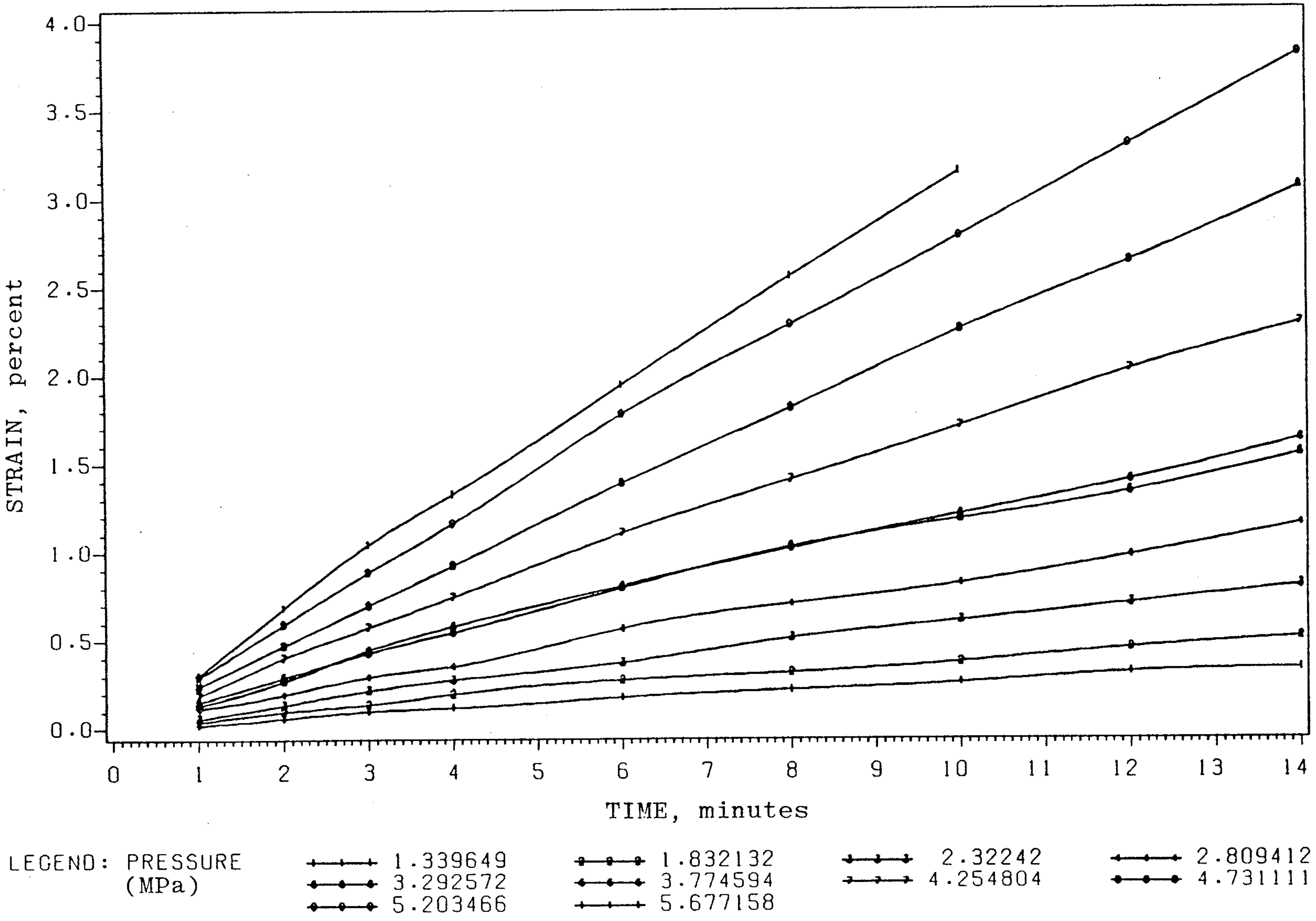


Figure 6: Plot of Strain vs. Time for PT102

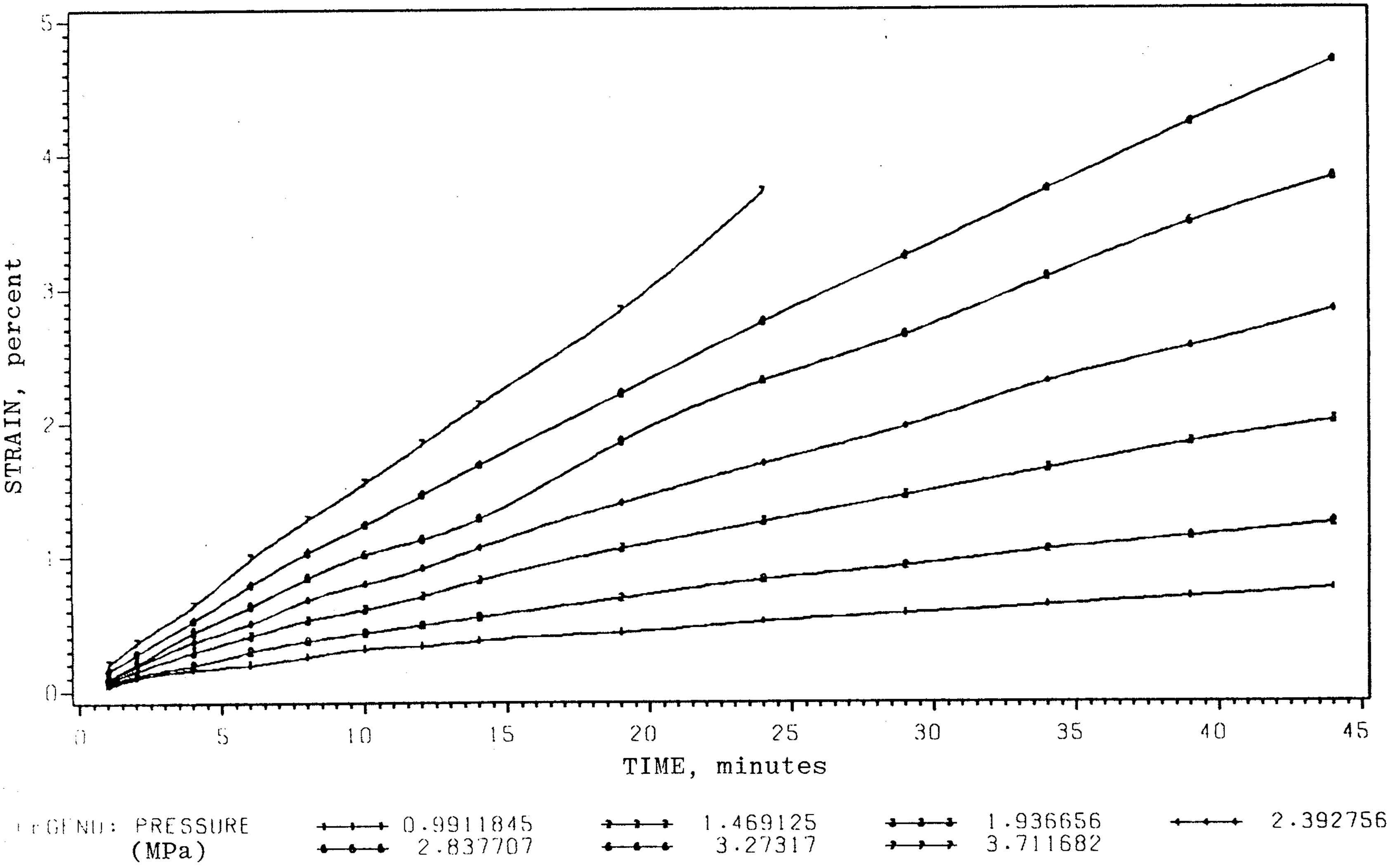


Figure 7: Plot of Strain vs. Time for PT103

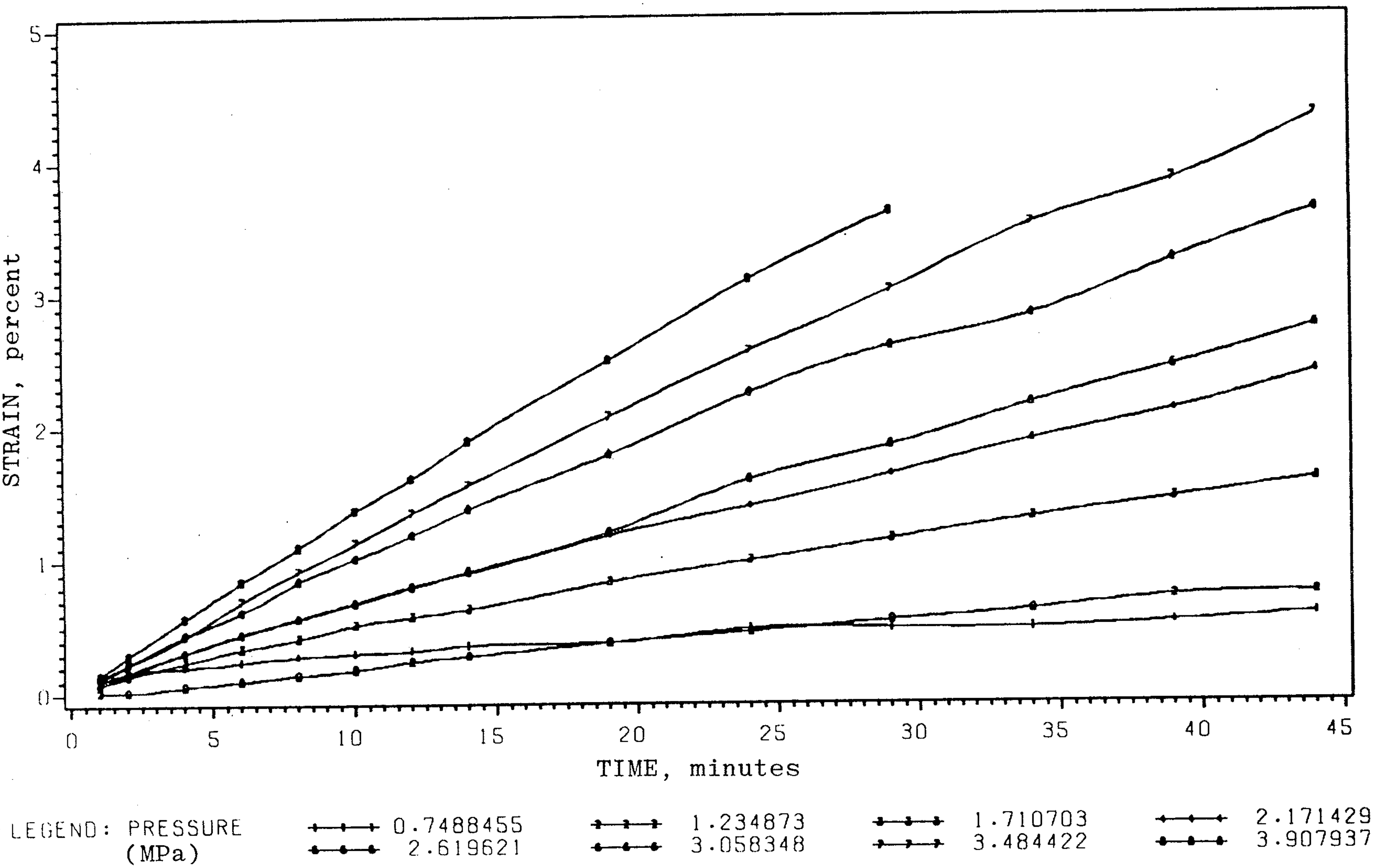


Figure 8: Plot of Strain vs. Time for PT201

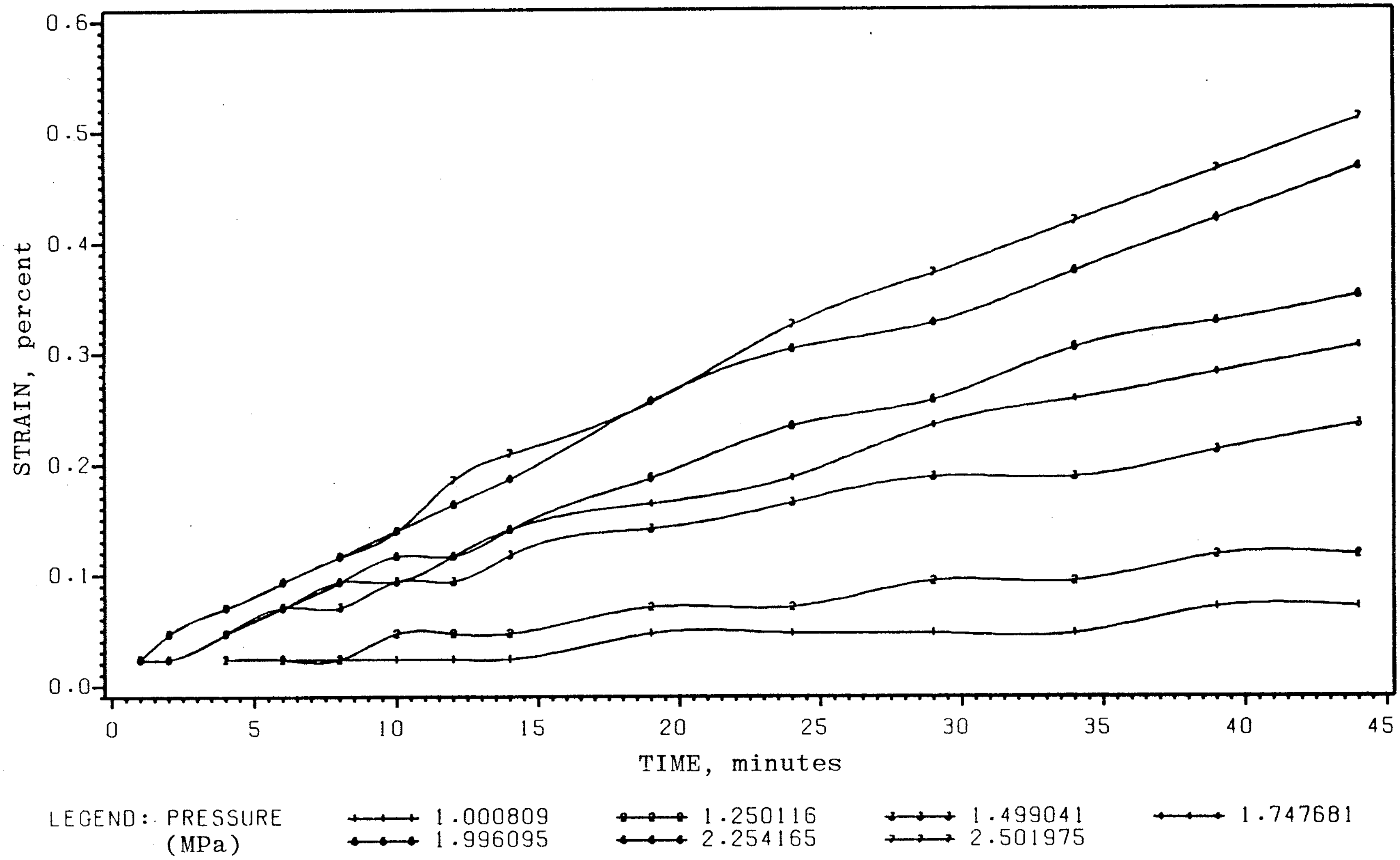


Figure 9: Plot of Strain vs. Time for PT211

4.2 LONG-TERM SINGLE-STAGE CREEP TESTS

The results of long-term creep tests at four different pressure levels can be found in Figures 10 to 15 inclusive. Figure 10 shows the plot of circumferential strain versus time for test PT202A at pressure p = 1.0 MPa. The curve shows the typical 'fracture and heal' pattern observed by various authors in frozen soil tests at low stress levels.

Figures 11 and 12 are two separate creep tests at p = 2.0 MPa. It should be noted that test PT202B in Figure 11 was run by increasing the pressure to 2.0 MPa on the same specimen as was used for test PT202A. Test PT202B is not, then, a true single-stage creep test. Figure 12 (test PT212) is a true single-stage test run on a virgin sample. A comparison between the two creep tests at p = 2.0 MPa can be found in Figure 13. It is believed that the previous stress application of 1 MPa altered the behaviour of sample PT202B and caused the deformation to be larger than the deformation found in a true single-stage test, PT212.

The creep curves from tests PT202A, PT202B and PT212 show that the strain rate decreased gradually with time.

Figure 14 and 15 show the results of single-stage creep tests at p = 3.0 MPa and p = 4.2 MPa, respectively.

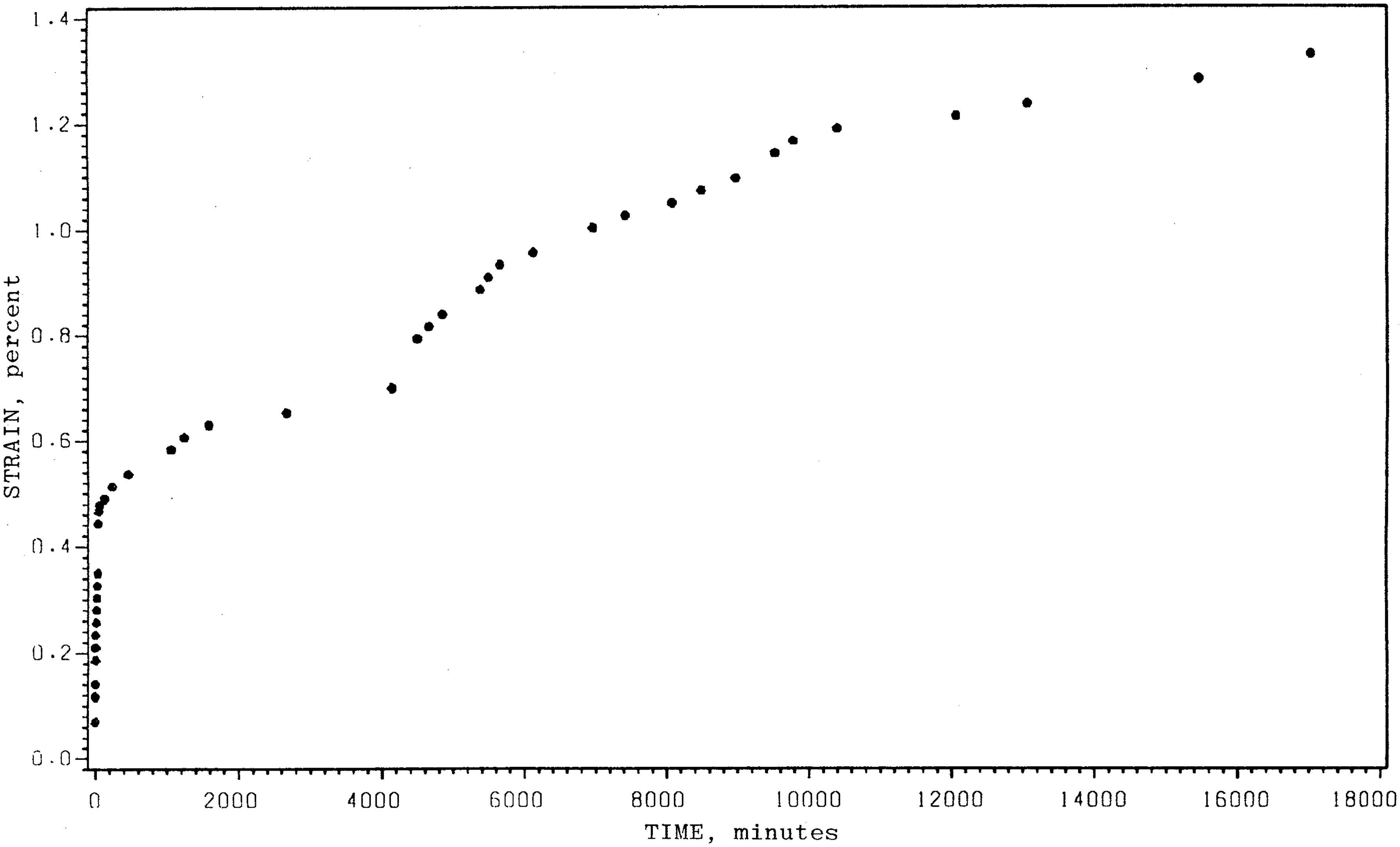


Figure 10: Plot of Strain vs. Time for PT202A

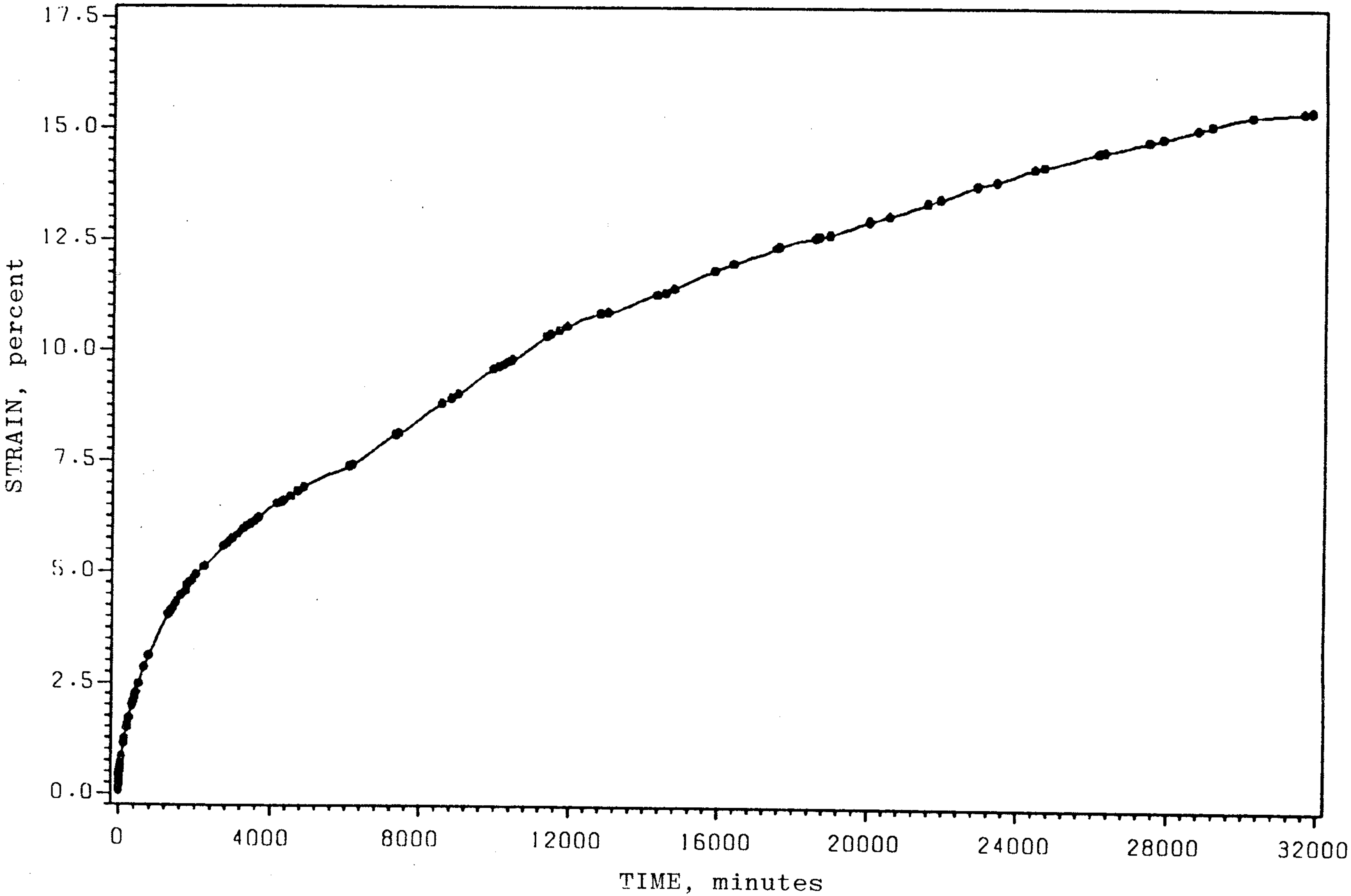


Figure 11: Plot of Strain vs. Time for PT202B

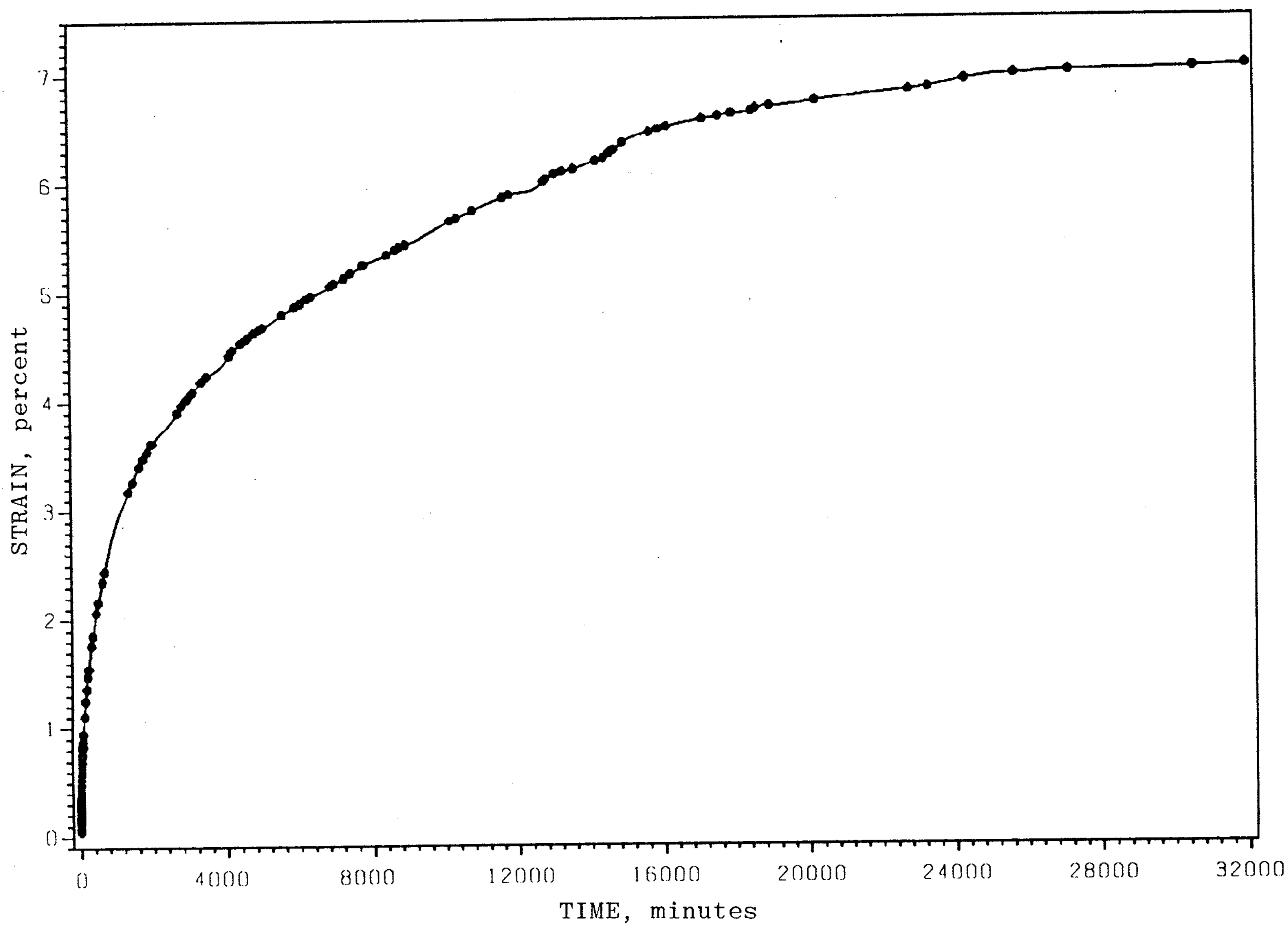


Figure 12: Plot of Strain vs. Time for PT212

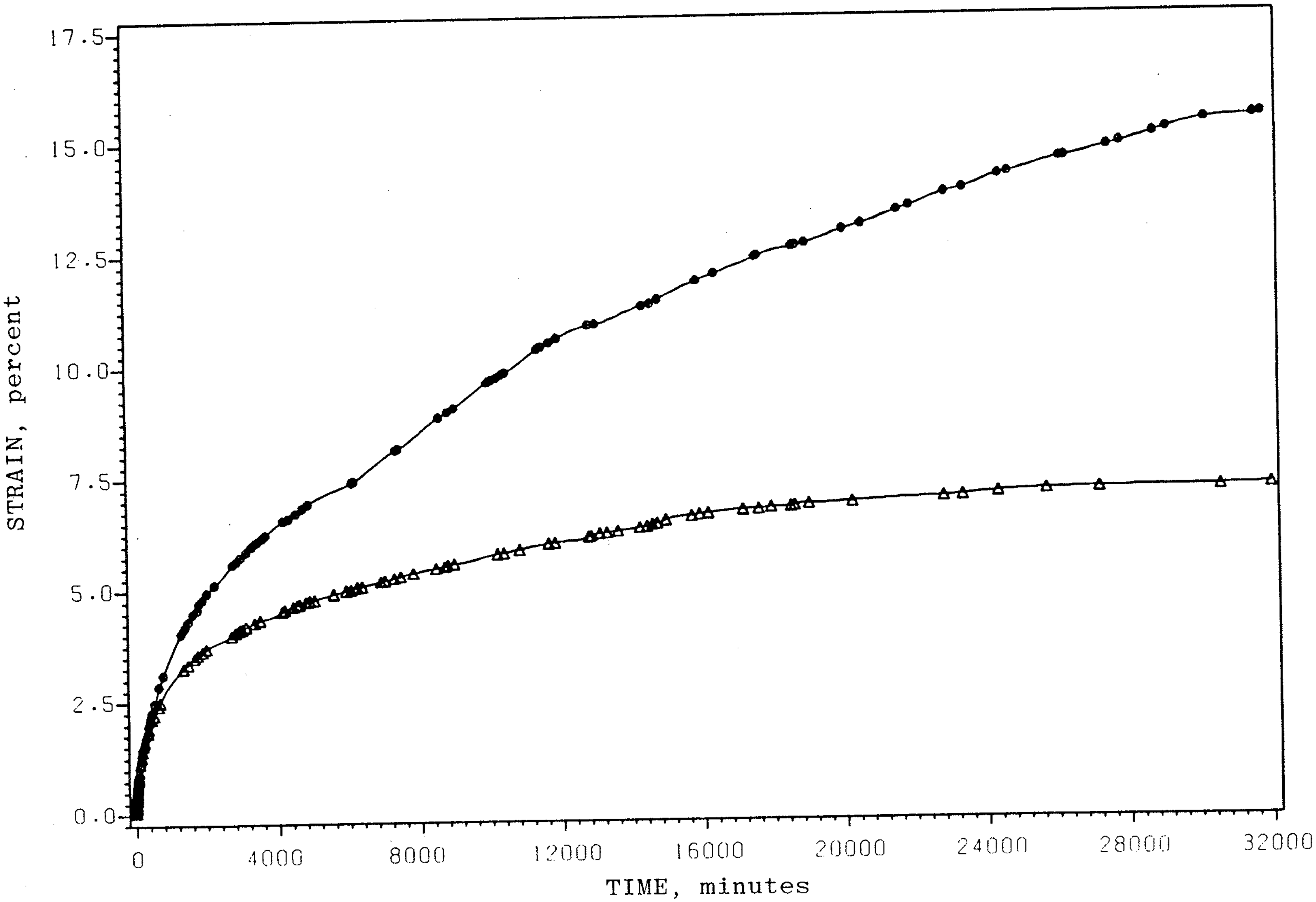


Figure 13: Comparison of Creep Curves between PT202B and PT212

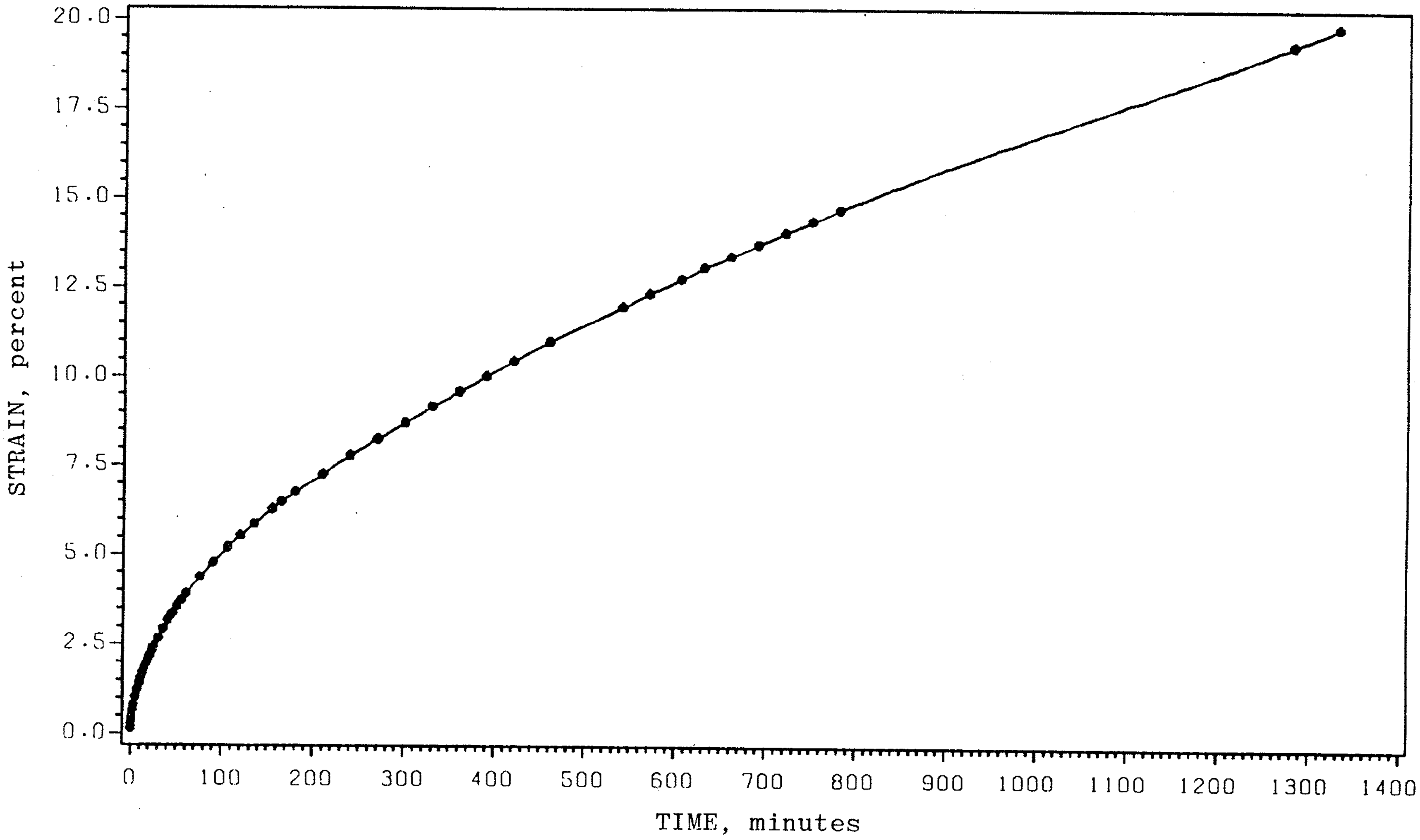


Figure 14: Plot of Strain vs. Time for PT204

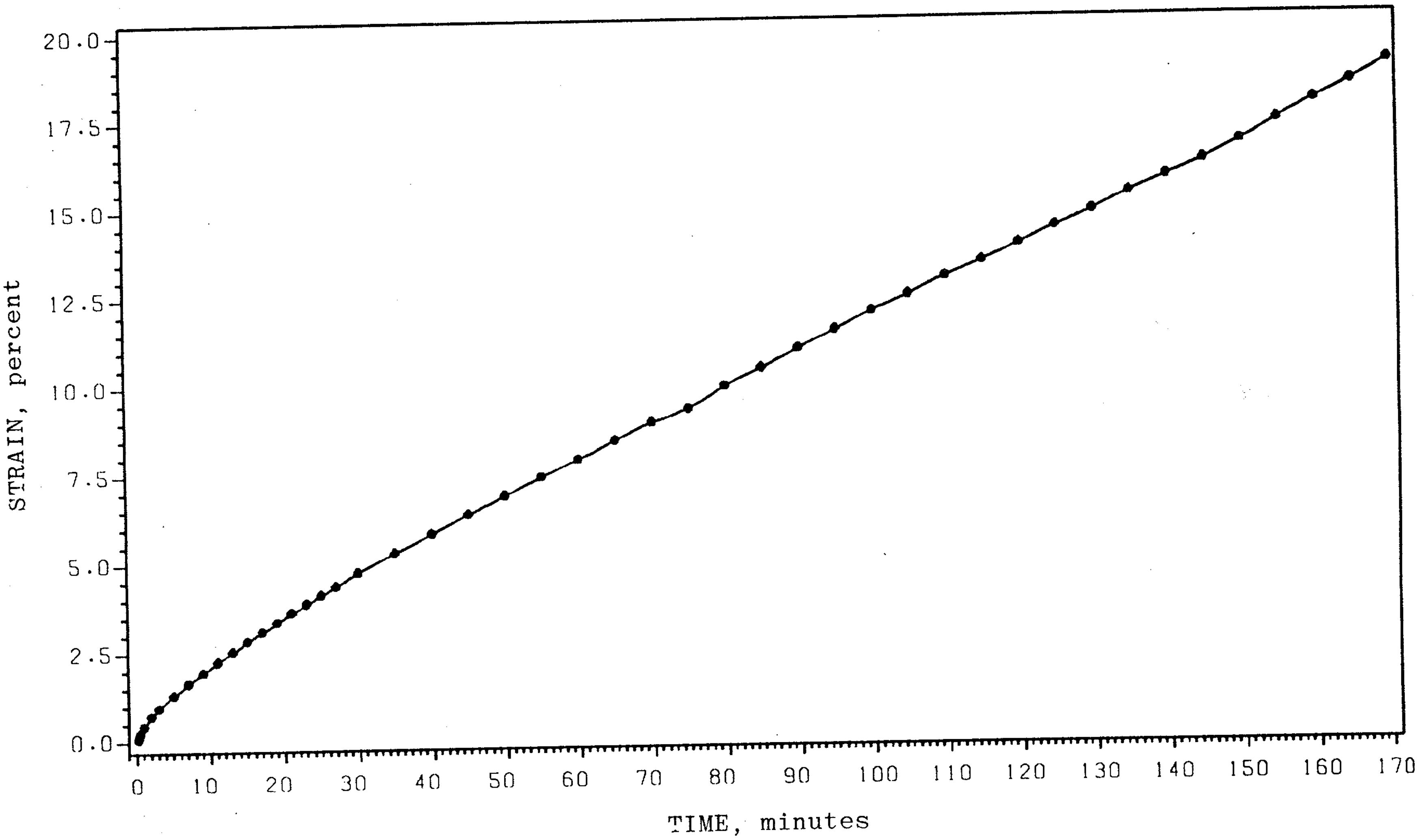


Figure 15: Plot of Strain vs. Time for PT203

4.3 STANDARD PRESSUREMETER TESTS

Standard pressuremeter tests were carried out to assess the limit pressure and the pressuremeter modulus of saturated unfrozen sand specimens at room temperature. Two different densities (loose and dense) of unfrozen sand were prepared for test; each density was investigated with two different boundary conditions (rigid and free).

4.3.1 Tests in the Thick-Walled Tanks (Rigid Boundary)

The corrected pressuremeter (pressure versus cavity radius) curves of two identical standard tests in loose sand, in thick-walled tanks are presented in Figures 16 and 17. The similarity in the shape and strain magnitude of the two curves indicates that standard pressuremeter tests in these laboratory-prepared specimens are repeatable.

Figures 18 and 19 show the corrected pressuremeter curves of two identical tests in dense sand, also in the thick-walled tanks. Again the shape and strain magnitude for the two curves are almost identical.

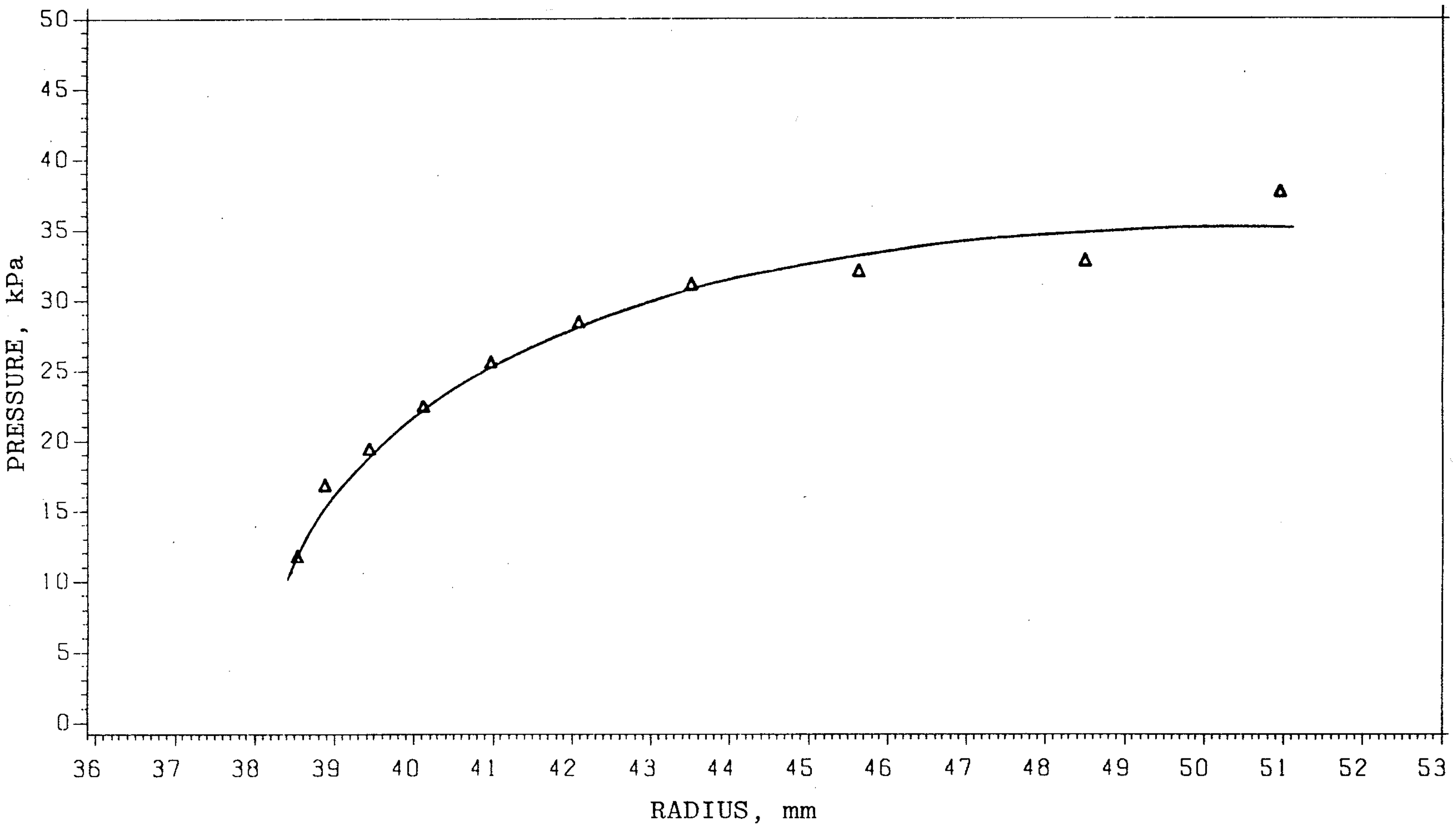


Figure 16: Standard Test in Loose Sand in Thcik Tank - PT205

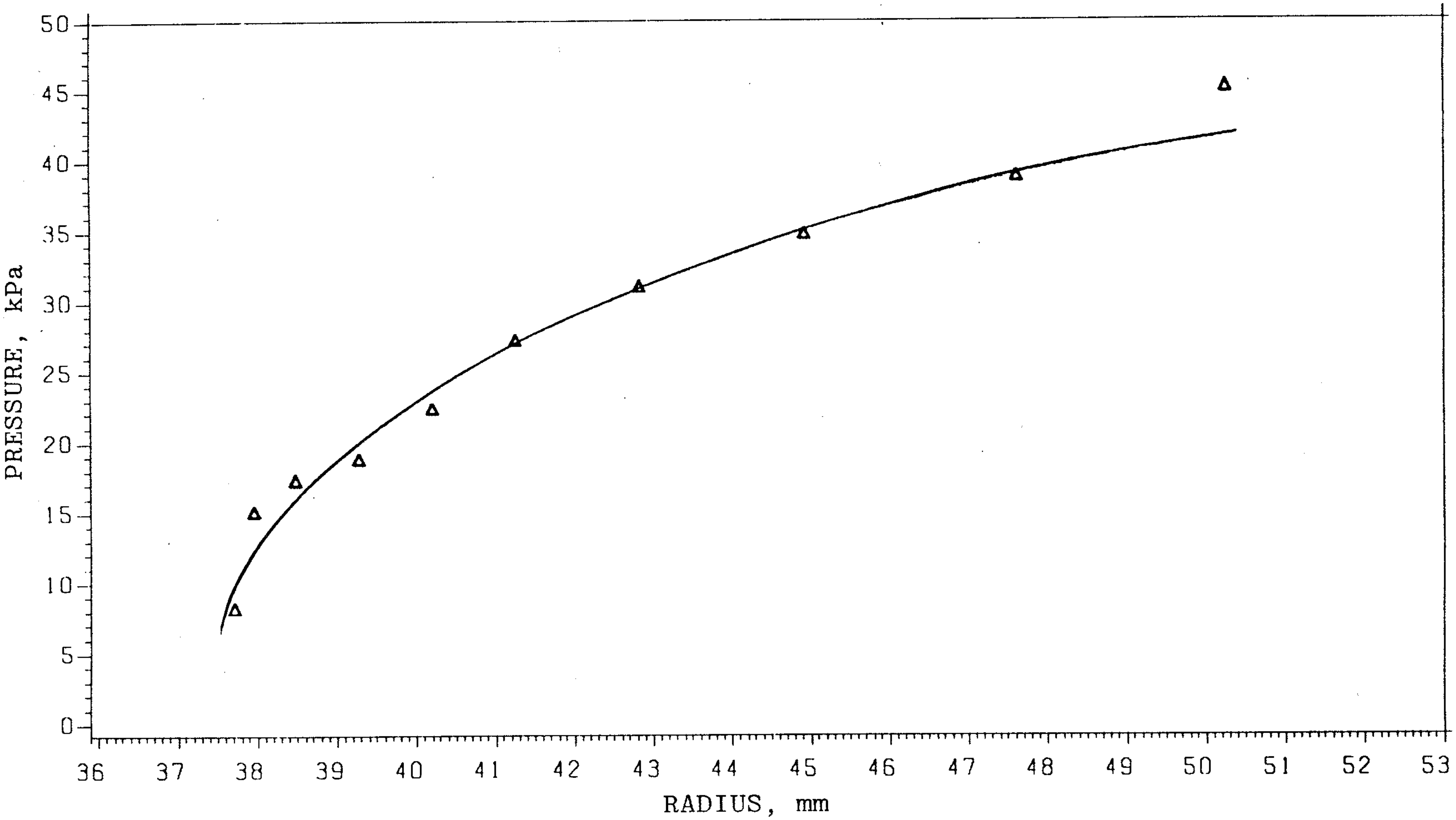


Figure 17: Standard Test in Loose Sand in Thick Tank - PT207

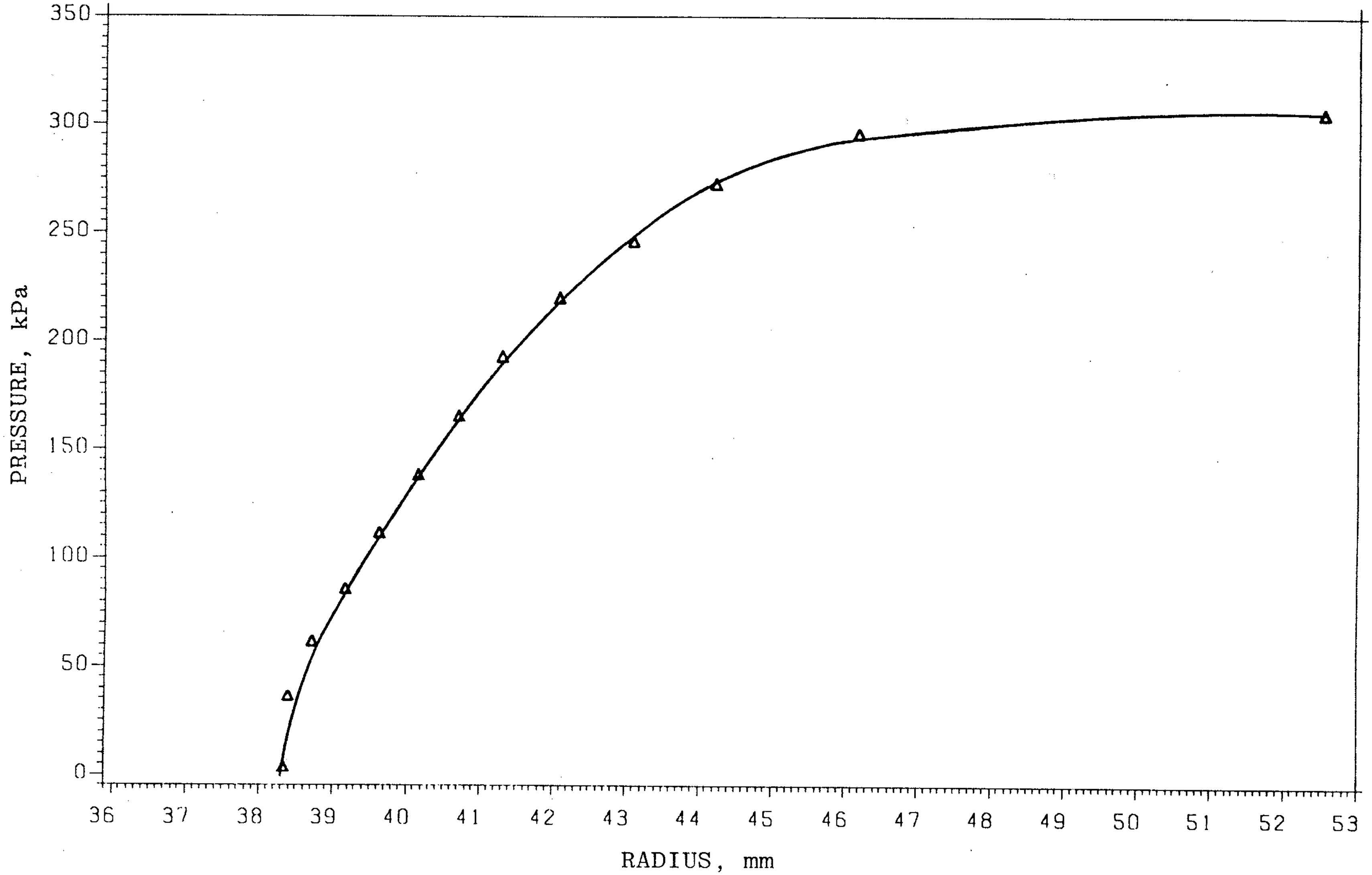


Figure 18: Standard Test in Dense Sand in Thick Tank - PT206

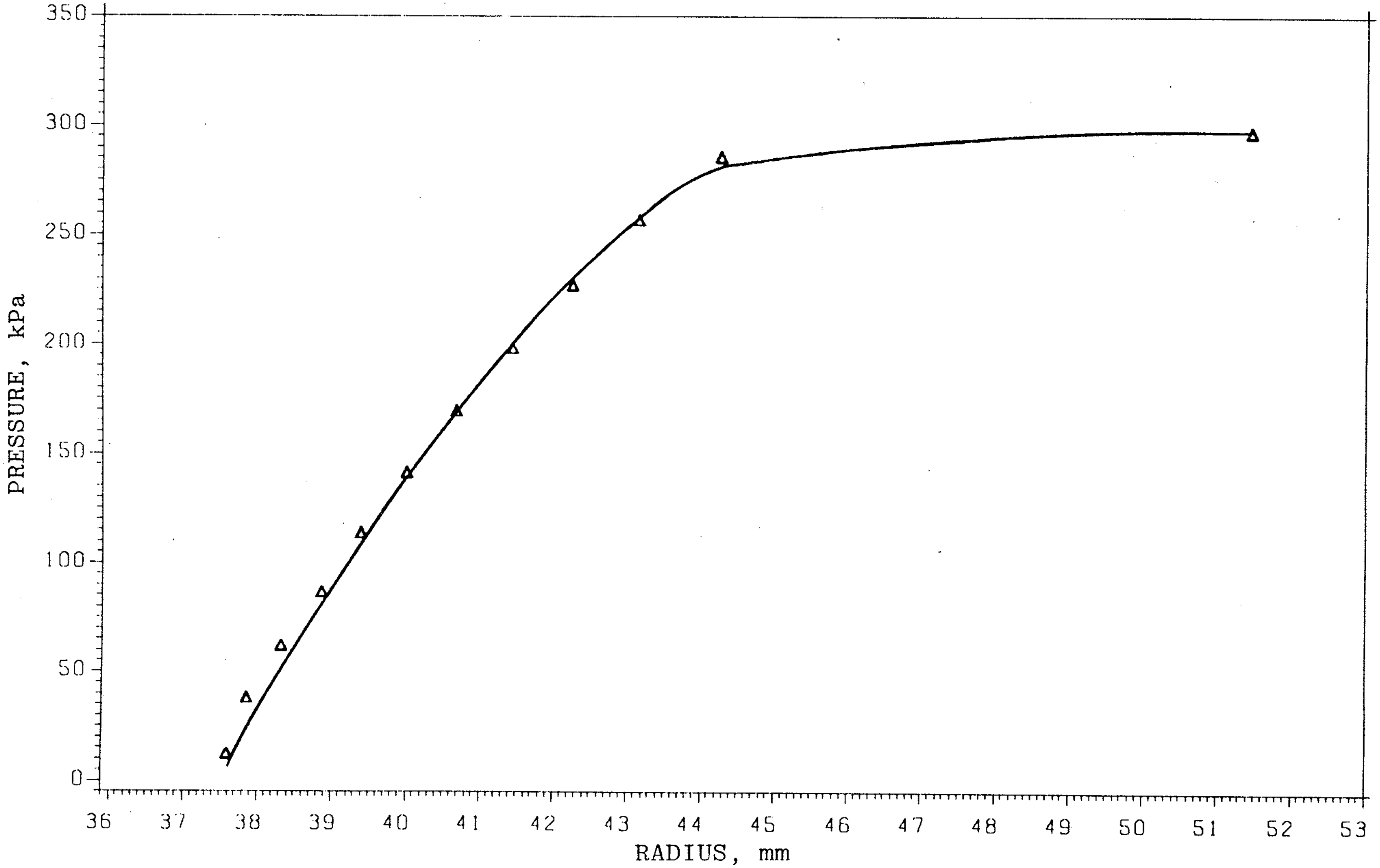


Figure 19: Standard Test in Dense Sand in Thick Tank - PT208

4.3.2 Tests in the Thin-Walled Tanks (Free Boundary)

Figures 20 and 21 show the corrected pressuremeter curves of standard tests in thin-walled tanks; the tests were run in loose sand and in dense sand, respectively.

A summary of the results of all the unfrozen sand tests can be found in Table 2 which was presented earlier (page 19). The limit pressure (p_ℓ) of the dense sand specimen is about 300 kPa, which is about 7 times larger than the limit pressure of the loose sand specimen. The pressuremeter modulus (E_M) of the dense sand specimen is approximately 3500 kPa, which is about 8 times the pressuremeter modulus of the loose sand specimen.

The results show little variation in the limit pressure for the two boundary conditions, either in dense sand or in loose sand.

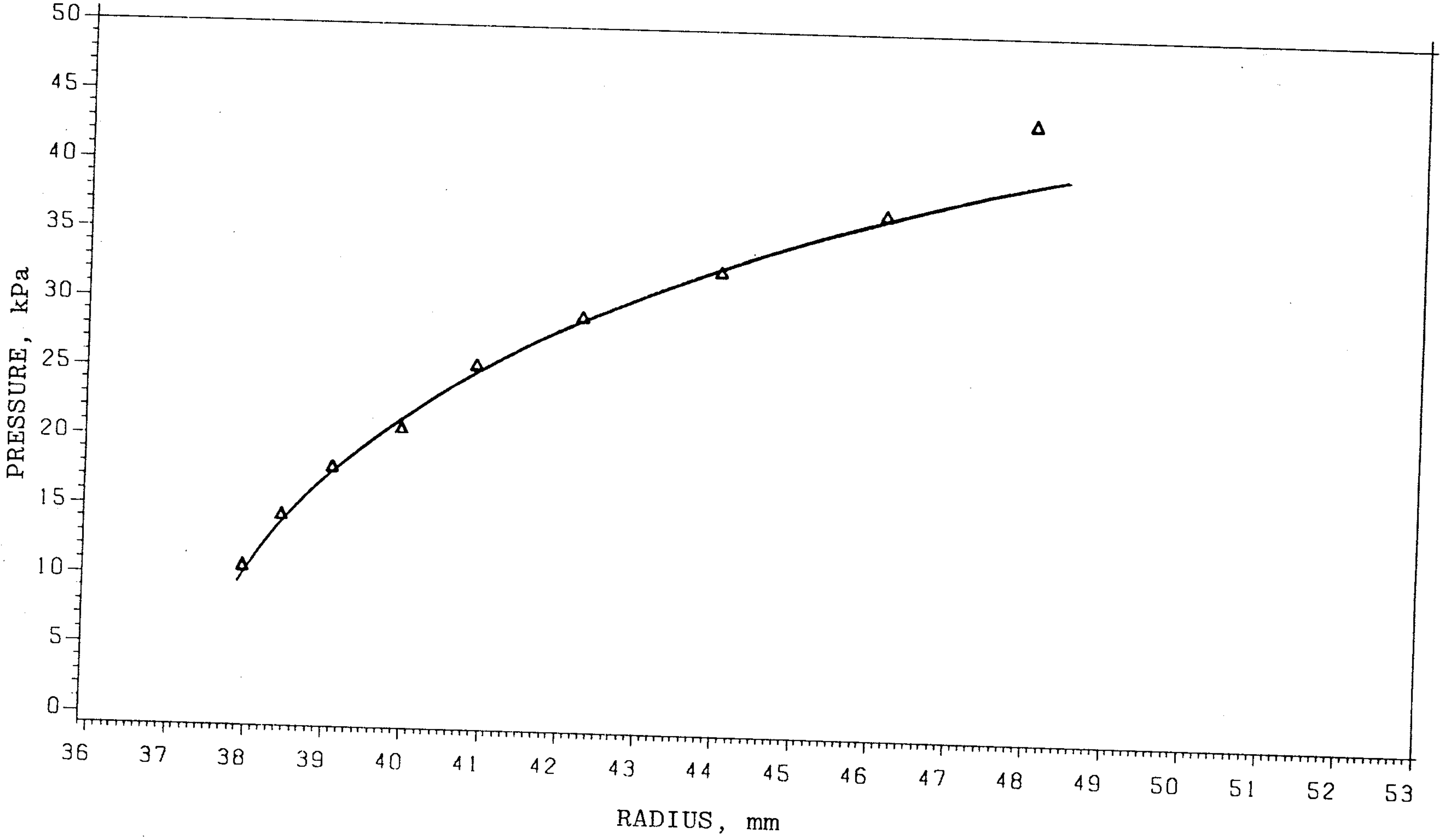


Figure 20: Standard Test in Loose Sand in Thin Tank - PT209

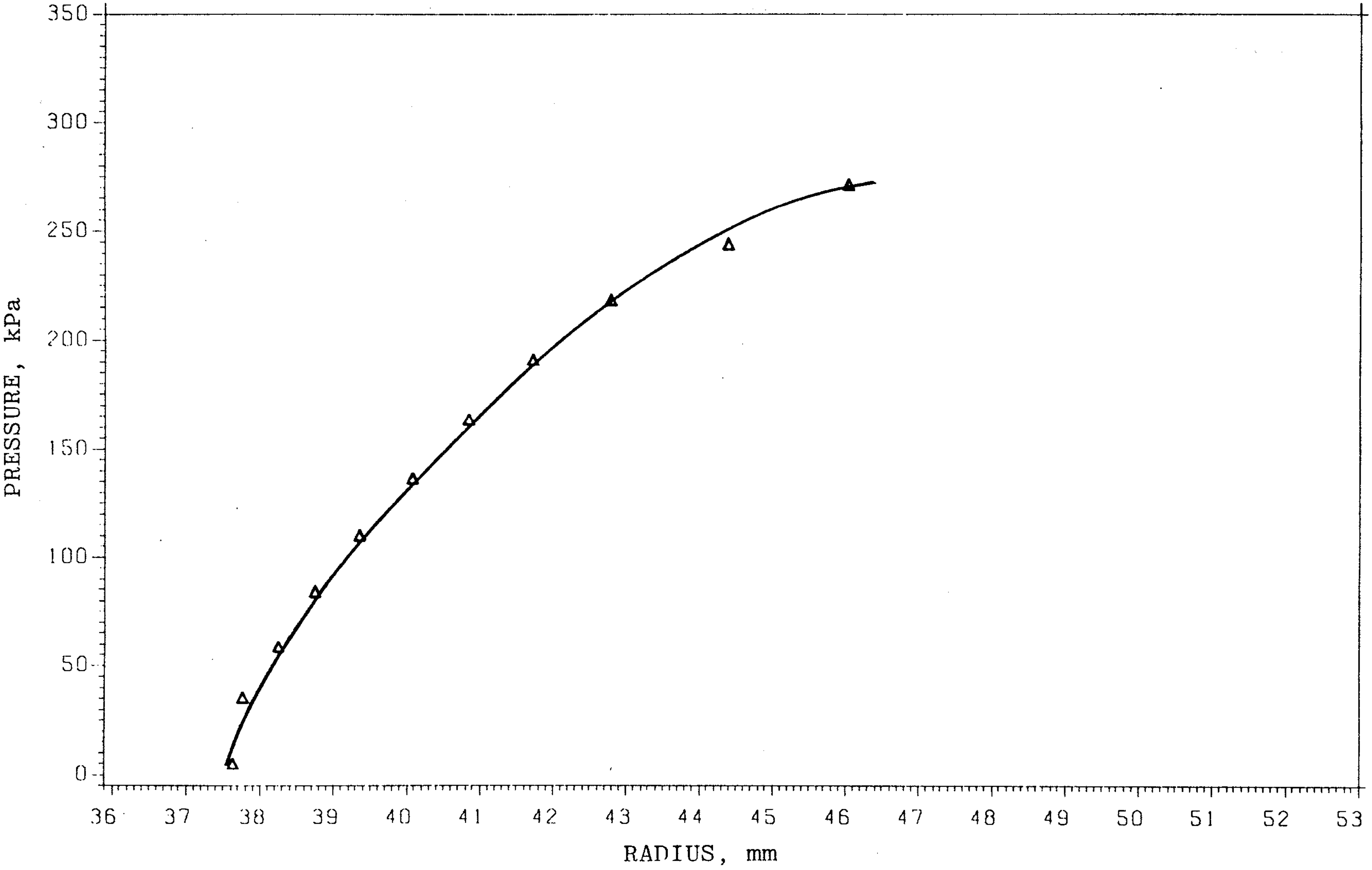


Figure 21: Standard Test in Dense Sand in Thin Tank - PT210

Chapter V

METHODS FOR DETERMINING CREEP PARAMETERS OF FROZEN SOIL

5.1 INTRODUCTION

In this chapter, the test results (presented in Chapter 4) will be analyzed. Ladanyi's method (presented in Chapter 2) will be used to obtain the creep parameters of the frozen sand using the information from the multi-stage creep tests (PT102, PT103, PT201 and PT211). These creep parameters are then used to predict the results of the long-term single-stage creep tests (PT202A, PT203, PT204 and PT212). As will be seen, the fit between actual and predicted results is poor.

5.2 LADANYI'S METHOD

The procedure for obtaining creep parameters described in Chapter 2 was followed to analyze the creep information obtained from all the multi-stage creep tests. Computer programs were developed to carry out Ladanyi's semi-graphical procedures. Either the program LADFOH or LADFOS was used to calculate: the values of '$\ln r/r_i$'; time 't' which is the real time minus one minute (to allow for the assumed one minute of the instantaneous strain time); the average pressure on the specimen at each pressure stage (after allowance for membrane resistance); etc. When the appropriate program LADFOH or LADFOS was run, a data set was created and stored in the computer for future use. The program LADPL took the data set created by LADFOH or LADFOS, analyzed it and plotted the results. This machine plotting procedure replaced the hand plotting technique suggested by Ladanyi and Johnston (1973, 1978).

The step by step procedure which was followed to analyze the results from the multi-stage test PT201 according to Ladanyi's method will be described below.

Step 1: Program LADFOH or LADFOS

It was mentioned in Chapter 3 that two types of rubber membranes (hard and soft) were used throughout the testing program. The calculations for membrane resistance and thickness change, and the outside radius of the probe are different for the two different types of rubber membranes. Therefore two separate but similar computer programs were developed:

1. Program LADFOH was written for a multi-stage test using a hard membrane for the pressuremeter probe.
2. Program LADFOS was written for a multi-stage test using a soft membrane.

The programs LADFOH and LADFOS were written in FORTRAN 77 for the mainframe computer system at the University of Manitoba. Reasons for choosing FORTRAN 77 were:

1. FORTRAN 77 is the most recent language in the FORTRAN series that is available at the University.
2. There are more programming options in FORTRAN 77 than in any previous FORTRAN series language.
3. Programs written in FORTRAN 77 can be placed in the University computer tape library for future use.

Listing, description of the variables used and input information for the programs LADFOH and LADFOS can be found in Appendix D.1. In this analysis, the test data from test PT201 is used. The calculated output for test PT201 is presented below in Table 3. A description of all the variables used can be found at the bottom of Table 3. For this particular example, the calculations were performed beginning with pressure stage 1 (STS = 1 in Table 3). Time t = 1 minute (STP = 4 in Table 3) was chosen to be the assumed time for the instantaneous strain as suggested by Ladanyi. The program LADFOH or LADFOS created a data set called username.SAS.LAD, which was then used in LADPL. Table 4 shows the printout of the data set created as a result of running LADFOH with PT201 test data. A description of all the variables is given at the bottom of Table 4.

TABLE 3

Calculated Output for Test PT201

```
PT201: MULTI-STAGE PRESSUREMETER TEST IN FROZEN SAND; TEMP= -2.9 C.

NUMBER OF STAGES =   8
DESIRED STARTING STAGE = 1
NUMBER OF DATA POINTS IN EACH STAGE = 18
ASSUMED STARTING POINT OF CREEP STRAIN (STP) =  4

THICKNESS CORRECTION CONSTANTS ARE: MT1 = 0.002 AND MT2 = 0.044 IN PG=MT1+MT2*PA
CONSTANTS FOR A/PI ARE:             A1 = 747.20 AND A2 =   5.84 IN A/PI=A1+A2*RN (MM2)
MEMBRANE REACTION CONSTANTS ARE:    MR1 =   0.08 AND MR2 =  0.78 IN RG=MR1xRN**MR2

APPLIED PRESSURE IN EACH STAGE IN MPA :
         1.00
         1.50
         2.00
         2.50
         3.00
         3.50
         4.00
         4.50


TIME (MINUTES) FOR TAKING DATA IN EACH STAGE :
         0.00
         0.25
         0.50
         1.00
         2.00
         3.00
         5.00
         7.00
         9.00
        11.00
        13.00
        15.00
        20.00
        25.00
        30.00
        35.00
        40.00
        45.00


 STAGE NO.  1  ;   APPLIED PRESSURE =    1.00 MPA

 TIME    RN      RG      PI      PG     RO    STRAIN    RATE         LNR
 (MIN)  (MM)   (MPA)   (MPA)    (MM)   (MM)    (%)    (%/MIN)

 -1.00   4.37   0.24    0.76    0.05  39.33  -0.28  0.000E+00 -0.279E-02
 -0.75   4.41   0.24    0.76    0.05  39.36  -0.20  0.318E+00 -0.199E-02
 -0.50   4.47   0.24    0.76    0.05  39.41  -0.08  0.477E+00 -0.796E-03
  0.00   4.51   0.25    0.75    0.05  39.44   0.00  0.159E+00  0.000E+00
  1.00   4.56   0.25    0.75    0.05  39.48   0.10  0.996E-01  0.995E-03
  2.00   4.59   0.25    0.75    0.05  39.50   0.16  0.598E-01  0.159E-02
  4.00   4.61   0.25    0.75    0.05  39.52   0.20  0.199E-01  0.199E-02
  6.00   4.63   0.25    0.75    0.05  39.53   0.24  0.199E-01  0.239E-02
  8.00   4.65   0.25    0.75    0.05  39.55   0.28  0.199E-01  0.279E-02
 10.00   4.66   0.25    0.75    0.05  39.56   0.30  0.998E-02  0.298E-02
 12.00   4.67   0.25    0.75    0.05  39.57   0.32  0.997E-02  0.318E-02
 14.00   4.69   0.25    0.75    0.05  39.58   0.36  0.200E-01  0.358E-02
 19.00   4.70   0.25    0.75    0.05  39.59   0.38  0.399E-02  0.378E-02
 24.00   4.75   0.26    0.74    0.05  39.63   0.48  0.200E-01  0.477E-02
 29.00   4.75   0.26    0.74    0.05  39.63   0.48  0.000E+00  0.477E-02
 34.00   4.75   0.26    0.74    0.05  39.63   0.48  0.000E+00  0.477E-02
 39.00   4.77   0.26    0.74    0.05  39.64   0.52  0.799E-02  0.517E-02
 44.00   4.80   0.26    0.74    0.05  39.67   0.58  0.120E-01  0.577E-02

 AVERAGE PRESSURE ON SPECIMEN = 0.75 MPA
```

TABLE 3-Continued.

STAGE NO. 2 ; APPLIED PRESSURE = 1.50 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	4.80	0.26	1.24	0.05	39.67	-0.04	0.000E+00	-0.397E-03
-0.75	4.84	0.26	1.24	0.07	39.68	0.00	0.159E+00	0.000E+00
-0.50	4.84	0.26	1.24	0.07	39.68	0.00	0.000E+00	0.000E+00
0.00	4.84	0.26	1.24	0.07	39.68	0.00	0.000E+00	0.000E+00
1.00	4.85	0.26	1.24	0.07	39.69	0.02	0.198E-01	0.198E-03
2.00	4.85	0.26	1.24	0.07	39.69	0.02	0.000E+00	0.198E-03
4.00	4.87	0.26	1.24	0.07	39.71	0.06	0.198E-01	0.594E-03
6.00	4.89	0.26	1.24	0.07	39.72	0.10	0.198E-01	0.991E-03
8.00	4.91	0.26	1.24	0.07	39.74	0.14	0.198E-01	0.139E-02
10.00	4.93	0.26	1.24	0.07	39.75	0.18	0.198E-01	0.178E-02
12.00	4.96	0.27	1.23	0.07	39.78	0.24	0.298E-01	0.238E-02
14.00	4.98	0.27	1.23	0.07	39.79	0.28	0.198E-01	0.277E-02
19.00	5.03	0.27	1.23	0.07	39.83	0.38	0.199E-01	0.376E-02
24.00	5.07	0.27	1.23	0.07	39.86	0.46	0.159E-01	0.455E-02
29.00	5.11	0.27	1.23	0.07	39.90	0.54	0.159E-01	0.534E-02
34.00	5.15	0.27	1.23	0.07	39.93	0.62	0.159E-01	0.614E-02
39.00	5.20	0.27	1.23	0.07	39.97	0.71	0.199E-01	0.712E-02
44.00	5.21	0.28	1.22	0.07	39.97	0.73	0.399E-02	0.732E-02

AVERAGE PRESSURE ON SPECIMEN = 1.23 MPA

STAGE NO. 3 ; APPLIED PRESSURE = 2.00 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	5.21	0.28	1.72	0.07	39.97	-0.08	0.000E+00	-0.791E-03
-0.75	5.24	0.28	1.72	0.09	39.98	-0.06	0.792E-01	-0.593E-03
-0.50	5.25	0.28	1.72	0.09	39.99	-0.04	0.790E-01	-0.395E-03
0.00	5.27	0.28	1.72	0.09	40.01	0.00	0.790E-01	0.000E+00
1.00	5.31	0.28	1.72	0.09	40.04	0.08	0.790E-01	0.790E-03
2.00	5.34	0.28	1.72	0.09	40.06	0.14	0.593E-01	0.138E-02
4.00	5.39	0.28	1.72	0.09	40.10	0.24	0.494E-01	0.237E-02
6.00	5.44	0.28	1.72	0.09	40.14	0.34	0.495E-01	0.336E-02
8.00	5.48	0.29	1.71	0.09	40.17	0.42	0.396E-01	0.415E-02
10.00	5.53	0.29	1.71	0.09	40.21	0.51	0.495E-01	0.513E-02
12.00	5.56	0.29	1.71	0.09	40.24	0.57	0.297E-01	0.572E-02
14.00	5.59	0.29	1.71	0.09	40.26	0.63	0.298E-01	0.632E-02
19.00	5.69	0.29	1.71	0.09	40.34	0.83	0.397E-01	0.829E-02
24.00	5.77	0.30	1.70	0.09	40.40	0.99	0.318E-01	0.986E-02
29.00	5.85	0.30	1.70	0.09	40.47	1.15	0.318E-01	0.114E-01
34.00	5.93	0.30	1.70	0.09	40.53	1.31	0.318E-01	0.130E-01
39.00	6.00	0.31	1.69	0.09	40.59	1.45	0.279E-01	0.144E-01
44.00	6.07	0.31	1.69	0.09	40.64	1.59	0.279E-01	0.158E-01

AVERAGE PRESSURE ON SPECIMEN = 1.71 MPA

TABLE 3-Continued.

STAGE NO. 4 ; APPLIED PRESSURE = 2.50 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	6.07	0.31	2.19	0.09	40.64	-0.08	0.000E+00	-0.785E-03
-0.75	6.11	0.31	2.19	0.11	40.66	-0.04	0.157E+00	-0.393E-03
-0.50	6.12	0.31	2.19	0.11	40.67	-0.02	0.785E-01	-0.196E-03
0.00	6.13	0.31	2.19	0.11	40.67	0.00	0.392E-01	0.000E+00
1.00	6.17	0.31	2.19	0.11	40.71	0.08	0.785E-01	0.785E-03
2.00	6.21	0.32	2.18	0.11	40.74	0.16	0.785E-01	0.157E-02
4.00	6.29	0.32	2.18	0.11	40.80	0.31	0.786E-01	0.314E-02
6.00	6.36	0.32	2.18	0.11	40.86	0.45	0.688E-01	0.451E-02
8.00	6.42	0.32	2.18	0.11	40.90	0.57	0.591E-01	0.568E-02
10.00	6.48	0.33	2.17	0.11	40.95	0.69	0.591E-01	0.686E-02
12.00	6.54	0.33	2.17	0.11	41.00	0.81	0.591E-01	0.803E-02
14.00	6.59	0.33	2.17	0.11	41.04	0.91	0.493E-01	0.901E-02
19.00	6.73	0.34	2.16	0.11	41.15	1.18	0.553E-01	0.117E-01
24.00	6.84	0.34	2.16	0.11	41.24	1.40	0.435E-01	0.139E-01
29.00	6.96	0.35	2.15	0.11	41.34	1.64	0.475E-01	0.162E-01
34.00	7.09	0.35	2.15	0.11	41.44	1.89	0.515E-01	0.188E-01
39.00	7.20	0.35	2.15	0.11	41.53	2.11	0.436E-01	0.209E-01
44.00	7.34	0.36	2.14	0.11	41.64	2.39	0.556E-01	0.236E-01

AVERAGE PRESSURE ON SPECIMEN = 2.17 MPA

STAGE NO. 5 ; APPLIED PRESSURE = 3.00 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	7.34	0.36	2.64	0.11	41.64	-0.16	0.000E+00	-0.155E-02
-0.75	7.39	0.36	2.64	0.13	41.67	-0.10	0.232E+00	-0.971E-03
-0.50	7.41	0.36	2.64	0.13	41.68	-0.06	0.155E+00	-0.583E-03
0.00	7.44	0.36	2.64	0.13	41.71	0.00	0.117E+00	0.000E+00
1.00	7.49	0.37	2.63	0.13	41.75	0.10	0.971E-01	0.970E-03
2.00	7.53	0.37	2.63	0.13	41.78	0.17	0.777E-01	0.175E-02
4.00	7.60	0.37	2.63	0.13	41.84	0.31	0.680E-01	0.310E-02
6.00	7.67	0.37	2.63	0.13	41.90	0.45	0.681E-01	0.446E-02
8.00	7.73	0.37	2.63	0.13	41.94	0.56	0.584E-01	0.562E-02
10.00	7.79	0.38	2.62	0.13	41.99	0.68	0.584E-01	0.678E-02
12.00	7.85	0.38	2.62	0.13	42.04	0.80	0.585E-01	0.795E-02
14.00	7.91	0.38	2.62	0.13	42.09	0.91	0.585E-01	0.911E-02
19.00	8.06	0.39	2.61	0.13	42.21	1.21	0.586E-01	0.120E-01
24.00	8.26	0.39	2.61	0.13	42.38	1.60	0.782E-01	0.159E-01
29.00	8.39	0.40	2.60	0.13	42.48	1.85	0.509E-01	0.184E-01
34.00	8.55	0.41	2.59	0.13	42.61	2.17	0.628E-01	0.214E-01
39.00	8.69	0.41	2.59	0.13	42.73	2.44	0.550E-01	0.241E-01
44.00	8.84	0.42	2.58	0.13	42.85	2.74	0.590E-01	0.270E-01

AVERAGE PRESSURE ON SPECIMEN = 2.62 MPA

TABLE 3-Continued.

STAGE NO. 6 ; APPLIED PRESSURE = 3.50 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	8.84	0.42	3.08	0.13	42.85	-0.11	0.000E+00	-0.115E-02
-0.75	8.87	0.42	3.08	0.16	42.86	-0.10	0.752E-01	-0.957E-03
-0.50	8.89	0.42	3.08	0.16	42.87	-0.06	0.153E+00	-0.574E-03
0.00	8.92	0.42	3.08	0.16	42.90	0.00	0.115E+00	0.000E+00
1.00	8.98	0.42	3.08	0.16	42.95	0.11	0.115E+00	0.115E-02
2.00	9.04	0.42	3.08	0.16	43.00	0.23	0.115E+00	0.230E-02
4.00	9.15	0.43	3.07	0.16	43.09	0.44	0.105E+00	0.440E-02
6.00	9.24	0.43	3.07	0.16	43.16	0.61	0.864E-01	0.612E-02
8.00	9.36	0.43	3.07	0.16	43.26	0.84	0.115E+00	0.840E-02
10.00	9.45	0.44	3.06	0.16	43.33	1.02	0.865E-01	0.101E-01
12.00	9.54	0.44	3.06	0.16	43.41	1.19	0.866E-01	0.118E-01
14.00	9.64	0.45	3.05	0.16	43.49	1.38	0.963E-01	0.137E-01
19.00	9.85	0.45	3.05	0.16	43.66	1.79	0.810E-01	0.177E-01
24.00	10.09	0.46	3.04	0.16	43.86	2.25	0.927E-01	0.223E-01
29.00	10.27	0.47	3.03	0.16	44.01	2.60	0.697E-01	0.257E-01
34.00	10.39	0.47	3.03	0.16	44.11	2.83	0.465E-01	0.279E-01
39.00	10.60	0.48	3.02	0.16	44.29	3.24	0.815E-01	0.319E-01
44.00	10.79	0.49	3.01	0.16	44.44	3.61	0.739E-01	0.355E-01

AVERAGE PRESSURE ON SPECIMEN = 3.06 MPA

STAGE NO. 7 ; APPLIED PRESSURE = 4.00 MPA

TIME (MIN)	RN (MM)	RG (MPA)	PI (MPA)	PG (MM)	RO (MM)	STRAIN (%)	RATE (%/MIN)	LNR
-1.00	10.79	0.49	3.51	0.16	44.44	-0.17	0.000E+00	-0.169E-02
-0.75	10.83	0.49	3.51	0.18	44.46	-0.13	0.148E+00	-0.131E-02
-0.50	10.86	0.49	3.51	0.18	44.49	-0.08	0.225E+00	-0.751E-03
0.00	10.90	0.49	3.51	0.18	44.52	0.00	0.150E+00	0.000E+00
1.00	10.97	0.49	3.51	0.18	44.58	0.13	0.131E+00	0.131E-02
2.00	11.02	0.49	3.51	0.18	44.62	0.23	0.939E-01	0.225E-02
4.00	11.13	0.50	3.50	0.18	44.71	0.43	0.103E+00	0.431E-02
6.00	11.27	0.50	3.50	0.18	44.83	0.70	0.132E+00	0.693E-02
8.00	11.39	0.51	3.49	0.18	44.93	0.92	0.113E+00	0.917E-02
10.00	11.50	0.51	3.49	0.18	45.02	1.13	0.104E+00	0.112E-01
12.00	11.62	0.51	3.49	0.18	45.12	1.36	0.113E+00	0.135E-01
14.00	11.73	0.52	3.48	0.18	45.21	1.56	0.104E+00	0.155E-01
19.00	12.00	0.53	3.47	0.18	45.44	2.07	0.102E+00	0.205E-01
24.00	12.26	0.54	3.46	0.18	45.66	2.57	0.986E-01	0.253E-01
29.00	12.50	0.55	3.45	0.18	45.86	3.02	0.912E-01	0.298E-01
34.00	12.76	0.55	3.45	0.18	46.08	3.52	0.989E-01	0.346E-01
39.00	12.93	0.56	3.44	0.18	46.23	3.84	0.648E-01	0.377E-01
44.00	13.18	0.57	3.43	0.18	46.44	4.32	0.954E-01	0.423E-01

AVERAGE PRESSURE ON SPECIMEN = 3.48 MPA

TABLE 3-Continued.

```
STAGE NO.  8  ;    APPLIED PRESSURE =    4.50 MPA

TIME     RN      RG      PI       PG     RO    STRAIN     RATE          LNR
(MIN)  (MM)    (MPA)   (MPA)    (MM)   (MM)    (%)    (%/MIN)

-1.00  13.18   0.57    3.93    0.18  46.44   -0.18   0.000E+00  -0.182E 02
-0.75  13.23   0.57    3.93    0.20  46.46   -0.13   0.217E+00  -0.128E 02
-0.50  13.26   0.57    3.93    0.20  46.49   -0.07   0.219E+00  -0.732E 03
 0.00  13.30   0.57    3.93    0.20  46.52    0.00   0.146E+00   0.000E+00
 1.00  13.38   0.57    3.93    0.20  46.59    0.15   0.146E+00   0.146E-02
 2.00  13.46   0.58    3.92    0.20  46.66    0.29   0.146E+00   0.292E 02
 4.00  13.61   0.58    3.92    0.20  46.79    0.57   0.137E+00   0.566E-02
 6.00  13.76   0.59    3.91    0.20  46.91    0.84   0.138E+00   0.839E-02
 8.00  13.90   0.59    3.91    0.20  47.03    1.10   0.129E+00   0.109E-01
10.00  14.05   0.60    3.90    0.20  47.16    1.38   0.138E+00   0.137E-01
12.00  14.18   0.60    3.90    0.20  47.27    1.61   0.120E+00   0.160E-01
14.00  14.33   0.61    3.89    0.20  47.40    1.89   0.138E+00   0.187E-01
19.00  14.66   0.62    3.88    0.20  47.68    2.50   0.122E+00   0.247E-01
24.00  14.99   0.63    3.87    0.20  47.97    3.11   0.122E+00   0.306E 01
29.00  15.26   0.64    3.86    0.20  48.20    3.61   0.100E+00   0.355E-01

AVERAGE PRESSURE ON SPECIMEN = 3.91 MPA
```

```
VARIABLES USED ARE:
NS = NO. OF STAGES IN THE TEST
STS = DESIRED STARTING STAGE
NP = NO. OF DATA POINTS IN EACH STAGE
STP = THE ASSUMED STARTING POINT OF CREEP STRAIN
T = TIME IN EACH STAGE
DT = TIME MINUS ASSUMED INSTANTANEOUS STRAIN TIME
RN = READING FROM ELECTRONIC BOX
PA = APPLIED PRESSURE
PRESSURE,PIAVG = AVERAGE CORRECTED INTERNAL PRESSURE
RG = MEMBRANE RESISTANCE IN AIR
PG = MEMBRANE THICKNESS CORRECTION (MM)
MT1,MT2,MR1,MR2 = PRESSUREMETER CALIBRATION CONSTANTS
                 MT1,MT2 IN: PG=MT1+MT2*PA
                 MR1,MR2 IN: RG=MR1*RN**MR2
PI = CORRECTED PRESSURE OR NET PRESSURE ON THE SPECIMEN
PSUM = CURRENT SUMMATION OF PI FOR PIAVG CALCULATION
I,J,K,L,COUNT = COUNTERS FOR EACH LOOP
TITLE = TITLE OF THE TEST OF UP TO 80 CHARACTERS
LNR = VALUE OF LN(R/R(I))
LOGLNR = LOG(LNR)
PGFST = FIRST VALUE OF PG IN EACH STAGE
PGREST = PG VALUES AT CURRENT STAGE OTHER THAN PGFST
```

TABLE 4

Data Set username.SAS.LAD Created by LADFOH and PT201

```
                DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME   LOGTIME      PI      PRESSURE    STRAIN       RATE          LNR       LOGLNR

  1    0.00000   0.75180   0.74885    0.09959   0.0995852   0.0009954   -3.0020
  2    0.30103   0.75052   0.74885    0.15936   0.0597745   0.0015923   -2.7980
  4    0.60206   0.74968   0.74885    0.19923   0.0199346   0.0019903   -2.7011
  6    0.77815   0.74883   0.74885    0.23911   0.0199424   0.0023883   -2.6219
  8    0.90309   0.74798   0.74885    0.27897   0.0199305   0.0027859   -2.5550
 10    1.00000   0.74756   0.74885    0.29894   0.0099819   0.0029849   -2.5251
 12    1.07918   0.74714   0.74885    0.31887   0.0099682   0.0031837   -2.4971
 14    1.14613   0.74630   0.74885    0.35879   0.0199579   0.0035815   -2.4459
 19    1.27875   0.74587   0.74885    0.37874   0.0039896   0.0037802   -2.4225
 24    1.38021   0.74377   0.74885    0.47855   0.0199628   0.0047741   -2.3211
 29    1.46240   0.74377   0.74885    0.47855   0.0000000   0.0047741   -2.3211
 34    1.53148   0.74377   0.74885    0.47855   0.0000000   0.0047741   -2.3211
 39    1.59106   0.74293   0.74885    0.51851   0.0079909   0.0051717   -2.2864
 44    1.64345   0.74167   0.74885    0.57844   0.0119866   0.0057677   -2.2390
  1    0.00000   1.23957   1.23487    0.01984   0.0198362   0.0001983   -3.7026
  2    0.30103   1.23957   1.23487    0.01984   0.0000000   0.0001983   -3.7026
  4    0.60206   1.23873   1.23487    0.05946   0.0198109   0.0005944   -3.2259
  6    0.77815   1.23790   1.23487    0.09911   0.0198263   0.0009906   -3.0041
  8    0.90309   1.23706   1.23487    0.13878   0.0198339   0.0013868   -2.8580
 10    1.00000   1.23622   1.23487    0.17845   0.0198377   0.0017829   -2.7489
 12    1.07918   1.23497   1.23487    0.23798   0.0297612   0.0023769   -2.6240
 14    1.14613   1.23414   1.23487    0.27765   0.0198374   0.0027727   -2.5571
 19    1.27875   1.23206   1.23487    0.37693   0.0198554   0.0037622   -2.4246
 24    1.38021   1.23040   1.23487    0.45641   0.0158958   0.0045537   -2.3416
 29    1.46240   1.22874   1.23487    0.53590   0.0158987   0.0053447   -2.2721
 34    1.53148   1.22709   1.23487    0.61542   0.0159046   0.0061354   -2.2122
 39    1.59106   1.22502   1.23487    0.71491   0.0198966   0.0071236   -2.1473
 44    1.64345   1.22461   1.23487    0.73483   0.0039853   0.0073215   -2.1354
  1    0.00000   1.72050   1.71070    0.07904   0.0790449   0.0007901   -3.1023
  2    0.30103   1.71927   1.71070    0.13839   0.0593475   0.0013830   -2.8592
  4    0.60206   1.71722   1.71070    0.23728   0.0494414   0.0023699   -2.6253
  6    0.77815   1.71517   1.71070    0.33624   0.0494840   0.0033568   -2.4741
  8    0.90309   1.71354   1.71070    0.41547   0.0396144   0.0041461   -2.3824
 10    1.00000   1.71150   1.71070    0.51452   0.0495254   0.0051320   -2.2897
 12    1.07918   1.71028   1.71070    0.57399   0.0297351   0.0057235   -2.2423
 14    1.14613   1.70907   1.71070    0.63351   0.0297593   0.0063151   -2.1996
 19    1.27875   1.70501   1.71070    0.83194   0.0396864   0.0082850   -2.0817
 24    1.38021   1.70178   1.71070    0.99088   0.0317867   0.0098600   -2.0061
 29    1.46240   1.69856   1.71070    1.14995   0.0318153   0.0114339   -1.9418
 34    1.53148   1.69535   1.71070    1.30917   0.0318437   0.0130068   -1.8858
 39    1.59106   1.69255   1.71070    1.44859   0.0278844   0.0143820   -1.8422
 44    1.64345   1.68976   1.71070    1.58816   0.0279123   0.0157568   -1.8025
  1    0.00000   2.18578   2.17143    0.07853   0.0785265   0.0007850   -3.1052
  2    0.30103   2.18419   2.17143    0.15707   0.0785387   0.0015694   -2.8043
  4    0.60206   2.18102   2.17143    0.31427   0.0786011   0.0031377   -2.5034
  6    0.77815   2.17826   2.17143    0.45192   0.0688258   0.0045090   -2.3459
  8    0.90309   2.17589   2.17143    0.57002   0.0590503   0.0056840   -2.2453
 10    1.00000   2.17353   2.17143    0.68818   0.0590801   0.0068582    2.1638
 12    1.07918   2.17118   2.17143    0.80641   0.0591135   0.0080317    2.0952
 14    1.14613   2.16922   2.17143    0.90501   0.0492998   0.0090094   -2.0453
 19    1.27875   2.16375   2.17143    1.18134   0.0552669   0.0117442   -1.9302
 24    1.38021   2.15947   2.17143    1.39876   0.0434838   0.0138907   -1.8573
 29    1.46240   2.15482   2.17143    1.63622   0.0474924   0.0162298    1.7897
 34    1.53148   2.14980   2.17143    1.89383   0.0515223   0.0187612   -1.7267
 39    1.59106   2.14557   2.17143    2.11208   0.0436492   0.0209008   -1.6798
 44    1.64345   2.14020   2.17143    2.39021   0.0556256   0.0236209   -1.6267
```

TABLE 4-Continued.

DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME	LOGTIME	PI	PRESSURE	STRAIN	RATE	LNR	LOGLNR
1	0.00000	2.63448	2.61962	0.09708	0.097084	0.0009704	-3.0131
2	0.30103	2.63296	2.61962	0.17482	0.077740	0.0017467	-2.7578
4	0.60206	2.63030	2.61962	0.31090	0.068038	0.0031042	-2.5081
6	0.77815	2.62765	2.61962	0.44710	0.068100	0.0044610	-2.3506
8	0.90309	2.62538	2.61962	0.56390	0.058402	0.0056232	-2.2500
10	1.00000	2.62311	2.61962	0.68078	0.058436	0.0067847	-2.1685
12	1.07918	2.62085	2.61962	0.79772	0.058473	0.0079456	-2.0999
14	1.14613	2.61859	2.61962	0.91474	0.058510	0.0091058	-2.0407
19	1.27875	2.61296	2.61962	1.20761	0.058573	0.0120037	-1.9207
24	1.38021	2.60549	2.61962	1.59874	0.078227	0.0158610	-1.7997
29	1.46240	2.60066	2.61962	1.85340	0.050932	0.0183643	-1.7360
34	1.53148	2.59473	2.61962	2.16723	0.062767	0.0214408	-1.6688
39	1.59106	2.58956	2.61962	2.44228	0.055008	0.0241293	-1.6175
44	1.64345	2.58404	2.61962	2.73733	0.059010	0.0270053	-1.5686
1	0.00000	3.07892	3.05835	0.11487	0.114870	0.0011480	-2.9400
2	0.30103	3.07672	3.05835	0.22981	0.114937	0.0022954	-2.6391
4	0.60206	3.07271	3.05835	0.44070	0.105448	0.0043973	-2.3568
6	0.77815	3.06944	3.05835	0.61343	0.086362	0.0061155	-2.2136
8	0.90309	3.06508	3.05835	0.84392	0.115246	0.0084038	-2.0755
10	1.00000	3.06182	3.05835	1.01695	0.086514	0.0101181	-1.9949
12	1.07918	3.05857	3.05835	1.19011	0.086582	0.0118308	-1.9270
14	1.14613	3.05497	3.05835	1.38270	0.096295	0.0137323	-1.8623
19	1.27875	3.04742	3.05835	1.78766	0.080992	0.0177187	-1.7516
24	1.38021	3.03884	3.05835	2.25141	0.092749	0.0222644	-1.6524
29	1.46240	3.03244	3.05835	2.59986	0.069690	0.0256664	-1.5906
34	1.53148	3.02818	3.05835	2.83243	0.046515	0.0279306	-1.5539
39	1.59106	3.02076	3.05835	3.24001	0.081516	0.0318863	-1.4964
44	1.64345	3.01407	3.05835	3.60940	0.073878	0.0354579	-1.4503
1	0.00000	3.50776	3.48442	0.13145	0.131452	0.0013137	-2.8815
2	0.30103	3.50601	3.48442	0.22539	0.093933	0.0022513	-2.6476
4	0.60206	3.50217	3.48442	0.43216	0.103389	0.0043123	-2.3653
6	0.77815	3.49729	3.48442	0.69560	0.131716	0.0069319	-2.1591
8	0.90309	3.49312	3.48442	0.92163	0.113015	0.0091741	-2.0374
10	1.00000	3.48931	3.48442	1.12902	0.103697	0.0112270	-1.9497
12	1.07918	3.48516	3.48442	1.35546	0.113220	0.0134636	-1.8708
14	1.14613	3.48136	3.48442	1.56322	0.103881	0.0155113	-1.8094
19	1.27875	3.47207	3.48442	2.07395	0.102145	0.0205274	-1.6877
24	1.38021	3.46317	3.48442	2.56674	0.098559	0.0253435	-1.5961
29	1.46240	3.45499	3.48442	3.02249	0.091150	0.0297772	-1.5261
34	1.53148	3.44617	3.48442	3.51713	0.098926	0.0345669	-1.4613
39	1.59106	3.44042	3.48442	3.84107	0.064789	0.0376914	-1.4238
44	1.64345	3.43200	3.48442	4.31815	0.095415	0.0422751	-1.3739
1	0.00000	3.92529	3.90794	0.14638	0.146376	0.0014627	-2.8348
2	0.30103	3.92261	3.90794	0.29284	0.146467	0.0029241	-2.5340
4	0.60206	3.91760	3.90794	0.56766	0.137411	0.0056606	-2.2471
6	0.77815	3.91260	3.90794	0.84280	0.137567	0.0083927	-2.0761
8	0.90309	3.90794	3.90794	1.09983	0.128514	0.0109382	-1.9611
10	1.00000	3.90296	3.90794	1.37548	0.137827	0.0136611	-1.8645
12	1.07918	3.89866	3.90794	1.61462	0.119571	0.0160173	-1.7954
14	1.14613	3.89370	3.90794	1.89079	0.138086	0.0187314	-1.7274
19	1.27875	3.88284	3.90794	2.49935	0.121712	0.0246863	-1.6075
24	1.38021	3.87203	3.90794	3.10922	0.121973	0.0306186	-1.5140
29	1.46240	3.86322	3.90794	3.60915	0.099987	0.0354555	-1.4503

TABLE 4-Continued.

```
VARIABLES USED ARE:
    TIME = TIME DIFFERENCE OR DT(I)
    LNR = LN(R-R(I))
    PI = PRESSURE ON THE SAMPLE AT TIME T (DURING THE TEST)
    PRESSURE = AVERAGE PRESSURE ON THE SAMPLE
    STRAIN = CIRCUMFERENTIAL STRAIN IN %
    RATE = STRAIN RATE IN %/MIN
    IN REGRESSION: LOG(LN(R/R(I-1)) VS LOG(TIME)
       LOGLNR = LOG(LN(R/R(I-1))
       LOGTIME = LOG(TIME)
       BSLOPE = SLOPE OF THE REGRESSION LINE AT EACH PRESSURE
                LEVEL
       FVALUE = INTERCEPT AT Y-AXIS AT EACH PRESSURE LEVEL
    IN REGRESSION: LOG(FVALUE) VS LOG(PRESSURE)
       LOGF = LOG(FVALUE)
       LOGPI = LOG(PI)
       NSLOPE = SLOPE OF THE REGRESSION LINE
       F1 = INTERCEPT AT Y-AXIS
```

Step 2: Program LADPL

The program LADPL is a program separate from LADFOH or LADFOS. LADPL was written in Statistical Analysis System (SAS) language instead of a FORTRAN 77. (For program listing and description of the variables used see Appendix D.2). Reasons for using SAS are:

1. SAS gives complete statistical information when performing a regression analysis.
2. The SAS language gives more options for graphical output than any of the other languages available at the University of Manitoba.

The data set created in Step 1 was read into the LADPL program and analyzed. Linear regression analysis was used in the program to process the data set to determine b, F, F1 and n.

Figure 22 (similar to Figure 2) shows a plot of the log of $\ln(r/r_i)$ (LOGLNR in Table 4) versus log of time (LOGTIME in Table 4) for different pressure levels. Table 5 shows the results of regression analysis for each fit line in Figure 22. The value of b is simply the slope of each regression line in Figure 22; b appears in Table 5 as the PARAMETER ESTIMATE of LOGTIME or BSLOPE in the summary at the bottom of Table 5. The correlation coefficient of each fit line is given as R-SQUARE in Table 5.

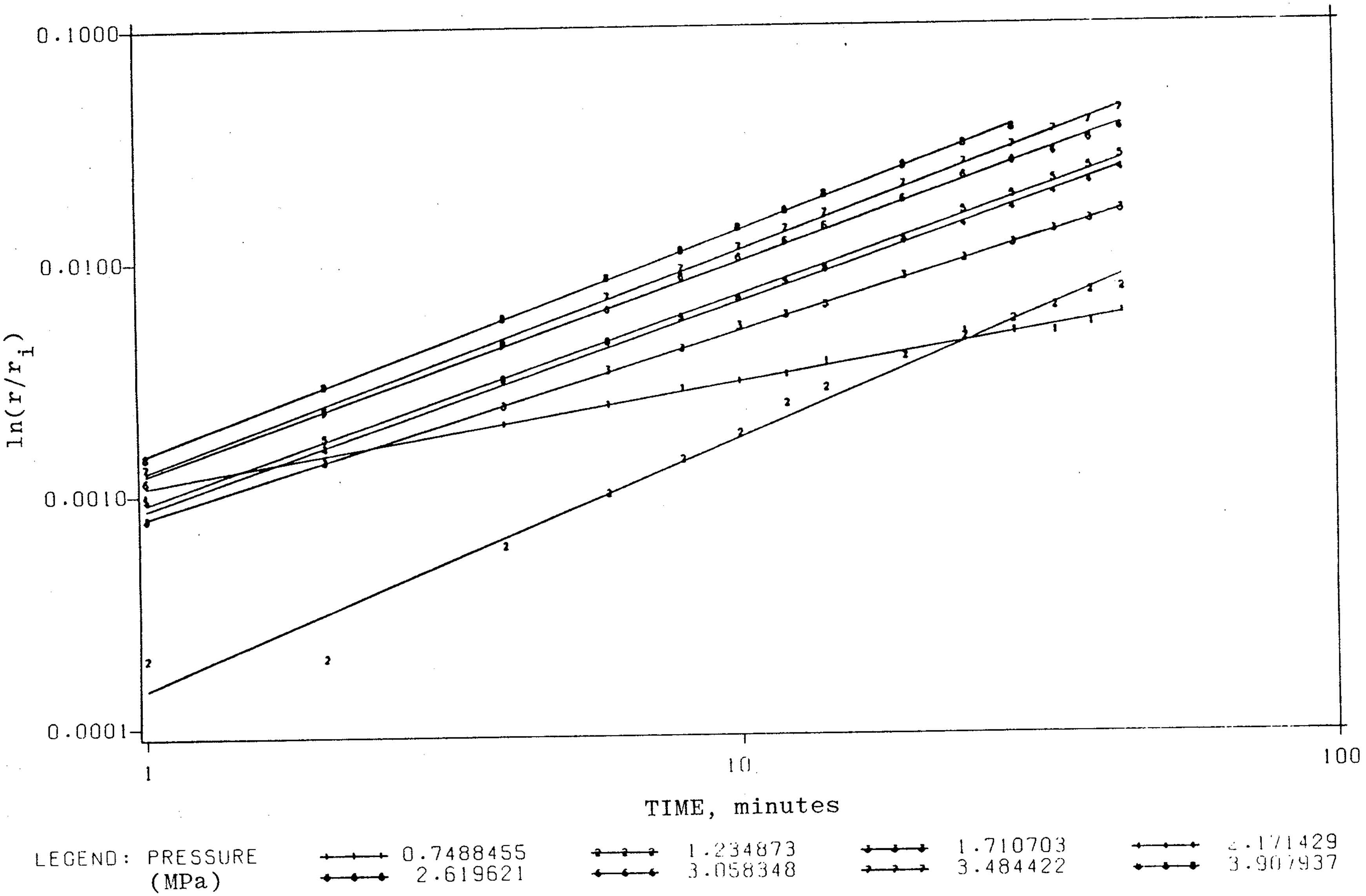


Figure 22: Determination of b and F for PT201

TABLE 5

Results from Regression Analysis for Figure 22

```
                                         ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                         PRESSURE=0.7488455


DEP VARIABLE: LOGLNR
                           SUM OF         MEAN
SOURCE        DF          SQUARES        SQUARE         F VALUE        PROB>F

MODEL          1         0.612156       0.612156       1207.460        0.0001
ERROR         12      0.006083738   0.0005069782
C TOTAL       13         0.618240

     ROOT MSE            0.022516      R-SQUARE          0.9902
     DEP MEAN           -2.504090      ADJ R-SQ          0.9893
     C.V.               -0.899176


                        PARAMETER       STANDARD     T FOR H0:
VARIABLE      DF         ESTIMATE          ERROR   PARAMETER=0    PROB > |T|

INTERCEP       1        -2.964657       0.014556      -203.667        0.0001
LOGTIME        1         0.438724       0.012626        34.749        0.0001

                                         ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                         PRESSURE=1.234873


DEP VARIABLE: LOGLNR
                           SUM OF         MEAN
SOURCE        DF          SQUARES        SQUARE         F VALUE        PROB>F

MODEL          1         3.613978       3.613978        648.354        0.0001
ERROR         12         0.066889    0.005574083
C TOTAL       13         3.680867

     ROOT MSE            0.074660      R-SQUARE          0.9818
     DEP MEAN           -2.711160      ADJ R-SQ          0.9803
     C.V.                -2.75379


                        PARAMETER       STANDARD     T FOR H0:
VARIABLE      DF         ESTIMATE          ERROR   PARAMETER=0    PROB > |T|

INTERCEP       1        -3.830221       0.048266       -79.356        0.0001
LOGTIME        1         1.065990       0.041865        25.463        0.0001
```

TABLE 5-Continued.

```
                         ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                          PRESSURE=1.710703

DEP VARIABLE: LOGLNR

                        SUM OF          MEAN
SOURCE      DF         SQUARES        SQUARE       F VALUE       PROB>F

MODEL        1        1.987732      1.987732     46297.858       0.0001
ERROR       12 0.0005152027 .00004293356
C TOTAL     13        1.988247

     ROOT MSE    0.006552371       R-SQUARE         0.9997
     DEP MEAN      -2.266788       ADJ R-SQ         0.9997
     C.V.           -0.28906

                  PARAMETER       STANDARD     T FOR H0:
VARIABLE    DF     ESTIMATE          ERROR   PARAMETER=0   PROB > |T|

INTERCEP     1    -3.096715    0.004236013      -731.045       0.0001
LOGTIME      1     0.790568    0.003674167       215.169       0.0001

                         ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                          PRESSURE=2.171429

DEP VARIABLE: LOGLNR

                        SUM OF          MEAN
SOURCE      DF         SQUARES        SQUARE       F VALUE       PROB>F

MODEL        1        2.456595      2.456595      5061.819       0.0001
ERROR       12     0.005823822  0.0004853185
C TOTAL     13        2.462418

     ROOT MSE       0.022030       R-SQUARE         0.9976
     DEP MEAN      -2.137055       ADJ R-SQ         0.9974
     C.V.           -1.03086

                  PARAMETER       STANDARD     T FOR H0:
VARIABLE    DF     ESTIMATE          ERROR   PARAMETER=0   PROB > |T|

INTERCEP     1    -3.059685       0.014242      -214.835       0.0001
LOGTIME      1     0.878875       0.012353        71.146       0.0001
```

TABLE 5-Continued.

```
                                       ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                   PRESSURE=2.619621


DEP VARIABLE: LOGLNR

                          SUM OF          MEAN
SOURCE        DF         SQUARES        SQUARE        F VALUE        PROB>F

MODEL          1        2.478906      2.478906      10522.533        0.0001
ERROR         12     0.002826968  0.0002355807
C TOTAL       13        2.481733

     ROOT MSE           0.015349      R-SQUARE         0.9989
     DEP MEAN          -2.107118      ADJ R-SQ         0.9988
     C.V.              -0.728419


                       PARAMETER      STANDARD     T FOR H0:
VARIABLE      DF        ESTIMATE         ERROR   PARAMETER=0     PROB > |T|

INTERCEP       1       -3.033928   0.009922674      -305.757         0.0001
LOGTIME        1        0.882857   0.008606574       102.579         0.0001

                                       ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                   PRESSURE=3.058348


DEP VARIABLE: LOGLNR

                          SUM OF          MEAN
SOURCE        DF         SQUARES        SQUARE        F VALUE        PROB>F

MODEL          1        2.578853      2.578853       8469.358        0.0001
ERROR         12     0.003653906  0.0003044922
C TOTAL       13        2.582507

     ROOT MSE           0.017450      R-SQUARE         0.9986
     DEP MEAN          -1.964601      ADJ R-SQ         0.9985
     C.V.              -0.888206


                       PARAMETER      STANDARD     T FOR H0:
VARIABLE      DF        ESTIMATE         ERROR   PARAMETER=0     PROB > |T|

INTERCEP       1       -2.909912      0.011281      -257.948         0.0001
LOGTIME        1        0.900479   0.009784722        92.029         0.0001
```

TABLE 5-Continued.

```
                                        ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                            PRESSURE=3.484422


DEP VARIABLE: LOGLNR

                        SUM OF        MEAN
SOURCE       DF        SQUARES      SQUARE         F VALUE       PROB>F

MODEL         1       2.803043    2.803043        8642.211       0.0001
ERROR        12 0.003892119 0.0003243433
C TOTAL      13       2.806935

     ROOT MSE        0.018010    R-SQUARE          0.9986
     DEP MEAN       -1.913558    ADJ R-SQ          0.9985
     C.V.           -0.941154


                     PARAMETER      STANDARD   T FOR H0:
VARIABLE   DF         ESTIMATE         ERROR  PARAMETER=0    PROB > |T|

INTERCEP    1        -2.899102      0.011643     -249.002        0.0001
LOGTIME     1         0.938805      0.010099       92.963        0.0001


                                        ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME
                                                            PRESSURE=3.907937


DEP VARIABLE: LOGLNR

                        SUM OF        MEAN
SOURCE       DF        SQUARES      SQUARE         F VALUE       PROB>F

MODEL         1       1.863077    1.863077       26210.874       0.0001
ERROR         9 0.0006397229 .00007108032
C TOTAL      10       1.863717

     ROOT MSE     0.008430915    R-SQUARE          0.9997
     DEP MEAN       -1.964761    ADJ R-SQ          0.9996
     C.V.           -0.429106


                     PARAMETER      STANDARD   T FOR H0:
VARIABLE   DF         ESTIMATE         ERROR  PARAMETER=0    PROB > |T|

INTERCEP    1        -2.822234   0.005874825     -480.395        0.0001
LOGTIME     1         0.949774   0.005866503      161.898        0.0001
```

TABLE 5-Continued.

SUMMARY OF CREEP PARAMETERS B AND F

PRESSURE	_TYPE_	_MODEL_	_DEPVAR_	_SIGMA_	LOGLNR	LOGTIME	LOGF	FVALUE	BSLOPE	LOGPI
0.74885	OLS		LOGLNR	0.0225162	-1	0.43872	-2.9647	0.00108478	0.43872	0.12561
1.23487	OLS		LOGLNR	0.0746598	-1	1.06599	-3.8302	0.00014784	1.06599	0.09162
1.71070	OLS		LOGLNR	0.0065524	-1	0.79057	-3.0967	0.00080036	0.79057	0.23317
2.17143	OLS		LOGLNR	0.0220299	-1	0.87888	-3.0597	0.00087159	0.87888	0.33675
2.61962	OLS		LOGLNR	0.0153486	-1	0.88286	-3.0339	0.00092485	0.88286	0.41824
3.05835	OLS		LOGLNR	0.0174497	-1	0.90048	-2.9099	0.00123052	0.90048	0.48549
3.48442	OLS		LOGLNR	0.0180095	-1	0.93880	-2.8991	0.00126153	0.93880	0.54213
3.90794	OLS		LOGLNR	0.0084309	-1	0.94977	-2.8222	0.00150579	0.94977	0.59195

Also found in the summary at the bottom of Table 5 is the value of F which appears as FVALUE and is the intercept of $\ln(r/r_i)$ at unit time for each pressure level in Figure 22. The value of F is discussed in Chapter 2, as Eq. 11.

Figure 23 (similar to Figure 3) shows a plot of log of F (LOGF in the summary in Table 5) versus log of pressure (LOGPI in the summary in Table 5). Table 6 shows the results of regression analysis for the fit line in Figure 23. The slope of the fit line in Figure 23 is the creep parameter n which appears as PARAMETER ESTIMATE of LOGPI in Table 6 and as NSLOPE in the summary at the bottom of Table 6. The intercept at unit pressure is equal to F1 in Eq. 18 of Chapter 2. The value of F1 can be found in the summary at the bottom of Table 6. The correlation coefficient R-SQUARE of 0.2365 in Table 6 indicates that the fit was poor. The data points from pressure stages 1 and 2 are scattered relative to the other data points in Figure 23; it is this scatter which accounts for the poor R-SQUARE value. Since the slope n has to be obtained from a straight fit line with a correlation coefficient greater than say, 0.90, the first two pressure stages were deleted and the entire procedure was repeated starting with stage 3 (STS = 3). The results from this new analysis can be summarized below:

$n = 0.775$

$F1 = 4.930\times10^{-4}$

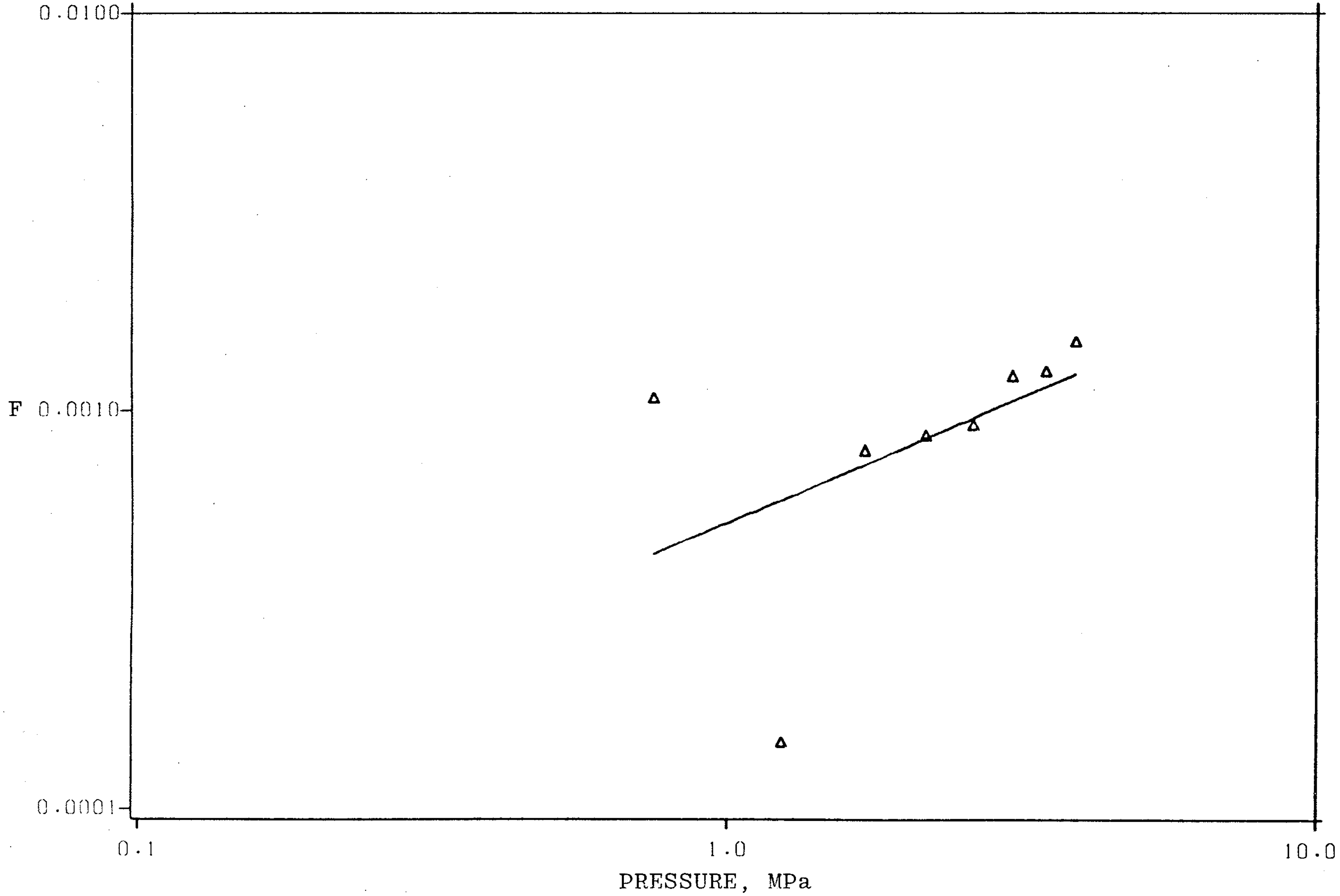


Figure 23: Determination of n for PT201

TABLE 6

Results from Regression Analysis for Figure 23

```
                                  ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT

                     SUM OF          MEAN
SOURCE      DF      SQUARES        SQUARE       F VALUE       PROB>F

MODEL        1     0.167208      0.167208         1.859       0.2217
ERROR        6     0.539771      0.089962
C TOTAL      7     0.706979

    ROOT MSE       0.299936      R-SQUARE        0.2365
    DEP MEAN      -3.077057      ADJ R-SQ        0.1093
    C.V.           -9.74751

                  PARAMETER      STANDARD    T FOR H0:                      VARIABLE
VARIABLE    DF     ESTIMATE         ERROR  PARAMETER=0    PROB > |T|         LABEL

INTERCEP     1    -3.280326      0.182963      -17.929        0.0001  INTERCEPT
LOGPI        1     0.631827      0.463446        1.363        0.2217



                         SUMMARY OF CREEP PARAMETERS F1 AND N

OBS    _TYPE_    _MODEL_    _DEPVAR_    _SIGMA_    LOGF    NSLOPE     LOGF1        F1

 1      OLS                   LOGF      0.299936    -1    0.631827   -3.2803   0.000524413
```

R-SQUARE = 0.9157 for this new fit line.

(Details of this new analysis are given in Appendix D.3).

Step 3: Variation of b with pressure

The variation of b with pressure for test PT201, as shown in Figure 24, (details are given in Appendix D.3) can be expressed by:

$$b = 0.725(p)^{0.203} \tag{22}$$

where p = pressure in MPa.

Step 4: Determination of σ_c

The creep parameter σ_c was calculated on the basis of the following:

Selecting $\dot{\varepsilon}_c = 10^{-5}$ min^{-1} at reference pressure

$p = 1.0$ MPa, then

$b = 0.725$	from Eq. 22
$n = 0.775$	
$M = 4.836\times10^{-4}$	from Eq. 17
$F1 = 4.930\times10^{-4}$	
$\sigma_c = (M/F1)^{1/n} = 0.98$ MPa	from Eq. 19

A similar procedure was followed for tests PT102, PT103 and PT211. A summary of the creep parameters from all multi-stage tests is presented in Table 7. The analyses of these three tests can be found in Appendices D.4, D.5 and D.6, respectively.

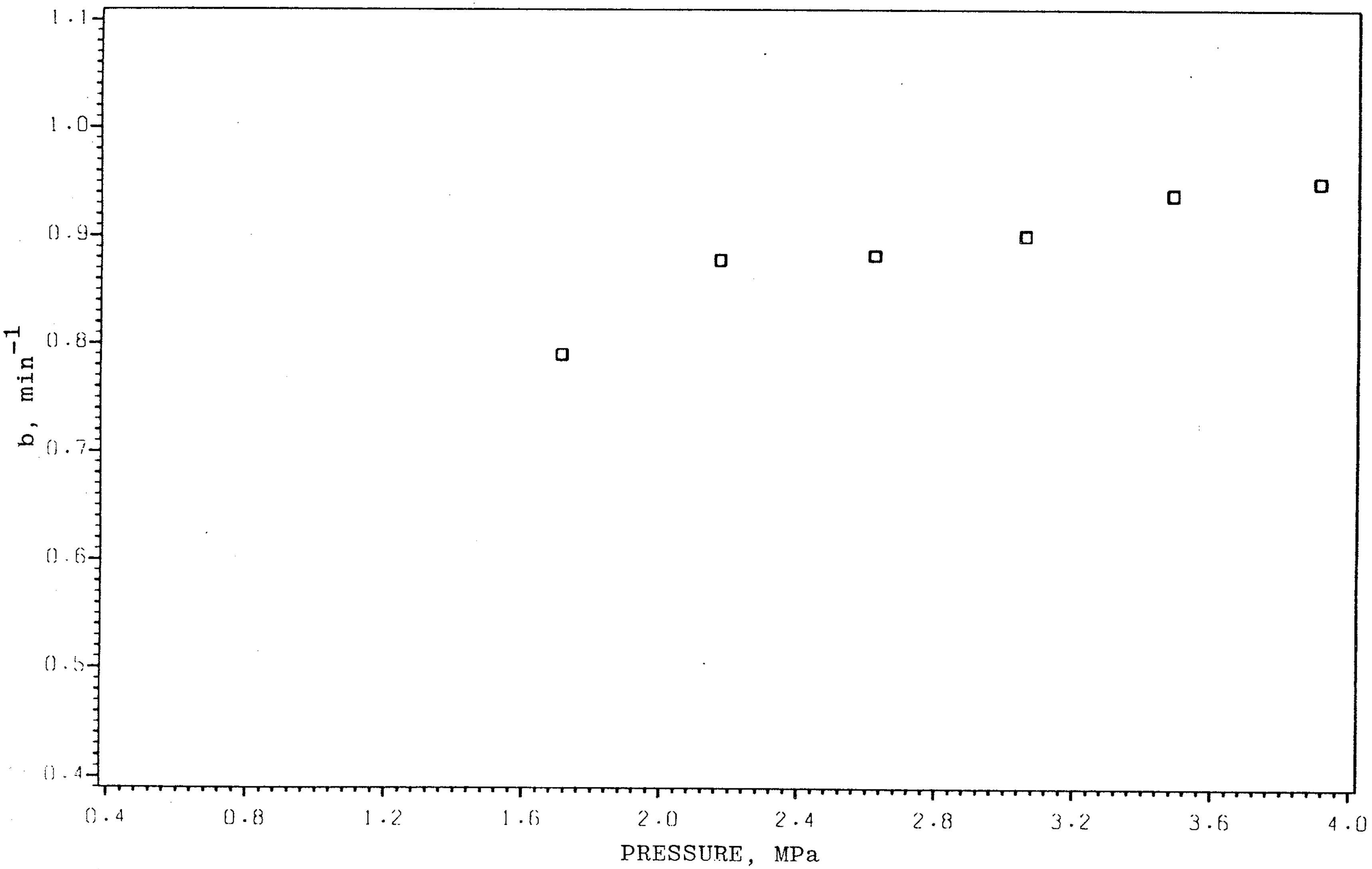


Figure 24: Variation of b with Pressure

TABLE 7

Creep Parameters from All the Tests on Frozen Sand

Test	Time interval (minute)	Pressure increment (MPa)	Pressure range (MPa)	$b = f(p)$	n	F1	σ_c (MPa)
PT102	15	0.5	1.34 - 5.68	$0.95\ p^{0.0}$	1.75	$1.64\text{x}10^{-4}$	0.26
PT103	45	0.5	0.99 - 3.71	$0.734\ p^{0.179}$	0.93	$4.87\text{x}10^{-4}$	0.84
PT201	45	0.5	1.71 - 3.91	$0.725\ p^{0.203}$	0.78	$4.93\text{x}10^{-4}$	0.98
PT211	45	0.25	1.00 - 2.50	$0.590\ p^{0.384}$	1.44	$7.21\text{x}10^{-5}$	11.0
PTMLM	45	-	1.0 - 4.2	$0.471\ p^{0.427}$	1.32	$4.85\text{x}10^{-4}$	8.2

Step 5: General equation

Having obtained the creep parameters from each test, the general creep equation, Eq. 3, of Chapter 2 can be solved. For example, using the results from PT201 and rewriting Eq. 3, the general creep equation is:

$$\varepsilon_e^{(c)} = \left(\frac{\dot{\varepsilon}_c}{b}\right)^b \left(\frac{\sigma_e}{\sigma_c}\right)^n t^b$$

where $b = 0.725(p)^{0.203}$

$n = 0.775$

$\sigma_c = 0.98$ MPa.

Similarly, the equivalent creep strength discussed in Chapter 2 and given by Eq. 20 can be rewritten as:

$$\sigma_{ef} = \sigma_c \, \varepsilon_{ef}^{1/n} \left(\frac{\dot{\varepsilon}_c \, t}{b}\right)^{-b/n}$$

where b, n and σ_c are as above and ε_{ef} is the equivalent failure strain, say 20%. The validity of the above equations will be discussed later.

5.2.1 Comparison of Actual and Predicted Strains

The creep parameters obtained from the multi-stage tests (Section 5.2) were employed to predict the long-term creep at four different pressures. The predictions were then compared to the actual creep strains which were measured at the same four pressures.

5.2.1.1 Calculation of Predicted Strains

According to Eq. 1, the total strain (ε) attained at time t, at a constant pressure p, is equal to the sum of the instantaneous strain ($\varepsilon^{(i)}$) and the creep strain ($\varepsilon^{(c)}$). The instantaneous strain is equal to the strain at one minute in the multi-stage test according to Ladanyi. Also, according to Ladanyi the creep strain (circumferential strain in a pressuremeter test) can be approximated from:

$$\varepsilon^{(c)} \simeq \ln(r/r_i) = F\ t^b \quad \text{(from Eq. 13)}$$

where $F = F1(p)^n$, t = time in minutes and p = pressure in MPa. Therefore the total circumferential strain can be calculated as

$$\varepsilon_\theta = \varepsilon^{(i)} + \varepsilon^{(c)} \tag{23}$$

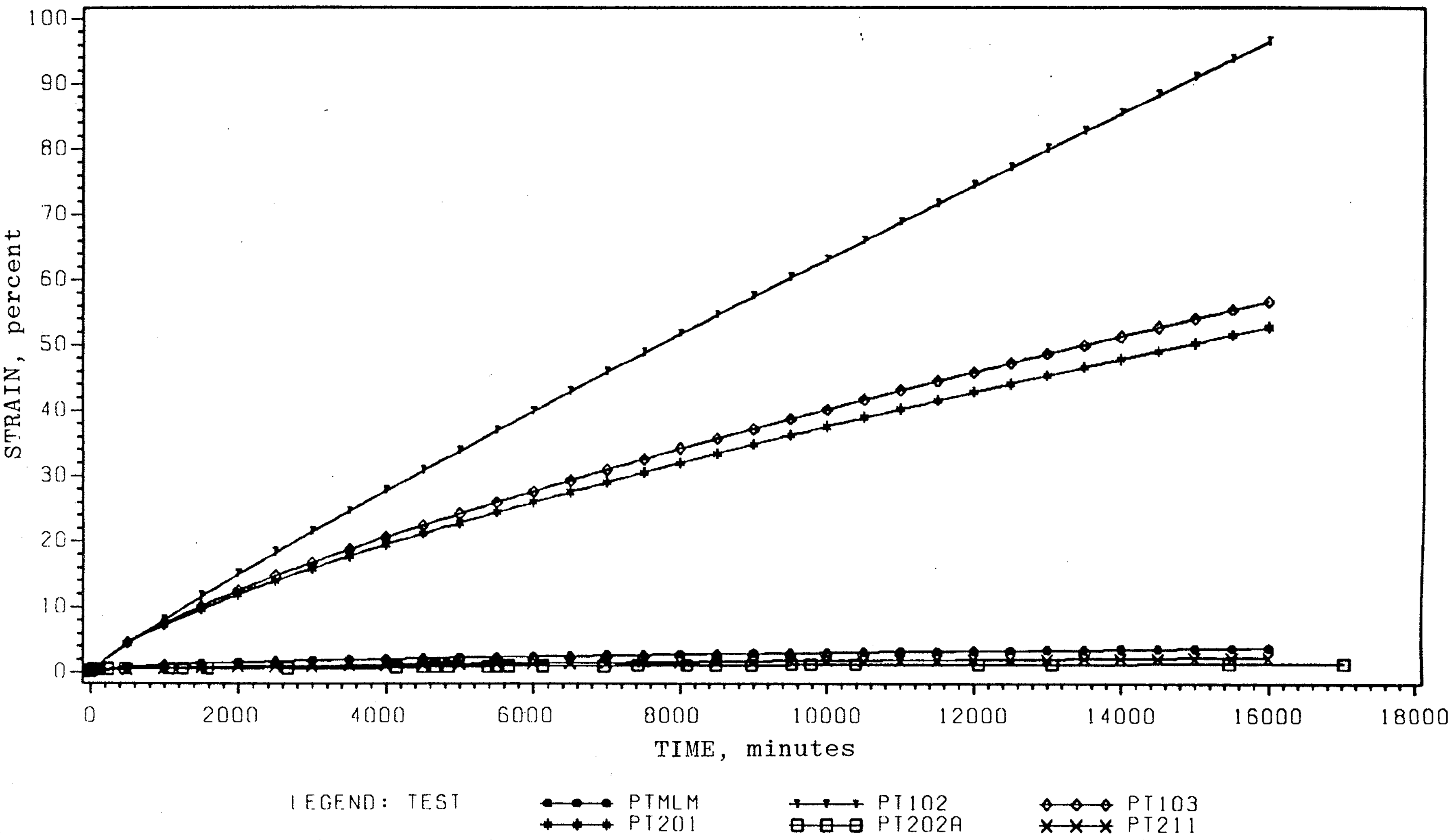
5.2.1.2 Actual versus Predicted Strains

A comparison of the maximum recorded actual strains and the predicted strains for four different pressure levels can be found in Table 8. Plots of the actual versus predicted curves are presented in Figures 25 to 28 inclusive. The predicted strains from all the tests can be found in Appendix E.

TABLE 8

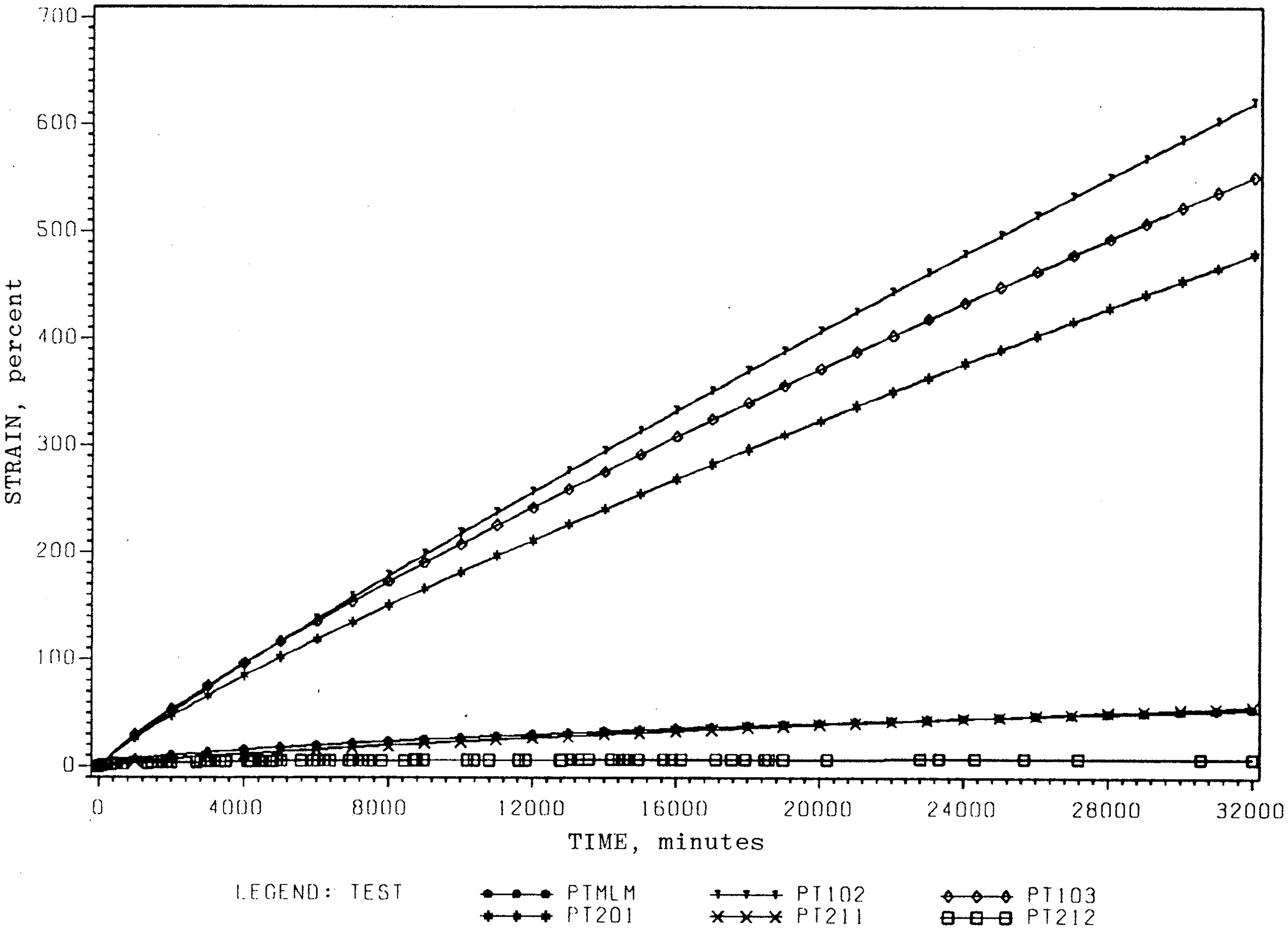
Comparison of Actual and Predicted Strains

Maximum strain (%)				
At time (minute)	16000	32000	1250	170
At pressure (MPa)	1.0	2.0	3.0	4.2
Actual				
	PT202A	PT212	PT204	PT203
	1.3	7.2	19.0	19.8
Predicted				
PT102	96	621	59	21
PT103	57	552	87	27
PT201	56	460	75	20
PT211	2.3	56	21	10
PTMLM	3.8	54	23	16



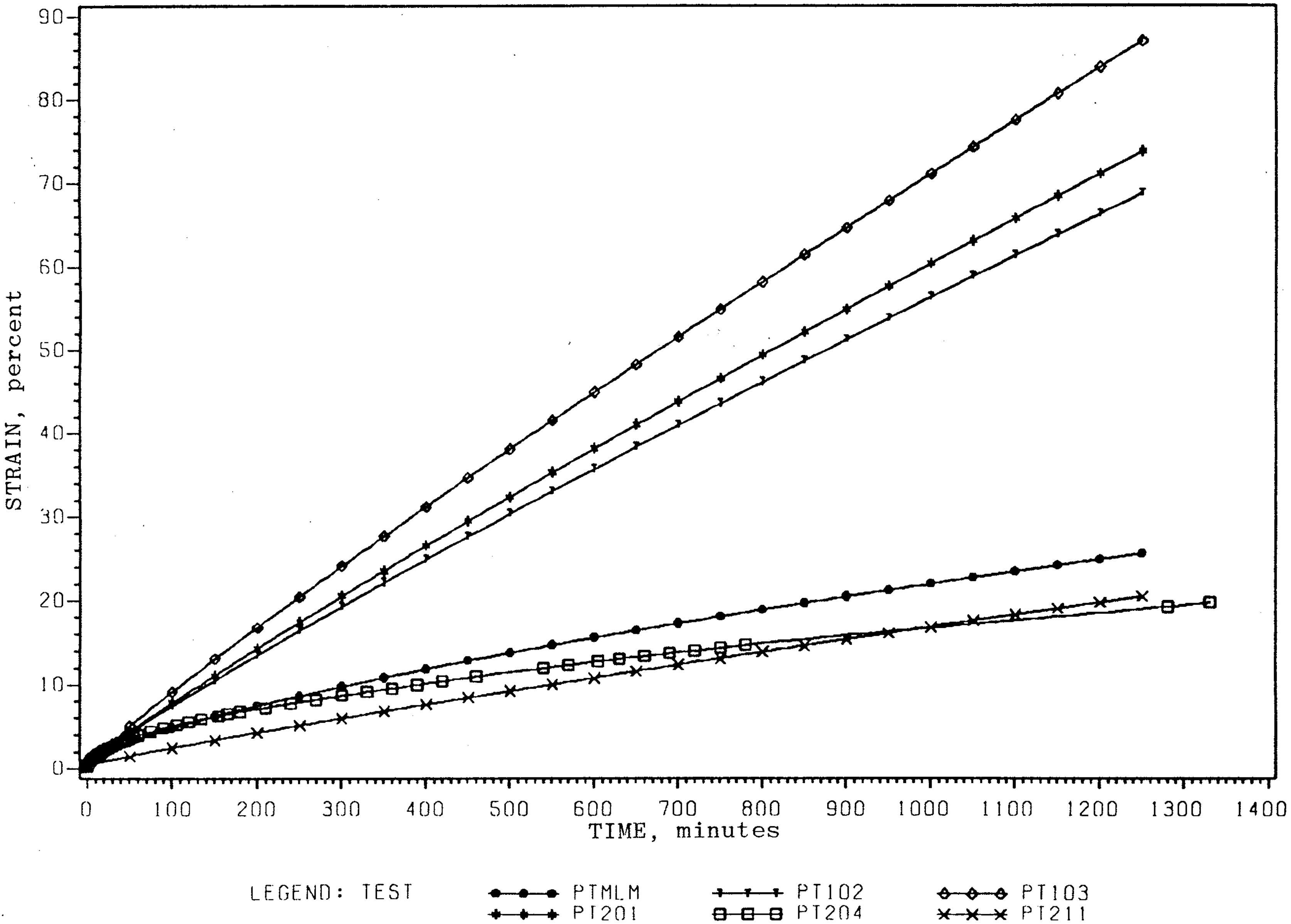
ALL CURVES ARE PREDICTED EXCEPT FOR ACTUAL TEST PT202A

Figure 25: Predicted vs. Actual Curves at p = 1.0 MPa



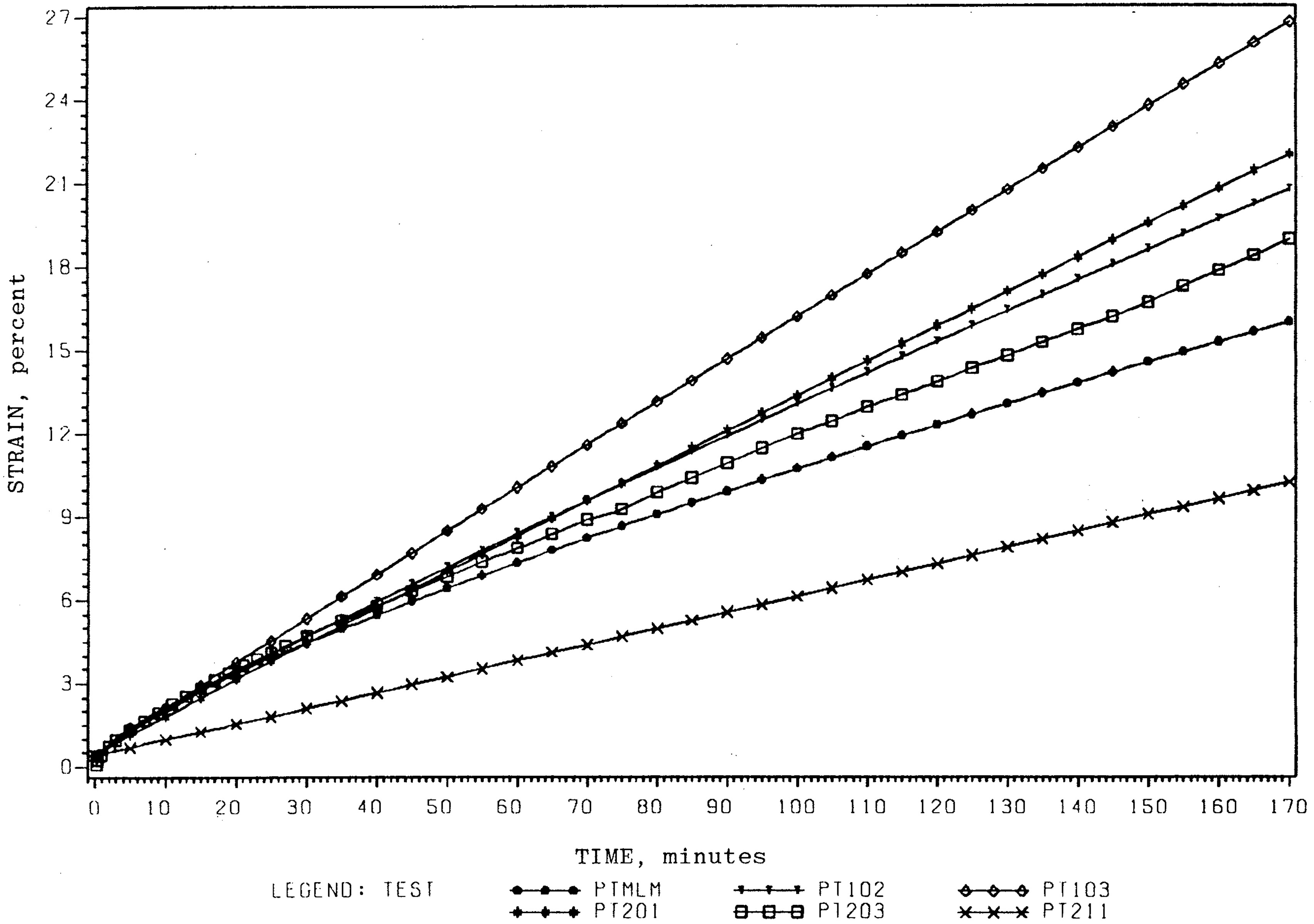
ALL CURVES ARE PREDICTED EXCEPT FOR ACTUAL TEST PT212

Figure 26: Predicted vs. Actual Curves at p = 2.0 MPa



ALL CURVES ARE PREDICTED EXCEPT FOR ACTUAL TEST PT204

Figure 27: Predicted vs. Actual Curves at p = 3.0 MPa



ALL CURVES ARE PREDICTED EXCEPT FOR ACTUAL TEST PT203

Figure 28: Predicted vs. Actual Curves at p = 4.2 MPa

Figure 25 shows the comparison of the actual and predicted creep curves at p = 1.0 MPa. Only one predicted curve, based on PT211, shows relatively good agreement with the actual curve.

Figure 26 shows the comparison of the actual and predicted curves at p = 2.0 MPa. Again only the one curve predicted from test PT211 is relatively close in magnitude to the actual creep curve, although the error is large.

A comparison of actual and predicted creep curves at p = 3.0 MPa is presented in Figure 27. As with the previous cases, only predicted curve PT211 shows good agreement (with an approximate error of 25%).

Figure 28 shows a comparison of actual and predicted creep curves at p = 4.2 MPa. Most predicted curves show good agreement with the actual curve except for the curve predicted from PT211. Test PT211 itself reached only a maximum pressure of 2.5 MPa. The poor comparison raises the question of whether Ladanyi's method can be used to predict creep behaviour of a material at a pressure that is outside the pressure range of the test being used to make the prediction. Also note that the total time for the actual single-stage creep test PT203 is only four times the 45 minute time interval which is used to run the multi-stage test on which the prediction is based. That is to say, the extrapolation is short, whereas in the comparisons at other (lower) pressure levels, the length of the actual single-stage creep tests ranges from 36 to 710 times the 45 minute time interval used to run the tests for the predictions.

It has been shown that in most cases, predictions based on test PT211 had good agreement with the actual test results. This good agreement could have been due to the small magnitude of pressure increment used in test PT211. It was speculated that this 0.25 MPa per increment test did not induce cracks in the specimen. Whereas in tests PT103 and PT201, which used 0.5 MPa pressure increment, cracks might have developed in the specimens so that the measured deformations (and hence the creep parameters) were large as compared to the 'true' creep parameters of a single-stage creep test at a given pressure.

5.3 MODIFIED LADANYI METHOD

A new method, which will be referred to as the Modified Ladanyi Method (MLM), was devised in an attempt to better predict the long-term behaviour of frozen soil. The procedure for obtaining the creep parameters is the same as the one described in Chapter 2 and Section 5.2 (Ladanyi's method) with the exception that the creep information is obtained from separate single-stage creep tests instead of multi-stage tests.

In the MLM procedure, the initial 45 minute creep information from each long-term creep test i.e. from PT202A, PT203, PT204 and PT212, was used to evaluate the creep parameters of the frozen sand. (Complete results of the analysis are presented in Appendix F.1). However, it was found that R-SQUARE for the fit line for creep parameter n as described in Step 2 of Section 5.2 was not acceptable (the correlation coefficient was 0.61). By excluding the information for test PT212 (test at p = 2.0 MPa) and using only the creep information from PT202A, PT203 and PT204 (referred to as PTMLM) the fit for n was improved to an acceptable level (R-SQUARE = 0.9927). The results of this latter analysis (PTMLM) are tabulated on Table 7 (on page 76); the details can be found in Appendix F.2.

Again, as in Section 5.2.1, the creep parameters obtained from PTMLM can be used to predict the long-term creep at four different pressure levels. Comparison of the actual and predicted creep curves at pressure 1.0 MPa, 2.0 MPa, 3.0 MPa and 4.2 MPa are included as the solid circles in Figures 25, 26, 27 and 28, respectively. It is obvious that for each pressure level the Modified Ladanyi method gave better predictions than did Ladanyi's method.

Chapter VI

DISCUSSION

During the preparation of this thesis the author also participated in writing a paper by Shields et al. (1985). The paper presents Ladanyi's method and comparisons of actual strains versus predicted strains at four pressure levels. A copy of the paper is included in this thesis in Appendix G.

Based on the analyses carried out in this study the following remarks can be made:

The creep parameters obtained from two separate but identical multi-stage creep tests PT103 and PT201 (in Table 7) are similar, indicating that the pressuremeter tests carried out on the laboratory-prepared frozen specimens are reproducible.

Ladanyi's method did not predict the long-term behaviour of frozen soil at low stress. As a result, calculations for predicted strain (Eq. 3) and equivalent creep strength (Eq. 10) will be in serious error.

The calculations of predicted strain reveal that the strain values (from $\varepsilon^{(c)} = Ft^{b}$) are very sensitive to b. It is important, therefore, that b be known accurately.

Effect of Magnitude of Pressure Increment

The comparisons of predicted strains and actual strains at various pressures (in Section 5.2.1) indicate that predictions from test PT211, which was a 45 minute interval, 0.25 MPa incremental test, gave good agreement with the actual creep strains, especially the predictions at pressures within the test pressure range. However, tests PT103 and PT201, which had 45 minute creep interval and 0.5 MPa increment, gave a higher prediction than the actual strain at a given pressure. It was speculated that cracks might have developed in the specimens of tests PT103 and PT201 because of the large (0.5 MPa) pressure increment, so that the measured deformations (and hence the creep parameters) were higher than the actual deformation in a single-stage test at a given pressure.

Effect of Stress History

The Modified Ladanyi method shows better promise than Ladanyi's original method. However the error using MLM was still approximately 300% for predictions at low stresses. One possible reason for the better predictions using MLM is that the creep information used in MLM was obtained from tests on virgin samples without a previous history of loading. In a multi-stage test, creep at stage 2 or higher is occurring in a material that has been subjected to a previous stress application. The previous stress application is believed to alter the subsequent creep behaviour of the material.

The effect of stress history is clearly shown in Figure 29, where the values of b versus pressure from all the tests are plotted. The values of b obtained from single-stage, long-term creep tests on virgin samples form a straight line; b values obtained from multi-stage tests are generally higher than those obtained from single-stage tests on virgin samples. Interestingly, the value of b from PT202B (p = 2.0 MPa) also falls within the pattern of the multi-stage tests since PT202B was a a creep test on a sample that had been subjected previously to a stress application of 1.0 MPa for a period of 10 days ie. test PT202A.

Effect of Test Procedure

The procedure followed in the early part of a test appears to have a decisive influence on the results, particularly on the value of b. Note, for example, that in Figure 29 the value of b from test PT212 falls in among the multi-stage b values even though test PT212 was supposedly a single-stage test on a virgin sample. The test procedure for PT212 was different from that of PT202A, PT203 and PT204. In PT212 the applied pressure was slowly raised from 0 to 0.2 MPa. This was done to allow the operator to determine accurately the moment when the pressuremeter membrane

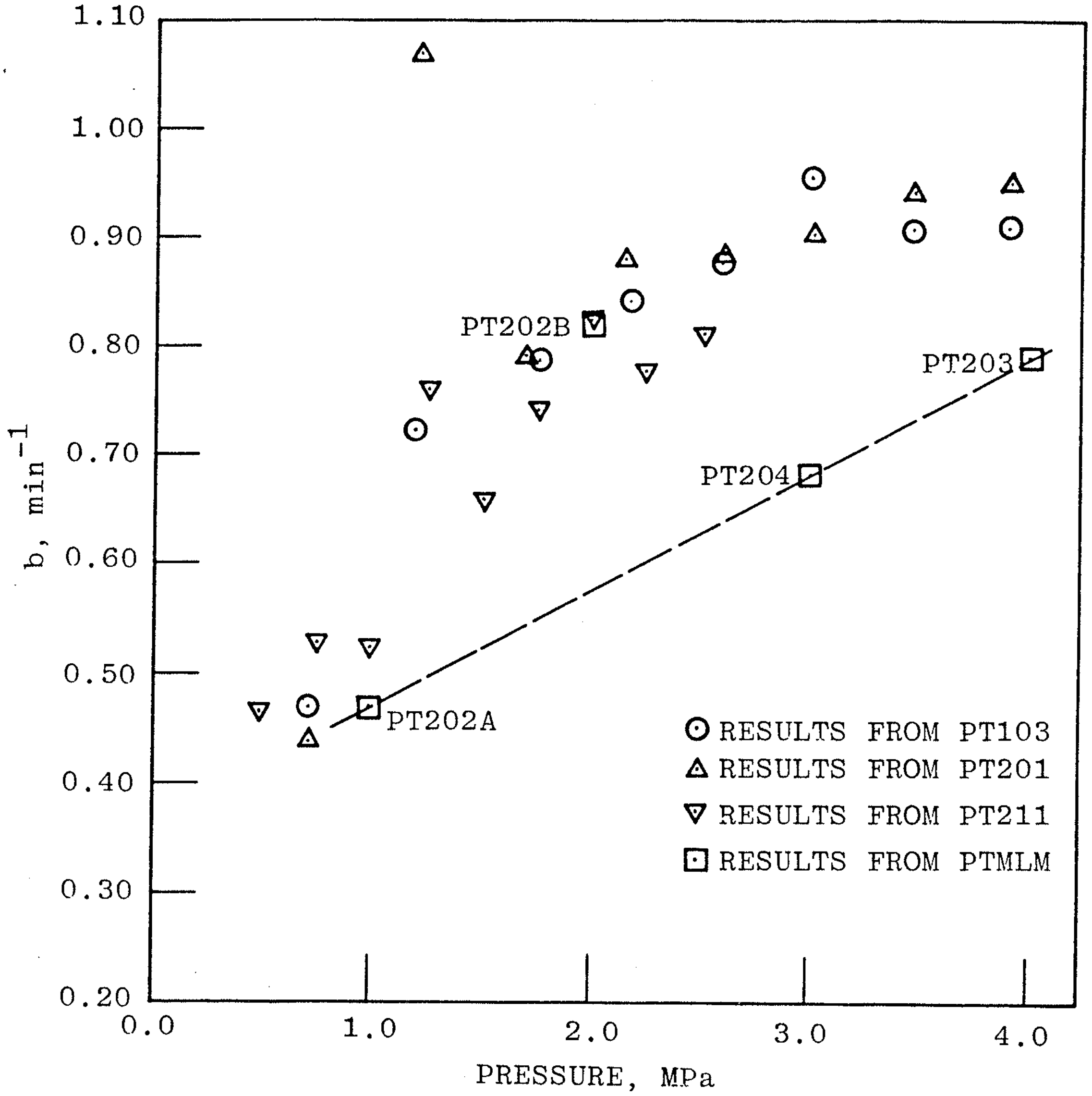


Figure 29: Plot of b vs. Pressure from All the Tests

reached full contact with the borehole wall of the specimen. At the point of contact the recorded radius would be the 'true' initial borehole radius and the time could be taken as time zero. It took approximately 4 minutes from the beginning of pressure application to reach full membrane contact. In all the other single-stage tests the pressure was increased instantaneously to the desired level and the readings of time were taken from that point on. It is speculated that the difference in the manner of pressure application and additional time taken in the early part of test PT212 caused the value of b to be higher than anticipated. It appears essential that a consistent test procedure be adhered to if pressuremeter tests in warm frozen soils are to give consistent results.

Effect of Varying the Instantaneous Strain Time

Analyses were also carried out to observe the effect on the creep parameters of varying the assumed instantaneous strain time. Take, for instance, test PT212. In previous analysis (see Appendix F.1) an assumed instantaneous time of 1 minute was used to determine the instantaneous strain; the instantaneous strain was subtracted from the total strain to determine $b = 0.82$ and $F = 2.90 \times 10^{-4}$. If the assumed instantaneous strain time interval were taken as 0.5 minutes, $b = 0.61$ and $F = 6.60 \times 10^{-4}$. Two things are observed: 1) not only does the new b value fall to among the lower b values in Figure 29 but 2) the value of F has increased. (There appears to be an inverse relationship between changes in b and F with instantaneous strain time). The value of F from test PT212 (as analyzed in Appendix F.1 and discussed in Section 5.3) can in fact be adjusted by varying the instantaneous strain time to make the fit line for obtaining the n parameter acceptable.

To further observe the above effect, data from tests PT202A, PT203 and PT204 were used to evaluate the creep parameters with 45 minute creep information. The assumed instantaneous strain time was varied from 0.0, 0.25, 0.5 and 1.0 minutes (corresponding to STP = 1, 2, 3 and 4). Table 9 shows the results from the above analyses. (Note that the analysis PTMLM in Section 5.3 is the same as the above analysis with STP = 4). The value of b was found to decrease with decreasing instantaneous strain time while F1 increased. It should be borne in mind that the correlation coefficient (R^2) for obtaining n slope has to be high (larger than 0.90) in order for the analysis to be acceptable.

Effect of Creep Time for Each Pressure

The effect on calculated creep parameters of varying the length of time creep information was recorded at each pressure was observed. In this case, creep information from tests PT202A, PT203 and PT204 was analyzed for 15, 30, 45, 60, 90, 120 minute creep intervals and also for the entire recorded length of test. (Again, note that the analysis

TABLE 9

Effect of Varying the Instantaneous Strain Time

Analysis using			b at pressure (MPa)			b vs. pressure		Determination of F1 and n			
Time (minute)	STS	STP	1.0	3.0	4.2	b = f(p)	R^2	F1	n	R^2	σ_c
45	1	1	0.307	0.571	0.760	$0.311\ p^{0.599}$	0.99	$1.426\text{x}10^{-3}$	0.747	0.92	166
45	1	2	0.378	0.594	0.695	$0.380\ p^{0.416}$	1.0	$8.720\text{x}10^{-4}$	1.157	0.99	18.2
45	1	3	0.512	0.663	0.747	$0.512\ p^{0.254}$	0.99	$4.829\text{x}10^{-4}$	1.439	0.99	4.6
45	1	4	0.469	0.681	0.788	$0.471\ p^{0.352}$	1.0	$4.848\text{x}10^{-4}$	1.321	0.99	8.2

PTMLM in Section 5.3 is the same as the above analysis using 45 minute creep information). In each case the assumed instantaneous strain time of 1 minute was used and the Modified Ladanyi method was employed to evaluate the creep parameters. The results from the above analyses are tabulated in Table 10 and indicate that creep parameters vary little with creep times of from 15 to 120 minutes.

The analysis using the entire recorded length of test shows that the correlation coefficient of the fit line for the creep information against time (which is represented by a power law, as shown in Figure 2) was high. The lowest correlation coefficient was found in PT212 ie. 0.9557. It can be argued that a power law can be used to represent the long-term behaviour of frozen sand (at least up to the 22 day period represented by test PT212).

TABLE 10

Effect of Varying Creep Time for Each Pressure

Analysis using			b at pressure (MPa)			b vs. pressure		Determination of F1 and n			
Time (minute)	STS	STP	1.0	3.0	4.2	b = f(p)	R^2	F1	n	R^2	σ_c (MPa)
15	1	4	0.408	0.711	0.792	$0.413\ p^{0.470}$	1.0	$5.204x10^{-4}$	1.252	1.0	15.5
30	1	4	0.417	0.690	0.791	$0.420\ p^{0.446}$	1.0	$5.156x10^{-4}$	1.266	0.99	14.1
45	1	4	0.469	0.681	0.788	$0.471\ p^{0.352}$	1.0	$4.848x10^{-4}$	1.321	0.99	8.2
60	1	4	0.476	0.672	0.784	$0.476\ p^{0.337}$	0.99	$4.814x10^{-4}$	1.335	0.99	7.7
90	1	4	0.476	0.662	0.781	$0.475\ p^{0.331}$	0.99	$4.825x10^{-4}$	1.343	0.99	7.6
120	1	4	0.476	0.652	0.782	$0.474\ p^{0.328}$	0.98	$4.842x10^{-4}$	1.347	0.99	7.6
ALL	1	4	0.281	0.583	0.784	$0.282\ p^{0.695}$	1.0	$7.559x10^{-4}$	1.061	0.96	81.6

Chapter VII

CONCLUSIONS AND RECOMMENDATIONS

7.1 CONCLUSIONS

A study of creep behaviour of frozen sand was carried out with a pressuremeter. Although the number of tests and available data are limited, some conclusions can be drawn based on the test results and their analyses.

1. The specimens prepared for this experimental study are reproducible.
2. The creep tests (PT202A, PT202B and PT212) in frozen sand samples show that at low pressures (2 MPa and less) the strain rate decreased with time.
3. A power law can be used to represent the long-term creep behaviour of frozen sand (at least up to the 22 day period represented by PT212).
4. Ladanyi's method based on a power law equation and multi-stage tests, in general, predicts higher than actual creep strain at a given pressure.
5. Calculated creep parameters using Ladanyi's method are test procedure sensitive. The results vary with the magnitude of the pressure increment at each stage of loading, the length of time which is assumed for

the instantaneous strain and the length of time that each stage of a multi-stage test is maintained.

6. The Modified Ladanyi method based on single-stage tests gives better predictions than does Ladanyi's method.

7.2 RECOMMENDATIONS FOR FUTURE RESEARCH

Based on the experience and the knowledge gained in this study, several suggestions for future studies on creep of frozen soil follow:

1. The wet pouring method is recommended for preparing sand/water specimens.
2. The use of automation in running a pressuremeter test in frozen soil is recommended. Measurements of soil temperatures, pressuremeter radius, the probe pressure, and the time at which readings are taken should be recorded by a data acquisition system at regular time intervals.
3. Additional multi-stage tests with a longer (than 45 minute) time interval per stage are suggested in order to observe the influence of stress redistribution time as discussed by Ladanyi and Eckardt (1983).
4. Additional multi-stage tests with various magnitudes of pressure increment are also suggested in order to study the effect that size of increment has on the creep parameters obtained using Ladanyi's method.

REFERENCES

Andersland, O.B., Sayles, F.H. and Ladanyi, B. 1978. Mechanical properties of frozen ground. Chapter 5 in "Geotechnical Engineering for Cold Regions", (O.B. Andersland and D. M. Anderson, Eds), pp. 216 - 275, McGraw-Hill, New York.

Baguelin, F., Jezequel, J.F. and Shields, D.H. 1978. The pressuremeter and foundation engineering. Trans Tech Publications, 1978.

Brand, E.W. 1973. Some observations on the control of density by vibration. Evaluation of Relative Density and Its Role in Geotechnical Projects Involving Cohesionless Soils, ASTM STP 523, Am. Soc. for Testing and Mats., pp. 121-132.

Briaud, J.-L. and Shields, D.H. 1981. Pressuremeter tests at very shallow depth. ASCE Geot. Eng. Div. Vol. 107, pp. 1023-1040.

Domaschuk, L. 1983. Mechanics of permafrost. (23-798 Course notes, University of Manitoba).

Eckardt, H. 1981. Laboratory borehole creep and relaxation tests in thick-wall cylinder samples of frozen sand. Report 222, Northern Engineering Centre, Ecole Polytechnique, Montreal, p. 125.

Gibson, R.E. and Anderson, W.F. 1961. In situ measurement of soil properties with the pressuremeter. Civ. Eng. Publ. Works Rev. (London), May, pp. 615-618.

Hughes, J.M.O., Wroth, C.P., and Windle, D. 1977. Pressuremeter tests in sands. Geotechnique 27, No. 4, pp. 455-477.

Hult, J.A.H. 1966. Creep in engineering structures. Blaisdell Publ. Co., Waltham, Massachusetts, 115 pages.

Jewell, R.J., Fahey, M. and Wroth, C.P. 1980. Laboratory studies of pressuremeter test in sand. Geotechnique 30, No. 4, pp. 507-531.

Johnston, G.H. 1981. Permafrost: Engineering design and construction. John Wiley and Sons, New York.

Kolbuszewski, J.J. and Jones, R.H. 1961. The preparation of sand samples for laboratory testings. Proc. Midl. Soil Mech. Fdn. Eng. Soc., 4.

Ladanyi, B. 1963. Evaluation of pressuremeter tests in granular soils. Proceedings of the Second Pan American Conference on Soil Mechanics and Foundation Engineering, Brasil, Vol. 1, pp. 3-20.

Ladanyi, B. 1963. Expansion of a cavity in a saturated clay medium. Journal of the Soil Mechanics and Foundation Division, Proceedings of the American Society of Civil Engineers, Vol. 89, No. SM4, Proc. Paper 3577, pp. 127-161.

Ladanyi, B. 1967. Discussion on "Plane strain tests on a saturated remolded clay", by D.J. Henkel and N.H. Wade. Proc. Am. Soc. Civ. Eng. 93, SM5, pp. 322-325.

Ladanyi, B. 1967. Expansion of cavities in brittle media. Int. Jour. Rock Mech. and Mining Sci., Vol. 4, No. 3, pp. 301-328.

Ladanyi, B. 1972. An engineering theory of creep of frozen soils. Canadian Geotechnical Journal, Vol. 9, No. 1, pp. 63-80.

Ladanyi, B. 1972. In situ determination of undrained stress-strain behaviour of sensitive clay with the pressuremeter. Canadian Geotechnical Journal, Vol. 9, No. 3, pp.313-319.

Ladanyi, B. 1975. Bearing capacity of strip footings in frozen soils. Canadian Geotechnical Journal, Vol. 12, No. 3, pp. 393-407.

Ladanyi, B. 1979. Borehole relaxation test as a means for determining the creep properties of ice covers. Proc. 5th POAC Conf., Trondheim, vol 1, pp.757 - 770.

Ladanyi, B. 1982. Borehole creep and relaxation tests in ice-rich permafrost, Proc 4th Canadian Permafrost Conference (The Roger J.E. Brown Memorial Volume), National Research Council of Canada, Ottawa, pp.406 - 415.

Ladanyi, B., Arteau, J. and Jessberger, H.L. (Editor). 1979. Effect of specimen shape on creep response of a frozen sand. Ground Freezing; Eng. Geol. (III), Vol. 13, No. 1-4, pp. 207-222.

Ladanyi, B., Barthelemy E. and Saint-Pierre, R. 1979. In situ determination of creep properties of ice covers by means of borehole creep and relaxation tests. Proc. Workshop on the Bearing Capacity of Ice Covers, Winnipeg NRCC-ACGR Tech. Memo., No. 123, pp. 44-64.

Ladanyi, B. and Eckardt, H. 1983. Dilatometer testing in thick cylinders of frozen sand. Permafrost: Proc 4th Int. Conference, Fairbanks, Alaska, Nat. Acad. Press, Wash. D. C., p 677 - 682.

Ladanyi, B. and Gill, D.E. 1981. Determination of creep parameters of rock salt by means of a borehole dilatometer. Proceedings, First Conf. on the Mech. Behaviour of Salt, Pennsylvania State University.

Ladanyi, B. and Gill, D.E. 1983. In-situ determination of creep properties of rock salt. International Congress of Rock Mechanics, Melbourne, Australia.

Ladanyi, B. and Johnston, G. H. 1973. Evaluation of in-situ creep properties of frozen soils with the pressuremeter. Proc. 2nd Int. Conf. on Permafrost, Yakutsk, North Amer. Contr. Vol 1, pp. 313 - 318.

Ladanyi, B. and Johnston, G.H. 1978. Field investigations in frozen ground. Chapter 9 in "Geotech. Eng. for Cold Regions" (O.B. Andersland and D. M. Anderson, Eds), pp. 459 - 504, McGraw-Hill, New York.

Ladanyi, B., Murat, J.R. and Huneault, P. 1984. A parametric study of long-term borehole dilatometer tests in ice. IAHR Ice Symposium 1984, Hamburg.

Ladanyi, B. and Saint-Pierre, R. 1978. Evaluation of creep properties of sea ice by means of a borehole dilatometer. Proc., IAHR Symp. on Ice Problems, Lulea, Sweden, Part 1, pp. 97-115.

Man, C.-S. 1983. Solution to the pressuremeter problem for the creeping flow of several incompressible nonlinear materials. University of Manitoba Geotechnical Engineering Seminar Series.

Man, C.-S., Shields, D.H., Kjartanson, B. and Sun, Q.X. 1985. Creep of ice as a fluid of complexity 2: The pressuremeter problem. Proceedings of the Tenth Canadian Congress of Applied Mechanics, University of Western Ontario, June, pp. A347-A348.

Odquist, F.K.G. 1966. Mathematical theory of creep and creep rupture. Oxford Math Monographs, Clarendon Press, Oxford.

Ohya, S. 1982. Modification of the ELASTMETER-100 to apply in more soft or loose soil ground. A report prepared for the OYO Corporation, August.

Ohya, S. and Morita, K. 1982. Application of a pressuremeter "ELASTMETER-100" for the foundation engineering study of the Interfirst Plaza construction site in San Antonio, Texas. A report prepared for the OYO Corporation, June.

Sayles, F.H. 1973. Triaxial and creep tests on frozen Ottawa sand. N.A. Contribution to 2nd Int. Conf. on Permafrost, pp. 383-391.

Shields, D.H., Domaschuk, L., Fensury, H. and Kenyon, R.M. 1985. The deformation properties of warm underocean permafrost. National Conference on Civil Engineering in Arctic Offshore, San Francisco.

Shields, D.H., Domaschuk, L., Man, C.-S. and Kenyon, R.M. 1984. The deformation properties of warm permafrost as measured both in situ and in the laboratory, to appear in ASTM Symposium on Lab and In Situ Strength Testing of Marine Soils.

Vialov, S.S. 1963. Rheology of frozen soils. Proc. NAS-NRC, Int. Permafrost Conf., Purdue Univ., Lafayette, Indiana, pp. 332-339.

Vialov, S.S. 1965. Rheological properties and bearing capacity of frozen soils. Transl. 74, U.S. Army CRREL, Hanover, N.H.

Yong, E.O.F. 1983. Creep behaviour of frozen saline silt under isotropic compression. (M. Sc. Thesis, University of Manitoba).

Appendix A

DESCRIPTION OF SAND

An average specific gravity of 2.70 was obtained for the sand using ASTM D854-58 method. (Data was supplied by R. Kenyon).

The maximum and minimum dry densities of the sand, obtained by the ASTM standard method, were 1650 and 1450 kg/m^3, respectively.

An average dry density of 1450 kg/m^3 and an ice content of 26% were obtained from all the frozen samples prepared using the dry pouring method.

'Model' tests in saturated loose sand when unfrozen, prepared using the wet pouring method, gave an average dry density of 1470 kg/m^3 and an average water content of 30%.

An average dry density of 1470 kg/m^3 and an ice content of 26% were obtained from all the frozen samples prepared using the wet pouring method.

A typical grain size distribution curve is shown in Figure A.1, having 94% between 0.1 and 1.0 mm, with less than 4% below 0.1 mm and less than 1% above 2.0 mm, and a coefficient of uniformity of about 2.0.

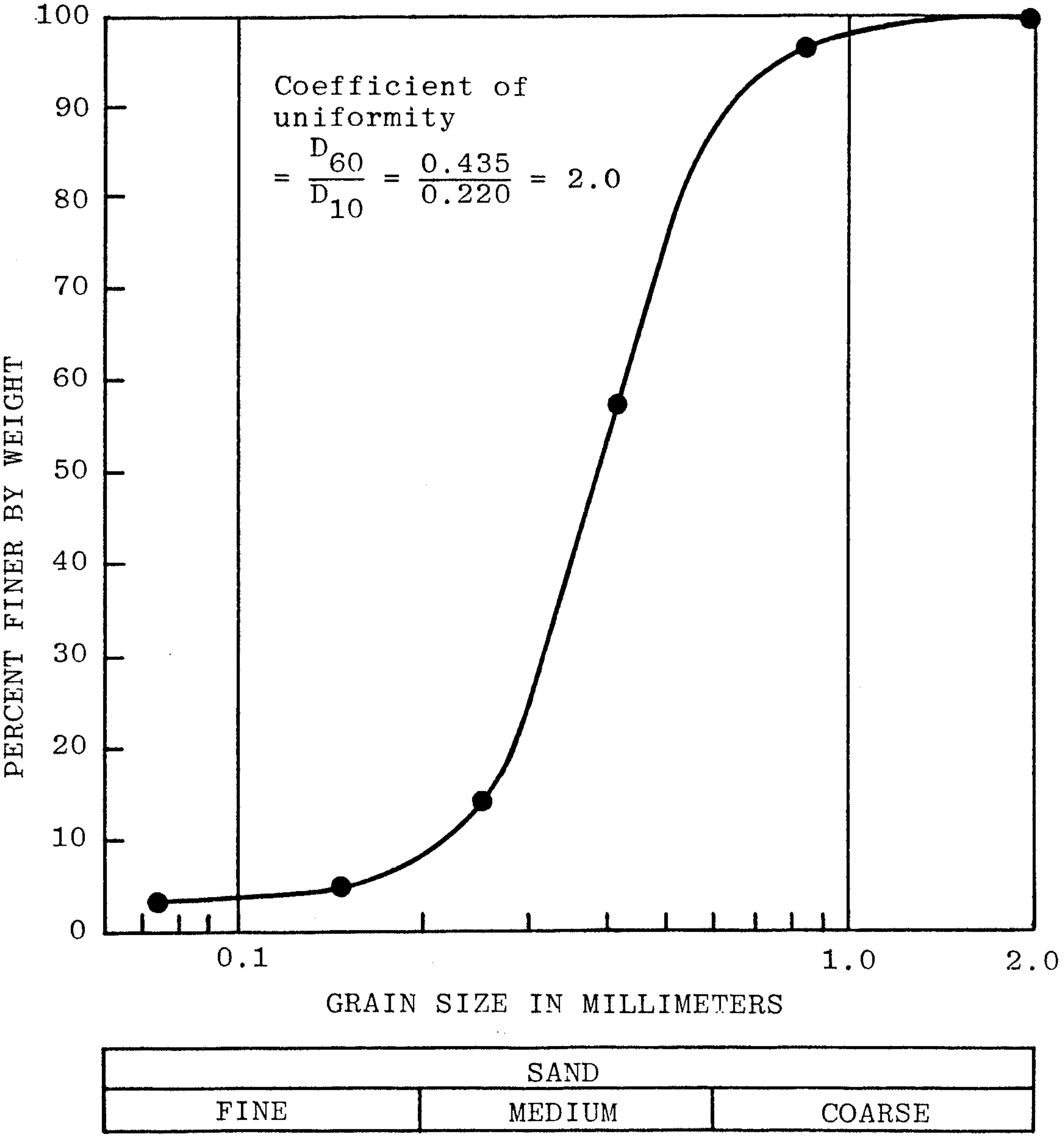


Figure A.1: Typical Grain Size Distribution Curve

Appendix B

VARIATION OF TEMPERATURES IN A FROZEN SAND SPECIMEN

A typical variation of recorded temperatures in a specimen during freezing process is presented below. The temperature profile across specimen PT212 was used and shown in Figure B.1. Time t is the duration from the time the temperature in the environmental chamber reached -20°C.

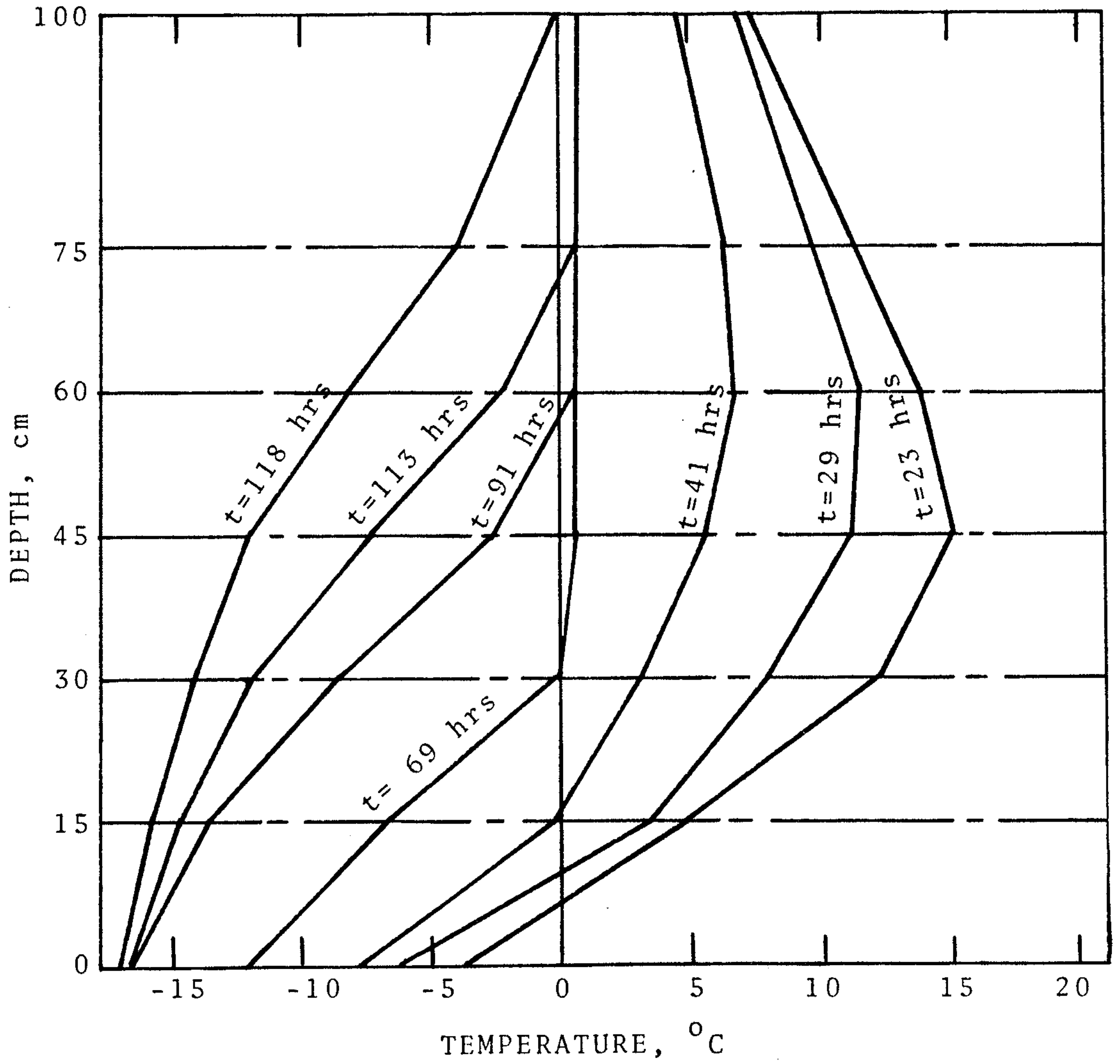


Figure B.1: Typical Variation of Recorded Temperatures in a Specimen

Appendix C

CHECKING AND CALIBRATING THE PRESSUREMETER

A typical checking and calibration of the pressuremeter prior to the actual test is presented below. The data from test PT201 was used. All the checking and calibration were carried out in the chamber at test temperature of -3°C.

C.1 CHECKING FOR ELECTRONIC DRIFT

The membrane of the pressuremeter was detached and a standard calibration ring was inserted around the pressuremeter probe. With this setup the radius reading (RN) from the electronic digital indicator should stay at a fixed reading if there was no drift. The radius readings were then recorded over time and are given below:

Date	Time	RN
28/09/83	13:25	10.36
28/09/83	15:00	10.37
28/09/83	21:00	10.36
29/09/83	10:00	10.36
29/09/83	13:30	10.36

The data showed insignificant electronic drift.

C.2 CALIBRATION FOR MEMBRANE THICKNESS CHANGE

This calibration was performed in a steel tube with known inner radius. The pressuremeter was placed inside the steel tube and a constant pressure was applied to the membrane while changes in RN with time were recorded. At the end of a specified time interval, the pressure was increased to another level and held constant while RN readings were recorded. It was found that after 5 minutes of pressure application the changes in RN were insignificant. Therefore in this calibration the changes in RN (PG) versus pressure were taken from changes in RN at the end of 5 minute interval. The recorded data is given below.

Pressure (MPa)	RN (mm) at time (min.) 0	1.0	3.0	5.0	PG (mm)
0.5	4.99	5.01	5.01	5.01	0.02
1.0	5.01	5.04	5.04	5.04	0.05
1.5	5.04	5.06	5.06	5.06	0.07
2.0	5.06	5.08	5.08	5.08	0.09
2.5	5.08	5.10	5.10	5.10	0.11
3.0	5.10	5.11	5.11	5.12	0.13

From the above data a correlation between PG and applied pressure PA can be obtained:

$$PG = 0.002 + 0.044\ PA; \text{ with } R^2 = 1.0$$

where PG is in mm and PA is in MPa.

C.3 CALCULATION OF CROSS-SECTIONAL AREA (A/PI)

This calculation was obtained by inflating the pressuremeter membrane in different steel tubes with known inner radii. When the membrane and the steel tube were in full contact, the outside radius of the membrane was equal to the inner radius of the steel tube; while the inside radius of the membrane of the membrane was calculated from RN reading. Knowing both the inside and outside radii, the cross-sectional area of the membrane was obtained. However, it was found that the cross-sectional area of the membrane varied with different size of steel tubes. It was decided to express the variation of cross-sectional area of the membrane for test PT201 in the form:

$$A/PI = 747.2 + 5.84\ RN$$

where A is in mm^2, PI = 3.1416 and RN is in mm.

C.4 CALIBRATION FOR MEMBRANE RESISTANCE IN AIR

In order to determine the net pressure the pressuremeter applied to a specimen it was necessary to first determine the resistance of the membrane as it was being inflated. A calibration test was carried out to simulate the movement of the membrane in an actual test except that the membrane was inflated in air instead of a confined boundary. A low incremental pressure (0.2 MPa) was applied to the membrane; each pressure was held constant for 45 minutes. The variation of pressure with RN at the end of each pressure increment was used to express the membrane resistance. For test PT201 this variation is given in the form:

RG = 0.076 x RN**0.78

where RG is in MPa and RN is in mm.

Appendix D

LADANYI'S METHOD

D.1 LISTING AND INPUT INFORMATION OF LADFOH/S

The input information for programs LADFOH and LADFOS will be described below.

All data uses free format input. Input should be in either integer, real or alphanumeric forms as required. Data present on one line should be separated by a space and should always be within 80 columns.

The order of input information is as the following:

format

1) TITLE — alphanumeric

   Title of the test of up to 80 characters.

2) NS STS — integer

   NS: Number of stages in the multi-stage creep test.

   STS: Desired starting stage.

3) NP STP — integer

   NP: Number of points in each stage.

   STP: Assumed starting point or end of the instantaneous strain, eg. when STP=4 the instantaneous strain time is 1 minute.

4) MT1 MT2 — real

   Constants for membrane thickness correction in PG=MT1+MT2xPA where PG is in mm and PA is in MPa.

5)	A1 A2	real
	Constants for AREA/PI value in A/PI=A1+A2xRN.	
6)	MR1 MR2	real
	Constants for membrane reaction correction in: RG=MR1xRN**MR2 for LADFOH program; RG=MR1+MR2xln(RN) for LADFOS program.	
7)	PA(I),I=1,NS	real
	PA: Applied pressure in each stage.	
8)	T(J),J=1,NP	real
	T: Times for recording data.	
9)	(RN(I,J),J=1,NP),I=1,NS	real
	RN: Readings from the OYO electronic readout box, including reading at time=0. For the last stage, input RN=50.0 for the rest of the unrecorded intervals.	

LISTING OF PROGRAM LADFOH

```
//username JOB ',,T=2','username'
// EXEC FORT7CLG
//FORT.SYSIN DD *
C*************************************************************
C
C PROGRAM: LADFOH - LADANYI'S METHOD; FORTRAN; OYO HARD MEMBRANE
C
C THIS PROGRAM READS IN AND EVALUATE OYO DATA, USING LADANYI'S
C METHOD FOR DETERMINING THE CREEP PARAMETERS OF A FROZEN SOIL
C
C*************************************************************
C VARIABLES USED ARE:
C NS = NO. OF STAGES IN THE TEST
C STS = DESIRED STARTING STAGE
C NP = NO. OF DATA POINTS IN EACH STAGE
C STP = THE ASSUMED STARTING POINT OF CREEP STRAIN
C T = TIME IN EACH STAGE
C DT = TIME MINUS ASSUMED INSTANTANEOUS STRAIN TIME
C RN = READING FROM ELECTRONIC BOX
C PA = APPLIED PRESSURE
C PRESSURE,PIAVG = AVERAGE CORRECTED INTERNAL PRESSURE
C RG = MEMBRANE RESISTANCE IN AIR
C PG = MEMBRANE THICKNESS CORRECTION (MM)
C MT1,MT2,MR1,MR2 = PRESSUREMETER CALIBRATION CONSTANTS
C                 MT1,MT2 IN: PG=MT1+MT2*PA
C                 MR1,MR2 IN: RG=MR1*RN**MR2
C PI = CORRECTED PRESSURE OR NET PRESSURE ON THE SPECIMEN
C PSUM = CURRENT SUMMATION OF PI FOR PIAVG CALCULATION
C I,J,K,L,COUNT = COUNTERS FOR EACH LOOP
C TITLE = TITLE OF THE TEST OF UP TO 80 CHARACTERS
C LNR = VALUE OF LN(R/R(I))
C LOGLNR = LOG(LNR)
C PGFST = FIRST VALUE OF PG IN EACH STAGE
C PGREST = PG VALUES AT CURRENT STAGE OTHER THAN PGFST
C*************************************************************
      REAL*8 T(50),RN(50,50),PA(50),STR(50,50),RO(50,50),LNR(50,50)
      REAL*8 RATE(50,50)
      REAL*8 RG,PI(50),PSUM,PIAVG,DELTAR,TSTART,RSTART,SOPI,MT1,MT2
      REAL*8 MR1,MR2,LOGT,LOGLNR,PG,PGFST,PGREST,RI,DT(50)
      INTEGER NS,NP,I,J,K,L,COUNT,STP,STS
      CHARACTER*80 TITLE
C*************************************************************
C TO READ IN NO. OF STAGES, DESIRED STARTING STAGE, NO. OF DATA
C POINTS IN EACH STAGE, PRESSUREMETER CALIBRATION CONSTANTS AND
C RN VALUES FROM THE TEST.
C*************************************************************
      PRINT '(//)'
      READ '(A)',TITLE
      PRINT '(1X,A)',TITLE
      PRINT* ,' '
      READ* ,NS,STS
      PRINT '(1X,A,I4)','NUMBER OF STAGES =',NS
      PRINT '(1X,A,I2)','DESIRED STARTING STAGE =',STS
      READ* ,NP,STP
      PRINT '(1X,A,I3)','NUMBER OF DATA POINTS IN EACH STAGE =',NP
      PRINT '(1X,2A,I2)','ASSUMED STARTING POINT OF CREEP STRAIN ',
     +'(STP) = ',STP
      PRINT* ,' '
      READ* ,MT1,MT2
      PRINT '(1X,A,F6.3,A,F6.3,A)','THICKNESS CORRECTION CONSTANTS ARE:
     +MT1 =',MT1,' AND MT2 =',MT2,' IN PG=MT1+MT2*PA'
      READ* ,A1,A2
      PRINT '(1X,A,F7.2,A,F7.2,A)','CONSTANTS FOR A/PI ARE:
     +A1 =',A1,' AND A2 =',A2,' IN A/PI=A1+A2*RN (MM2)'
```

```
      READ* ,MR1,MR2
      PRINT '(1X,A,F6.2,A,F6.2,A)','MEMBRANE REACTION CONSTANTS ARE:
     +MR1 =',MR1,' AND MR2 =',MR2,' IN RG=MR1+MR2*LN(RN)'
      PRINT* ,' '
      READ* ,(PA(I),I=1,NS)
      PRINT* ,'APPLIED PRESSURE IN EACH STAGE IN MPA :'
      PRINT '(5X,F7.2)',(PA(I),I=1,NS)
      PRINT '(/)'
      READ* ,(T(J),J=1,NP)
      PRINT* ,'TIME (MINUTES) FOR TAKING DATA IN EACH STAGE :'
      PRINT '(5X,F7.2)',(T(J),J=1,NP)
      PRINT '(/)'
      READ* ,((RN(K,L),L=1,NP),K=1,NS)
C
C TO CALCULATE INITIAL PG AT STAGE STS
C
      PG=MT1+MT2*PA(STS)
      IF (PG .LE. 0.0) THEN
         PG=0.0
      END IF
C***************************************************
C CALCULATE ALL THE VALUES FOR EACH STAGE AND PRINT
C***************************************************
      DO 120 K=STS,NS
      PRINT '(1X,A,I3,A,F7.2,A)',' STAGE NO.',K,'  ;   APPLIED PRESSURE
     + =',PA(K),' MPA'
      PRINT* ,' '
      PRINT* ,' TIME    RN     RG     PI      PG    RO   STRAIN',
     +'    RATE       LNR'
      PRINT* ,' (MIN)  (MM)   (MPA)  (MPA)   (MM)  (MM)   (%)  ',
     +'  (%/MIN)'
      PRINT* ,' '
         PGFST = PG
C
C CALCULATE ALL PG VALUES EXCEPT FOR THE FIRST PG
C
         PGREST=MT1+MT2*PA(K)
         IF (PGREST .LE. 0.0) THEN
            PGREST=0.0
         END IF
C
C CHECK PG AGAINST THE FIRST PG
C
         IF (STP .EQ. 1) THEN
            PG = PGFST
         ELSE
            PG = PGREST
         ENDIF
C
C CALCULATE RO AT POINT STP AND ASSIGN T AT POINT STP
C
         RI=RN(K,STP)+23.5
         RS=RI-PG
         SOPI=A1+A2*RN(K,STP)
         RSTART=SQRT(RS**2+SOPI)
         TSTART=T(STP)
         PSUM=0.0
         COUNT = 0
         DO 100 L=1,NP
          IF (RN(K,L) .EQ. 50.0) GOTO 100
           COUNT = COUNT + 1
           IF (L .EQ. 1 ) THEN
              PG=PGFST
           ELSE
```

```
              PG=PGREST
           END IF
           RG=MR1*RN(K,L)**MR2
           PI(L)=(PA(K)-RG)
           PSUM=PSUM+PI(L)
           RI=RN(K,L)+23.5
           RS=RI-PG
           SOPI=A1+A2*RN(K,L)
           RO(K,L)=SQRT(RS**2+SOPI)
           DELTAR=RO(K,L)-RSTART
           STR(K,L)=(DELTAR/RO(K,1))*100.0
           IF (L .EQ.1) THEN
              RATE(K,L)=0.0
           ELSE
              RATE(K,L)=(STR(K,L)-STR(K,L-1))/(T(L)-T(L-1))
           END IF
           LNR(K,L)=DLOG(1.0+DELTAR/RO(K,1))
           DT(L)=T(COUNT)-TSTART
           PRINT '(1X,7F7.2,2E11.3)', DT(L),RN(K,L),RG,PI(L),PG,
     +     RO(K,L),STR(K,L),RATE(K,L),LNR(K,L)
 100     CONTINUE
        PIAVG=PSUM/COUNT
        PRINT* ,' '
        PRINT '(1X,A,F5.2,A)',' AVERAGE PRESSURE ON SPECIMEN =',
     +  PIAVG,' MPA'
        PRINT '(/)'
C******************************************************************
C WRITE THE RESULTS TO DATA SET USERNAME.SAS.LAD FOR LADPL PROGRAM
C******************************************************************
        DO 110 L = STP,COUNT
          IF ((DT(L) .LE. 0.0) .OR. (LNR(K,L) .LE. 0.0)) GOTO 110
            LOGT = DLOG10(DT(L))
            LOGLNR = DLOG10(LNR(K,L))
           WRITE(4,*) DT(L),LOGT,PI(L),PIAVG,STR(K,L),RATE(K,L),
     +     LNR(K,L),LOGLNR
 110    CONTINUE
 120    CONTINUE
      STOP
      END
/*
//GO.FT04F001  DD DSN=username.SAS.LAD,
//             DCB=(RECFM=VB,BLKSIZE=255),
//             SPACE=(TRK,(5,1)),
//             DISP=(NEW,CATLG,DELETE),
//             UNIT=DISK,VOL=SER=WEEK01
//GO.SYSIN DD *


input data


/*
```

LISTING OF PROGRAM LADFOS

```
//username JOB ',,T=2','username'
// EXEC FORT7CLG
//FORT.SYSIN DD *
C****************************************************************
C
C PROGRAM: LADFOS - LADANYI'S METHOD; FORTRAN; OYO SOFT MEMBRANE
C
C THIS PROGRAM READS IN AND EVALUATE OYO DATA, USING LADANYI'S
C METHOD FOR DETERMINING THE CREEP PARAMETERS OF A FROZEN SOIL
C
C****************************************************************
C VARIABLES USED ARE:
C NS = NO. OF STAGES IN THE TEST
C STS = DESIRED STARTING STAGE
C NP = NO. OF DATA POINTS IN EACH STAGE
C STP = THE ASSUMED STARTING POINT OF CREEP STRAIN
C T = TIME IN EACH STAGE
C RN = READING FROM ELECTRONIC BOX
C PA = APPLIED PRESSURE
C PRESSURE,PIAVG = AVERAGE CORRECTED INTERNAL PRESSURE
C RG = MEMBRANE RESISTANCE IN AIR
C PG = MEMBRANE THICKNESS CORRECTION (MM)
C MT1,MT2,MR1,MR2 = PRESSUREMETER CALIBRATION CONSTANTS
C                MT1,MT2 IN: PG=MT1+MT2*PA
C                MR1,MR2 IN: RG=MR1+MR2*LN(RN)
C PI = CORRECTED PRESSURE OR NET PRESSURE ON THE SPECIMEN
C PSUM = CURRENT SUMMATION OF PI FOR PIAVG CALCULATION
C I,J,K,L,COUNT = COUNTERS FOR EACH LOOP
C TITLE = TITLE OF THE TEST OF UP TO 80 CHARACTERS
C LNR = VALUE OF LN(R/R(I))
C LOGLNR = LOG(LNR)
C PGFST = FIRST VALUE OF PG IN EACH STAGE
C PGREST = PG VALUES AT CURRENT STAGE OTHER THAN PGFST
C AOPI = CROSS SECTIONAL AREA OF THE MEMBRANE OVER PI
C****************************************************************
      REAL*8 T(50),RN(50,50),PA(50),STR(50,50),RO(50,50),LNR(50,50)
      REAL*8 RATE(50,50)
      REAL*8 RG,PI(50),PSUM,PIAVG,DELTAR,TSTART,RSTART,AOPI,MT1,MT2
      REAL*8 MR1,MR2,LOGT,LOGLNR,PG,PGFST,PGREST,RI,DT(50)
      INTEGER NS,NP,I,J,K,L,COUNT,STP,STS
      CHARACTER*80 TITLE
C****************************************************************
C TO READ IN NO. OF STAGES, DESIRED STARTING STAGE, NO. OF DATA
C POINTS IN EACH STAGE, PRESSUREMETER CALIBRATION CONSTANTS AND
C RN VALUES FROM THE TEST.
C****************************************************************
      PRINT '(//)'
      READ '(A)',TITLE
      PRINT '(1X,A)',TITLE
      PRINT* ,' '
      READ* ,NS,STS
      PRINT '(1X,A,I4)','NUMBER OF PRESSURE INCREMENTS =',NS
      PRINT '(1X,A,I2)','DESIRED STARTING STAGE =',STS
      READ* ,NP,STP
      PRINT '(1X,A,I3)','NUMBER OF DATA POINTS IN EACH STAGE =',NP
      PRINT '(1X,A,I2)','ASSUMED STARTING POINT OF CREEP STRAIN =',STP
      PRINT* ,' '
      READ* ,MT1,MT2
      PRINT '(1X,A,F6.3,A,F6.3,A)','THICKNESS CORRECTION CONSTANTS ARE:
     +MT1 =',MT1,' AND MT2 =',MT2,' IN PG=MT1+MT2*PA'
      READ* ,A1,A2
      PRINT '(1X,A,F7.2,A,F7.2,A)','CONSTANTS FOR A/PI ARE:
     +A1 =',A1,' AND A2 =',A2,' IN A/PI=A1+A2*RN (MM2)'
      READ* ,MR1,MR2
```

```
      PRINT '(1X,A,F6.2,A,F6.2,A)','MEMBRANE REACTION CONSTANTS ARE:
     +MR1 =',MR1,' AND MR2 =',MR2,' IN RG=MR1+MR2*LN(RN)'
      PRINT* ,' '
      READ* ,(PA(I),I=1,NS)
      PRINT* ,'APPLIED PRESSURE IN EACH STAGE IN MPA :'
      PRINT '(5X,F7.2)',(PA(I),I=1,NS)
      PRINT '(/)'
      READ* ,(T(J),J=1,NP)
      PRINT* ,'TIME (MINUTES) FOR TAKING DATA IN EACH STAGE :'
      PRINT '(5X,F7.2)',(T(J),J=1,NP)
      PRINT '(/)'
      READ* ,((RN(K,L),L=1,NP),K=1,NS)
C
C TO CALCULATE INITIAL PG AT STAGE STS
C
      PG=MT1+MT2*PA(STS)
      IF (PG .LE. 0.0) THEN
         PG=0.0
      END IF
C*****************************************************************
C CALCULATE ALL THE VALUES FOR EACH STAGE AND PRINT
C*****************************************************************
      DO 120 K=STS,NS
      PRINT '(1X,A,I3,A,F7.2,A)','  STAGE NO.',K,'  ;   APPLIED PRESSURE
     + =',PA(K),' MPA'
      PRINT* ,' '
      PRINT* ,'  TIME    RN     RG     PI     PG    RO   STRAIN',
     +'    RATE      LNR'
      PRINT* ,'  (MIN)  (MM)   (MPA)  (MPA)   (MM)  (MM)    (%)   ',
     +'  (%/MIN)'
      PRINT* ,' '
         PGFST = PG
C
C CALCULATE ALL PG VALUES EXCEPT FOR THE FIRST PG
C
         PGREST=MT1+MT2*PA(K)
         IF (PGREST .LE. 0.0) THEN
            PGREST=0.0
         END IF
C
C CHECK PG AGAINST THE FIRST PG
C
         IF (STP .EQ. 1) THEN
            PG = PGFST
         ELSE
            PG = PGREST
         ENDIF
C
C CALCULATE RO AT POINT STP AND ASSIGN T AT POINT STP
C
         X=0.50819*RN(K,STP)+5.8333
         RI=2.0*X + 6*SQRT(1.0-((X/25.0)**2)) + 16.0
         RS=RI-PG
         AOPI=A1+A2*RN(K,STP)
         RSTART=SQRT(RS**2+AOPI)
         TSTART=T(STP)
         PSUM=0.0
         COUNT = 0
         DO 100 L=1,NP
          IF (RN(K,L) .EQ. 50.0) GOTO 100
           COUNT = COUNT + 1
           IF (L .EQ. 1 ) THEN
              PG=PGFST
           ELSE
```

```
              PG=PGREST
           END IF
           IF (K .EQ. 1 .AND. L .EQ. 1) THEN
              PG=0.0
           END IF
           RG=MR1+MR2*DLOG(RN(K,L))
           PI(L)=(PA(K)-RG)
           PSUM=PSUM+PI(L)
           X=0.50819*RN(K,L)+5.8333
           RI=2.0*X + 6*SQRT(1.0-((X/25.0)**2)) + 16.0
           RS=RI-PG
           AOPI=A1+A2*RN(K,L)
           RO(K,L)=SQRT(RS**2+AOPI)
           DELTAR=RO(K,L)-RSTART
           STR(K,L)=(DELTAR/RO(K,1))*100.0
           IF (L .EQ.1) THEN
              RATE(K,L)=0.0
           ELSE
              RATE(K,L)=(STR(K,L)-STR(K,L-1))/(T(L)-T(L-1))
           END IF
           LNR(K,L)=DLOG(1.0+DELTAR/RO(K,1))
           DT(L)=T(COUNT)-TSTART
           PRINT '(1X,7F7.2,2E11.3)', DT(L),RN(K,L),RG,PI(L),PG,
     +     RO(K,L),STR(K,L),RATE(K,L),LNR(K,L)
 100     CONTINUE
        PIAVG=PSUM/COUNT
        PRINT* ,' '
        PRINT '(1X,A,F5.2,A)','  AVERAGE PRESSURE ON SOIL =',PIAVG,
     +  ' MPA'
        PRINT '(/)'
C******************************************************************
C WRITE THE RESULTS TO DATA SET USERNAME.SAS.LAD FOR LADPL PROGRAM
C******************************************************************
        DO 110 L = STP,COUNT
          IF ((DT(L) .LE. 0.0) .OR. (LNR(K,L) .LE. 0.0)) GOTO 110
            LOGT = DLOG10(DT(L))
            LOGLNR = DLOG10(LNR(K,L))
           WRITE(4,*) DT(L),LOGT,PI(L),PIAVG,STR(K,L),RATE(K,L),
     +     LNR(K,L),LOGLNR
 110    CONTINUE
 120    CONTINUE
      STOP
      END
/*
//GO.FT04F001   DD DSN=username.SAS.LAD,
//              DCB=(RECFM=VB,BLKSIZE=255),
//              SPACE=(TRK,(5,1)),
//              DISP=(NEW,CATLG,DELETE),
//              UNIT=DISK,VOL=SER=WEEK01
//GO.SYSIN DD *


input data


/*
```

INPUT INFORMATION FROM TEST PT201

```
 10. PT201: MULTI-STAGE PRESSUREMETER TEST IN FROZEN SAND; TEMP= -2.9 C.
 20. 8 1
 30. 18 4
 40. 0.002 0.044
 50. 747.2 5.84
 60. 0.076 0.78
 70. 1.00 1.50 2.00 2.50 3.00  3.50 4.00 4.50
 80. 0.0 0.25 0.5 1.0 2.0 3.0 5.0 7.0 9.0 11.0 13.0 15.0 20.0 25.0
 90. 30.0 35.0 40.0 45.0
100. 4.37 4.41 4.47 4.51 4.56 4.59 4.61 4.63 4.65 4.66 4.67 4.69
110. 4.70 4.75 4.75 4.75 4.77 4.80
120. 4.80 4.84 4.84 4.84 4.85 4.85 4.87 4.89 4.91 4.93 4.96 4.98
130. 5.03 5.07 5.11 5.15 5.20 5.21
140. 5.21 5.24 5.25 5.27 5.31 5.34 5.39 5.44 5.48 5.53 5.56 5.59
150. 5.69 5.77 5.85 5.93 6.00 6.07
160. 6.07 6.11 6.12 6.13 6.17 6.21 6.29 6.36 6.42 6.48 6.54 6.59
170. 6.73 6.84 6.96 7.09 7.20 7.34
180. 7.34 7.39 7.41 7.44 7.49 7.53 7.60 7.67 7.73 7.79 7.85 7.91
190. 8.06 8.26 8.39 8.55 8.69 8.84
200. 8.84 8.87 8.89 8.92 8.98 9.04 9.15 9.24 9.36 9.45 9.54 9.64
210. 9.85 10.09 10.27 10.39 10.60 10.79
220. 10.79 10.83 10.86 10.90 10.97 11.02 11.13 11.27 11.39 11.50
230. 11.62 11.73 12.00 12.26 12.50 12.76 12.93 13.18
240. 13.18 13.23 13.26 13.30 13.38 13.46 13.61 13.76 13.90 14.05
250. 14.18 14.33 14.66 14.99 15.26 50.00 50.00 50.00
```

D.2 LISTING OF LADPL PROGRAM

LISTING OF PROGRAM LADPL

```
//username  JOB  ',,T=30,I=90','username'
//       EXEC SASPLOT
//SASDATA DD  DSN=username.SAS.LAD,DISP=SHR
//SYSIN   DD *
****************************************************************
* PROGRAM: LADPL
*     INPUT THE DATASET (SAS.LAD) CREATED IN LADFOH/S
*     PROCESS IT USING LADANYI'S METHOD FOR OBTAINING THE CREEP
*     PARAMETERS OF A FROZEN SOIL, AND PLOT
*
* VARIABLES USED ARE:
*     TIME = TIME DIFFERENCE OR DT(I)
*     LNR = LN(R-R(I))
*     PI = PRESSURE ON THE SAMPLE AT TIME T (DURING THE TEST)
*     PRESSURE = AVERAGE PRESSURE ON THE SAMPLE
*     STRAIN = CIRCUMFERENTIAL STRAIN IN %
*     RATE = STRAIN RATE IN %/MIN
*     IN REGRESSION: LOG(LN(R/R(I-1)) VS LOG(TIME)
*        LOGLNR = LOG(LN(R/R(I-1))
*        LOGTIME = LOG(TIME)
*        BSLOPE = SLOPE OF THE REGRESSION LINE AT EACH PRESSURE
*                 LEVEL
*        FVALUE = INTERCEPT AT Y-AXIS AT EACH PRESSURE LEVEL
*     IN REGRESSION: LOG(FVALUE) VS LOG(PRESSURE)
*        LOGF = LOG(FVALUE)
*        LOGPI = LOG(PI)
*        NSLOPE = SLOPE OF THE REGRESSION LINE
*        F1 = INTERCEPT AT Y-AXIS
****************************************************************;
GOPTIONS DEVICE=XEROX ROTATE HSIZE=10.75 VSIZE=8.25
         COLORS=(BLACK,RED,BLUE,GREEN);
DATA ALL;
INFILE SASDATA;
INPUT TIME LOGTIME PI PRESSURE STRAIN RATE LNR LOGLNR;
PROC SORT DATA=ALL;
 BY PRESSURE;
PROC PRINT;
    TITLE 'DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S';
RUN;
PROC REG OUTEST=EST;
 MODEL LOGLNR = LOGTIME;
 BY PRESSURE;
    TITLE 'ESTIMATES FROM LINEAR REG. ANAL. OF LOGLNR VS LOGTIME';
RUN;
DATA FDATA;
   SET EST;
   FVALUE = 10.0 ** INTERCEP;
   BSLOPE = LOGTIME;
   RENAME INTERCEP = LOGF;
   LOGPI = LOG10(PRESSURE);
PROC PRINT DATA=FDATA;
    TITLE 'SUMMARY OF CREEP PARAMETERS B AND F';
RUN;
PROC REG DATA=FDATA OUTEST=EST2;
 MODEL LOGF = LOGPI;
    TITLE 'ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI';
RUN;
DATA NDATA;
 SET EST2;
 F1 = 10.0 ** INTERCEP;
 RENAME LOGPI = NSLOPE;
 RENAME INTERCEP = LOGF1;
PROC PRINT DATA = NDATA;
    TITLE 'SUMMARY OF CREEP PARAMETERS F1 AND N';
```

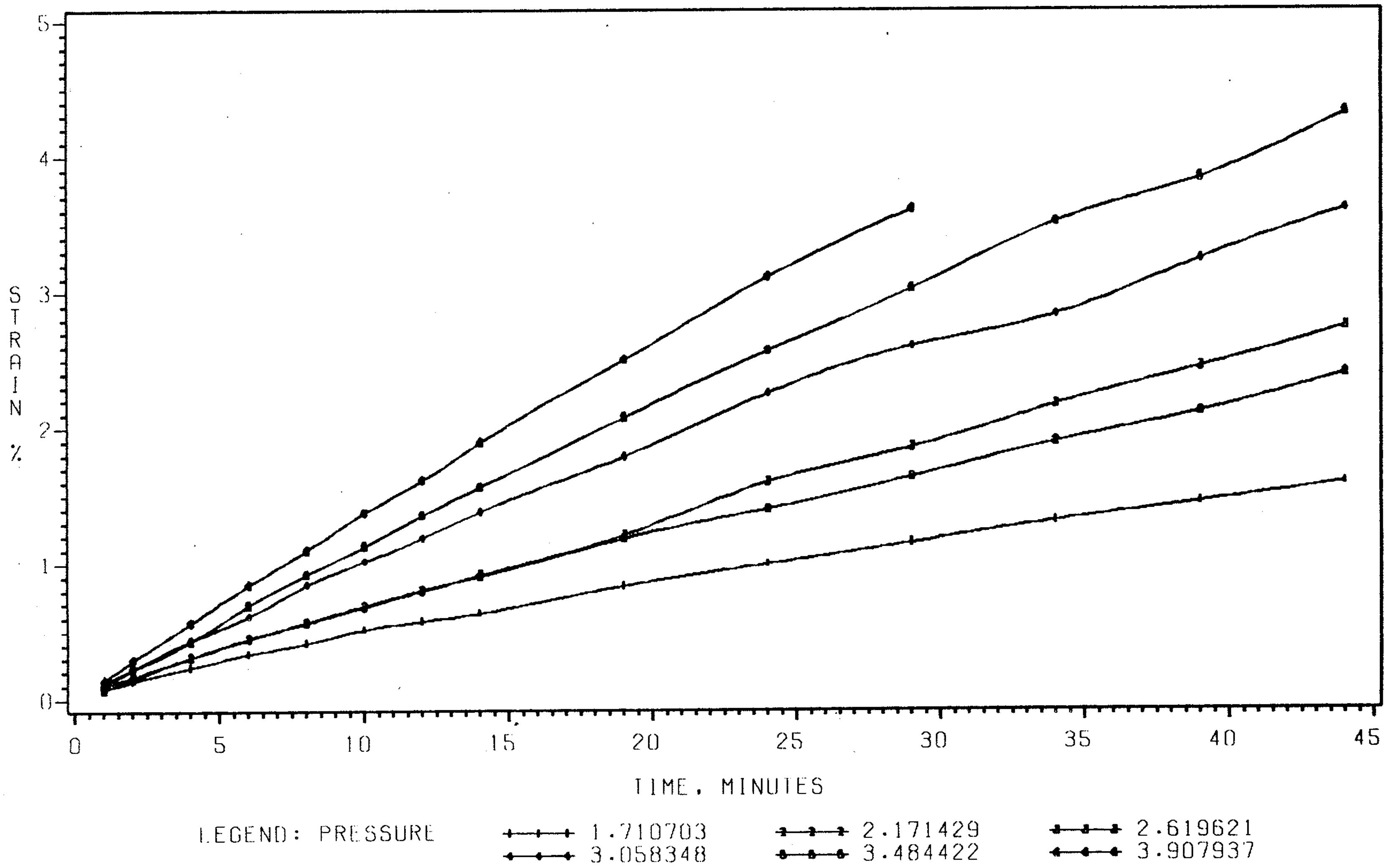
```
RUN;
PROC GPLOT DATA=ALL GOUT=P1;
 TITLE1 ;
 TITLE2 .H=2 .F=DUPLEX PLOT OF STRAIN VS TIME AT EACH PRESSURE;
 TITLE3 .H=1 .F=SIMPLEX MULTI STAGE PRESSUREMETER TEST;
 FOOTNOTE1 .H=1 .F=SIMPLEX PRESSURE IN MPA;
 FOOTNOTE2;
 LABEL STRAIN= STRAIN %
       TIME = TIME, MINUTES;
 PLOT STRAIN*TIME=PRESSURE/VREF=50 HREF=50000 CAXIS=RED;
  SYMBOL1 V=1 I=SPLINE C=RED;
  SYMBOL2 V=2 I=SPLINE C=RED;
  SYMBOL3 V=3 I=SPLINE C=RED;
  SYMBOL4 V=4 I=SPLINE C=RED;
  SYMBOL5 V=5 I=SPLINE C=RED;
  SYMBOL6 V=6 I=SPLINE C=RED;
  SYMBOL7 V=7 I=SPLINE C=RED;
  SYMBOL8 V=8 I=SPLINE C=RED;
  SYMBOL9 V=9 I=SPLINE C=RED;
  SYMBOL10 V=- I=SPLINE C=RED;
  SYMBOL11 V=TRIANGLE I=SPLINE C=RED;
  SYMBOL12 V=SQUARE I=SPLINE C=RED;
  SYMBOL13 V=DIAMOND I=SPLINE C=RED;
  SYMBOL14 V=+ I=SPLINE C=RED;
PROC GPLOT DATA=ALL GOUT=P2;
 LABEL TIME= TIME, MINUTES
       LNR= LNR;
 TITLE1 ;
 TITLE2 .H=2 .F=DUPLEX SOLUTION OF CREEP PARAMETERS;
 TITLE3 .H=1 .F=SIMPLEX MULTI STAGE PRESSUREMETER TEST;
 FOOTNOTE1 .H=1 .F=SIMPLEX PRESSURE IN MPA;
 FOOTNOTE2;
 PLOT LNR*TIME=PRESSURE/VAXIS=0.0001 0.001 0.01 0.1 HAXIS=1 10 100
                         VREF=0.1 HREF=100 CAXIS=RED;
  SYMBOL1 V=1 I=SM99 C=RED;
  SYMBOL2 V=2 I=SM99 C=RED;
  SYMBOL3 V=3 I=SM99 C=RED;
  SYMBOL4 V=4 I=SM99 C=RED;
  SYMBOL5 V=5 I=SM99 C=RED;
  SYMBOL6 V=6 I=SM99 C=RED;
  SYMBOL7 V=7 I=SM99 C=RED;
  SYMBOL8 V=8 I=SM99 C=RED;
  SYMBOL9 V=9 I=SM99 C=RED;
  SYMBOL10 V=· I=SM99 C=RED;
  SYMBOL11 V=TRIANGLE I=SM99 C=RED;
  SYMBOL12 V=SQUARE I=SM99 C=RED;
  SYMBOL13 V=DIAMOND I=SM99 C=RED;
  SYMBOL14 V=+ I=SM99 C=RED;
RUN;
PROC GPLOT DATA=FDATA GOUT=P3;
 LABEL FVALUE=F
       PRESSURE=PRESSURE, MPA;
 TITLE1 ;
 TITLE2 .H=2 .F=DUPLEX SOLUTION OF CREEP PARAMETERS;
 TITLE3 .H=1 .F=SIMPLEX MULTI STAGE PRESSUREMETER TEST;
 FOOTNOTE1;
 FOOTNOTE2;
 PLOT FVALUE*PRESSURE/VAXIS= 0.0001 0.001 0.01 HAXIS=0.1 1 10
                       VREF=0.01 HREF=10 CAXIS=RED;
 SYMBOL1 V=TRIANGLE I=SM99 C=RED;
PROC GPLOT DATA=FDATA GOUT=P4;
 LABEL BSLOPE = B
       PRESSURE=PRESSURE, MPA;
 TITLE1 ;
```

```
 TITLE2 .H=2 .F=DUPLEX VARIATION OF B WITH PRESSURE;
 TITLE3 .H=1 .F=SIMPLEX MULTI STAGE PRESSUREMETER TEST;
 FOOTNOTE1;
 FOOTNOTE2;
 PLOT BSLOPE*PRESSURE/VREF=2 HREF=10 CAXIS=RED;
 SYMBOL1 V=SQUARE I=NONE C=RED;
DATA PLOTS;
 SET P1 P2 P3 P4;
PROC GREPLAY DATA=PLOTS;
//   EXEC XPLOT
```

D.3 ANALYSIS OF PT201

PLOT OF STRAIN VS TIME AT EACH PRESSURE

MULTI-STAGE PRESSUREMETER TEST PT201



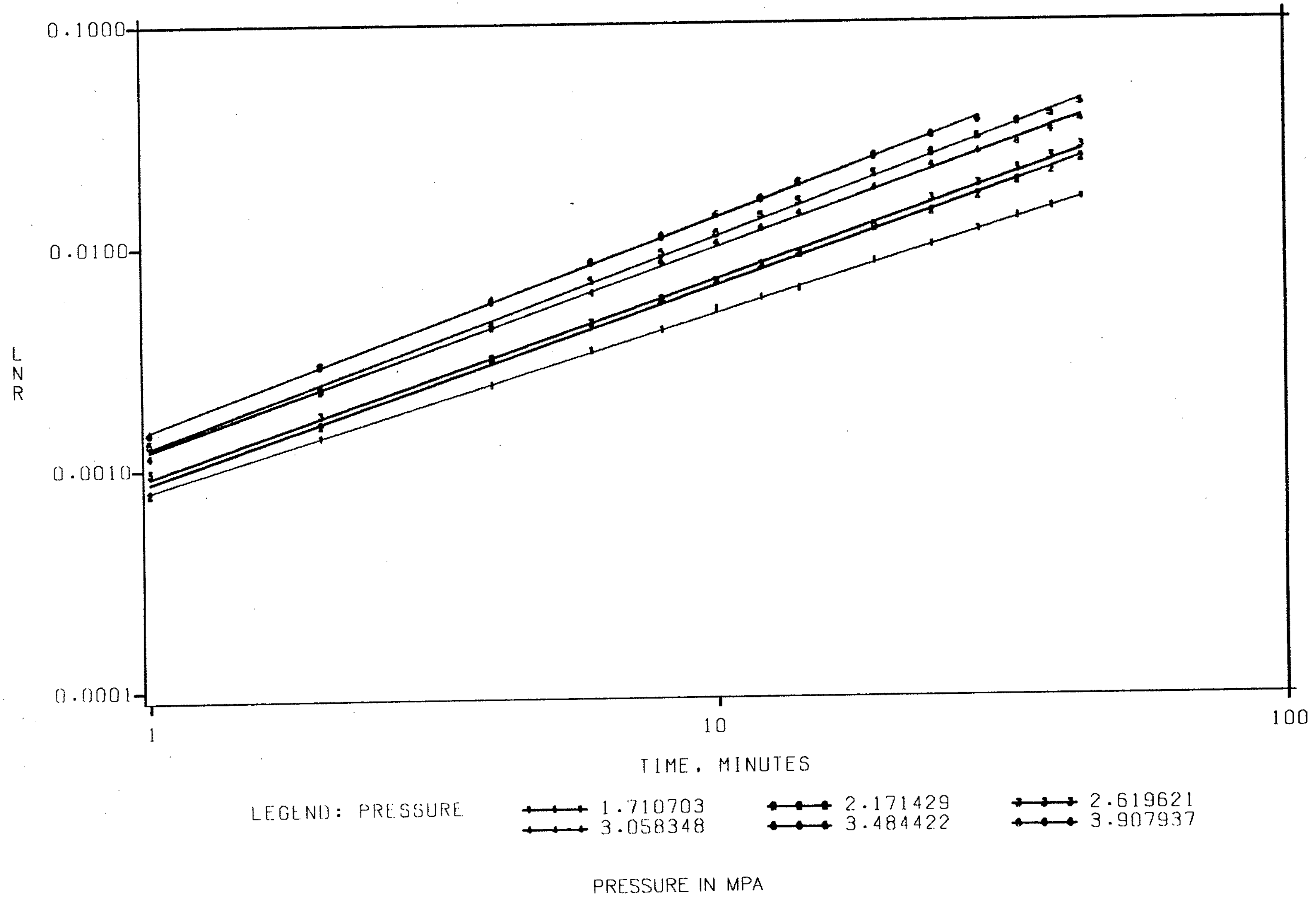
PRESSURE IN MPA

```
                DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME     LOGTIME      PI        PRESSURE     STRAIN       RATE          LNR        LOGLNR

   1     0.00000    1.72050    1.71070     0.07908    0.079076    0.0007904     3.1021
   2     0.30103    1.71927    1.71070     0.13845    0.059371    0.0013835     2.8590
   4     0.60206    1.71722    1.71070     0.23737    0.049461    0.0023709     2.6251
   6     0.77815    1.71517    1.71070     0.33638    0.049504    0.0033581     2.4739
   8     0.90309    1.71354    1.71070     0.41564    0.039630    0.0041477     2.3822
  10     1.00000    1.71150    1.71070     0.51473    0.049545    0.0051341     2.2895
  12     1.07918    1.71028    1.71070     0.57422    0.029747    0.0057258     2.2422
  14     1.14613    1.70907    1.71070     0.63376    0.029771    0.0063176     2.1994
  19     1.27875    1.70501    1.71070     0.83227    0.039702    0.0082883     2.0815
  24     1.38021    1.70178    1.71070     0.99127    0.031799    0.0098639     2.0060
  29     1.46240    1.69856    1.71070     1.15041    0.031828    0.0114384     1.9416
  34     1.53148    1.69535    1.71070     1.30969    0.031856    0.0130119     1.8857
  39     1.59106    1.69255    1.71070     1.44917    0.027895    0.0143877     1.8420
  44     1.64345    1.68976    1.71070     1.58878    0.027923    0.0157629     1.8024
   1     0.00000    2.18578    2.17143     0.07853    0.078526    0.0007850     3.1052
   2     0.30103    2.18419    2.17143     0.15707    0.078539    0.0015694     2.8043
   4     0.60206    2.18102    2.17143     0.31427    0.078601    0.0031377     2.5034
   6     0.77815    2.17826    2.17143     0.45192    0.068826    0.0045090     2.3459
   8     0.90309    2.17589    2.17143     0.57002    0.059050    0.0056840     2.2453
  10     1.00000    2.17353    2.17143     0.68818    0.059080    0.0068582     2.1638
  12     1.07918    2.17118    2.17143     0.80641    0.059113    0.0080317     2.0952
  14     1.14613    2.16922    2.17143     0.90501    0.049300    0.0090094     2.0453
  19     1.27875    2.16375    2.17143     1.18134    0.055267    0.0117442     1.9302
  24     1.38021    2.15947    2.17143     1.39876    0.043484    0.0138907     1.8573
  29     1.46240    2.15482    2.17143     1.63622    0.047492    0.0162298     1.7897
  34     1.53148    2.14980    2.17143     1.89383    0.051522    0.0187612     1.7267
  39     1.59106    2.14557    2.17143     2.11208    0.043649    0.0209008     1.6798
  44     1.64345    2.14020    2.17143     2.39021    0.055626    0.0236209     1.6267
   1     0.00000    2.63448    2.61962     0.09708    0.097084    0.0009704     3.0131
   2     0.30103    2.63296    2.61962     0.17482    0.077740    0.0017467     2.7578
   4     0.60206    2.63030    2.61962     0.31090    0.068038    0.0031042     2.5081
   6     0.77815    2.62765    2.61962     0.44710    0.068100    0.0044610     2.3506
   8     0.90309    2.62538    2.61962     0.56390    0.058402    0.0056232     2.2500
  10     1.00000    2.62311    2.61962     0.68078    0.058436    0.0067847     2.1685
  12     1.07918    2.62085    2.61962     0.79772    0.058473    0.0079456     2.0999
  14     1.14613    2.61859    2.61962     0.91474    0.058510    0.0091058     2.0407
  19     1.27875    2.61296    2.61962     1.20761    0.058573    0.0120037     1.9207
  24     1.38021    2.60549    2.61962     1.59874    0.078227    0.0158610     1.7997
  29     1.46240    2.60066    2.61962     1.85340    0.050932    0.0183643     1.7360
  34     1.53148    2.59473    2.61962     2.16723    0.062767    0.0214408     1.6688
  39     1.59106    2.58956    2.61962     2.44228    0.055008    0.0241293     1.6175
  44     1.64345    2.58404    2.61962     2.73733    0.059010    0.0270053     1.5686
   1     0.00000    3.07892    3.05835     0.11487    0.114870    0.0011480     2.9400
   2     0.30103    3.07672    3.05835     0.22981    0.114937    0.0022954     2.6391
   4     0.60206    3.07271    3.05835     0.44070    0.105448    0.0043973     2.3568
   6     0.77815    3.06944    3.05835     0.61343    0.086362    0.0061155     2.2136
   8     0.90309    3.06508    3.05835     0.84392    0.115246    0.0084038     2.0755
  10     1.00000    3.06182    3.05835     1.01695    0.086514    0.0101181     1.9949
  12     1.07918    3.05857    3.05835     1.19011    0.086582    0.0118308     1.9270
  14     1.14613    3.05497    3.05835     1.38270    0.096295    0.0137323     1.8623
  19     1.27875    3.04742    3.05835     1.78766    0.080992    0.0177187     1.7516
  24     1.38021    3.03884    3.05835     2.25141    0.092749    0.0222644     1.6524
  29     1.46240    3.03244    3.05835     2.59986    0.069690    0.0256664     1.5906
  34     1.53148    3.02818    3.05835     2.83243    0.046515    0.0279306     1.5539
  39     1.59106    3.02076    3.05835     3.24001    0.081516    0.0318863     1.4964
  44     1.64345    3.01407    3.05835     3.60940    0.073878    0.0354579     1.4503
```

```
                DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME   LOGTIME      PI      PRESSURE    STRAIN      RATE         LNR       LOGLNR

  1    0.00000   3.50776   3.48442    0.13145    0.131452    0.0013137    2.8815
  2    0.30103   3.50601   3.48442    0.22539    0.093933    0.0022513    2.6476
  4    0.60206   3.50217   3.48442    0.43216    0.103389    0.0043123    2.3653
  6    0.77815   3.49729   3.48442    0.69560    0.131716    0.0069319    2.1591
  8    0.90309   3.49312   3.48442    0.92163    0.113015    0.0091741    2.0374
 10    1.00000   3.48931   3.48442    1.12902    0.103697    0.0112270    1.9497
 12    1.07918   3.48516   3.48442    1.35546    0.113220    0.0134636    1.8708
 14    1.14613   3.48136   3.48442    1.56322    0.103881    0.0155113    1.8094
 19    1.27875   3.47207   3.48442    2.07395    0.102145    0.0205274    1.6877
 24    1.38021   3.46317   3.48442    2.56674    0.098559    0.0253435    1.5961
 29    1.46240   3.45499   3.48442    3.02249    0.091150    0.0297772    1.5261
 34    1.53148   3.44617   3.48442    3.51713    0.098926    0.0345669    1.4613
 39    1.59106   3.44042   3.48442    3.84107    0.064789    0.0376914    1.4238
 44    1.64345   3.43200   3.48442    4.31815    0.095415    0.0422751    1.3739
  1    0.00000   3.92529   3.90794    0.14638    0.146376    0.0014627    2.8348
  2    0.30103   3.92261   3.90794    0.29284    0.146467    0.0029241    2.5340
  4    0.60206   3.91760   3.90794    0.56766    0.137411    0.0056606    2.2471
  6    0.77815   3.91260   3.90794    0.84280    0.137567    0.0083927    2.0761
  8    0.90309   3.90794   3.90794    1.09983    0.128514    0.0109382    1.9611
 10    1.00000   3.90296   3.90794    1.37548    0.137827    0.0136611    1.8645
 12    1.07918   3.89866   3.90794    1.61462    0.119571    0.0160173    1.7954
 14    1.14613   3.89370   3.90794    1.89079    0.138086    0.0187314    1.7274
 19    1.27875   3.88284   3.90794    2.49935    0.121712    0.0246863    1.6075
 24    1.38021   3.87203   3.90794    3.10922    0.121973    0.0306186    1.5140
 29    1.46240   3.86322   3.90794    3.60915    0.099987    0.0354555    1.4503
```

SOLUTION OF CREEP PARAMETERS

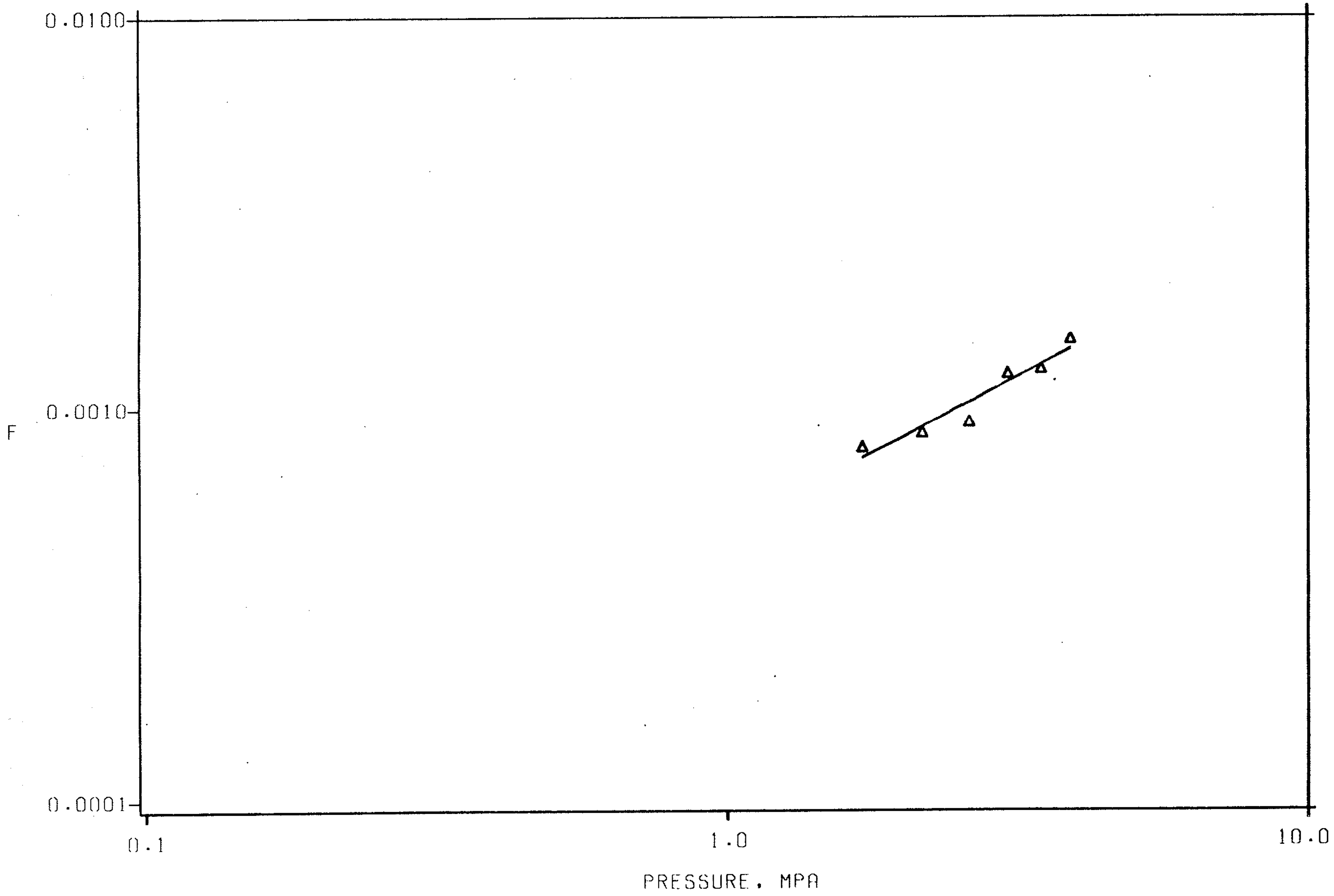
MULTI-STAGE PRESSUREMETER TEST PT201



```
                                                    SUMMARY OF CREEP PARAMETERS B AND F

 OBS    PRESSURE    _TYPE_    _MODEL_    _DEPVAR_     _SIGMA_     LOGLNR    LOGTIME      LOGF       FVALUE        BSLOPE      LOGPI

  1     1.71070      OLS                  LOGLNR     0.0065524      -1     0.790567    -3.0965   0.00080068    0.790567    0.233175
  2     2.17143      OLS                  LOGLNR     0.0220299      -1     0.878875     3.0597   0.00087159    0.878875    0.336746
  3     2.61962      OLS                  LOGLNR     0.0153486       1     0.882857     3.0339   0.00092485    0.882857    0.418238
  4     3.05835      OLS                  LOGLNR     0.0174497       1     0.900479     2.9099   0.00123052    0.900479    0.485487
  5     3.48442      OLS                  LOGLNR     0.0180095      -1     0.938805     2.8991   0.00126153    0.938805    0.542131
  6     3.90794      OLS                  LOGLNR     0.0084309       1     0.949774     2.8222   0.00150579    0.949774    0.591948
```

SOLUTION OF CREEP PARAMETERS

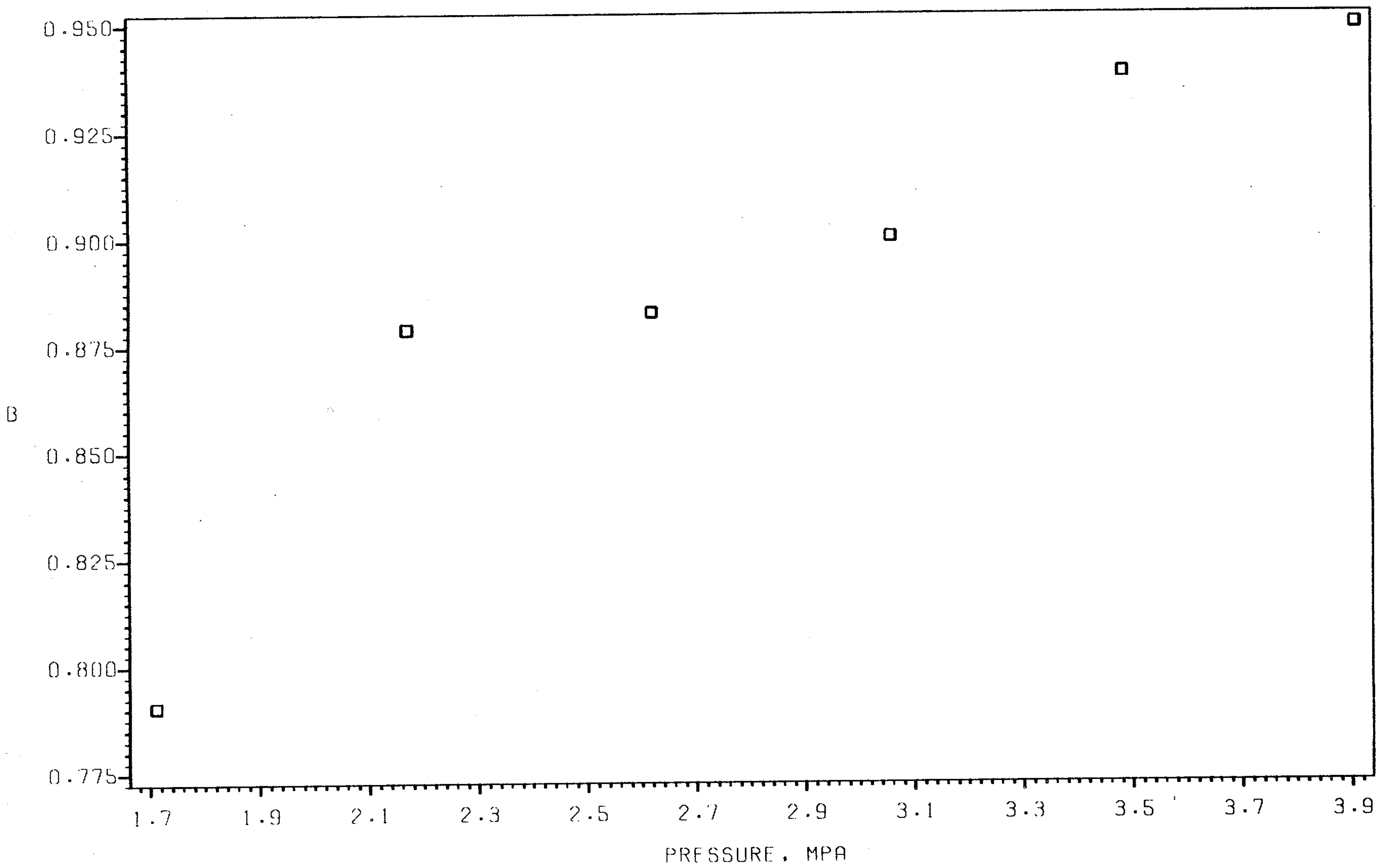
MULTI-STAGE PRESSUREMETER TEST PT201



```
                                        ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT

                        SUM OF        MEAN
SOURCE      DF         SQUARES       SQUARE        F VALUE       PROB>F

MODEL        1        0.053676     0.053676         43.466       0.0027
ERROR        4     0.004939551  0.001234888
C TOTAL      5        0.058615

    ROOT MSE          0.035141     R-SQUARE         0.9157
    DEP MEAN         -2.970234     ADJ R SQ         0.8947
    C.V.                1.1831

                     PARAMETER     STANDARD   T FOR H0:                     VARIABLE
VARIABLE    DF        ESTIMATE        ERROR  PARAMETER=0   PROB > |T|         LABEL

INTERCEP     1       -3.307141     0.053077      -62.308       0.0001  INTERCEPT
LOGPI        1        0.775174     0.117578        6.593       0.0027



                              SUMMARY OF CREEP PARAMETERS F1 AND N

 OBS    _TYPE_    _MODEL_    _DEPVAR_    _SIGMA_     LOGF    NSLOPE     LOGF1        F1

  1      OLS                   LOGF      0.035141     -1    0.775174    3.3071    0.000493014
```

VARIATION OF B WITH PRESSURE

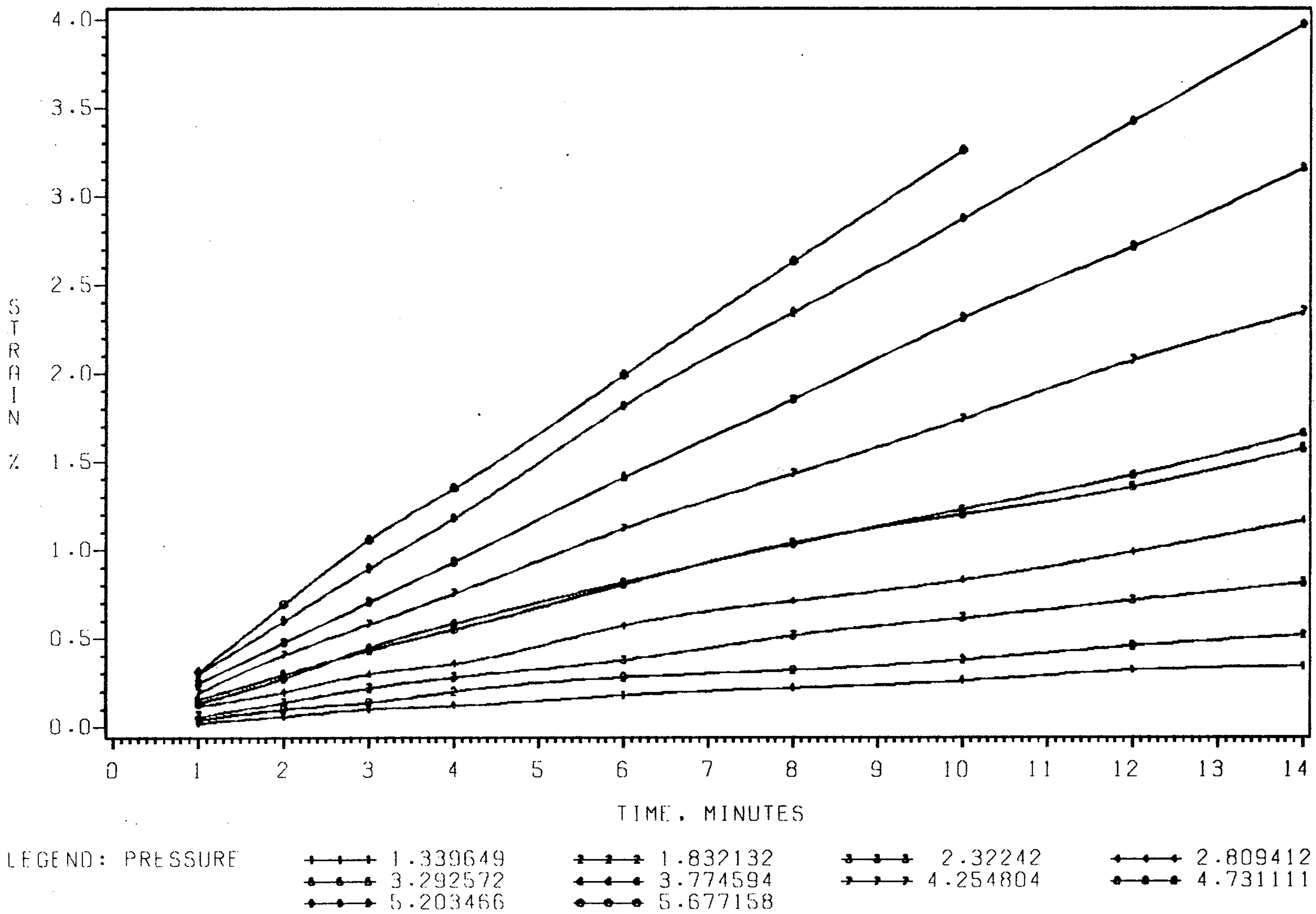
MULTI-STAGE PRESSUREMETER TEST PT201



D.4 ANALYSIS OF PT102

PLOT OF STRAIN VS TIME AT EACH PRESSURE

MULTI-STAGE PRESSUREMETER TEST PT102



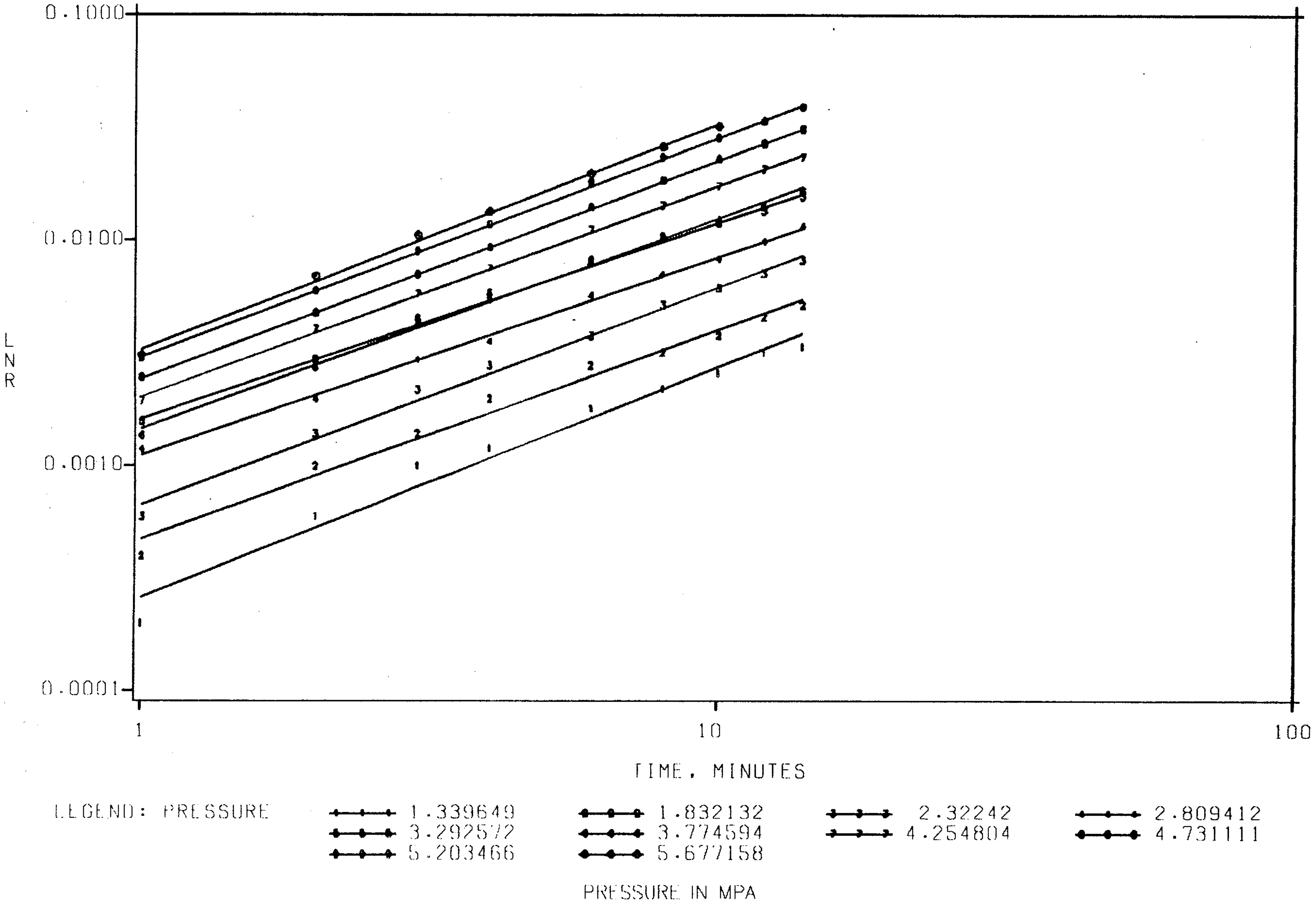
PRESSURE IN MPA

```
                         DATA SET SAS.LAD CREATED BY LADFO PROGRAM

TIME     LOGTIME      PI        PRESSURE     STRAIN      RATE          LNR        LOGLNR

  1      0.00000    1.34083    1.33965    0.01988    0.019878    0.0001988    -3.7017
  2      0.30103    1.34027    1.33965    0.05957    0.039697    0.0005956    -3.2251
  3      0.47712    1.33972    1.33965    0.09932    0.039743    0.0009927     3.0032
  4      0.60206    1.33945    1.33965    0.11920    0.019881    0.0011913     2.9240
  6      0.77815    1.33862    1.33965    0.17882    0.029810    0.0017866    -2.7480
  8      0.90309    1.33808    1.33965    0.21856    0.019871    0.0021832     2.6609
 10      1.00000    1.33753    1.33965    0.25834    0.019887    0.0025800    -2.5884
 12      1.07918    1.33672    1.33965    0.31801    0.029835    0.0031750     2.4983
 14      1.14613    1.33645    1.33965    0.33792    0.009958    0.0033735    -2.4719
  1      0.00000    1.83378    1.83213    0.03965    0.039650    0.0003964    -3.4018
  2      0.30103    1.83298    1.83213    0.09912    0.059472    0.0009907    -3.0040
  3      0.47712    1.83245    1.83213    0.13879    0.039672    0.0013870    -2.8579
  4      0.60206    1.83167    1.83213    0.19830    0.059506    0.0019810    -2.7031
  6      0.77815    1.83062    1.83213    0.27767    0.039687    0.0027729    -2.5571
  8      0.90309    1.83010    1.83213    0.31739    0.019859    0.0031689    -2.4991
 10      1.00000    1.82932    1.83213    0.37696    0.029785    0.0037625    -2.4245
 12      1.07918    1.82829    1.83213    0.45645    0.039743    0.0045541    -2.3416
 14      1.14613    1.82753    1.83213    0.51607    0.029813    0.0051475    -2.2884
  1      0.00000    2.32499    2.32242    0.05930    0.059298    0.0005928    -3.2271
  2      0.30103    2.32399    2.32242    0.13842    0.079119    0.0013832    -2.8591
  3      0.47712    2.32299    2.32242    0.21755    0.079133    0.0021731    -2.6629
  4      0.60206    2.32224    2.32242    0.27693    0.059375    0.0027654    -2.5582
  6      0.77815    2.32101    2.32242    0.37594    0.049508    0.0037524    -2.4257
  8      0.90309    2.31930    2.32242    0.51465    0.069353    0.0051333    -2.2896
 10      1.00000    2.31809    2.32242    0.61381    0.049580    0.0061193    -2.2133
 12      1.07918    2.31688    2.32242    0.71302    0.049607    0.0071049    -2.1484
 14      1.14613    2.31569    2.32242    0.81229    0.049634    0.0080901    -2.0920
  1      0.00000    2.81239    2.80941    0.11818    0.118185    0.0011811    -2.9277
  2      0.30103    2.81146    2.80941    0.19701    0.078827    0.0019682    -2.7059
  3      0.47712    2.81030    2.80941    0.29562    0.098608    0.0029518    -2.5299
  4      0.60206    2.80961    2.80941    0.35480    0.059182    0.0035417    -2.4508
  6      0.77815    2.80710    2.80941    0.57200    0.108597    0.0057037    -2.2438
  8      0.90309    2.80552    2.80941    0.71036    0.069184    0.0070785     2.1501
 10      1.00000    2.80418    2.80941    0.82904    0.059338    0.0082562    -2.0832
 12      1.07918    2.80241    2.80941    0.98740    0.079181    0.0098256    -2.0076
 14      1.14613    2.80044    2.80941    1.16571    0.089156    0.0115897    -1.9359
  1      0.00000    3.29656    3.29257    0.15678    0.156775    0.0015665    -2.8051
  2      0.30103    3.29508    3.29257    0.29407    0.137297    0.0029364    -2.5322
  3      0.47712    3.29361    3.29257    0.43145    0.137379    0.0043052    -2.3660
  4      0.60206    3.29235    3.29257    0.54929    0.117839    0.0054779    -2.2614
  6      0.77815    3.28967    3.29257    0.80489    0.127801    0.0080167    -2.0960
  8      0.90309    3.28723    3.29257    1.04113    0.118120    0.0103575     1.9847
 10      1.00000    3.28562    3.29257    1.19880    0.078834    0.0119167    -1.9238
 12      1.07918    3.28403    3.29257    1.35661    0.078903    0.0134749    -1.8705
 14      1.14613    3.28186    3.29257    1.57380    0.108595    0.0156154    -1.8064
  1      0.00000    3.77856    3.77459    0.13607    0.136074    0.0013598    -2.8665
  2      0.30103    3.77722    3.77459    0.27227    0.136200    0.0027190    -2.5656
  3      0.47712    3.77551    3.77459    0.44751    0.175233    0.0044651    -2.3502
  4      0.60206    3.77420    3.77459    0.58390    0.136396    0.0058220     2.2349
  6      0.77815    3.77196    3.77459    0.81799    0.117045    0.0081466     2.0890
  8      0.90309    3.76993    3.77459    1.03280    0.107404    0.0102750     1.9882
 10      1.00000    3.76811    3.77459    1.22827    0.097734    0.0122079     1.9134
 12      1.07918    3.76631    3.77459    1.42396    0.097846    0.0141392     1.8496
 14      1.14613    3.76416    3.77459    1.65903    0.117533    0.0164541     1.7837
  1      0.00000    4.25978    4.25480    0.19284    0.192843    0.0019266     2.7152
  2      0.30103    4.25788    4.25480    0.40518    0.212333    0.0040436     2.3932
```

```
                    DATA SET SAS.LAD CREATED BY LADFO PROGRAM

TIME     LOGTIME        PI       PRESSURE      STRAIN        RATE          LNR         LOGLNR

   3     0.47712     4.25635     4.25480     0.57906     0.173889     0.0057739      2.2385
   4     0.60206     4.25482     4.25480     0.75312     0.174055     0.0075030      2.1248
   6     0.77815     4.25165     4.25480     1.12100     0.183940     0.0111476      1.9528
   8     0.90309     4.24901     4.25480     1.43132     0.155161     0.0142118     -1.8474
  10     1.00000     4.24642     4.25480     1.74210     0.155391     0.0172710     -1.7627
  12     1.07918     4.24370     4.25480     2.07279     0.165343     0.0205160     -1.6879
  14     1.14613     4.24149     4.25480     2.34551     0.136359     0.0231842     -1.6348
   1     0.00000     4.73699     4.73111     0.24739     0.247392     0.0024709     -2.6072
   2     0.30103     4.73516     4.73111     0.47604     0.228647     0.0047491     -2.3234
   3     0.47712     4.73335     4.73111     0.70490     0.228860     0.0070243     -2.1534
   4     0.60206     4.73155     4.73111     0.93400     0.229097     0.0092966     -2.0317
   6     0.77815     4.72787     4.73111     1.41205     0.239026     0.0140217     -1.8532
   8     0.90309     4.72454     4.73111     1.85277     0.220361     0.0183582     -1.7362
  10     1.00000     4.72113     4.73111     2.31352     0.230373     0.0228716      1.6407
  12     1.07918     4.71819     4.73111     2.71743     0.201958     0.0268117      1.5717
  14     1.14613     4.71502     4.73111     3.16059     0.221576     0.0311167      1.5070
   1     0.00000     5.21003     5.20347     0.29893     0.298931     0.0029848     -2.5251
   2     0.30103     5.20791     5.20347     0.59826     0.299334     0.0059648     -2.2244
   3     0.47712     5.20582     5.20347     0.89796     0.299698     0.0089395      2.0487
   4     0.60206     5.20387     5.20347     1.17925     0.281284     0.0117235     -1.9309
   6     0.77815     5.19954     5.20347     1.81802     0.319385     0.0180169     -1.7443
   8     0.90309     5.19603     5.20347     2.34529     0.263638     0.0231821     -1.6348
  10     1.00000     5.19259     5.20347     2.87362     0.264164     0.0283311     -1.5477
  12     1.07918     5.18909     5.20347     3.42191     0.274146     0.0336467     -1.4731
  14     1.14613     5.18565     5.20347     3.97133     0.274706     0.0389450      1.4095
   1     0.00000     5.68099     5.67716     0.30962     0.309622     0.0030914      2.5098
   2     0.30103     5.67859     5.67716     0.69258     0.382954     0.0069019      2.1610
   3     0.47712     5.67633     5.67716     1.05782     0.365248     0.0105227      1.9779
   4     0.60206     5.67454     5.67716     1.35033     0.292505     0.0134129     -1.8725
   6     0.77815     5.67068     5.67716     1.99129     0.320482     0.0197173     -1.7052
   8     0.90309     5.66689     5.67716     2.63369     0.321197     0.0259960     -1.5851
  10     1.00000     5.66327     5.67716     3.25905     0.312683     0.0320707      1.4939
```

SOLUTION OF CREEP PARAMETERS

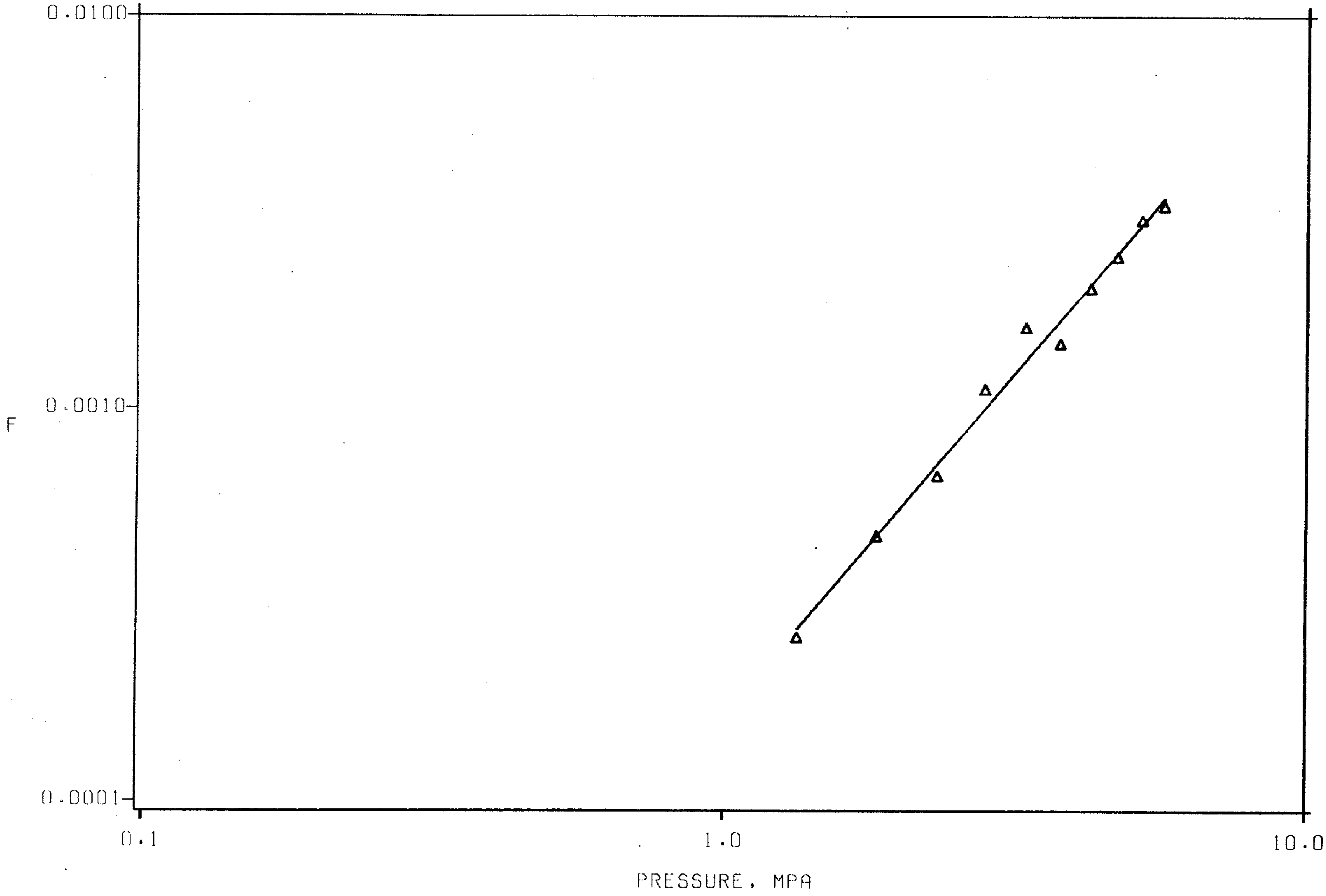
MULTI STAGE PRESSUREMETER TEST PT102



```
                                                    SUMMARY OF CREEP PARAMETERS B AND F

OBS    PRESSURE    _TYPE_    _MODEL_    _DEPVAR_     _SIGMA_     LOGLNR    LOGTIME     LOGF       FVALUE       BSLOPE      LOGPI

  1    1.33965      OLS                 LOGLNR     0.0689864       1      1.02127    -3.5824   0.00026156    1.02127    0.126991
  2    1.83213      OLS                 LOGLNR     0.0481941      -1      0.92763    -3.3233   0.00047504    0.92763    0.262957
  3    2.32242      OLS                 LOGLNR     0.0341152       1      0.96260    -3.1698   0.00067642    0.96260    0.365941
  4    2.80941      OLS                 LOGLNR     0.0190774      -1      0.87500    -2.9484   0.00112606    0.87500    0.448615
  5    3.29257      OLS                 LOGLNR     0.0150634       1      0.87038    -2.7909   0.00161847    0.87038    0.517535
  6    3.77459      OLS                 LOGLNR     0.0279929       1      0.93035    -2.8322   0.00147155    0.93035    0.576870
  7    4.25480      OLS                 LOGLNR     0.0136396       1      0.93350    -2.6918   0.00203341    0.93350    0.628880
  8    4.73111      OLS                 LOGLNR     0.0041729      -1      0.96531    -2.6103   0.00245278    0.96531    0.674963
  9    5.20347      OLS                 LOGLNR     0.0079779      -1      0.97289    -2.5172   0.00303937    0.97289    0.716293
 10    5.67716      OLS                 LOGLNR     0.0206437      -1      1.00096    -2.4815   0.00329965    1.00096    0.754131
```

SOLUTION OF CREEP PARAMETERS

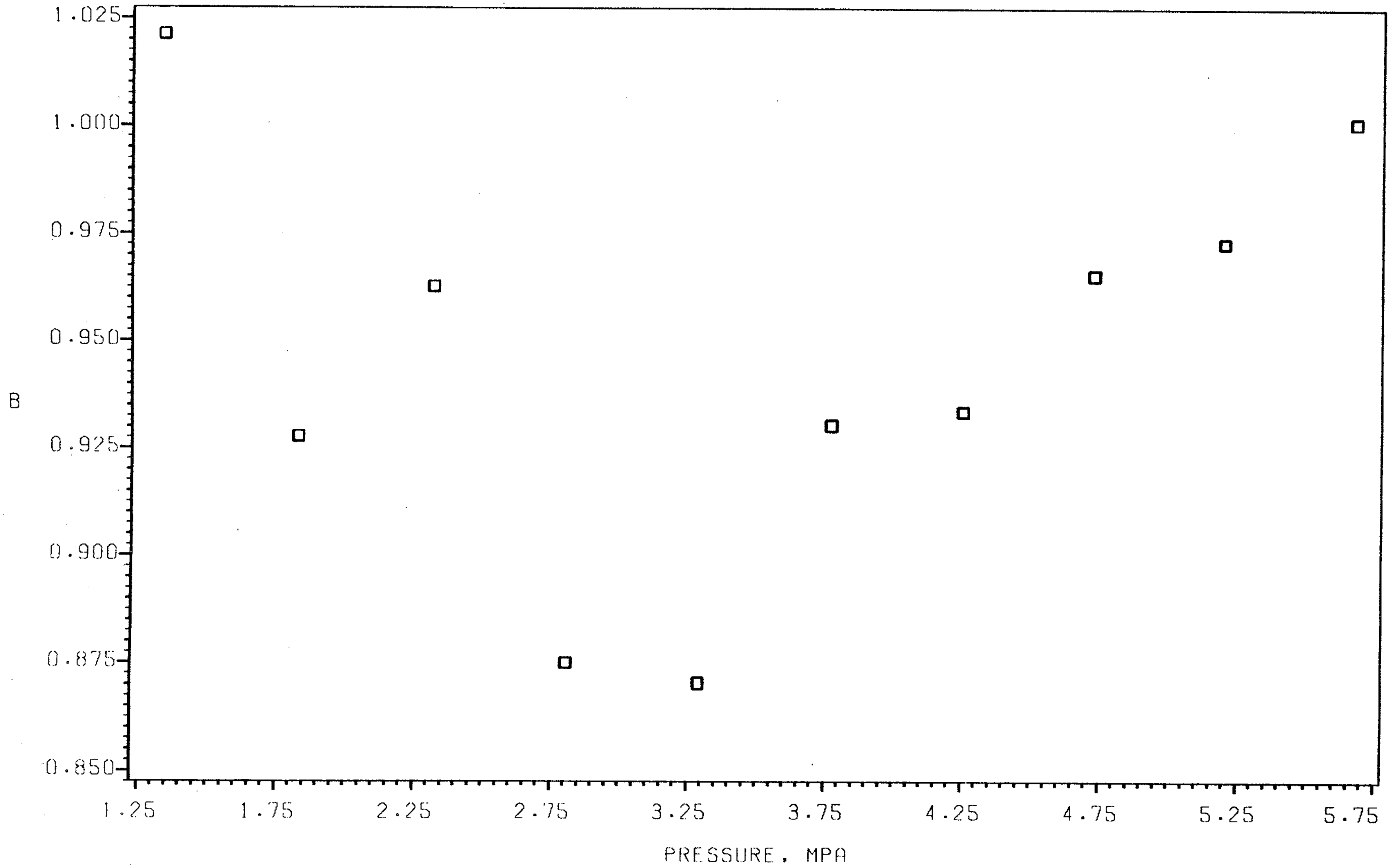
MULTI STAGE PRESSUREMETER TEST PT102



```
                                   ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF      INTERCEPT

                        SUM OF         MEAN
SOURCE        DF       SQUARES        SQUARE       F VALUE       PROB>F

MODEL          1      1.169901      1.169901       615.264       0.0001
ERROR          8      0.015212   0.001901463
C TOTAL        9      1.185113

    ROOT MSE          0.043606      R-SQUARE        0.9872
    DEP MEAN         -2.894790      ADJ R-SQ        0.9856
    C.V.              -1.50635

                     PARAMETER      STANDARD    T FOR H0:                       VARIABLE
VARIABLE      DF      ESTIMATE         ERROR  PARAMETER=0    PROB > |T|          LABEL

INTERCEP       1     -3.784698      0.038436      -98.469        0.0001   INTERCEPT
LOGPI          1      1.754145      0.070719       24.805        0.0001



                               SUMMARY OF CREEP PARAMETER N

OBS    _TYPE_    _MODEL_    _DEPVAR_     _SIGMA_     LOGF    NSLOPE     LOGF1          F1

 1      OLS                   LOGF      0.0436058     -1    1.75414   -3.7847    0.000164173
```

VARIATION OF B WITH PRESSURE

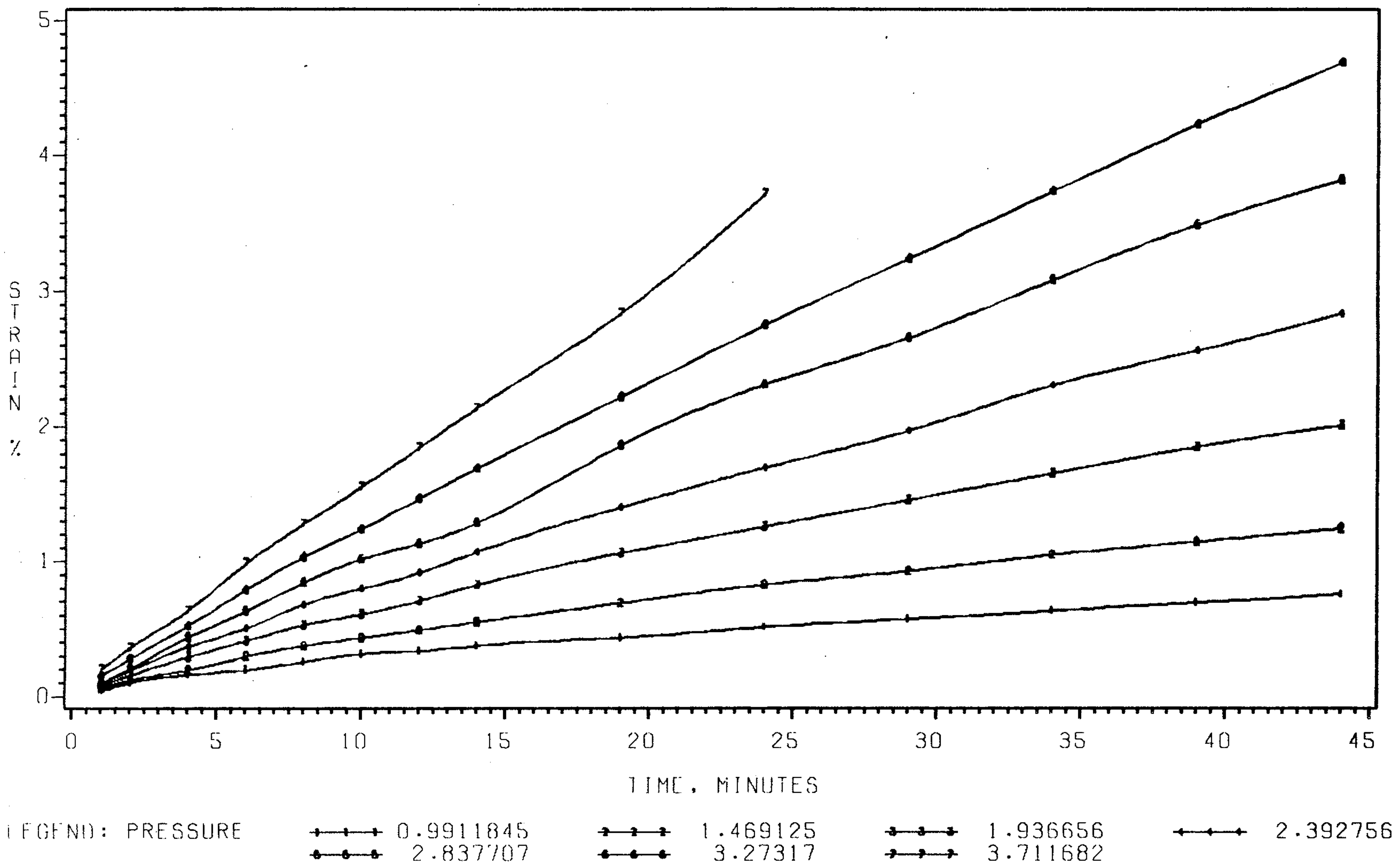
MULTI-STAGE PRESSUREMETER TEST PT102



D.5 ANALYSIS OF PT103

PLOT OF STRAIN VS TIME AT EACH PRESSURE

MULTI-STAGE PRESSUREMETER TEST PT103



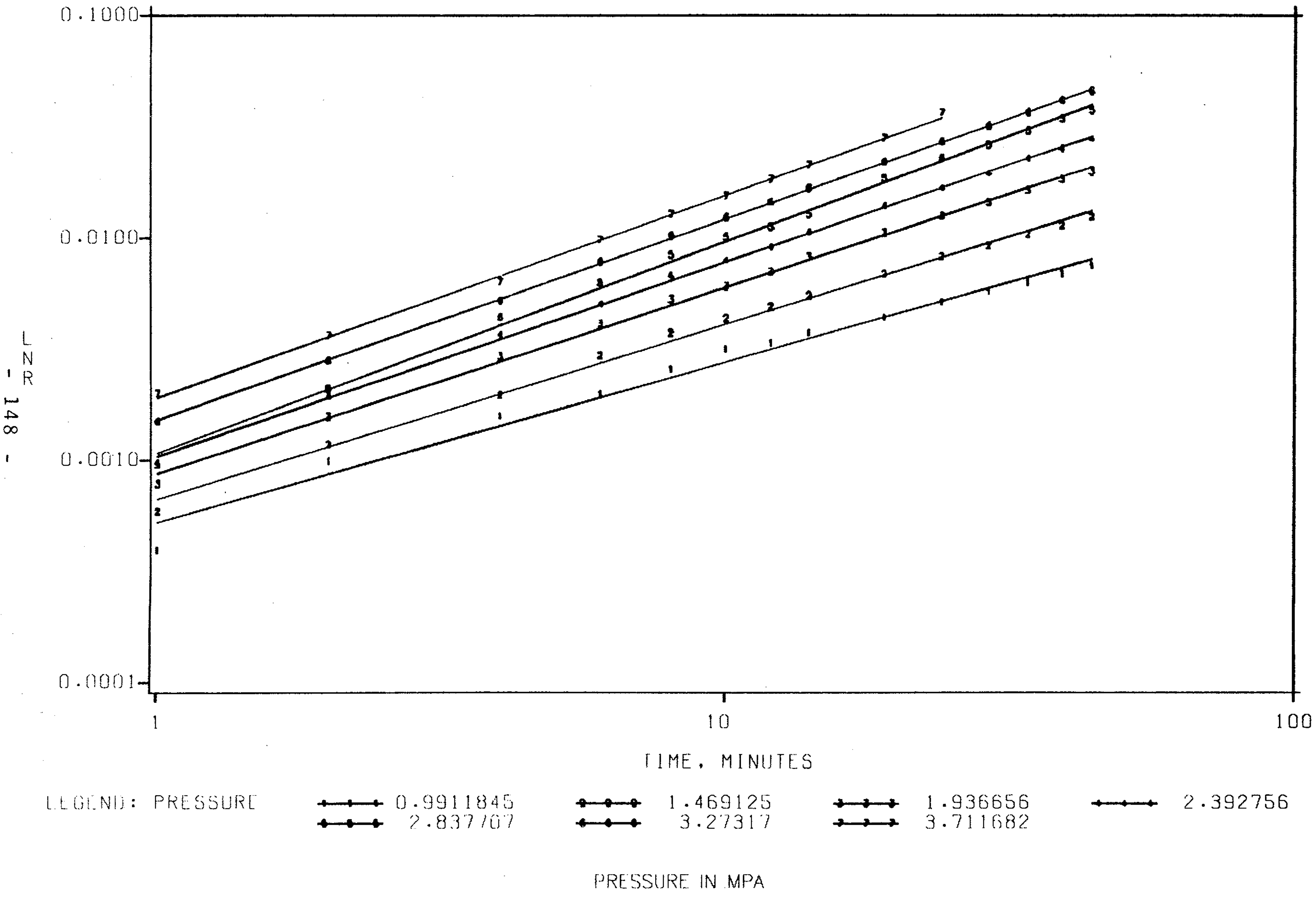
PRESSURE IN MPA

```
                DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME    LOGTIME      PI       PRESSURE    STRAIN       RATE         LNR        LOGLNR

  1     0,00000    0.99636    0.99118    0.03955    0.0395537    0.0003955    3.4029
  2     0.30103    0.99508    0.99118    0.09896    0.0594045    0.0009891    3.0048
  4     0.60206    0.99380    0.99118    0.15836    0.0296999    0.0015823    2.8007
  6     0.77815    0.99295    0.99118    0.19796    0.0197991    0.0019776    2.7039
  8     0.90309    0.99168    0.99118    0.25739    0.0297164    0.0025706    2.5900
 10     1.00000    0.99042    0.99118    0.31688    0.0297446    0.0031638    2.4998
 12     1.07918    0.99000    0.99118    0.33669    0.0099059    0.0033612    2.4735
 14     1.14613    0.98915    0.99118    0.37636    0.0198326    0.0037565    2.4252
 19     1.27875    0.98790    0.99118    0.43585    0.0118990    0.0043490    2.3616
 24     1.38021    0.98622    0.99118    0.51521    0.0158717    0.0051389    2.2891
 29     1.46240    0.98497    0.99118    0.57476    0.0119100    0.0057311    2.2418
 34     1.53148    0.98373    0.99118    0.63433    0.0119136    0.0063232    2.1991
 39     1.59106    0.98249    0.99118    0.69391    0.0119172    0.0069152    2.1602
 44     1.64345    0.98125    0.99118    0.75353    0.0119224    0.0075070    2.1245
  1     0.00000    1.47714    1.46912    0.05911    0.0591120    0.0005909    3.2285
  2     0.30103    1.47592    1.46912    0.11826    0.0591522    0.0011819    2.9274
  4     0.60206    1.47430    1.46912    0.19713    0.0394352    0.0019694    2.7057
  6     0.77815    1.47227    1.46912    0.29578    0.0493235    0.0029535    2.5297
  8     0.90309    1.47066    1.46912    0.37473    0.0394741    0.0037403    2.4271
 10     1.00000    1.46946    1.46912    0.43397    0.0296218    0.0043303    2.3635
 12     1.07918    1.46826    1.46912    0.49323    0.0296305    0.0049202    2.3080
 14     1.14613    1.46706    1.46912    0.55251    0.0296392    0.0055099    2.2589
 19     1.27875    1.46428    1.46912    0.69094    0.0276844    0.0068856    2.1621
 24     1.38021    1.46152    1.46912    0.82946    0.0277046    0.0082604    2.0830
 29     1.46240    1.45955    1.46912    0.92845    0.0197981    0.0092417    2.0343
 34     1.53148    1.45721    1.46912    1.04732    0.0237750    0.0104188    1.9822
 39     1.59106    1.45527    1.46912    1.14646    0.0198269    0.0113994    1.9431
 44     1.64345    1.45333    1.46912    1.24564    0.0198372    0.0123795    1.9073
  1     0.00000    1.94834    1.93666    0.07838    0.0783763    0.0007835    3.1060
  2     0.30103    1.94682    1.93666    0.15682    0.0784392    0.0015669    2.8050
  4     0.60206    1.94416    1.93666    0.29412    0.0686546    0.0029369    2.5321
  6     0.77815    1.94190    1.93666    0.41191    0.0588939    0.0041107    2.3861
  8     0.90309    1.93965    1.93666    0.52977    0.0589306    0.0052838    2.2771
 10     1.00000    1.93815    1.93666    0.60841    0.0393203    0.0060657    2.2171
 12     1.07918    1.93629    1.93666    0.70674    0.0491626    0.0070425    2.1523
 14     1.14613    1.93406    1.93666    0.82479    0.0590270    0.0082141    2.0854
 19     1.27875    1.92965    1.93666    1.06113    0.0472679    0.0105554    1.9765
 24     1.38021    1.92600    1.93666    1.25832    0.0394375    0.0125047    1.9029
 29     1.46240    1.92238    1.93666    1.45570    0.0394749    0.0144520    1.8401
 34     1.53148    1.91879    1.93666    1.65331    0.0395222    0.0163979    1.7852
 39     1.59106    1.91523    1.93666    1.85112    0.0395634    0.0183420    1.7366
 44     1.64345    1.91239    1.93666    2.00949    0.0316728    0.0198956    1.7012
  1     0.00000    2.40748    2.39276    0.09705    0.0970483    0.0009700    3.0132
  2     0.30103    2.40574    2.39276    0.19414    0.0970945    0.0019395    2.7123
  4     0.60206    2.40262    2.39276    0.36903    0.0874436    0.0036835    2.4337
  6     0.77815    2.40020    2.39276    0.50517    0.0680722    0.0050390    2.2977
  8     0.90309    2.39712    2.39276    0.68034    0.0875849    0.0067804    2.1687
 10     1.00000    2.39507    2.39276    0.79721    0.0584307    0.0079404    2.1002
 12     1.07918    2.39303    2.39276    0.91414    0.0584674    0.0090999    2.0410
 14     1.14613    2.39033    2.39276    1.07017    0.0780156    0.0106449    1.9729
 19     1.27875    2.38463    2.39276    1.40214    0.0663930    0.0139240    1.8562
 24     1.38021    2.37966    2.39276    1.69549    0.0586711    0.0168128    1.7744
 29     1.46240    2.37506    2.39276    1.96972    0.0548448    0.0195057    1.7098
 34     1.53148    2.36954    2.39276    2.30315    0.0666876    0.0227703    1.6426
 39     1.59106    2.36535    2.39276    2.55848    0.0510653    0.0252630    1.5975
 44     1.64345    2.36089    2.39276    2.83382    0.0550671    0.0279441    1.5537
```

```
                DATA SET USERNAME.SAS.LAD CREATED BY LADFOH/S PROGRAM

TIME    LOGTIME      PI      PRESSURE    STRAIN      RATE        LNR        LOGLNR

  1     0.00000   2.85583   2.83771    0.09566   0.095665   0.0009562    3.0195
  2     0.30103   2.85394   2.83771    0.21050   0.114838   0.0021028    2.6772
  4     0.60206   2.85019   2.83771    0.44038   0.114938   0.0043941    2.3571
  6     0.77815   2.84709   2.83771    0.63216   0.095888   0.0063017    2.2005
  8     0.90309   2.84370   2.83771    0.84330   0.105570   0.0083976    2.0758
 10     1.00000   2.84094   2.83771    1.01620   0.086450   0.0101107    1.9952
 12     1.07918   2.83911   2.83771    1.13153   0.057669   0.0112518    1.9488
 14     1.14613   2.83667   2.83771    1.28543   0.076947   0.0127724    1.8937
 19     1.27875   2.82765   2.83771    1.86349   0.115613   0.0184634    1.7337
 24     1.38021   2.82083   2.83771    2.30768   0.088837   0.0228146    1.6418
 29     1.46240   2.81555   2.83771    2.65590   0.069645   0.0262125    1.5815
 34     1.53148   2.80917   2.83771    3.08225   0.085270   0.0303571    1.5177
 39     1.59106   2.80315   2.83771    3.48996   0.081541   0.0343044    1.4647
 44     1.64345   2.79832   2.83771    3.82050   0.066109   0.0374933    1.4260
  1     0.00000   3.29297   3.27317    0.14984   0.149842   0.0014973    2.8247
  2     0.30103   3.29102   3.27317    0.28104   0.131198   0.0028065    2.5518
  4     0.60206   3.28740   3.27317    0.52487   0.121914   0.0052350    2.2811
  6     0.77815   3.28353   3.27317    0.78773   0.131432   0.0078465    2.1053
  8     0.90309   3.27995   3.27317    1.03205   0.122160   0.0102676    1.9885
 10     1.00000   3.27695   3.27317    1.23901   0.103476   0.0123139    1.9096
 12     1.07918   3.27369   3.27317    1.46498   0.112988   0.0145435    1.8373
 14     1.14613   3.27045   3.27317    1.69114   0.113080   0.0167700    1.7755
 19     1.27875   3.26295   3.27317    2.21966   0.105705   0.0219539    1.6585
 24     1.38021   3.25555   3.27317    2.74930   0.105927   0.0271219    1.5667
 29     1.46240   3.24876   3.27317    3.24207   0.098554   0.0319062    1.4961
 34     1.53148   3.24204   3.27317    3.73579   0.098745   0.0366770    1.4356
 39     1.59106   3.23540   3.27317    4.23041   0.098923   0.0414337    1.3826
 44     1.64345   3.22933   3.27317    4.68779   0.091477   0.0458123    1.3390
  1     0.00000   3.72332   3.71168    0.20031   0.200308   0.0020011    2.6987
  2     0.30103   3.72108   3.71168    0.36431   0.163998   0.0036364    2.4393
  4     0.60206   3.71737   3.71168    0.63785   0.136772   0.0063582    2.1967
  6     0.77815   3.71270   3.71168    0.98475   0.173450   0.0097993    2.0088
  8     0.90309   3.70879   3.71168    1.27722   0.146236   0.0126913    1.8965
 10     1.00000   3.70515   3.71168    1.55168   0.137228   0.0153976    1.8125
 12     1.07918   3.70129   3.71168    1.84474   0.146532   0.0182793    1.7380
 14     1.14613   3.69745   3.71168    2.13811   0.146684   0.0211557    1.6746
 19     1.27875   3.68842   3.71168    2.83605   0.139587   0.0279657    1.5534
 24     1.38021   3.67719   3.71168    3.72000   0.176790   0.0365247    1.4374
```

SOLUTION OF CREEP PARAMETERS

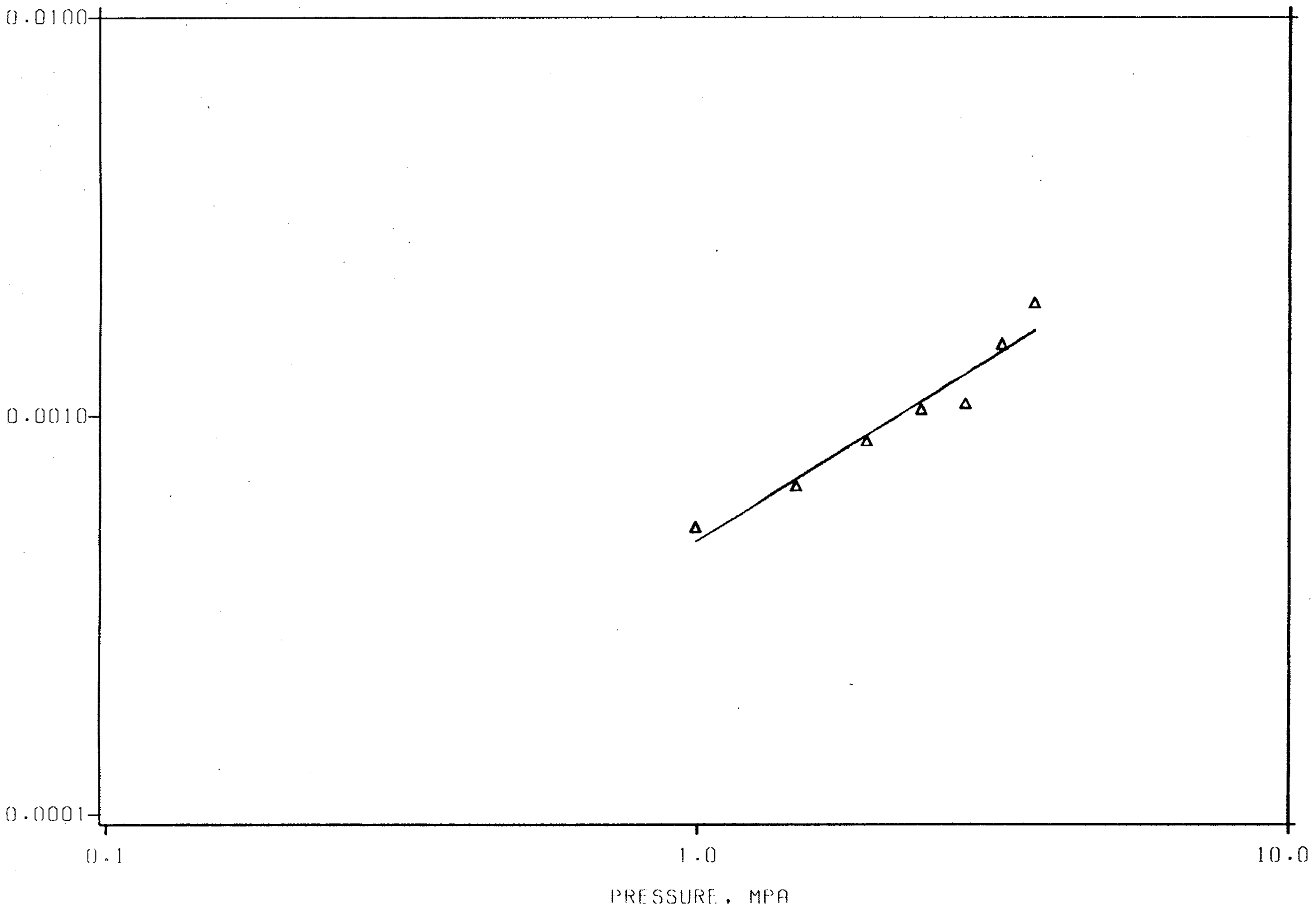
MULTI-STAGE PRESSUREMETER TEST PT103



```
                                                SUMMARY OF CREEP PARAMETERS B AND F

OBS   PRESSURE   _TYPE_   _MODEL_   _DEPVAR_   _SIGMA_     LOGLNR   LOGTIME    LOGF     FVALUE       BSLOPE     LOGPI

 1    0.99118     OLS               LOGLNR     0.0497386      1     0.722141   3.2779   0.00052738   0.722141   0.003846
 2    1.46912     OLS               LOGLNR     0.0257171      1     0.788059   3.1745   0.00066915   0.788059   0.167059
 3    1.93666     OLS               LOGLNR     0.0197913      1     0.840301   3.0610   0.00086904   0.840301   0.287053
 4    2.39276     OLS               LOGLNR     0.0140105      1     0.875791   2.9818   0.00104276   0.875791   0.378898
 5    2.83771     OLS               LOGLNR     0.0254074      1     0.952433   2.9665   0.00108015   0.952433   0.452967
 6    3.27317     OLS               LOGLNR     0.0066782      1     0.905974   2.8191   0.00151667   0.905974   0.514969
 7    3.71168     OLS               LOGLNR     0.0145738      1     0.909995   2.7162   0.00192205   0.909995   0.569571
```

SOLUTION OF CREEP PARAMETERS

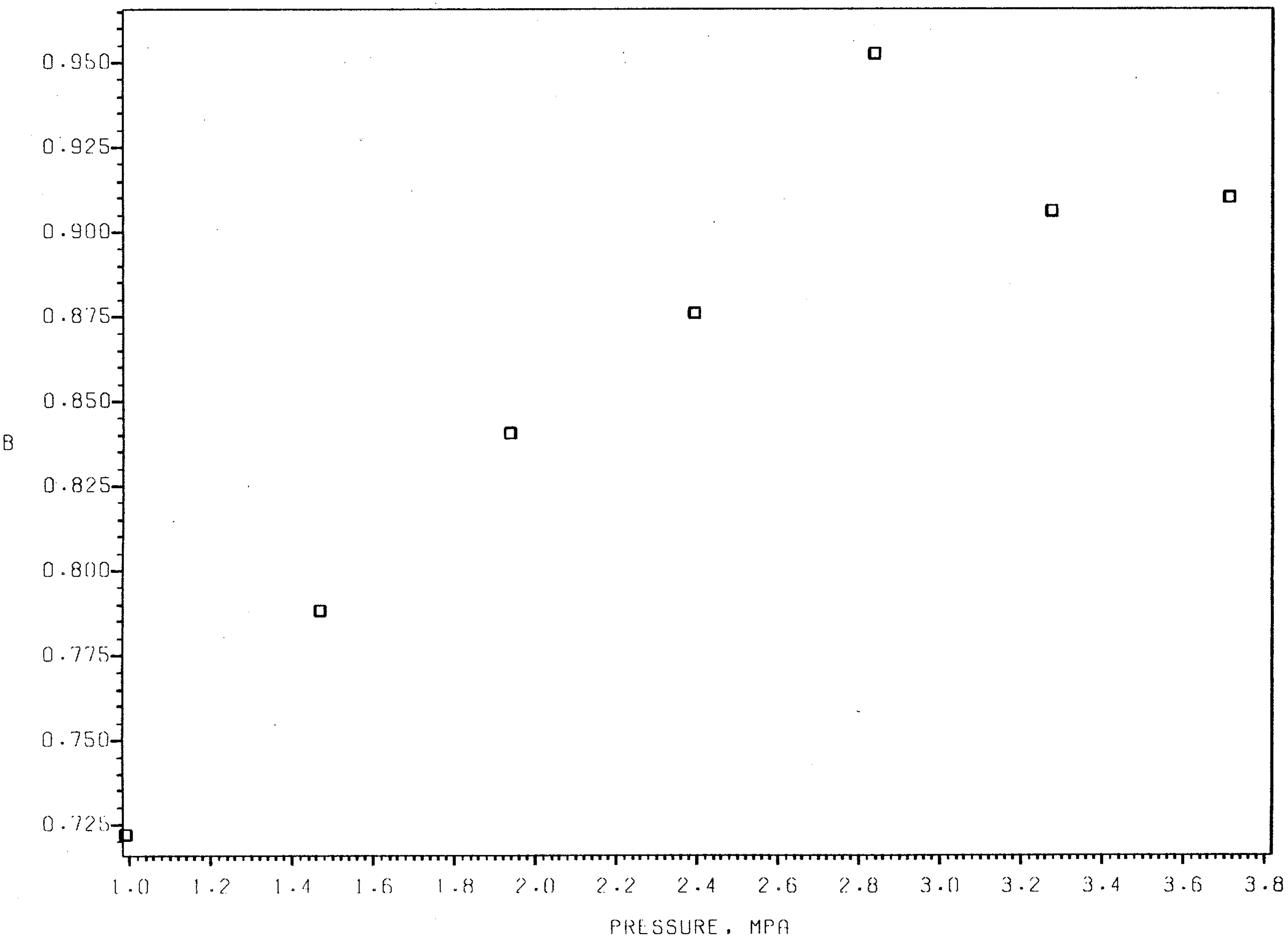
MULTI-STAGE PRESSUREMETER TEST PT103



```
                                      ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT

                       SUM OF          MEAN
SOURCE        DF      SQUARES        SQUARE       F VALUE       PROB>F

MODEL          1     0.213313      0.213313        83.615       0.0003
ERROR          5     0.012756   0.002551136
C TOTAL        6     0.226068

    ROOT MSE         0.050509      R-SQUARE        0.9436
    DEP MEAN        -2.999570      ADJ R-SQ        0.9323
    C.V.              1.68387

                    PARAMETER      STANDARD    T FOR H0:                     VARIABLE
VARIABLE      DF     ESTIMATE         ERROR  PARAMETER=0     PROB > |T|         LABEL

INTERCEP       1     3.312811      0.039216       84.475        0.0001  INTERCEPT
LOGPI          1     0.926485      0.101320        9.144        0.0003



                                SUMMARY OF CREEP PARAMETERS F1 AND N

OBS     _TYPE_     _MODEL_     _DEPVAR_      _SIGMA_      LOGF     NSLOPE      LOGF1          F1

 1       OLS                     LOGF       0.0505088      1      0.926485     3.3128   0.000486619
```

VARIATION OF B WITH PRESSURE

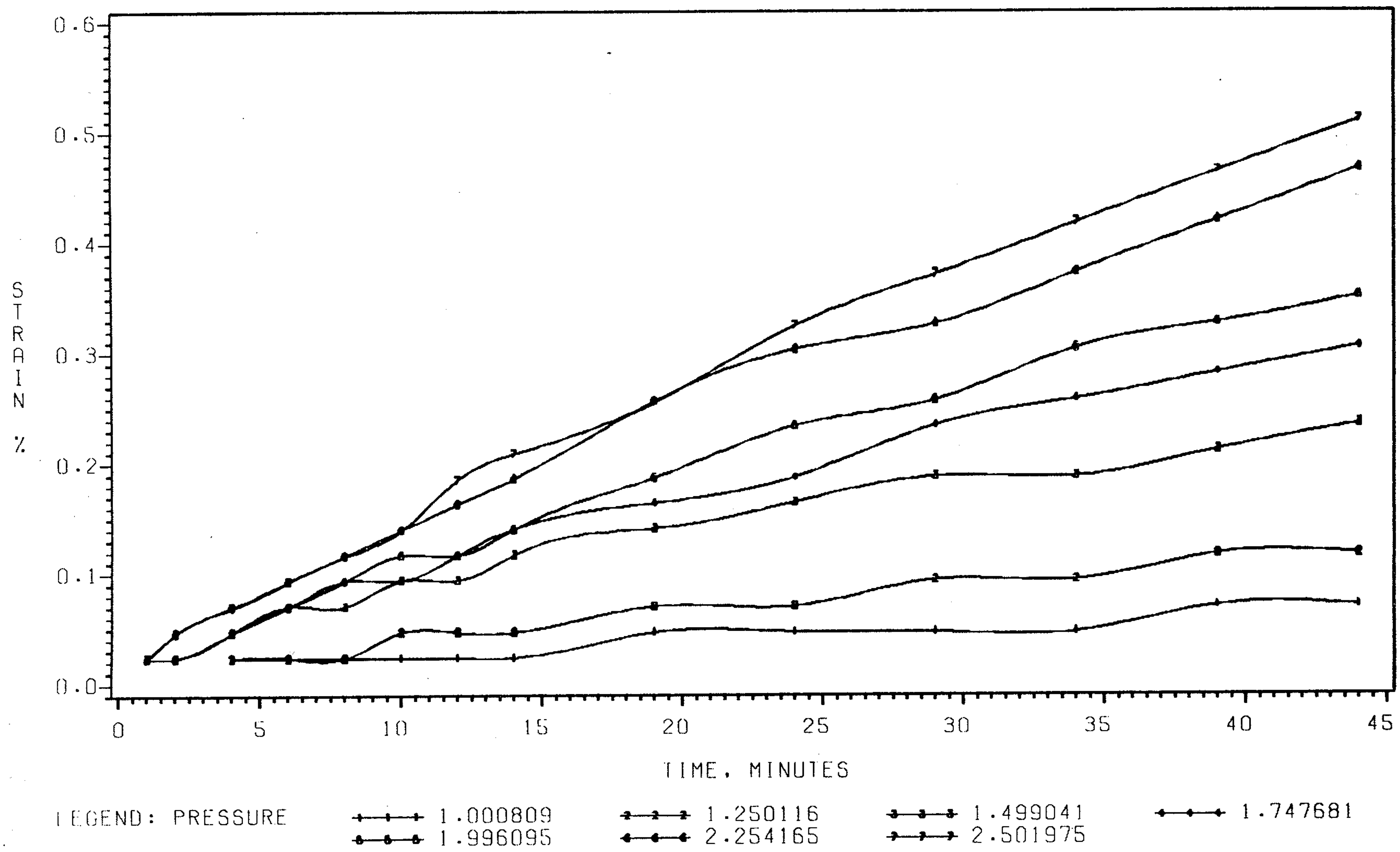
MULTI-STAGE PRESSUREMETER TEST PT103



D.6 ANALYSIS OF PT211

PLOT OF STRAIN VS TIME AT EACH PRESSURE

MULTI-STAGE PRESSUREMETER TEST PT211



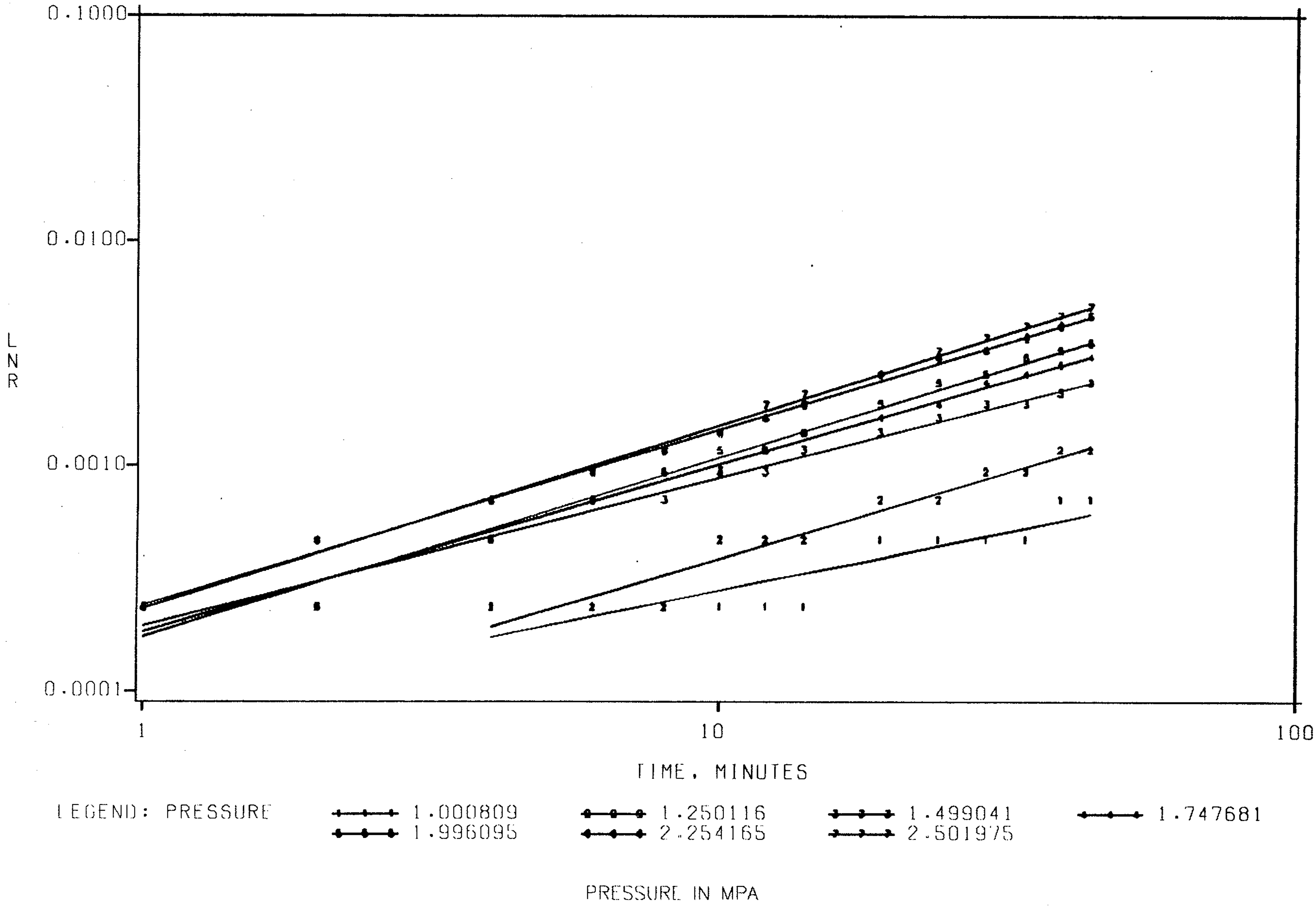
PRESSURE IN MPA

```
                    DATA SET SAS.LAD CREATED BY LADFO PROGRAM

TIME   LOGTIME      PI       PRESSURE     STRAIN       RATE          LNR        LOGLNR

  4    0.60206   1.00081    1.00081    0.023617    0.0118087    0.00023615    3.6268
  6    0.77815   1.00081    1.00081    0.023617    0.0000000    0.00023615    3.6268
  8    0.90309   1.00081    1.00081    0.023617    0.0000000    0.00023615    3.6268
 10    1.00000   1.00081    1.00081    0.023617    0.0000000    0.00023615    3.6268
 12    1.07918   1.00081    1.00081    0.023617    0.0000000    0.00023615    3.6268
 14    1.14613   1.00081    1.00081    0.023617    0.0000000    0.00023615    3.6268
 19    1.27875   1.00069    1.00081    0.047237    0.0047240    0.00047226    3.3258
 24    1.38021   1.00069    1.00081    0.047237    0.0000000    0.00047226    3.3258
 29    1.46240   1.00069    1.00081    0.047237    0.0000000    0.00047226    3.3258
 34    1.53148   1.00069    1.00081    0.047237    0.0000000    0.00047226    3.3258
 39    1.59106   1.00056    1.00081    0.070860    0.0047245    0.00070835    3.1498
 44    1.64345   1.00056    1.00081    0.070860    0.0000000    0.00070835   -3.1498
  4    0.60206   1.25020    1.25012    0.023600    0.0117998    0.00023597    3.6271
  6    0.77815   1.25020    1.25012    0.023600    0.0000000    0.00023597    3.6271
  8    0.90309   1.25020    1.25012    0.023600    0.0000000    0.00023597    3.6271
 10    1.00000   1.25008    1.25012    0.047194    0.0117970    0.00047183    3.3262
 12    1.07918   1.25008    1.25012    0.047194    0.0000000    0.00047183    3.3262
 14    1.14613   1.25008    1.25012    0.047194    0.0000000    0.00047183    3.3262
 19    1.27875   1.24996    1.25012    0.070750    0.0047112    0.00070725   -3.1504
 24    1.38021   1.24996    1.25012    0.070750    0.0000000    0.00070725   -3.1504
 29    1.46240   1.24984    1.25012    0.094349    0.0047198    0.00094305   -3.0255
 34    1.53148   1.24984    1.25012    0.094349    0.0000000    0.00094305    3.0255
 39    1.59106   1.24972    1.25012    0.117951    0.0047203    0.00117881    2.9286
 44    1.64345   1.24972    1.25012    0.117951    0.0000000    0.00117881   -2.9286
  1    0.00000   1.49937    1.49904    0.023565    0.0235654    0.00023563   -3.6278
  2    0.30103   1.49937    1.49904    0.023565    0.0000000    0.00023563    3.6278
  4    0.60206   1.49925    1.49904    0.047133    0.0117839    0.00047122   -3.3268
  6    0.77815   1.49914    1.49904    0.070704    0.0117852    0.00070679   -3.1507
  8    0.90309   1.49914    1.49904    0.070704    0.0000000    0.00070679   -3.1507
 10    1.00000   1.49902    1.49904    0.094236    0.0117663    0.00094192   -3.0260
 12    1.07918   1.49902    1.49904    0.094236    0.0000000    0.00094192   -3.0260
 14    1.14613   1.49890    1.49904    0.117804    0.0117837    0.00117734   -2.9291
 19    1.27875   1.49879    1.49904    0.141374    0.0047140    0.00141274    2.8499
 24    1.38021   1.49867    1.49904    0.164906    0.0047064    0.00164770    2.7831
 29    1.46240   1.49856    1.49904    0.188481    0.0047150    0.00188303    2.7251
 34    1.53148   1.49856    1.49904    0.188481    0.0000000    0.00188303    2.7251
 39    1.59106   1.49844    1.49904    0.212018    0.0047074    0.00211793    2.6741
 44    1.64345   1.49833    1.49904    0.235590    0.0047144    0.00235312   -2.6284
  1    0.00000   1.74810    1.74768    0.023481    0.0234815    0.00023479    3.6293
  2    0.30103   1.74810    1.74768    0.023481    0.0000000    0.00023479    3.6293
  4    0.60206   1.74799    1.74768    0.046990    0.0117540    0.00046978    3.3281
  6    0.77815   1.74788    1.74768    0.070468    0.0117392    0.00070443    3.1522
  8    0.90309   1.74776    1.74768    0.093981    0.0117565    0.00093937    3.0272
 10    1.00000   1.74776    1.74768    0.093981    0.0000000    0.00093937    3.0272
 12    1.07918   1.74765    1.74768    0.117465    0.0117417    0.00117396    2.9303
 14    1.14613   1.74754    1.74768    0.140942    0.0117390    0.00140843    2.8513
 19    1.27875   1.74743    1.74768    0.164463    0.0047041    0.00164328    2.7843
 24    1.38021   1.74732    1.74768    0.187946    0.0046966    0.00187770    2.7264
 29    1.46240   1.74710    1.74768    0.234943    0.0093995    0.00234668    2.6295
 34    1.53148   1.74699    1.74768    0.258426    0.0046965    0.00258092    2.5882
 39    1.59106   1.74688    1.74768    0.281951    0.0047050    0.00281554    2.5504
 44    1.64345   1.74677    1.74768    0.305438    0.0046975    0.00304973    2.5157
  1    0.00000   1.99656    1.99609    0.023419    0.0234186    0.00023416    3.6305
  2    0.30103   1.99656    1.99609    0.023419    0.0000000    0.00023416    3.6305
  4    0.60206   1.99645    1.99609    0.046864    0.0117225    0.00046853    3.3293
  6    0.77815   1.99634    1.99609    0.070279    0.0117078    0.00070254    3.1533
```

```
                          DATA SET SAS.LAD CREATED BY LADFO PROGRAM

TIME    LOGTIME      PI       PRESSURE     STRAIN       RATE          LNR         LOGLNR

  8     0.90309    1.99623    1.99609    0.093697    0.0117090    0.00093653    -3.0285
 10     1.00000    1.99613    1.99609    0.117118    0.0117103    0.00117049    -2.9316
 12     1.07918    1.99613    1.99609    0.117118    0.0000000    0.00117049    -2.9316
 14     1.14613    1.99602    1.99609    0.140572    0.0117274    0.00140474    -2.8524
 19     1.27875    1.99581    1.99609    0.187410    0.0093675    0.00187235    -2.7276
 24     1.38021    1.99560    1.99609    0.234257    0.0093695    0.00233984    -2.6308
 29     1.46240    1.99549    1.99609    0.257677    0.0046839    0.00257346    -2.5895
 34     1.53148    1.99528    1.99609    0.304523    0.0093693    0.00304061    -2.5170
 39     1.59106    1.99518    1.99609    0.327950    0.0046854    0.00327414    -2.4849
 44     1.64345    1.99508    1.99609    0.351372    0.0046843    0.00350756    -2.4550
  1     0.00000    2.25477    2.25416    0.023345    0.0233448    0.00023342    -3.6319
  2     0.30103    2.25466    2.25416    0.046692    0.0233472    0.00046681    -3.3309
  4     0.60206    2.25456    2.25416    0.070042    0.0116748    0.00070017    -3.1548
  6     0.77815    2.25446    2.25416    0.093386    0.0116721    0.00093342    -3.0299
  8     0.90309    2.25436    2.25416    0.116733    0.0116733    0.00116665    -2.9331
 10     1.00000    2.25426    2.25416    0.140082    0.0116746    0.00139984    -2.8539
 12     1.07918    2.25416    2.25416    0.163394    0.0116561    0.00163261    -2.7871
 14     1.14613    2.25406    2.25416    0.186748    0.0116770    0.00186574    -2.7291
 19     1.27875    2.25376    2.25416    0.256801    0.0140107    0.00256472    -2.5910
 24     1.38021    2.25356    2.25416    0.303468    0.0093334    0.00303009    -2.5185
 29     1.46240    2.25346    2.25416    0.326829    0.0046722    0.00326296    -2.4864
 34     1.53148    2.25326    2.25416    0.373503    0.0093348    0.00372807    -2.4285
 39     1.59106    2.25307    2.25416    0.420179    0.0093352    0.00419299    -2.3775
 44     1.64345    2.25288    2.25416    0.466865    0.0093372    0.00465779    -2.3318
  1     0.00000    2.50259    2.50197    0.023212    0.0232120    0.00023209    -3.6343
  2     0.30103    2.50249    2.50197    0.046458    0.0232458    0.00046447    -3.3330
  4     0.60206    2.50239    2.50197    0.069667    0.0116045    0.00069643    -3.1571
  6     0.77815    2.50230    2.50197    0.092917    0.0116253    0.00092874    -3.0321
  8     0.90309    2.50220    2.50197    0.116131    0.0116070    0.00116064    -2.9353
 10     1.00000    2.50211    2.50197    0.139379    0.0116238    0.00139282    -2.8561
 12     1.07918    2.50192    2.50197    0.185811    0.0232161    0.00185639    -2.7313
 14     1.14613    2.50183    2.50197    0.209066    0.0116275    0.00208848    -2.6802
 19     1.27875    2.50164    2.50197    0.255505    0.0092878    0.00255179    -2.5932
 24     1.38021    2.50136    2.50197    0.325198    0.0139385    0.00324670    -2.4886
 29     1.46240    2.50118    2.50197    0.371677    0.0092958    0.00370988    -2.4306
 34     1.53148    2.50099    2.50197    0.418119    0.0092884    0.00417247    -2.3796
 39     1.59106    2.50081    2.50197    0.464609    0.0092981    0.00463533    -2.3339
 44     1.64345    2.50063    2.50197    0.511063    0.0092907    0.00509761    -2.2926
```

SOLUTION OF CREEP PARAMETERS

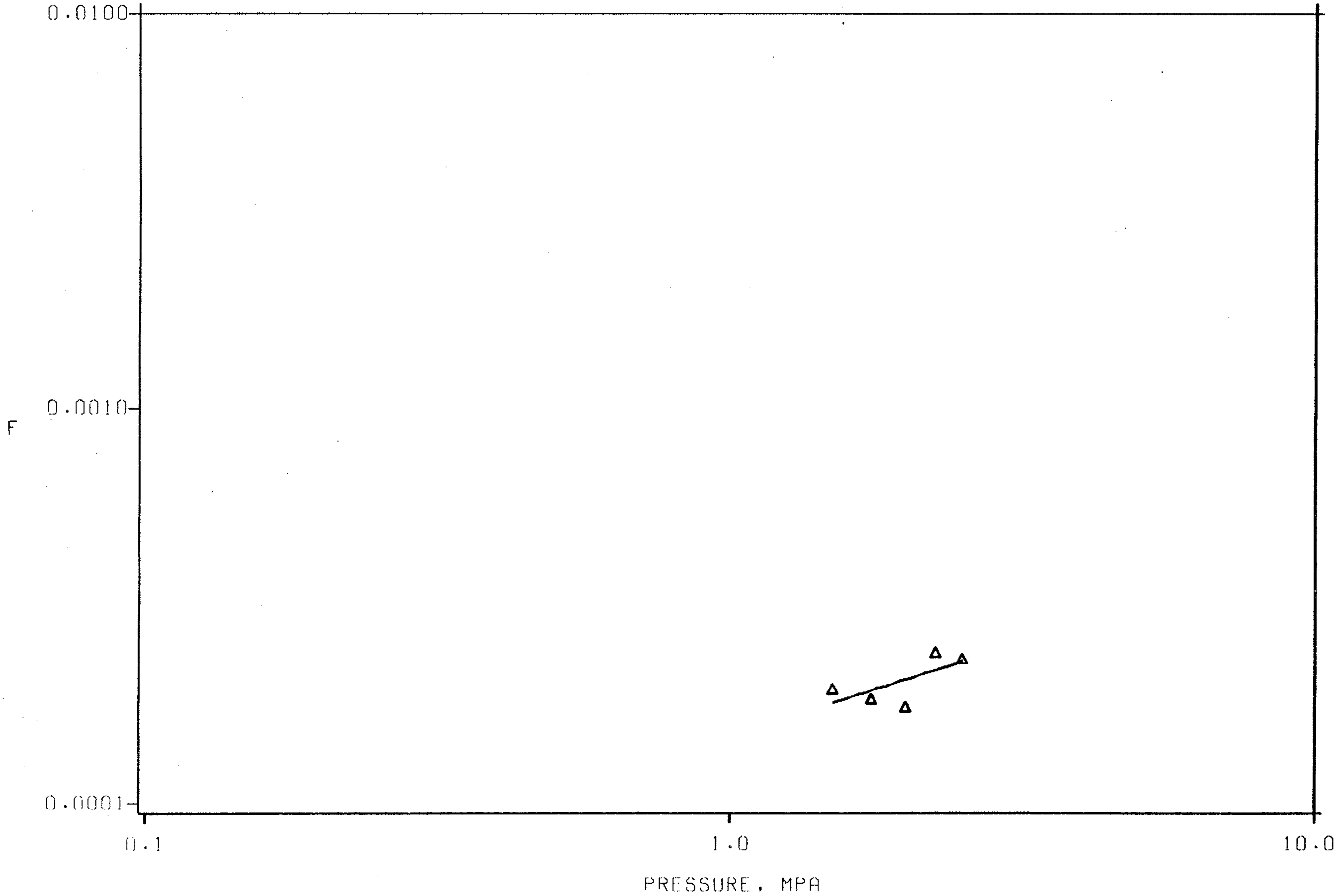
MULTI-STAGE PRESSUREMETER TEST PT211



```
                                        SUMMARY OF CREEP PARAMETERS B AND F

OBS  PRESSURE  _TYPE_  _MODEL_  _DEPVAR_    _SIGMA_   LOGLNR  LOGTIME      LOGF        FVALUE      BSLOPE     LOGPI

 1   1.00081    OLS             LOGLNR    0.0922763    -1    0.525225   -4.0771   0.000083740   0.525225   0.000351
 2   1.25012    OLS             LOGLNR    0.0664556    -1    0.763143   -4.1713   0.000067412   0.763143   0.096950
 3   1.49904    OLS             LOGLNR    0.0480479    -1    0.658621   -3.7093   0.000195294   0.658621   0.175814
 4   1.74768    OLS             LOGLNR    0.0509177    -1    0.743196   -3.7352   0.000184010   0.743196   0.242462
 5   1.99609    OLS             LOGLNR    0.0541995    -1    0.795118   -3.7556   0.000175549   0.795118   0.300181
 6   2.25416    OLS             LOGLNR    0.0216577    -1    0.778940   -3.6166   0.000241766   0.778940   0.352986
 7   2.50197    OLS             LOGLNR    0.0267775    -1    0.815248    3.6328   0.000232896   0.815248   0.398283
```

SOLUTION OF CREEP PARAMETERS

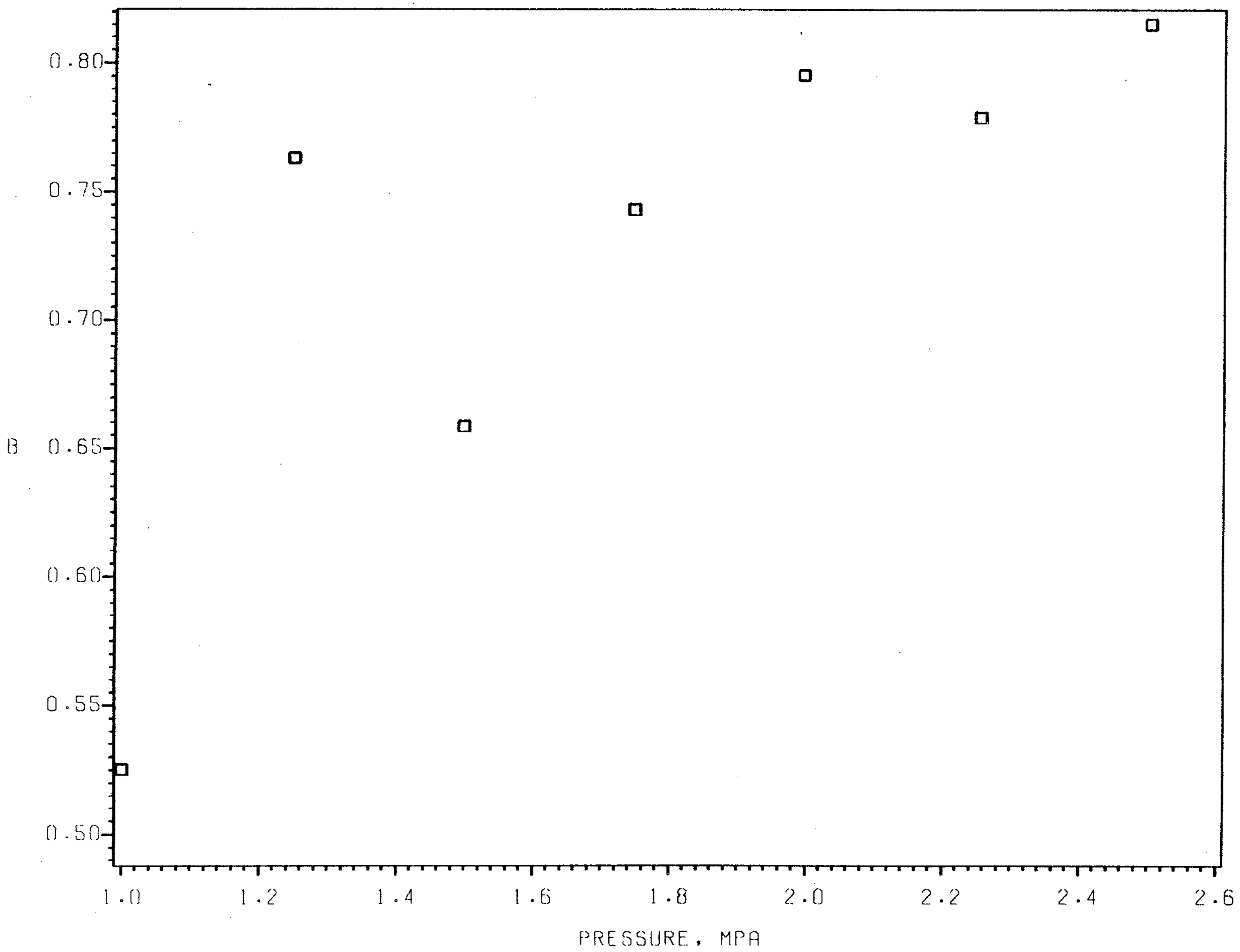
MULTI-STAGE PRESSUREMETER TEST PT211



```
                                     ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT

                        SUM OF          MEAN
SOURCE      DF         SQUARES        SQUARE        F VALUE       PROB>F

MODEL        1        0.216073      0.216073         14.771       0.0121
ERROR        5        0.073140      0.014628
C TOTAL      6        0.289213

    ROOT MSE          0.120946      R-SQUARE         0.7471
    DEP MEAN         -3.813978      ADJ R-SQ         0.6965
    C.V.             -3.17113

                     PARAMETER      STANDARD     T FOR H0:                      VARIABLE
VARIABLE    DF        ESTIMATE         ERROR   PARAMETER=0    PROB > |T|         LABEL

INTERCEP     1       -4.112340      0.090091        45.647        0.0001   INTERCEPT
LOGPI        1        1.332801      0.346783         3.843        0.0121



                                 SUMMARY OF CREEP PARAMETER N

OBS     _TYPE_     _MODEL_     _DEPVAR_     _SIGMA_     LOGF    NSLOPE     LOGF1          F1

 1       OLS                     LOGF       0.120946      1     1.3328    -4.1123    0.0000772075
```

VARIATION OF B WITH PRESSURE

MULTI-STAGE PRESSUREMETER TEST PT211



Appendix E

PREDICTIONS FROM ALL THE TESTS

```
PT102
PREDICTED STRAINS VS TIME USING FENPR,PT102; STS=4; STP=4
C1=0.900 ; C2=0.000 IN B=C1*PI**C2
SLOPE N = 1.750
VALUE OF F1 = 0.1642E-03


PRESSURE =  0.98 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.14 %
TIME INCREMENT =  500.0 MINUTES
TIME AT THE END =  16200.0 MINUTES
SLOPE B =  0.900
F1*PIAVG(I)**N =    0.158E-03

      TIME        STRAIN        RATE
      (MIN)        (%)         (%/MIN)

       0.00        0.14        0.000E+00
     500.00        4.40        0.851E-02
    1000.00        8.08        0.737E-02
    1500.00       11.58        0.700E-02
    2000.00       14.96        0.676E-02
    2500.00       18.26        0.659E-02
    3000.00       21.49        0.646E-02
    3500.00       24.67        0.636E-02
    4000.00       27.80        0.626E-02
    4500.00       30.89        0.619E-02
    5000.00       33.95        0.612E-02
    5500.00       36.98        0.606E-02
    6000.00       39.98        0.600E-02
    6500.00       42.96        0.595E-02
    7000.00       45.91        0.591E-02
    7500.00       48.85        0.586E-02
    8000.00       51.76        0.583E-02
    8500.00       54.65        0.579E-02
    9000.00       57.53        0.576E-02
    9500.00       60.39        0.572E-02
   10000.00       63.24        0.569E-02
   10500.00       66.07        0.566E-02
   11000.00       68.89        0.564E-02
   11500.00       71.70        0.561E-02
   12000.00       74.49        0.559E-02
   12500.00       77.27        0.556E-02
   13000.00       80.04        0.554E-02
   13500.00       82.80        0.552E-02
   14000.00       85.55        0.550E-02
   14500.00       88.30        0.548E-02
   15000.00       91.03        0.546E-02
   15500.00       93.75        0.544E-02
   16000.00       96.46        0.543E-02


PRESSURE =   1.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.12 %
TIME INCREMENT = 1000.0 MINUTES
TIME AT THE END =  32000.0 MINUTES
SLOPE B =  0.900
F1*PIAVG(I)**N =    0.547E-03

      TIME        STRAIN        RATE
```

```
     (MIN)        (%)        (%/MIN)

      0.00        0.12       0.000E+00
   1000.00       27.56       0.274E-01
   2000.00       51.32       0.238E-01
   3000.00       73.87       0.225E-01
   4000.00       95.67       0.218E-01
   5000.00      116.92       0.213E-01
   6000.00      137.75       0.208E-01
   7000.00      158.23       0.205E-01
   8000.00      178.42       0.202E-01
   9000.00      198.36       0.199E-01
  10000.00      218.07       0.197E-01
  11000.00      237.60       0.195E-01
  12000.00      256.94       0.193E-01
  13000.00      276.12       0.192E-01
  14000.00      295.16       0.190E-01
  15000.00      314.06       0.189E-01
  16000.00      332.84       0.188E-01
  17000.00      351.49       0.187E-01
  18000.00      370.04       0.185E-01
  19000.00      388.49       0.184E-01
  20000.00      406.84       0.183E-01
  21000.00      425.10       0.183E-01
  22000.00      443.27       0.182E-01
  23000.00      461.35       0.181E-01
  24000.00      479.36       0.180E-01
  25000.00      497.30       0.179E-01
  26000.00      515.16       0.179E-01
  27000.00      532.96       0.178E-01
  28000.00      550.68       0.177E-01
  29000.00      568.35       0.177E-01
  30000.00      585.95       0.176E-01
  31000.00      603.50       0.175E-01
  32000.00      620.99       0.175E-01


PRESSURE =  2.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.42 %
TIME INCREMENT =   50.0 MINUTES
TIME AT THE END =   1280.0 MINUTES
SLOPE B =  0.900
F1*PIAVG(I)**N =   0.112E-02

      TIME        STRAIN      RATE
     (MIN)         (%)       (%/MIN)

      0.00        0.42       0.000E+00
     50.00        4.19       0.755E-01
    100.00        7.46       0.654E-01
    150.00       10.57       0.620E-01
    200.00       13.56       0.600E-01
    250.00       16.49       0.585E-01
    300.00       19.35       0.573E-01
    350.00       22.17       0.564E-01
    400.00       24.95       0.555E-01
    450.00       27.69       0.549E-01
    500.00       30.40       0.542E-01
    550.00       33.09       0.537E-01
    600.00       35.75       0.532E-01
    650.00       38.39       0.528E-01
    700.00       41.01       0.524E-01
    750.00       43.61       0.520E-01
    800.00       46.19       0.517E-01
    850.00       48.76       0.513E-01
```

```
         900.00        51.31        0.510E-01
         950.00        53.85        0.507E-01
        1000.00        56.37        0.505E-01
        1050.00        58.88        0.502E-01
        1100.00        61.38        0.500E-01
        1150.00        63.87        0.498E-01
        1200.00        66.35        0.495E-01
        1250.00        68.81        0.493E-01


  PRESSURE =  4.17 MPA
  CUMULATIVE INSTANTANEOUS STRAIN = 0.44 %
  TIME INCREMENT =     5.0 MINUTES
  TIME AT THE END =     170.0 MINUTES
  SLOPE B =  0.900
  F1*PIAVG(I)**N =    0.200E-02

       TIME       STRAIN       RATE
       (MIN)       (%)        (%/MIN)

          0.00       0.44        0.000E+00
          5.00       1.29        0.170E+00
         10.00       2.03        0.147E+00
         15.00       2.73        0.140E+00
         20.00       3.40        0.135E+00
         25.00       4.06        0.132E+00
         30.00       4.71        0.129E+00
         35.00       5.34        0.127E+00
         40.00       5.97        0.125E+00
         45.00       6.58        0.124E+00
         50.00       7.20        0.122E+00
         55.00       7.80        0.121E+00
         60.00       8.40        0.120E+00
         65.00       9.00        0.119E+00
         70.00       9.59        0.118E+00
         75.00      10.17        0.117E+00
         80.00      10.75        0.116E+00
         85.00      11.33        0.116E+00
         90.00      11.91        0.115E+00
         95.00      12.48        0.114E+00
        100.00      13.05        0.114E+00
        105.00      13.61        0.113E+00
        110.00      14.18        0.113E+00
        115.00      14.74        0.112E+00
        120.00      15.30        0.112E+00
        125.00      15.85        0.111E+00
        130.00      16.40        0.111E+00
        135.00      16.96        0.110E+00
        140.00      17.51        0.110E+00
        145.00      18.05        0.110E+00
        150.00      18.60        0.109E+00
        155.00      19.14        0.109E+00
        160.00      19.69        0.108E+00
        165.00      20.23        0.108E+00
        170.00      20.76        0.108E+00
```

```
PT103
PREDICTED STRAINS VS TIME USING FENPR,PT103; STS=3; STP=4
C1=0.734 ; C2=0.193 IN B=C1*PI**C2
SLOPE N = 0.930
VALUE OF F1 = 0.4866E-03


PRESSURE =  0.98 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.14 %
TIME INCREMENT =  500.0 MINUTES
TIME AT THE END =  16200.0 MINUTES
SLOPE B =  0.731
F1*PIAVG(I)**N =   0.478E-03

      TIME        STRAIN        RATE
      (MIN)        (%)         (%/MIN)

       0.00        0.14       0.000E+00
     500.00        4.63       0.898E-02
    1000.00        7.59       0.593E-02
    1500.00       10.17       0.515E-02
    2000.00       12.51       0.469E-02
    2500.00       14.71       0.439E-02
    3000.00       16.79       0.415E-02
    3500.00       18.77       0.397E-02
    4000.00       20.68       0.382E-02
    4500.00       22.53       0.369E-02
    5000.00       24.32       0.359E-02
    5500.00       26.07       0.349E-02
    6000.00       27.77       0.341E-02
    6500.00       29.44       0.333E-02
    7000.00       31.07       0.326E-02
    7500.00       32.67       0.320E-02
    8000.00       34.24       0.314E-02
    8500.00       35.78       0.309E-02
    9000.00       37.30       0.304E-02
    9500.00       38.80       0.300E-02
   10000.00       40.28       0.296E-02
   10500.00       41.74       0.292E-02
   11000.00       43.18       0.288E-02
   11500.00       44.60       0.284E-02
   12000.00       46.00       0.281E-02
   12500.00       47.39       0.278E-02
   13000.00       48.77       0.275E-02
   13500.00       50.13       0.272E-02
   14000.00       51.48       0.269E-02
   14500.00       52.81       0.267E-02
   15000.00       54.13       0.264E-02
   15500.00       55.44       0.262E-02
   16000.00       56.74       0.260E-02


PRESSURE =  1.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.12 %
TIME INCREMENT = 1000.0 MINUTES
TIME AT THE END =  32000.0 MINUTES
SLOPE B =  0.838
F1*PIAVG(I)**N =   0.923E-03

      TIME        STRAIN        RATE
```

```
         (MIN)       (%)        (%/MIN)

          0.00       0.12       0.000E+00
       1000.00      30.31       0.302E-01
       2000.00      54.10       0.238E-01
       3000.00      75.94       0.218E-01
       4000.00      96.62       0.207E-01
       5000.00     116.47       0.198E-01
       6000.00     135.69       0.192E-01
       7000.00     154.38       0.187E-01
       8000.00     172.66       0.183E-01
       9000.00     190.56       0.179E-01
      10000.00     208.14       0.176E-01
      11000.00     225.45       0.173E-01
      12000.00     242.50       0.170E-01
      13000.00     259.32       0.168E-01
      14000.00     275.93       0.166E-01
      15000.00     292.35       0.164E-01
      16000.00     308.59       0.162E-01
      17000.00     324.68       0.161E-01
      18000.00     340.60       0.159E-01
      19000.00     356.39       0.158E-01
      20000.00     372.04       0.157E-01
      21000.00     387.57       0.155E-01
      22000.00     402.98       0.154E-01
      23000.00     418.27       0.153E-01
      24000.00     433.46       0.152E-01
      25000.00     448.54       0.151E-01
      26000.00     463.53       0.150E-01
      27000.00     478.43       0.149E-01
      28000.00     493.23       0.148E-01
      29000.00     507.95       0.147E-01
      30000.00     522.59       0.146E-01
      31000.00     537.15       0.146E-01
      32000.00     551.64       0.145E-01


PRESSURE =   2.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.42 %
TIME INCREMENT =    50.0 MINUTES
TIME AT THE END =    1280.0 MINUTES
SLOPE B =  0.907
F1*PIAVG(I)**N =    0.135E-02

         TIME       STRAIN       RATE
         (MIN)       (%)        (%/MIN)

          0.00       0.42       0.000E+00
         50.00       5.10       0.936E-01
        100.00       9.19       0.819E-01
        150.00      13.09       0.780E-01
        200.00      16.87       0.755E-01
        250.00      20.55       0.738E-01
        300.00      24.17       0.724E-01
        350.00      27.74       0.713E-01
        400.00      31.25       0.703E-01
        450.00      34.73       0.695E-01
        500.00      38.17       0.688E-01
        550.00      41.58       0.682E-01
        600.00      44.96       0.676E-01
        650.00      48.31       0.671E-01
        700.00      51.64       0.666E-01
        750.00      54.94       0.661E-01
        800.00      58.23       0.657E-01
        850.00      61.50       0.653E-01
```

```
    900.00      64.75       0.650E-01
    950.00      67.98       0.646E-01
   1000.00      71.19       0.643E-01
   1050.00      74.40       0.640E-01
   1100.00      77.58       0.637E-01
   1150.00      80.76       0.635E-01
   1200.00      83.92       0.632E-01
   1250.00      87.07       0.630E-01


PRESSURE =  4.17 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.44 %
TIME INCREMENT =     5.0 MINUTES
TIME AT THE END =     170.0 MINUTES
SLOPE B =  0.967
F1*PIAVG(I)**N =   0.184E-02

     TIME       STRAIN      RATE
     (MIN)       (%)        (%/MIN)

      0.00       0.44       0.000E+00
      5.00       1.31       0.174E+00
     10.00       2.14       0.166E+00
     15.00       2.96       0.163E+00
     20.00       3.77       0.162E+00
     25.00       4.57       0.160E+00
     30.00       5.36       0.159E+00
     35.00       6.15       0.158E+00
     40.00       6.94       0.157E+00
     45.00       7.72       0.157E+00
     50.00       8.51       0.156E+00
     55.00       9.28       0.156E+00
     60.00      10.06       0.155E+00
     65.00      10.83       0.155E+00
     70.00      11.61       0.154E+00
     75.00      12.38       0.154E+00
     80.00      13.15       0.154E+00
     85.00      13.91       0.153E+00
     90.00      14.68       0.153E+00
     95.00      15.44       0.153E+00
    100.00      16.21       0.153E+00
    105.00      16.97       0.152E+00
    110.00      17.73       0.152E+00
    115.00      18.49       0.152E+00
    120.00      19.24       0.152E+00
    125.00      20.00       0.151E+00
    130.00      20.76       0.151E+00
    135.00      21.51       0.151E+00
    140.00      22.27       0.151E+00
    145.00      23.02       0.151E+00
    150.00      23.77       0.150E+00
    155.00      24.52       0.150E+00
    160.00      25.28       0.150E+00
    165.00      26.03       0.150E+00
    170.00      26.77       0.150E+00
```

```
PT201
PREDICTED STRAIN VS TIME USING RESULTS FROM PT201
C1=0.725 ; C2=0.203 IN B=C1*PI**C2
SLOPE N = 0.775
VALUE OF F1 = 0.4930E-03


PRESSURE =   0.98 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.14 %
TIME INCREMENT =   500.0 MINUTES
TIME AT THE END =   16200.0 MINUTES
SLOPE B =   0.722
F1*PIAVG(I)**N =    0.485E-03

     TIME         STRAIN        RATE
     (MIN)         (%)         (%/MIN)

      0.00        0.14        0.000E+00
    500.00        4.45        0.863E-02
   1000.00        7.25        0.560E-02
   1500.00        9.67        0.484E-02
   2000.00       11.88        0.440E-02
   2500.00       13.93        0.410E-02
   3000.00       15.87        0.388E-02
   3500.00       17.72        0.370E-02
   4000.00       19.50        0.356E-02
   4500.00       21.22        0.344E-02
   5000.00       22.88        0.333E-02
   5500.00       24.50        0.324E-02
   6000.00       26.08        0.316E-02
   6500.00       27.62        0.309E 02
   7000.00       29.14        0.302E-02
   7500.00       30.62        0.296E-02
   8000.00       32.07        0.291E-02
   8500.00       33.50        0.286E-02
   9000.00       34.90        0.281E-02
   9500.00       36.29        0.277E-02
  10000.00       37.65        0.273E-02
  10500.00       39.00        0.269E-02
  11000.00       40.33        0.265E-02
  11500.00       41.64        0.262E-02
  12000.00       42.93        0.259E-02
  12500.00       44.21        0.256E-02
  13000.00       45.48        0.253E-02
  13500.00       46.73        0.250E-02
  14000.00       47.97        0.248E-02
  14500.00       49.20        0.245E-02
  15000.00       50.41        0.243E-02
  15500.00       51.62        0.241E-02
  16000.00       52.81        0.239E 02


PRESSURE =   1.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.12 %
TIME INCREMENT = 1000.0 MINUTES
TIME AT THE END =   32000.0 MINUTES
SLOPE B =   0.834
F1*PIAVG(I)**N =    0.840E-03

     TIME         STRAIN        RATE
```

```
      (MIN)         (%)          (%/MIN)

       0.00         0.12         0.000E+00
    1000.00        26.76         0.266E-01
    2000.00        47.60         0.208E 01
    3000.00        66.69         0.191E 01
    4000.00        84.74         0.180E-01
    5000.00       102.04         0.173E 01
    6000.00       118.77         0.167E 01
    7000.00       135.04         0.163E 01
    8000.00       150.93         0.159E 01
    9000.00       166.49         0.156E 01
   10000.00       181.76         0.153E 01
   11000.00       196.79         0.150E-01
   12000.00       211.58         0.148E-01
   13000.00       226.18         0.146E 01
   14000.00       240.58         0.144E 01
   15000.00       254.82         0.142E 01
   16000.00       268.90         0.141E-01
   17000.00       282.83         0.139E-01
   18000.00       296.63         0.138E-01
   19000.00       310.30         0.137E-01
   20000.00       323.85         0.136E-01
   21000.00       337.29         0.134E-01
   22000.00       350.63         0.133E-01
   23000.00       363.86         0.132E 01
   24000.00       377.00         0.131E-01
   25000.00       390.05         0.130E-01
   26000.00       403.01         0.130E-01
   27000.00       415.88         0.129E-01
   28000.00       428.68         0.128E-01
   29000.00       441.41         0.127E-01
   30000.00       454.06         0.127E-01
   31000.00       466.64         0.126E-01
   32000.00       479.15         0.125E 01


PRESSURE =   2.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.42 %
TIME INCREMENT =    50.0 MINUTES
TIME AT THE END =    1280.0 MINUTES
SLOPE B =  0.906
F1*PIAVG(I)**N =    0.115E-02

      TIME         STRAIN        RATE
      (MIN)         (%)          (%/MIN)

       0.00         0.42         0.000E+00
      50.00         4.40         0.796E-01
     100.00         7.88         0.695E-01
     150.00        11.18         0.662E-01
     200.00        14.39         0.641E-01
     250.00        17.52         0.626E-01
     300.00        20.58         0.614E-01
     350.00        23.60         0.604E 01
     400.00        26.58         0.596E-01
     450.00        29.53         0.589E-01
     500.00        32.44         0.583E-01
     550.00        35.33         0.577E-01
     600.00        38.19         0.572E-01
     650.00        41.03         0.568E 01
     700.00        43.85         0.564E-01
     750.00        46.65         0.560E-01
     800.00        49.43         0.556E-01
     850.00        52.20         0.553E-01
```

```
     900.00        54.95        0.550E-01
     950.00        57.68        0.547E-01
    1000.00        60.41        0.545E-01
    1050.00        63.12        0.542E-01
    1100.00        65.81        0.540E-01
    1150.00        68.50        0.537E-01
    1200.00        71.18        0.535E-01
    1250.00        73.84        0.533E-01


PRESSURE =  4.17 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.44 %
TIME INCREMENT =     5.0 MINUTES
TIME AT THE END =     170.0 MINUTES
SLOPE B =  0.969
F1*PIAVG(I)**N =   0.149E-02

      TIME        STRAIN        RATE
      (MIN)        (%)        (%/MIN)

       0.00        0.44        0.000E+00
       5.00        1.15        0.142E+00
      10.00        1.83        0.136E+00
      15.00        2.50        0.134E+00
      20.00        3.16        0.132E+00
      25.00        3.81        0.131E+00
      30.00        4.46        0.130E+00
      35.00        5.11        0.130E+00
      40.00        5.75        0.129E+00
      45.00        6.40        0.128E+00
      50.00        7.04        0.128E+00
      55.00        7.68        0.128E+00
      60.00        8.31        0.127E+00
      65.00        8.95        0.127E+00
      70.00        9.58        0.127E+00
      75.00       10.21        0.126E+00
      80.00       10.84        0.126E+00
      85.00       11.47        0.126E+00
      90.00       12.10        0.126E+00
      95.00       12.73        0.125E+00
     100.00       13.35        0.125E+00
     105.00       13.98        0.125E+00
     110.00       14.60        0.125E+00
     115.00       15.22        0.125E+00
     120.00       15.85        0.124E+00
     125.00       16.47        0.124E+00
     130.00       17.09        0.124E+00
     135.00       17.71        0.124E+00
     140.00       18.33        0.124E+00
     145.00       18.95        0.124E+00
     150.00       19.57        0.124E+00
     155.00       20.18        0.123E+00
     160.00       20.80        0.123E+00
     165.00       21.42        0.123E+00
     170.00       22.03        0.123E+00
```

```
PT211
PREDICTED STRAINS VS TIME USING FENPR,PT211; STS=3; STP=4
C1=0.590 ; C2=0.384 IN B=C1*PI**C2
SLOPE N = 1.333
VALUE OF F1 = 0.7721E-04


PRESSURE =  0.98 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.14 %
TIME INCREMENT =  500.0 MINUTES
TIME AT THE END =  16200.0 MINUTES
SLOPE B =  0.585
F1*PIAVG(I)**N =    0.752E-04

      TIME        STRAIN        RATE
      (MIN)        (%)         (%/MIN)

       0.00        0.14        0.000E+00
     500.00        0.43        0.572E-03
    1000.00        0.57        0.286E-03
    1500.00        0.68        0.230E-03
    2000.00        0.78        0.199E-03
    2500.00        0.87        0.180E-03
    3000.00        0.96        0.165E 03
    3500.00        1.03        0.154E-03
    4000.00        1.11        0.145E-03
    4500.00        1.17        0.138E-03
    5000.00        1.24        0.132E-03
    5500.00        1.30        0.126E-03
    6000.00        1.36        0.122E-03
    6500.00        1.42        0.117E-03
    7000.00        1.48        0.114E-03
    7500.00        1.54        0.110E-03
    8000.00        1.59        0.107E-03
    8500.00        1.64        0.105E-03
    9000.00        1.69        0.102E-03
    9500.00        1.74        0.998E-04
   10000.00        1.79        0.977E 04
   10500.00        1.84        0.957E-04
   11000.00        1.89        0.938E-04
   11500.00        1.93        0.921E-04
   12000.00        1.98        0.904E-04
   12500.00        2.02        0.889E-04
   13000.00        2.07        0.874E-04
   13500.00        2.11        0.860E-04
   14000.00        2.15        0.847E-04
   14500.00        2.19        0.835E-04
   15000.00        2.23        0.823E-04
   15500.00        2.27        0.811E-04
   16000.00        2.31        0.801E-04


PRESSURE =  1.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.12 %
TIME INCREMENT = 1000.0 MINUTES
TIME AT THE END =  32000.0 MINUTES
SLOPE B =  0.768
F1*PIAVG(I)**N =    0.193E 03

      TIME        STRAIN        RATE
```

```
     (MIN)         (%)          (%/MIN)

      0.00         0.12         0.000E+00
   1000.00         4.02         0.390E-02
   2000.00         6.77         0.275E-02
   3000.00         9.20         0.243E-02
   4000.00        11.44         0.225E-02
   5000.00        13.56         0.212E-02
   6000.00        15.58         0.202E-02
   7000.00        17.53         0.194E-02
   8000.00        19.41         0.188E-02
   9000.00        21.24         0.183E-02
  10000.00        23.02         0.178E-02
  11000.00        24.76         0.174E-02
  12000.00        26.46         0.170E-02
  13000.00        28.13         0.167E-02
  14000.00        29.78         0.164E-02
  15000.00        31.39         0.161E-02
  16000.00        32.98         0.159E-02
  17000.00        34.55         0.157E-02
  18000.00        36.09         0.155E-02
  19000.00        37.62         0.153E-02
  20000.00        39.13         0.151E-02
  21000.00        40.62         0.149E-02
  22000.00        42.09         0.147E-02
  23000.00        43.55         0.146E-02
  24000.00        44.99         0.144E-02
  25000.00        46.42         0.143E-02
  26000.00        47.84         0.142E-02
  27000.00        49.24         0.140E-02
  28000.00        50.64         0.139E-02
  29000.00        52.02         0.138E-02
  30000.00        53.39         0.137E-02
  31000.00        54.75         0.136E-02
  32000.00        56.10         0.135E-02


PRESSURE =   2.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.42 %
TIME INCREMENT =    50.0 MINUTES
TIME AT THE END =    1280.0 MINUTES
SLOPE B =  0.898
F1*PIAVG(I)**N =    0.332E-03

     TIME        STRAIN        RATE
     (MIN)        (%)          (%/MIN)

      0.00        0.42         0.000E+00
     50.00        1.54         0.223E-01
    100.00        2.50         0.193E-01
    150.00        3.42         0.183E-01
    200.00        4.30         0.177E-01
    250.00        5.17         0.172E-01
    300.00        6.01         0.169E-01
    350.00        6.84         0.166E-01
    400.00        7.66         0.164E-01
    450.00        8.47         0.162E-01
    500.00        9.27         0.160E-01
    550.00       10.06         0.158E-01
    600.00       10.84         0.157E-01
    650.00       11.62         0.155E-01
    700.00       12.39         0.154E-01
    750.00       13.15         0.153E-01
    800.00       13.91         0.152E-01
    850.00       14.67         0.151E-01
```

```
      900.00        15.42        0.150E-01
      950.00        16.17        0.149E-01
     1000.00        16.91        0.149E-01
     1050.00        17.65        0.148E-01
     1100.00        18.38        0.147E-01
     1150.00        19.12        0.146E-01
     1200.00        19.84        0.146E-01
     1250.00        20.57        0.145E-01


PRESSURE =   4.17 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.44 %
TIME INCREMENT =     5.0 MINUTES
TIME AT THE END =     170.0 MINUTES
SLOPE B =  1.021
F1*PIAVG(I)**N =   0.518E-03

       TIME         STRAIN        RATE
       (MIN)         (%)         (%/MIN)

        0.00         0.44        0.000E+00
        5.00         0.71        0.536E-01
       10.00         0.98        0.551E-01
       15.00         1.26        0.557E-01
       20.00         1.54        0.561E-01
       25.00         1.83        0.564E-01
       30.00         2.11        0.567E-01
       35.00         2.39        0.569E-01
       40.00         2.68        0.570E-01
       45.00         2.96        0.572E-01
       50.00         3.25        0.573E-01
       55.00         3.54        0.574E-01
       60.00         3.83        0.576E-01
       65.00         4.11        0.577E-01
       70.00         4.40        0.577E-01
       75.00         4.69        0.578E-01
       80.00         4.98        0.579E-01
       85.00         5.27        0.580E-01
       90.00         5.56        0.581E-01
       95.00         5.85        0.581E-01
      100.00         6.14        0.582E-01
      105.00         6.43        0.583E-01
      110.00         6.73        0.583E-01
      115.00         7.02        0.584E-01
      120.00         7.31        0.584E-01
      125.00         7.60        0.585E-01
      130.00         7.89        0.585E-01
      135.00         8.19        0.586E-01
      140.00         8.48        0.586E-01
      145.00         8.77        0.587E-01
      150.00         9.07        0.587E-01
      155.00         9.36        0.587E-01
      160.00         9.66        0.588E-01
      165.00         9.95        0.588E 01
      170.00        10.24        0.589E 01
```

```
PTMLM
PREDICTED STRAINS VS TIME USING FENPR ALL 45 MIN; STP=4(=2 FOR 2 MPA)
C1=0.472 ; C2=0.351 IN B=C1*PI**C2
SLOPE N = 1.377
VALUE OF F1 = 0.3982E-03


PRESSURE =  0.98 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.14 %
TIME INCREMENT =  500.0 MINUTES
TIME AT THE END =  16200.0 MINUTES
SLOPE B =  0.469
F1*PIAVG(I)**N =    0.387E-03

     TIME       STRAIN       RATE
     (MIN)       (%)        (%/MIN)

      0.00       0.14       0.000E+00
    500.00       0.85       0.143E-02
   1000.00       1.13       0.547E-03
   1500.00       1.33       0.413E-03
   2000.00       1.50       0.344E-03
   2500.00       1.66       0.301E-03
   3000.00       1.79       0.270E-03
   3500.00       1.91       0.247E-03
   4000.00       2.03       0.229E-03
   4500.00       2.14       0.214E-03
   5000.00       2.24       0.202E-03
   5500.00       2.33       0.192E-03
   6000.00       2.42       0.183E-03
   6500.00       2.51       0.175E-03
   7000.00       2.60       0.168E-03
   7500.00       2.68       0.161E-03
   8000.00       2.75       0.156E-03
   8500.00       2.83       0.151E-03
   9000.00       2.90       0.146E-03
   9500.00       2.97       0.142E-03
  10000.00       3.04       0.138E-03
  10500.00       3.11       0.134E-03
  11000.00       3.17       0.131E-03
  11500.00       3.24       0.128E-03
  12000.00       3.30       0.125E-03
  12500.00       3.36       0.122E-03
  13000.00       3.42       0.120E-03
  13500.00       3.48       0.117E-03
  14000.00       3.54       0.115E-03
  14500.00       3.59       0.113E-03
  15000.00       3.65       0.111E-03
  15500.00       3.70       0.109E-03
  16000.00       3.76       0.107E-03


PRESSURE =  2.00 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.21 %
TIME INCREMENT = 1000.0 MINUTES
TIME AT THE END =  32000.0 MINUTES
SLOPE B =  0.602
F1*PIAVG(I)**N =    0.103E-02

     TIME       STRAIN       RATE
```

```
         (MIN)        (%)          (%/MIN)

          0.00        0.21         0.000E+00
       1000.00        6.83         0.662E-02
       2000.00       10.25         0.343E-02
       3000.00       13.03         0.278E-02
       4000.00       15.45         0.242E-02
       5000.00       17.65         0.219E-02
       6000.00       19.67         0.202E-02
       7000.00       21.56         0.189E-02
       8000.00       23.35         0.179E-02
       9000.00       25.05         0.170E-02
      10000.00       26.67         0.163E-02
      11000.00       28.24         0.156E-02
      12000.00       29.74         0.151E-02
      13000.00       31.20         0.146E-02
      14000.00       32.62         0.141E-02
      15000.00       33.99         0.137E-02
      16000.00       35.33         0.134E-02
      17000.00       36.63         0.131E-02
      18000.00       37.91         0.128E-02
      19000.00       39.16         0.125E-02
      20000.00       40.38         0.122E-02
      21000.00       41.58         0.120E-02
      22000.00       42.75         0.117E-02
      23000.00       43.90         0.115E-02
      24000.00       45.04         0.113E-02
      25000.00       46.15         0.112E-02
      26000.00       47.25         0.110E-02
      27000.00       48.33         0.108E-02
      28000.00       49.40         0.107E-02
      29000.00       50.45         0.105E-02
      30000.00       51.48         0.104E-02
      31000.00       52.51         0.102E-02
      32000.00       53.51         0.101E-02


PRESSURE =   2.99 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.42 %
TIME INCREMENT =    50.0 MINUTES
TIME AT THE END =    1280.0 MINUTES
SLOPE B =  0.693
F1*PIAVG(I)**N =    0.180E-02

         TIME         STRAIN        RATE
         (MIN)         (%)         (%/MIN)

          0.00        0.42         0.000E+00
         50.00        3.13         0.542E-01
        100.00        4.80         0.334E-01
        150.00        6.22         0.284E-01
        200.00        7.50         0.256E-01
        250.00        8.69         0.237E-01
        300.00        9.80         0.223E-01
        350.00       10.86         0.212E-01
        400.00       11.88         0.203E-01
        450.00       12.85         0.195E-01
        500.00       13.79         0.188E-01
        550.00       14.71         0.183E-01
        600.00       15.59         0.178E-01
        650.00       16.46         0.173E-01
        700.00       17.31         0.169E-01
        750.00       18.13         0.165E-01
        800.00       18.94         0.162E-01
        850.00       19.74         0.159E-01
```

```
     900.00        20.52        0.156E-01
     950.00        21.29        0.154E-01
    1000.00        22.04        0.151E-01
    1050.00        22.79        0.149E-01
    1100.00        23.52        0.147E-01
    1150.00        24.24        0.145E-01
    1200.00        24.96        0.143E-01
    1250.00        25.66        0.141E-01


PRESSURE =   4.17 MPA
CUMULATIVE INSTANTANEOUS STRAIN = 0.44 %
TIME INCREMENT =      5.0 MINUTES
TIME AT THE END =      170.0 MINUTES
SLOPE B =   0.779
F1*PIAVG(I)**N =     0.284E-02

       TIME         STRAIN        RATE
       (MIN)         (%)         (%/MIN)

        0.00         0.44        0.000E+00
        5.00         1.44        0.199E+00
       10.00         2.15        0.143E+00
       15.00         2.79        0.127E+00
       20.00         3.38        0.118E+00
       25.00         3.93        0.111E+00
       30.00         4.47        0.107E+00
       35.00         4.98        0.103E+00
       40.00         5.48        0.996E-01
       45.00         5.96        0.968E-01
       50.00         6.43        0.945E-01
       55.00         6.90        0.924E-01
       60.00         7.35        0.906E-01
       65.00         7.79        0.889E-01
       70.00         8.23        0.874E-01
       75.00         8.66        0.861E-01
       80.00         9.09        0.848E-01
       85.00         9.50        0.836E-01
       90.00         9.92        0.826E-01
       95.00        10.32        0.815E-01
      100.00        10.73        0.806E-01
      105.00        11.13        0.797E-01
      110.00        11.52        0.789E-01
      115.00        11.91        0.781E-01
      120.00        12.30        0.773E-01
      125.00        12.68        0.766E-01
      130.00        13.06        0.760E-01
      135.00        13.44        0.753E-01
      140.00        13.81        0.747E-01
      145.00        14.18        0.741E-01
      150.00        14.55        0.736E-01
      155.00        14.91        0.730E-01
      160.00        15.28        0.725E-01
      165.00        15.64        0.720E-01
      170.00        15.99        0.715E-01
```

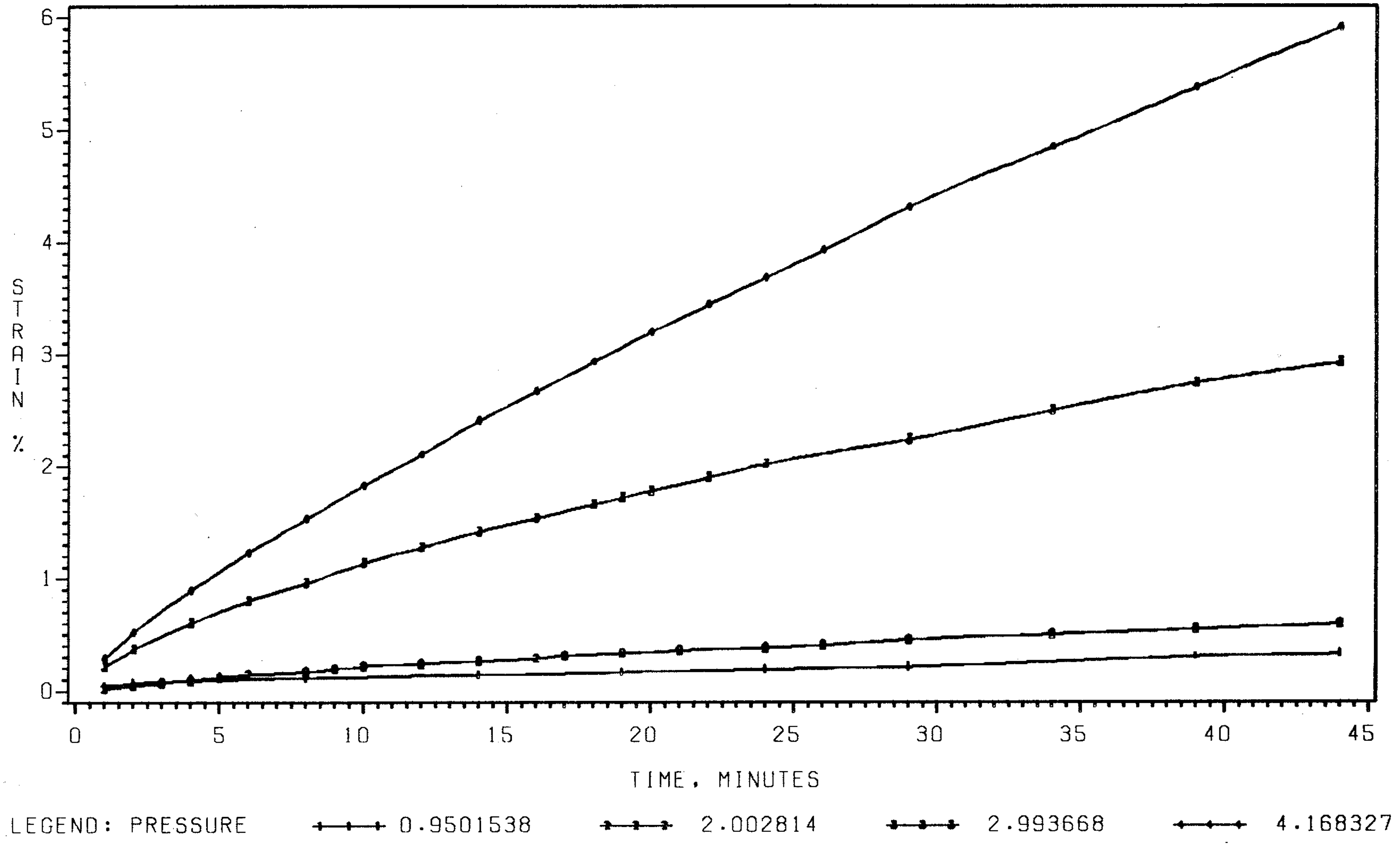
Appendix F

MODIFIED LADANYI METHOD (MLM)

F.1 MLM WITH PT202A, PT203, PT204 AND PT212

PLOT OF STRAIN VS TIME AT EACH PRESSURE

SINGLE-STAGE PRESSUREMETER TESTS

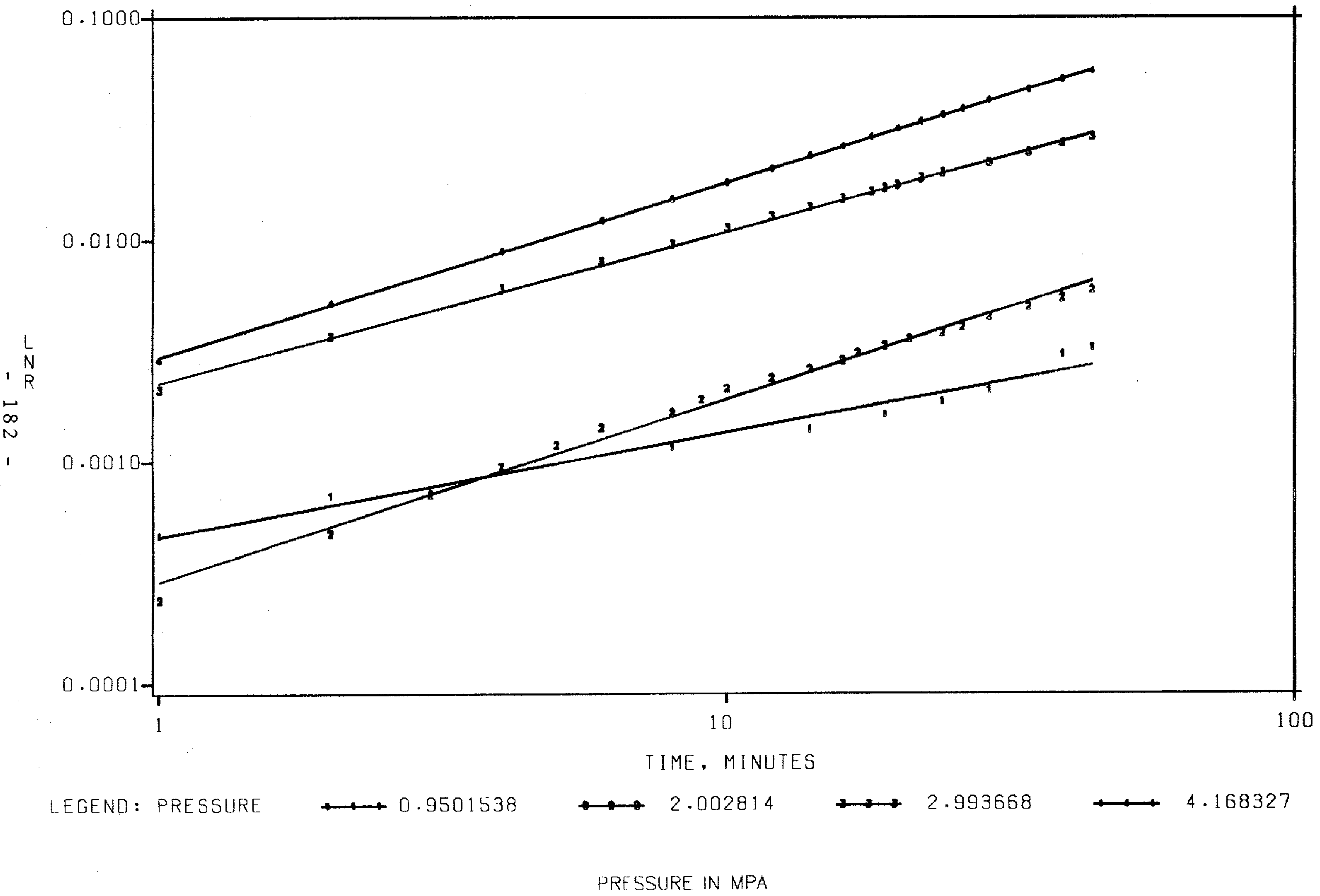


PRESSURE IN MPA

```
                DATA SET USERNAME.SAS.PT# CREATED BY ACTH/S PROGRAM

TIME    LOGTIME       PI      PRESSURE     STRAIN       RATE          LNR         LOGLNR

  1     0.00000    0.92573    0.95015    0.04663    0.046626    0.0004662      3.3314
  2     0.30103    0.92457    0.95015    0.06997    0.023340    0.0006995      3.1552
  4     0.60206    0.92842    0.95015    0.09330    0.011667    0.0009326      3.0303
  8     0.90309    0.92526    0.95015    0.11660    0.005824    0.0011653      2.9335
 14     1.14613    0.92511    0.95015    0.13994    0.003890    0.0013984      2.8544
 19     1.27875    0.92495    0.95015    0.16324    0.004661    0.0016311      2.7875
 24     1.38021    0.92480    0.95015    0.18658    0.004667    0.0018641      2.7295
 29     1.46240    1.00765    0.95015    0.20989    0.004662    0.0020967      2.6785
 39     1.59106    1.01004    0.95015    0.30318    0.009329    0.0030272     -2.5190
 44     1.64345    1.00989    0.95015    0.32648    0.004661    0.0032595      2.4868
  1     0.00000    2.00523    2.00281    0.02385    0.023837    0.0002385      3.6225
  2     0.30103    2.00509    2.00281    0.04770    0.023848    0.0004769      3.3216
  3     0.47712    2.00495    2.00281    0.07150    0.023801    0.0007148     -3.1458
  4     0.60206    2.00481    2.00281    0.09535    0.023845    0.0009530      3.0209
  5     0.69897    2.00467    2.00281    0.11915    0.023806    0.0011908     -2.9241
  6     0.77815    2.00453    2.00281    0.14300    0.023842    0.0014289      2.8450
  8     0.90309    2.00439    2.00281    0.16681    0.011906    0.0016667     -2.7781
  9     0.95424    2.00426    2.00281    0.19065    0.023847    0.0019047     -2.7202
 10     1.00000    2.00412    2.00281    0.21446    0.023808    0.0021423     -2.6691
 12     1.07918    1.99398    2.00281    0.23827    0.011905    0.0023799     -2.6234
 14     1.14613    1.99385    2.00281    0.26212    0.011923    0.0026178     -2.5821
 16     1.20412    1.99371    2.00281    0.28593    0.011908    0.0028553      2.5444
 17     1.23045    1.99358    2.00281    0.30979    0.023851    0.0030931     -2.5096
 19     1.27875    2.01344    2.00281    0.33360    0.011906    0.0033304     -2.4775
 21     1.32222    2.01331    2.00281    0.35741    0.011908    0.0035678     -2.4476
 24     1.38021    2.01317    2.00281    0.38127    0.007950    0.0038054     -2.4196
 26     1.41497    2.01304    2.00281    0.40509    0.011910    0.0040427     -2.3933
 29     1.46240    2.01278    2.00281    0.45276    0.015891    0.0045174     -2.3451
 34     1.53148    2.00251    2.00281    0.50039    0.009527    0.0049915     -2.3018
 39     1.59106    2.00225    2.00281    0.54804    0.009529    0.0054654     -2.2624
 44     1.64345    2.00199    2.00281    0.59572    0.009536    0.0059395     -2.2263
  1     0.00000    2.98895    2.99367    0.21265    0.212629    0.0021242     -2.6728
  2     0.30103    2.98549    2.99367    0.36856    0.155912    0.0036788     -2.4343
  4     0.60206    2.98033    2.99367    0.60374    0.117591    0.0060193     -2.2205
  6     0.77815    2.97605    2.99367    0.80100    0.098626    0.0079780     -2.0981
  8     0.90309    3.00265    2.99367    0.95915    0.079076    0.0095458     -2.0202
 10     1.00000    2.99883    2.99367    1.13814    0.089498    0.0113171      1.9463
 12     1.07918    2.99587    2.99367    1.27739    0.069623    0.0126930     -1.8964
 14     1.14613    2.99293    2.99367    1.41700    0.069805    0.0140705     -1.8517
 16     1.20412    2.99041    2.99367    1.53675    0.059875    0.0152506     -1.8167
 18     1.25527    2.98790    2.99367    1.65675    0.059998    0.0164317     -1.7843
 19     1.27875    2.98664    2.99367    1.71682    0.060075    0.0170225     -1.7690
 20     1.30103    3.00539    2.99367    1.77694    0.060119    0.0176134     -1.7542
 22     1.34242    3.00289    2.99367    1.89731    0.060184    0.0187953     -1.7259
 24     1.38021    3.00040    2.99367    2.01785    0.060270    0.0199776     -1.6995
 29     1.46240    2.99585    2.99367    2.23877    0.044184    0.0221407      1.6548
 34     1.53148    2.99050    2.99367    2.50087    0.052422    0.0247011     -1.6073
 39     1.59106    2.98558    2.99367    2.74326    0.048477    0.0270631      1.5676
 44     1.64345    2.98191    2.99367    2.92508    0.036365    0.0288312      1.5401
  1     0.00000    4.11420    4.16833    0.28805    0.288021    0.0028764      2.5412
  2     0.30103    4.10905    4.16833    0.52149    0.233435    0.0052013      2.2839
  4     0.60206    4.10095    4.16833    0.89409    0.186300    0.0089011      2.0506
  6     0.77815    4.09377    4.16833    1.23034    0.168127    0.0122283      1.9126
  8     0.90309    4.08748    4.16833    1.52838    0.149020    0.0151682      1.8191
 10     1.00000    4.13123    4.16833    1.82788    0.149748    0.0181137      1.7420
 12     1.07918    4.12544    4.16833    2.10822    0.140170    0.0208630      1.6806
 14     1.14613    4.11927    4.16833    2.40977    0.150778    0.0238120      1.6232
 16     1.20412    4.11395    4.16833    2.67151    0.130868    0.0263645      1.5790
 18     1.25527    4.10866    4.16833    2.93389    0.131193    0.0289168      1.5388
 20     1.30103    4.12340    4.16833    3.19687    0.131490    0.0314684      1.5021
 22     1.34242    4.11856    4.16833    3.44001    0.121568    0.0338216      1.4708
 24     1.38021    4.11375    4.16833    3.68358    0.121787    0.0361736      1.4416
 26     1.41497    4.10896    4.16833    3.92763    0.122021    0.0385246      1.4143
 29     1.46240    4.13142    4.16833    4.31497    0.129115    0.0422447      1.3742
 34     1.53148    4.12118    4.16833    4.84614    0.106233    0.0473237      1.3249
 39     1.59106    4.11102    4.16833    5.37916    0.106604    0.0523947      1.2807
 44     1.64345    4.10096    4.16833    5.91396    0.106961    0.0574569      1.2407
```

SOLUTION OF CREEP PARAMETERS

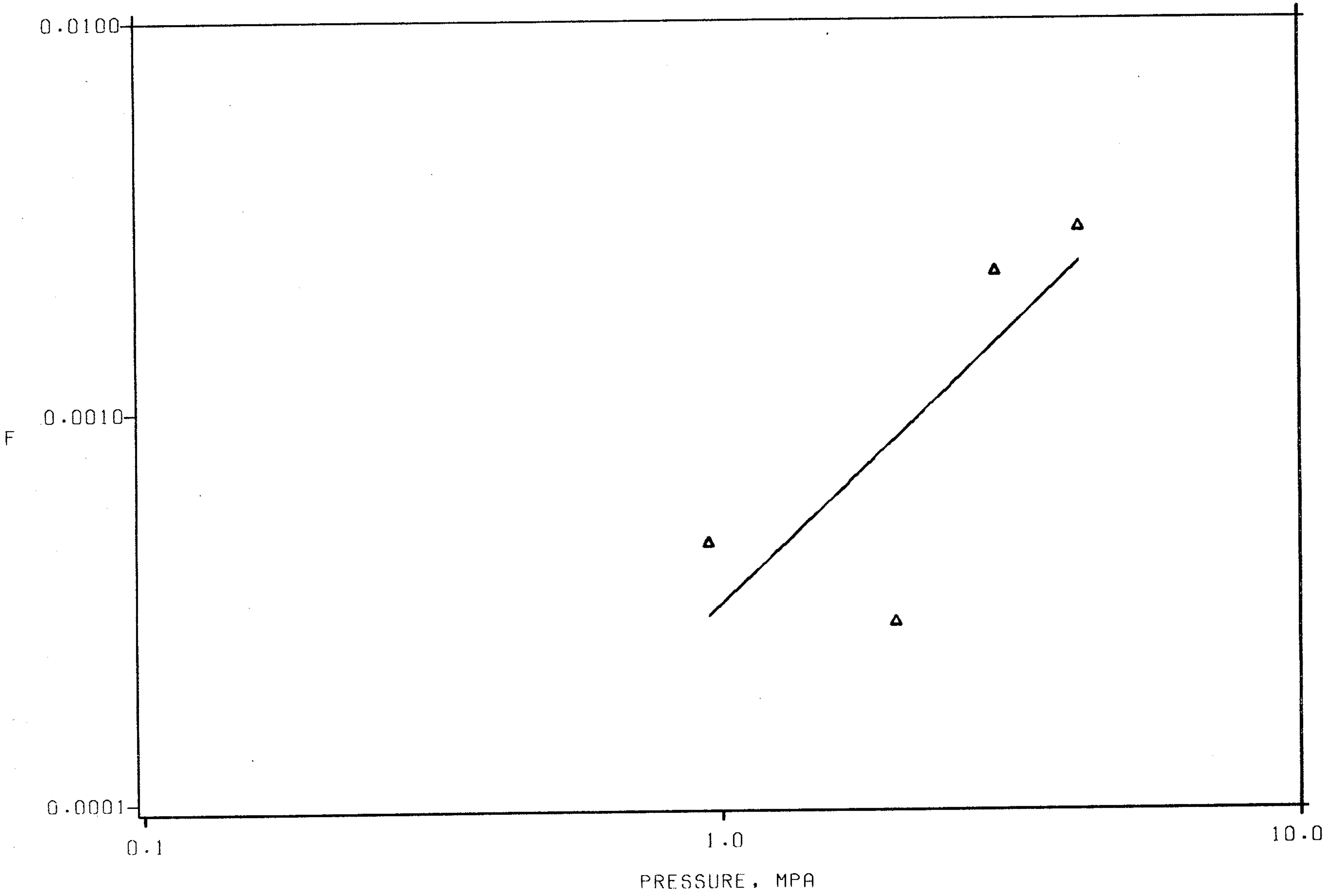
SINGLE-STAGE PRESSUREMETER TESTS



```
                                                   SUMMARY OF CREEP PARAMETERS B AND F

 OBS   PRESSURE   _TYPE_   _MODEL_   _DEPVAR_    _SIGMA_    LOGLNR   LOGTIME     LOGF       FVALUE      BSLOPE      LOGPI

  1    0.95015     OLS               LOGLNR    0.0523470     -1     0.469400   -3.3345   0.00046293   0.469400   -0.022206
  2    2.00281     OLS               LOGLNR    0.0337618     -1     0.823815   -3.5383   0.00028956   0.823815    0.301641
  3    2.99367     OLS               LOGLNR    0.0120656      1     0.681363   -2.6417   0.00228194   0.681363    0.476204
  4    4.16833     OLS               LOGLNR    0.0046152     -1     0.787593    2.5290   0.00295810   0.787593    0.619962
```

SOLUTION OF CREEP PARAMETERS

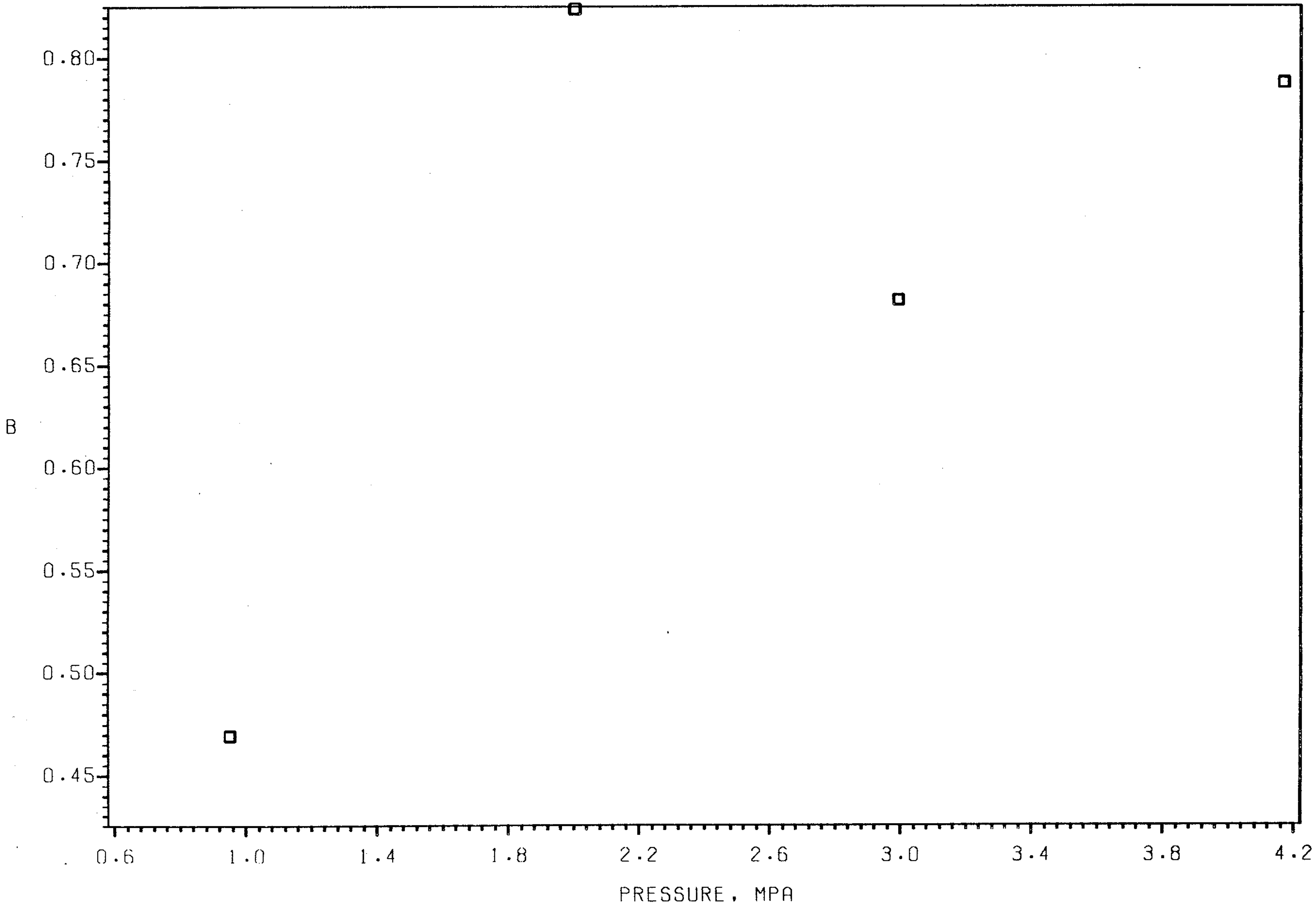
SINGLE-STAGE PRESSUREMETER TESTS



```
                                         ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT
                   SUM OF         MEAN
SOURCE    DF      SQUARES       SQUARE      F VALUE       PROB>F

MODEL      1     0.453505     0.453505        3.045       0.2231
ERROR      2     0.297865     0.148933
C TOTAL    3     0.751371

    ROOT MSE     0.385918     R-SQUARE       0.6036
    DEP MEAN    -3.010858     ADJ R-SQ       0.4054
    C.V.         -12.8175

                PARAMETER     STANDARD   T FOR H0:                    VARIABLE
VARIABLE  DF     ESTIMATE        ERROR  PARAMETER=0   PROB > |T|       LABEL

INTERCEP   1    -3.494250     0.337595      -10.350       0.0092  INTERCEPT
LOGPI      1     1.405620     0.805511        1.745       0.2231



                             SUMMARY OF CREEP PARAMETERS F1 AND N

OBS    _TYPE_    _MODEL_    _DEPVAR_    _SIGMA_     LOGF    NSLOPE      LOGF1         F1

 1      OLS                   LOGF      0.385918     -1     1.40562     3.4943    0.000320442
```

VARIATION OF B WITH PRESSURE

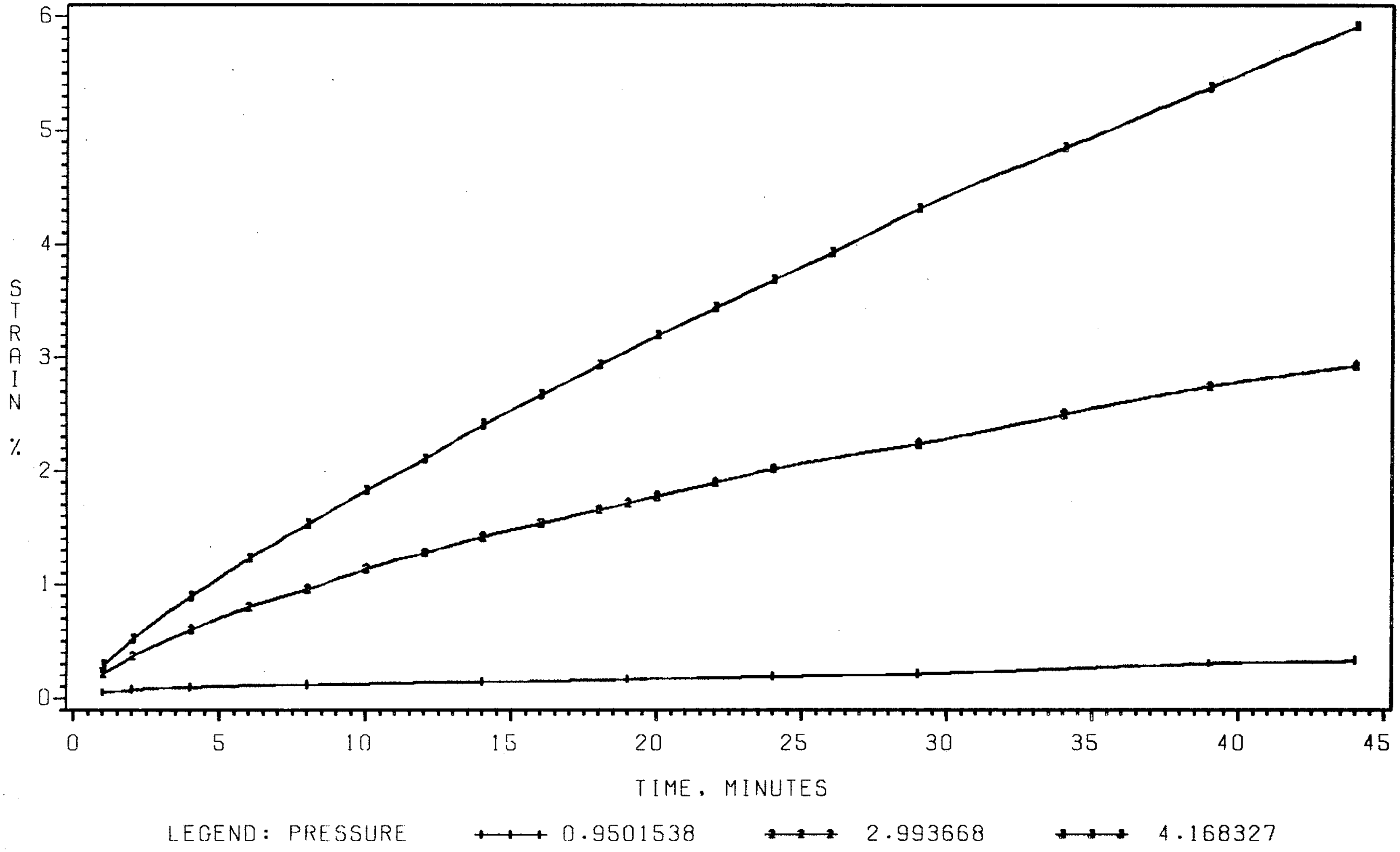
SINGLE-STAGE PRESSUREMETER TESTS



F.2 <u>MLM WITH PT202A, PT203 AND PT204</u>

PLOT OF STRAIN VS TIME AT EACH PRESSURE

SINGLE-STAGE PRESSUREMETER TESTS

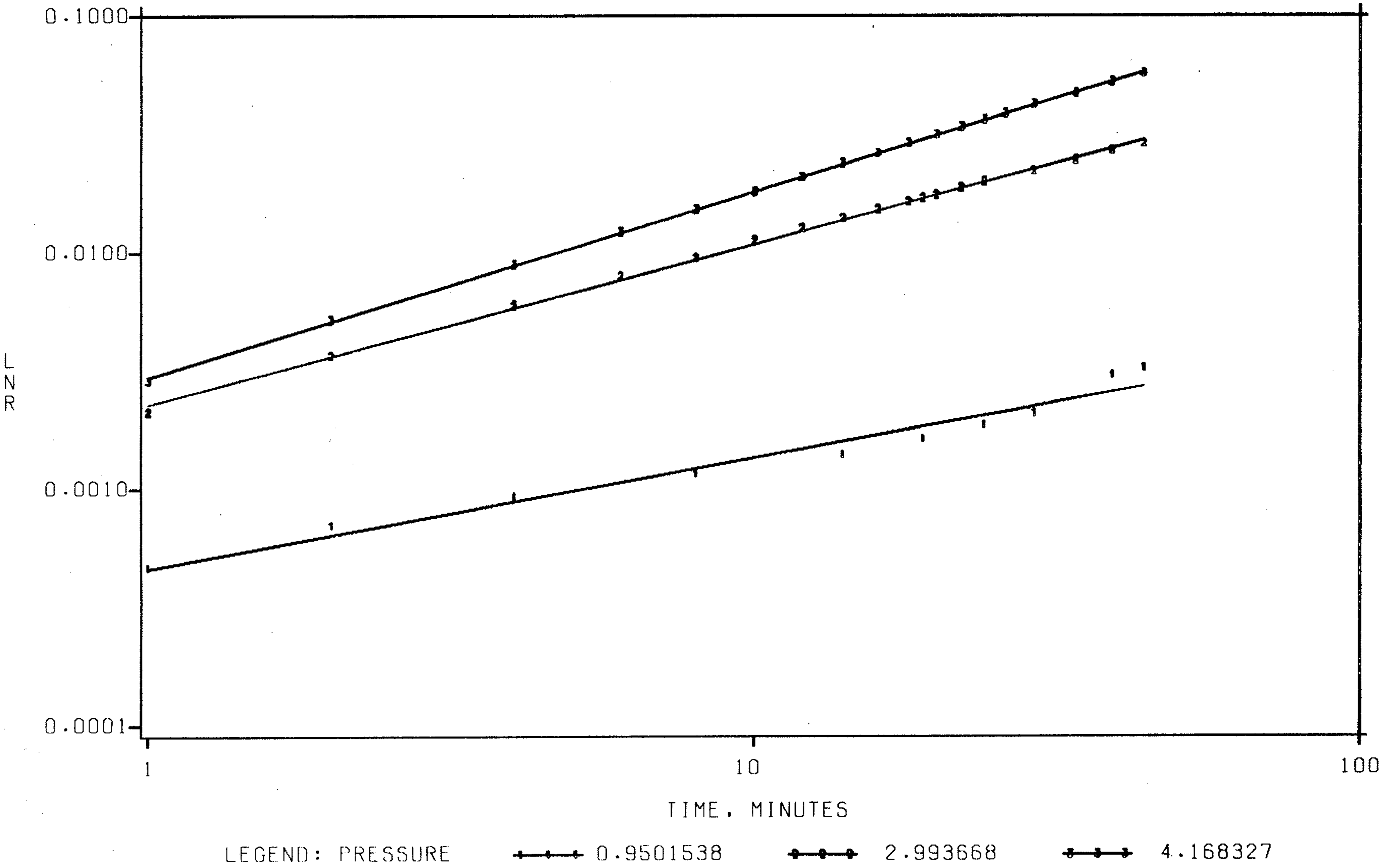


PRESSURE IN MPA

```
              DATA SET USERNAME.SAS.PT# CREATED BY ACTH/S PROGRAM

TIME    LOGTIME      PI       PRESSURE    STRAIN      RATE         LNR       LOGLNR

  1     0.00000    0.92573    0.95015    0.04663    0.046626    0.0004662    3.3314
  2     0.30103    0.92457    0.95015    0.06997    0.023340    0.0006995    3.1552
  4     0.60206    0.92842    0.95015    0.09330    0.011667    0.0009326    3.0303
  8     0.90309    0.92526    0.95015    0.11660    0.005824    0.0011653    2.9335
 14     1.14613    0.92511    0.95015    0.13994    0.003890    0.0013984    2.8544
 19     1.27875    0.92495    0.95015    0.16324    0.004661    0.0016311    2.7875
 24     1.38021    0.92480    0.95015    0.18658    0.004667    0.0018641    2.7295
 29     1.46240    1.00765    0.95015    0.20989    0.004662    0.0020967    2.6785
 39     1.59106    1.01004    0.95015    0.30318    0.009329    0.0030272    2.5190
 44     1.64345    1.00989    0.95015    0.32648    0.004661    0.0032595    2.4868
  1     0.00000    2.98895    2.99367    0.21265    0.212629    0.0021242    2.6728
  2     0.30103    2.98549    2.99367    0.36856    0.155912    0.0036788    2.4343
  4     0.60206    2.98033    2.99367    0.60374    0.117591    0.0060193    2.2205
  6     0.77815    2.97605    2.99367    0.80100    0.098626    0.0079780    2.0981
  8     0.90309    3.00265    2.99367    0.95915    0.079076    0.0095458    2.0202
 10     1.00000    2.99883    2.99367    1.13814    0.089498    0.0113171    1.9463
 12     1.07918    2.99587    2.99367    1.27739    0.069623    0.0126930    1.8964
 14     1.14613    2.99293    2.99367    1.41700    0.069805    0.0140705    1.8517
 16     1.20412    2.99041    2.99367    1.53675    0.059875    0.0152506    1.8167
 18     1.25527    2.98790    2.99367    1.65675    0.059998    0.0164317    1.7843
 19     1.27875    2.98664    2.99367    1.71682    0.060075    0.0170225    1.7690
 20     1.30103    3.00539    2.99367    1.77694    0.060119    0.0176134    1.7542
 22     1.34242    3.00289    2.99367    1.89731    0.060184    0.0187953    1.7259
 24     1.38021    3.00040    2.99367    2.01785    0.060270    0.0199776    1.6995
 29     1.46240    2.99585    2.99367    2.23877    0.044184    0.0221407    1.6548
 34     1.53148    2.99050    2.99367    2.50087    0.052422    0.0247011    1.6073
 39     1.59106    2.98558    2.99367    2.74326    0.048477    0.0270631    1.5676
 44     1.64345    2.98191    2.99367    2.92508    0.036365    0.0288312    1.5401
  1     0.00000    4.11420    4.16833    0.28805    0.288021    0.0028764    2.5412
  2     0.30103    4.10905    4.16833    0.52149    0.233435    0.0052013    2.2839
  4     0.60206    4.10095    4.16833    0.89409    0.186300    0.0089011    2.0506
  6     0.77815    4.09377    4.16833    1.23034    0.168127    0.0122283    1.9126
  8     0.90309    4.08748    4.16833    1.52838    0.149020    0.0151682    1.8191
 10     1.00000    4.13123    4.16833    1.82788    0.149748    0.0181137    1.7420
 12     1.07918    4.12544    4.16833    2.10822    0.140170    0.0208630    1.6806
 14     1.14613    4.11927    4.16833    2.40977    0.150778    0.0238120    1.6232
 16     1.20412    4.11395    4.16833    2.67151    0.130868    0.0263645    1.5790
 18     1.25527    4.10866    4.16833    2.93389    0.131193    0.0289168    1.5388
 20     1.30103    4.12340    4.16833    3.19687    0.131490    0.0314684    1.5021
 22     1.34242    4.11856    4.16833    3.44001    0.121568    0.0338216    1.4708
 24     1.38021    4.11375    4.16833    3.68358    0.121787    0.0361736    1.4416
 26     1.41497    4.10896    4.16833    3.92763    0.122021    0.0385246    1.4143
 29     1.46240    4.13142    4.16833    4.31497    0.129115    0.0422447    1.3742
 34     1.53148    4.12118    4.16833    4.84614    0.106233    0.0473237    1.3249
 39     1.59106    4.11102    4.16833    5.37916    0.106604    0.0523947    1.2807
 44     1.64345    4.10096    4.16833    5.91396    0.106961    0.0574569    1.2407
```

SOLUTION OF CREEP PARAMETERS

SINGLE-STAGE PRESSUREMETER TESTS

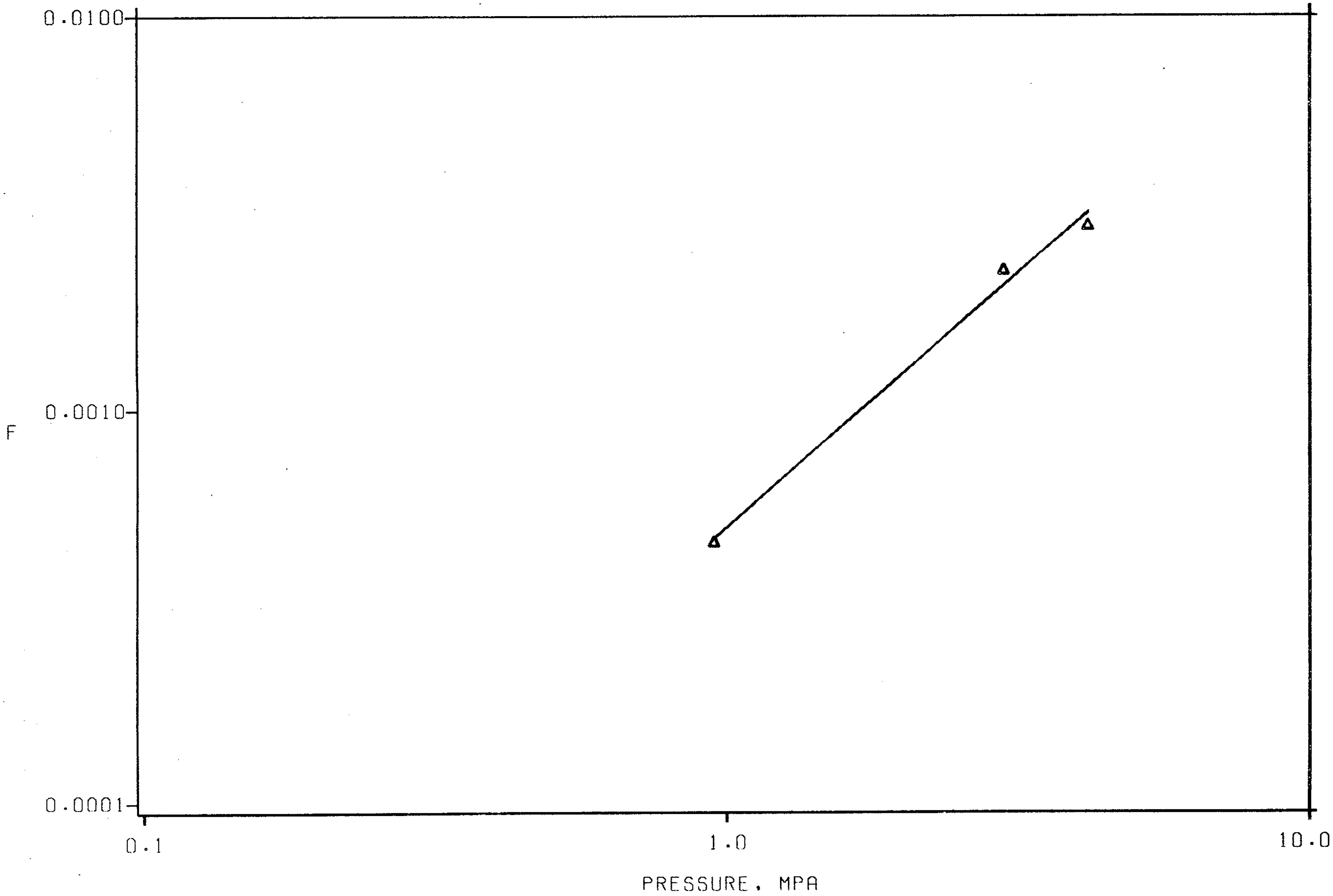


PRESSURE IN MPA

```
                                         SUMMARY OF CREEP PARAMETERS B AND F

OBS   PRESSURE   _TYPE_   _MODEL_   _DEPVAR_    _SIGMA_    LOGLNR   LOGTIME      LOGF       FVALUE       BSLOPE      LOGPI

 1    0.95015     OLS               LOGLNR    0.0523470     -1    0.469400   -3.3345   0.00046293   0.469400   -0.022206
 2    2.99367     OLS               LOGLNR    0.0120656     -1    0.681363   -2.6417   0.00228194   0.681363    0.476204
 3    4.16833     OLS               LOGLNR    0.0046152     -1    0.787593   -2.5290   0.00295810   0.787593    0.619962
```

SOLUTION OF CREEP PARAMETERS

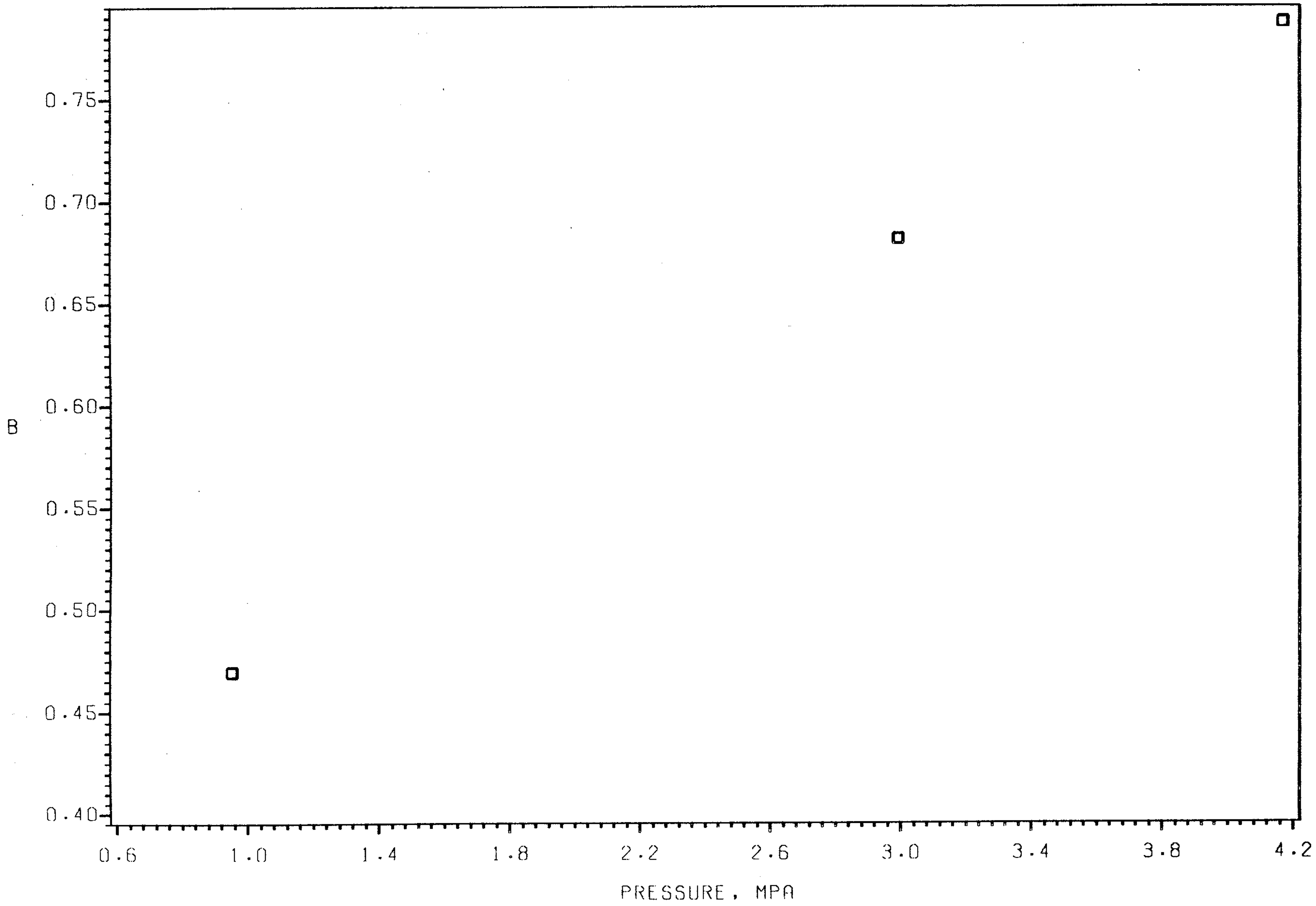
SINGLE-STAGE PRESSUREMETER TESTS



```
                                          ESTIMATES FROM LINEAR REG. ANAL. OF LOGF VS LOGPI

DEP VARIABLE: LOGF     INTERCEPT

                          SUM OF          MEAN
SOURCE      DF           SQUARES        SQUARE       F VALUE       PROB>F

MODEL        1          0.377729      0.377729       136.539       0.0543
ERROR        1        0.00276645    0.00276645
C TOTAL      2          0.380496

    ROOT MSE            0.052597      R-SQUARE        0.9927
    DEP MEAN           -2.835056      ADJ R-SQ        0.9855
    C.V.                -1.85524

                       PARAMETER      STANDARD    T FOR H0:                        VARIABLE
VARIABLE    DF          ESTIMATE         ERROR  PARAMETER=0    PROB > |T|           LABEL

INTERCEP     1         -3.296690      0.049829      -66.160        0.0096  INTERCEPT
LOGPI        1          1.289530      0.110358       11.685        0.0543



                             SUMMARY OF CREEP PARAMETERS F1 AND N

OBS    _TYPE_    _MODEL_    _DEPVAR_     _SIGMA_     LOGF    NSLOPE      LOGF1          F1

 1      OLS                   LOGF     0.0525971      -1    1.28953    -3.2967    0.000505021
```

VARIATION OF B WITH PRESSURE

SINGLE-STAGE PRESSUREMETER TESTS



Appendix G

PAPER BY SHIELDS ET AL. (1985)

THE DEFORMATION PROPERTIES OF WARM UNDEROCEAN PERMAFROST

Donald Shields, M.A.S.C.E.*, Leonard Domaschuk*,
Herbert Fensury**, and Robert Kenyon**

Abstract

Two quasi-conventional incremental pressuremeter tests were carried out on man-made specimens of 'warm' (-3°C) frozen, saturated sand. Instead of each increment of pressure lasting one minute, as is the case in the conventional pressuremeter test, each increment was maintained for 45 minutes. The results of these two tests were used to determine the creep parameters b, n and σ_c which are required for Ladanyi's theory for the long term creep behaviour of frozen soil.

Ladanyi's theory was then used to predict the creep strain during four long term constant pressure pressuremeter tests on the same warm frozen sand. Of the four tests, which were carried out at pressures of 1, 2, 3 and 4 MPa, Ladanyi's theory showed promise in only one case, namely the test at the highest pressure (4 MPa). One reason why the 'fit' was good at 4 MPa was the short duration of this constant pressure test in comparison with the others; the 4 MPa constant pressure test reached the limit of strain for the pressuremeter in only 170 minutes, that is to say that the test lasted only four times longer than the incremental test, whereas the other tests lasted from 27 to 667 times longer than the incremental test.

Introduction

In 1980 the oil and gas industry in Canada identified three 'unknowns' of engineering concern for the future development of the Beaufort Sea petroleum reserves. One of these unknowns was the long term deformation properties of undersea warm permafrost. (The other two were 1) ice scour depth and frequency and 2) the behaviour of gas hydrates.) The paper will address the problem of permafrost behaviour.

Artificial islands or atolls will be built in the Beaufort Sea to serve as production platforms for the recovery of oil and gas. Directional drilling will be used to develop as many as twenty (inclined) production wells from one island. A real concern facing the petroleum industry is the magnitude of the settlement the islands will undergo during their working lives. A realistic assessment of the probable settlement is required if the well casings are to be designed to withstand the resulting deformation and stresses without fracture. Many of the islands will be built over warm (-2° to -3°C)

---

*Professor, **Graduate Student, Civil Engineering Department, University of Manitoba, Winnipeg, Manitoba R3T 2N2.

permafrost; very little is known about the long term (creep) deformation behaviour of this material.

In the case of gas wells, settlement will be due (mainly) to the long term deformation of the permafrost under relatively constant temperature conditions. In the case of oil wells, the natural warmth of the oil will add the complication of thaw-settlement to the stress induced, creep deformation settlement. We at Manitoba are investigating the constant temperature creep deformation properties of warm permafrost with financial support from the Natural Sciences and Engineering Research Council of Canada under the Strategic Grants Program.

Two approaches are being taken: 1) laboratory triaxial tests to measure bulk and shear creep deformation properties and 2) pressuremeter tests to measure creep parameters in situ. Given the difficulty of recovering and testing representative specimens of warm, marine permafrost, in situ tests of the pressuremeter type will probably be used in practice. A method has to be found for the prediction of long-term creep characteristics from short-term pressurementer data. As far as we know, only one attempt in this regard has appeared in the literature. In this paper we examine this attempt, being state-of-the-art because of its uniqueness, in light of our own test results. Our pressuremeter creep-tests were performed on warm frozen sand of a kind found under the Beaufort Sea.

State-of-the-Art - Ladanyi's Theory

A method for determining the creep parameters of frozen soil has been suggested by Ladanyi and Johnston (1973) ,(1978). A recent paper describing the pressuremeter test in frozen sand is that of Ladanyi and Eckardt (1983). According to above-mentioned papers the total strain attained on an ice-rich frozen soil, after a given time, under a constant stress, was given by

$$\varepsilon_e = \varepsilon_e^{(i)} + \varepsilon_e^{(c)} , \tag{1}$$

where $\varepsilon_e^{(i)}$ is the instantaneous portion of the total strain and $\varepsilon_e^{(c)}$ is the time dependent creep strain, which is expressed by a power law equation:

$$\varepsilon_e^{(c)} = \left(\frac{\dot{\varepsilon}_c}{b}\right)^b \left(\frac{\sigma_e}{\sigma_c}\right)^n t^b , \tag{2}$$

where the subscript e denotes the von Mises equivalent stress and strain, σ_c is the reference stress at the arbitrarily selected strain rate $\dot{\varepsilon}_c$, b and n are creep parameters and t is the time.

The creep expansion in a cylindrical cavity under plane strain conditions, at a constant stress $p = p_i - p_o$, applied during stage i, was in the form:

$$\ell n \ (r/r_{i-1}) = F \ t^b , \tag{3}$$

where p_i is the internal pressure on the cavity wall, p_o is the lateral pressure acting at infinity, r is the cavity radius, r_{i-1} is the cavity radius at t=0 ie. at the start of a given constant pressure creep stage, and F is defined as:

$$F = \left[\frac{\sqrt{3}}{2}\right]^{n+1} \left[\frac{\dot{\varepsilon}_c}{b}\right]^{b} \left[\frac{2\,p}{n\,\bar{\sigma}_c}\right]^{n} \tag{4}$$

in which $\bar{\sigma}_c = m\,\sigma_c$, and $m = 1 - \alpha^{2/n}$ (5)

Here m is the correction factor for the size of the sample and α is the ratio of the inner cavity radius to the outside radius of the sample.

Using the semi-graphical method described in the above mentioned references, the values of creep parameters b, n and $\bar{\sigma}_c$ were determined from a multi-stage creep test, by plotting the results in a log-log plot, firstly $[\ell n(r/r_{i-1})]$ versus time and then (F) versus the pressure p.

Test Setup and Testing Procedure

Figure 1 shows the setup of the test equipment and the frozen sand specimen. A uniform quartz-carbonate medium grain sand was used in all the tests. The sand was poured uniformly into the mold, saturated from the bottom upward with tap water, and frozen one dimensionally at a chamber temperature of -20°C. When freezing was complete, the chamber temperature was raised to -3°C. The specimens had an average dry unit weight of 14.3 kN/m^3.

The pressuremeter tests were carried out with an OYO ELASTMETER -100 pressuremeter. The instrument is a monocellular borehole extensometer which uses a caliper to measure changes in borehole radius. A hole was bored in the centre of the specimen using a modified CRREL-type hollow barrel auger. The 76.2 mm diameter cutting-head of the auger produced a smooth-walled cylindrical cavity of 78 to 79 mm in diameter. The pressuremeter was then inserted in the hole.

During a test, the pressuremeter applied a given constant pressure to the inner wall of the thick frozen sand cylinder. The pressure was held constant for a given length of time during which the change in radius of the probe was recorded. For a multi-stage test, at the end of the specified time interval (45 minutes), the pressure was increased to another level and readings were taken once again of radius change. A more detailed description of sample preparation and testing procedure can be found in Shields et al (1984).

Creep Parameters Obtained Using Ladanyi's Method

Two independent multi-stage loading tests were performed and Ladanyi's theory was applied to the results. The total strains for each loading stage of both tests PT201 and PT103 can be found in Figures 2 and 3 respectively. Following the Ladanyi and Johnston (1978) procedure the creep data were processed with pseudo-instantaneous strains to time t=1 minute, subtracted from the total strains in determining creep parameters b, n and $\bar{\sigma}_c$. The values of b for tests PT201 and PT103 were obtained from the plots in Figures 4 and 5, and an n value was obtained from the plot in Figure 6.

For PT201, the b valued range from 0.439 to 0.951, n was 1.70 and σ_c was 1.29 MPa at $\dot{\varepsilon}_c = 10^{-5}\ \text{min}^{-1}$. For PT103, the b values ranged from 0.211 to 0.911, n was 1.07 and σ_c was 1.39 MPa at $\dot{\varepsilon}_c = 10^{-1}\ \text{min}^{-1}$.

The of b values are shown plotted against pressure in Figure 7. The best fit line is given by:

$$b = 1/(0.374 + 0.101\ p + 1.219/p) \qquad (6)$$

Predicted Versus Actual Long-Term Test Strains

In equation 3,

$$\varepsilon_\theta = (e^{F\ t^b} - 1.0) \times 100\% \qquad (7)$$

since $r/r_{i-1} = 1 + {}^{\Delta r}/r_{i-1} = 1 + \varepsilon_\theta$ where ε_θ is the circumferential strain and Δr is the change in radius. Predicted total strain for any pressure level and at any time can be written as:

$$\varepsilon_{total} = \varepsilon_{ci} + \varepsilon_\theta \qquad (8)$$

where ε_{ci} is the cumulative pseudo-instantaneous strain (at 1 min) that was subtracted from the creep data for the evaluation procedure.

Using equations 4, 6, 7 and 8, predicted strains were plotted against actual strains for pressures of 1, 2, 3 and 4 MPa in Figures 8, 9, 10 and 11 respectively.

Discussion of Results

This is a straightforward test of Ladanyi's method for the creep of frozen soil. The procedures suggested by Ladanyi and Johnston and by Ladanyi and Eckardt on how to run incremental pressuremeter tests to measure the creep parameters b, n and σ_c were followed rigorously. These parameters were then used to predict the creep deformation over time of four, independent, constant pressure pressuremeter tests. The sand, sample preparation, and temperature conditions were identical for both the incremental tests and constant pressure tests. Figures 8, 9, 10 and 11 give the result.

Referring to the four figures, it is seen that for three of the four constant pressure tests, the predicted creep strain was wide of the mark. Only at the highest stress level (4 MPa) were the predicted and actual results close. In engineering terms 4 MPa represents a very high stress since it is equivalent to the vertical total stress at 200 metres depth in the ground. The results in the 1 to 3 MPa range are of greater engineering interest, that is to say in the pressure range where agreement was poor.

One reason why the predicted curve fits the actual test results at 4 MPa is the relatively short time that the corresponding incremental test result had to be extrapolated. The incremental test lasted 45 minutes whereas the 4 MPa test lasted only 170 minutes. When the 45 minute results had to be extrapolated (extended) to thousands of minutes (see for example the constant pressure test at 2 MPa which ran for 29,000 minutes), the fit was poor.

Conclusion

It has been shown that the Ladanyi's method was not able to predict the long term creep behaviour of a warm frozen sand on the basis of short term (forty-five minutes) tests.

Acknowledgements

The work described in this paper was supported financially by the Natural Sciences and Engineering Research Council of Canada and by the University of Manitoba. Special acknowledgement is due the OYO Corporation of Japan for providing the pressuremeter.

References

1. Ladanyi, B. and Eckardt, H., 1983. Dilatometer testing in thick cylinders of frozen sand. Permafrost: Proc. 4th Int. Conference, Fairbanks, Alaska, Nat. Acad. Press, Wash. D.C., pp. 677-682.

2. Ladanyi, B. and Johnston, G.H., 1973. Evaluation of in-situ creep properties of frozen soils with the pressuremeter. Proc. 2nd Int. Conf. on Permafrost, Yakutsk, North Amer. Contr. Vol. 1, pp. 13-318.

3. Ladanyi, B. and Johnston, G.H., 1978. Field investigations in frozen ground. Chap. 9 in "Geotech. Eng. for Cold Regions" (O. B Andersland and D.M. Anderson, Eds.), pp. 459-504, McGraw-Hill, New York.

4. Shields, D.H., Domaschuk, L., Man, C.-S., and Kenyon, R., 1984. The Deformation Properties of Warm Permafrost as Measured both In Situ and in the Laboratory, to appear in ASTM Symposium on Lab and In situ Strength Testing of Marine Soils.

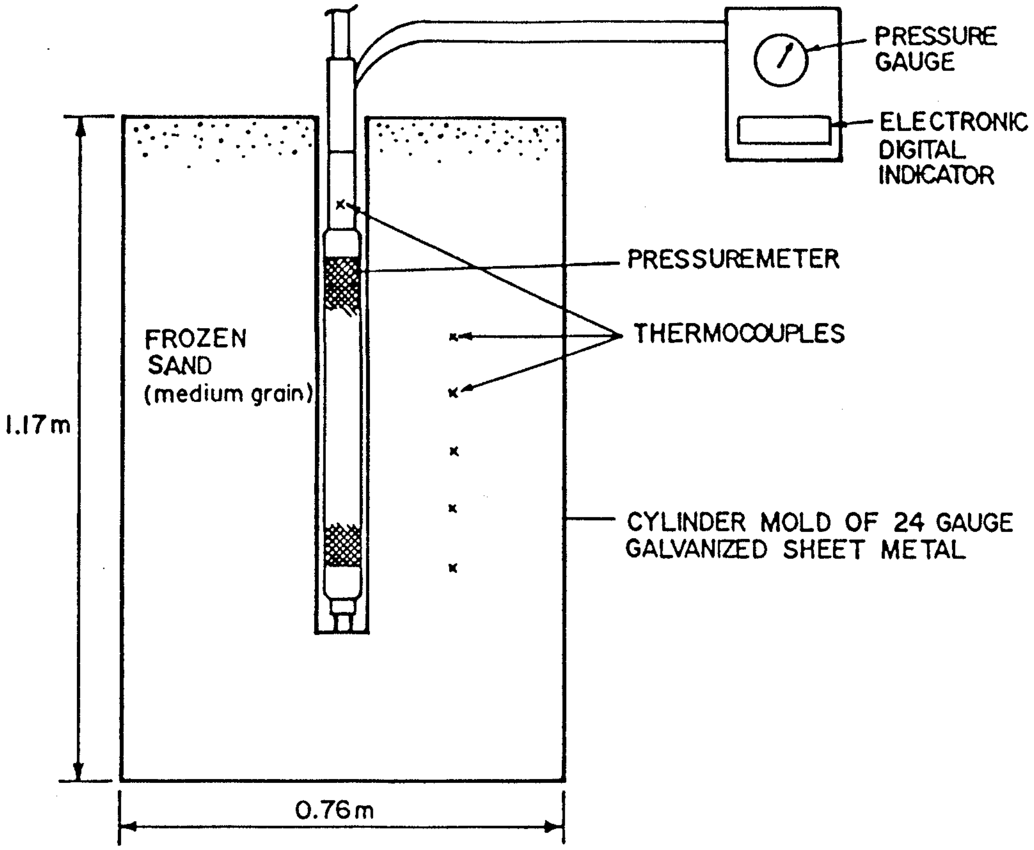


Figure 1. Schematic of Pressuremeter Test in Frozen Sand

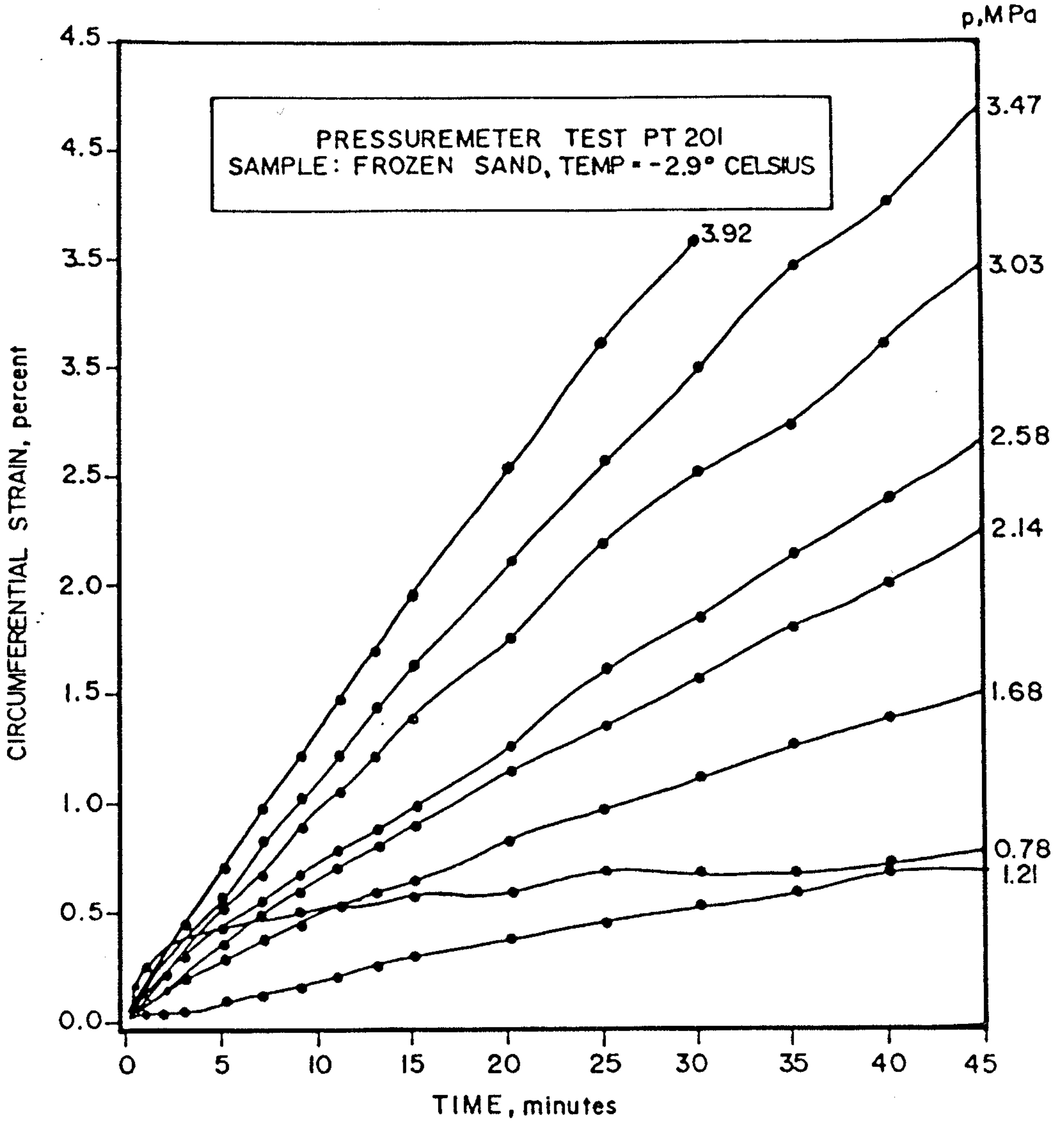


Figure 2. Strain vs. Time for Each Loading Stage

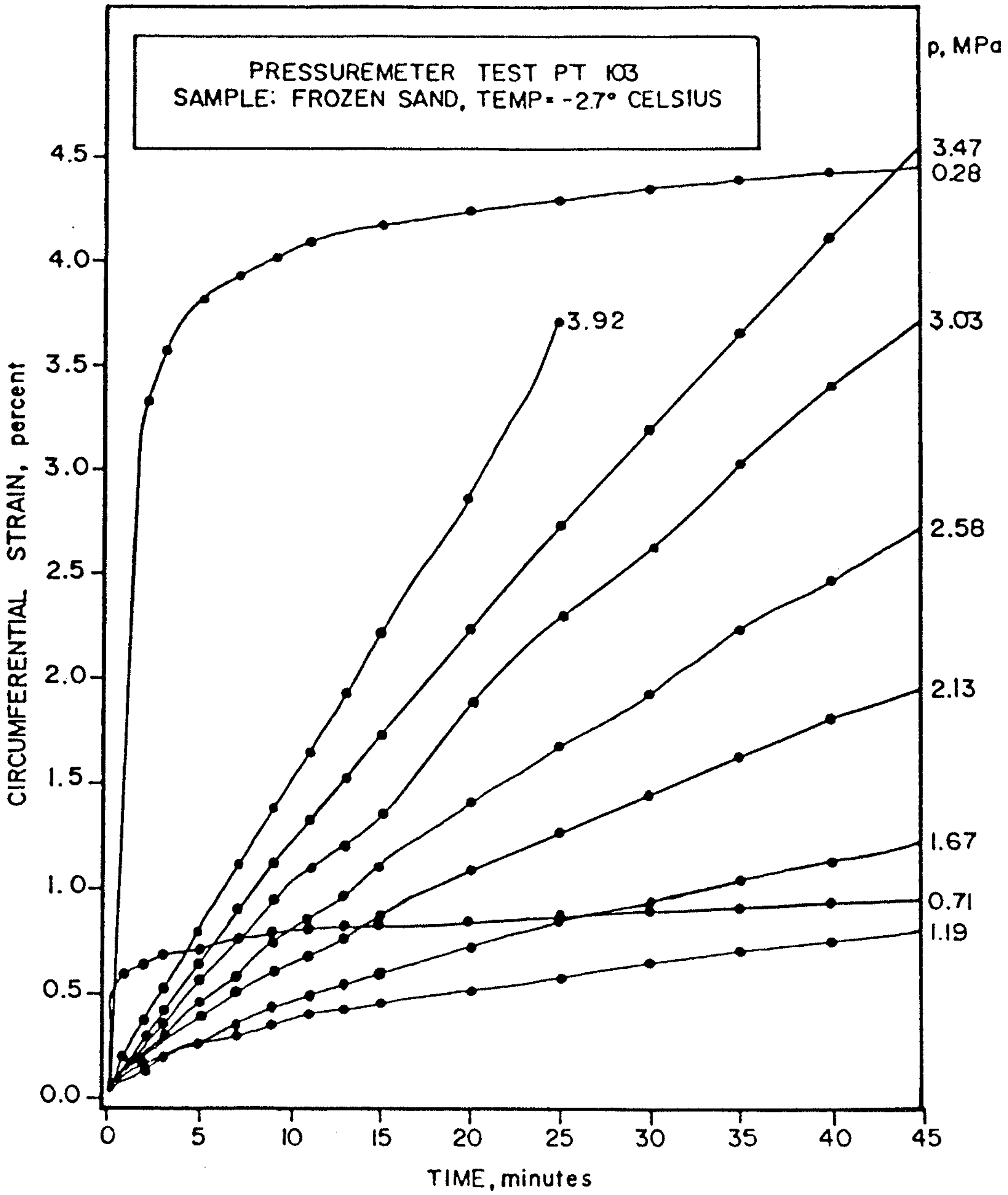


Figure 3. Strain vs. Time for Each Loading Stage

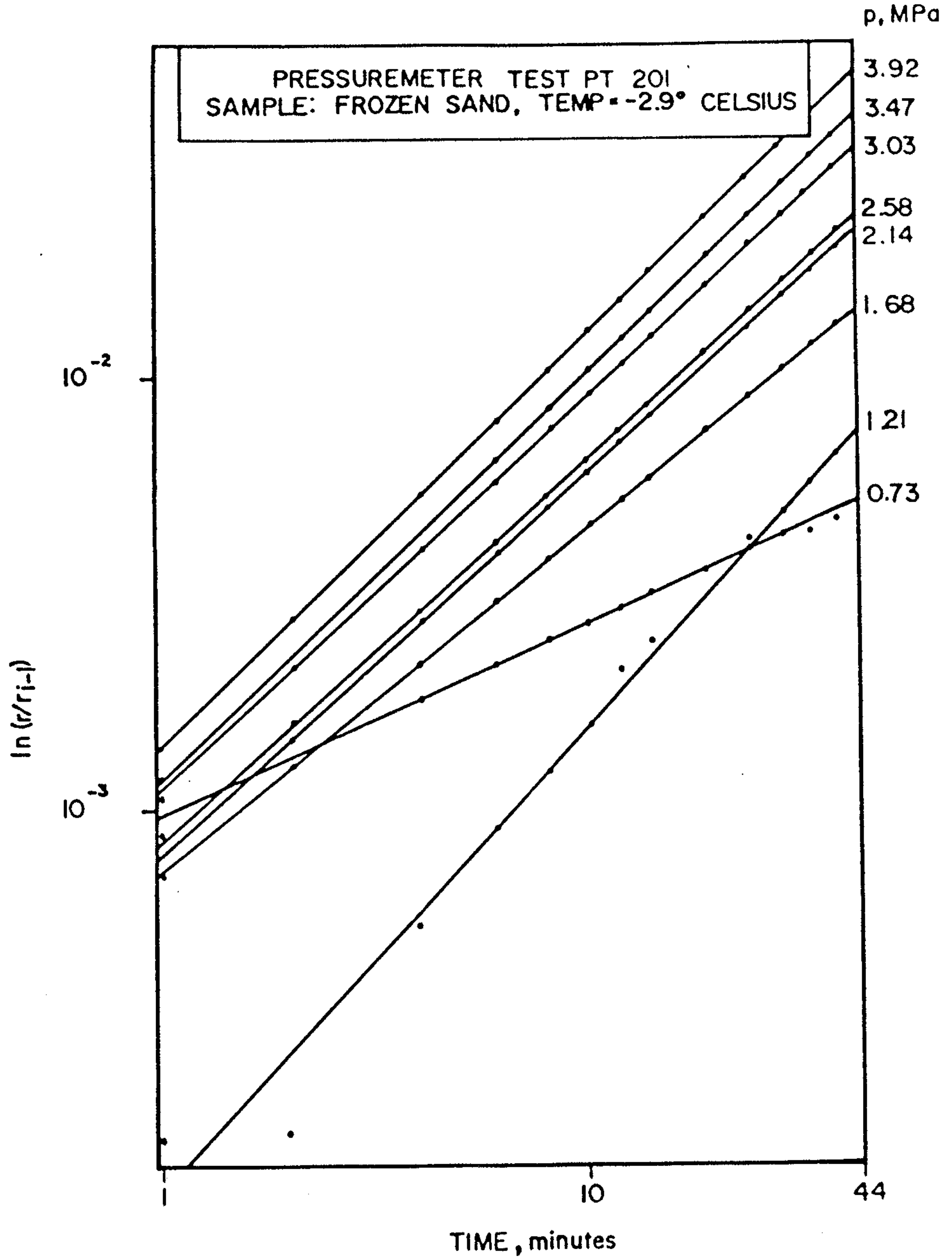


Figure 4. Determination of b and F values

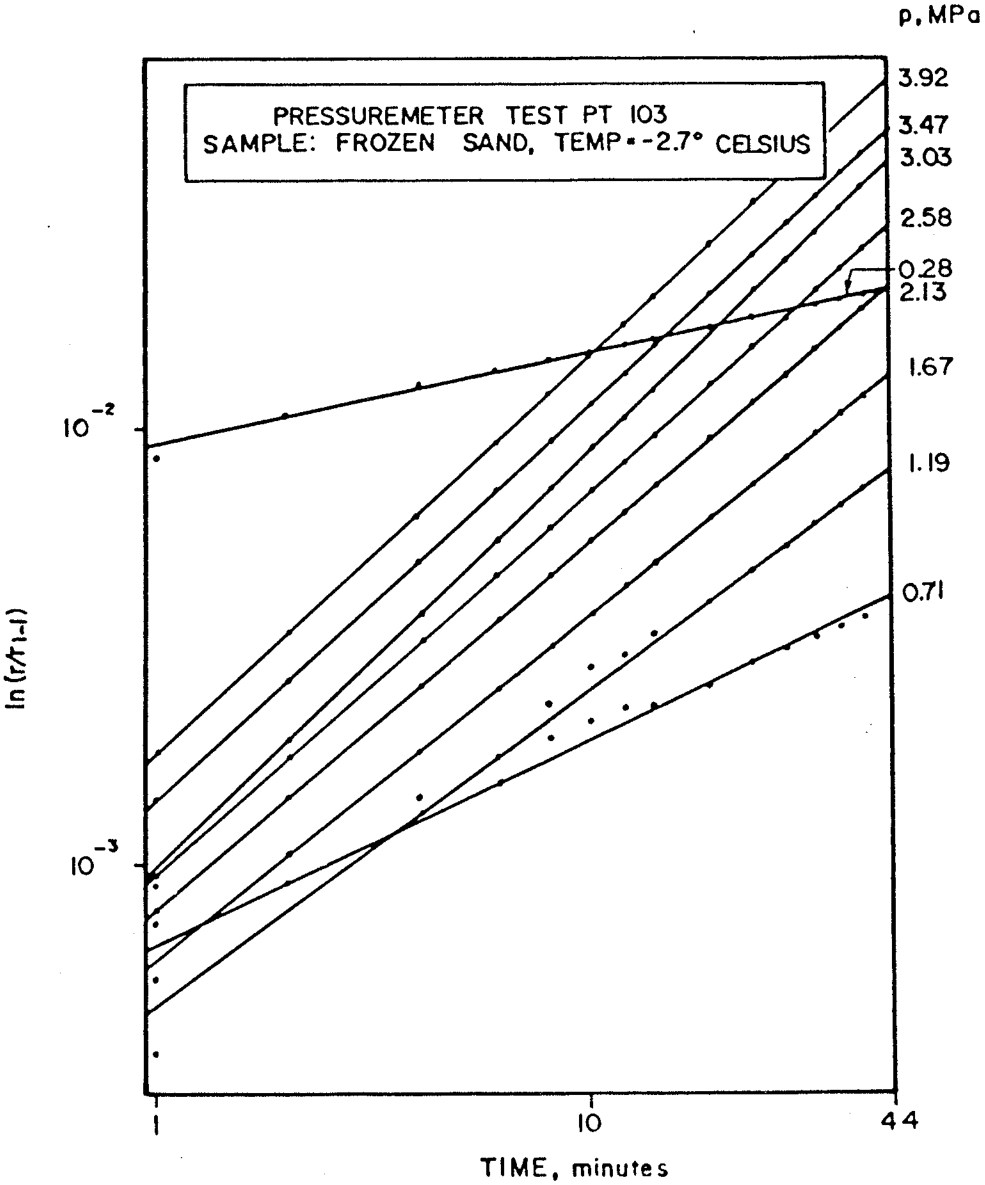


Figure 5. Determination of b and F values

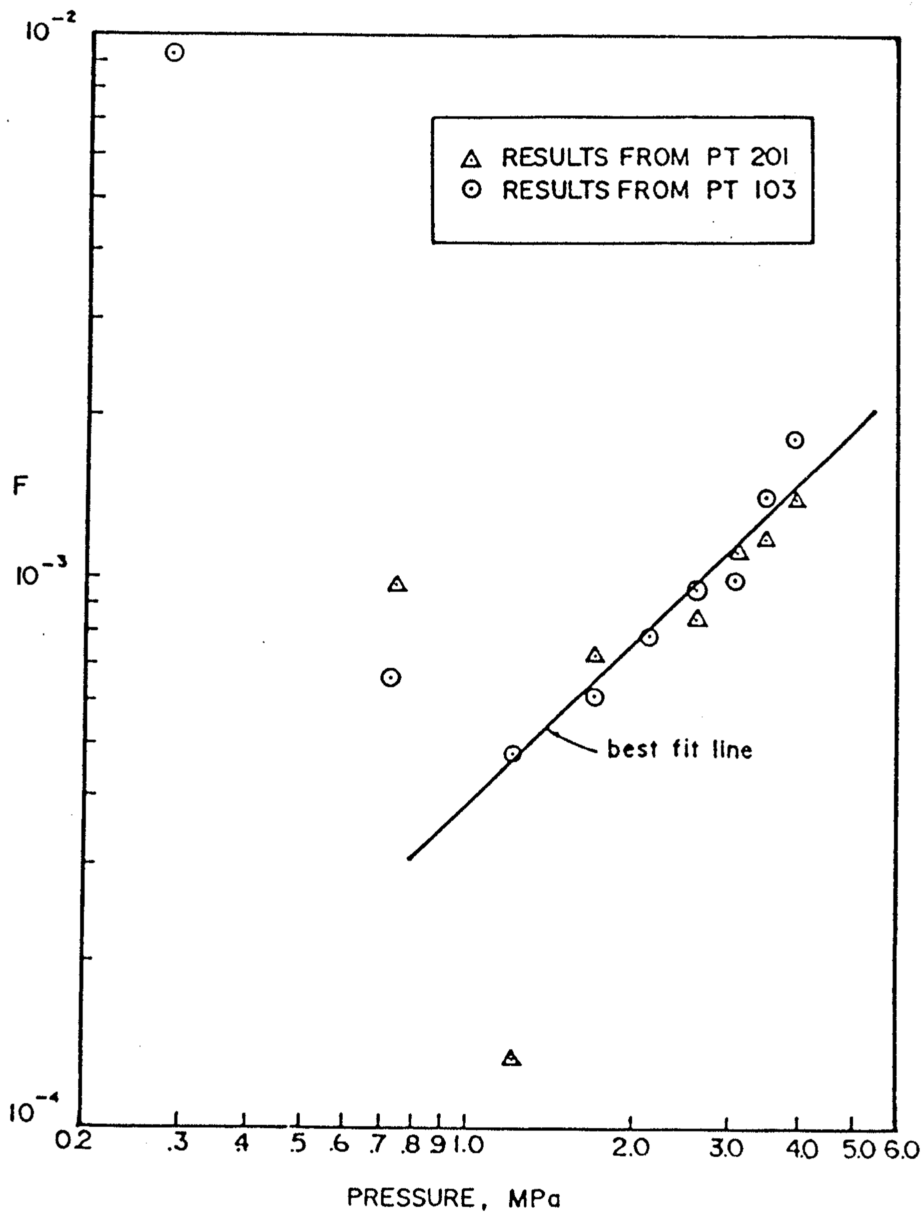


Figure 6. Determination of n and σ_c

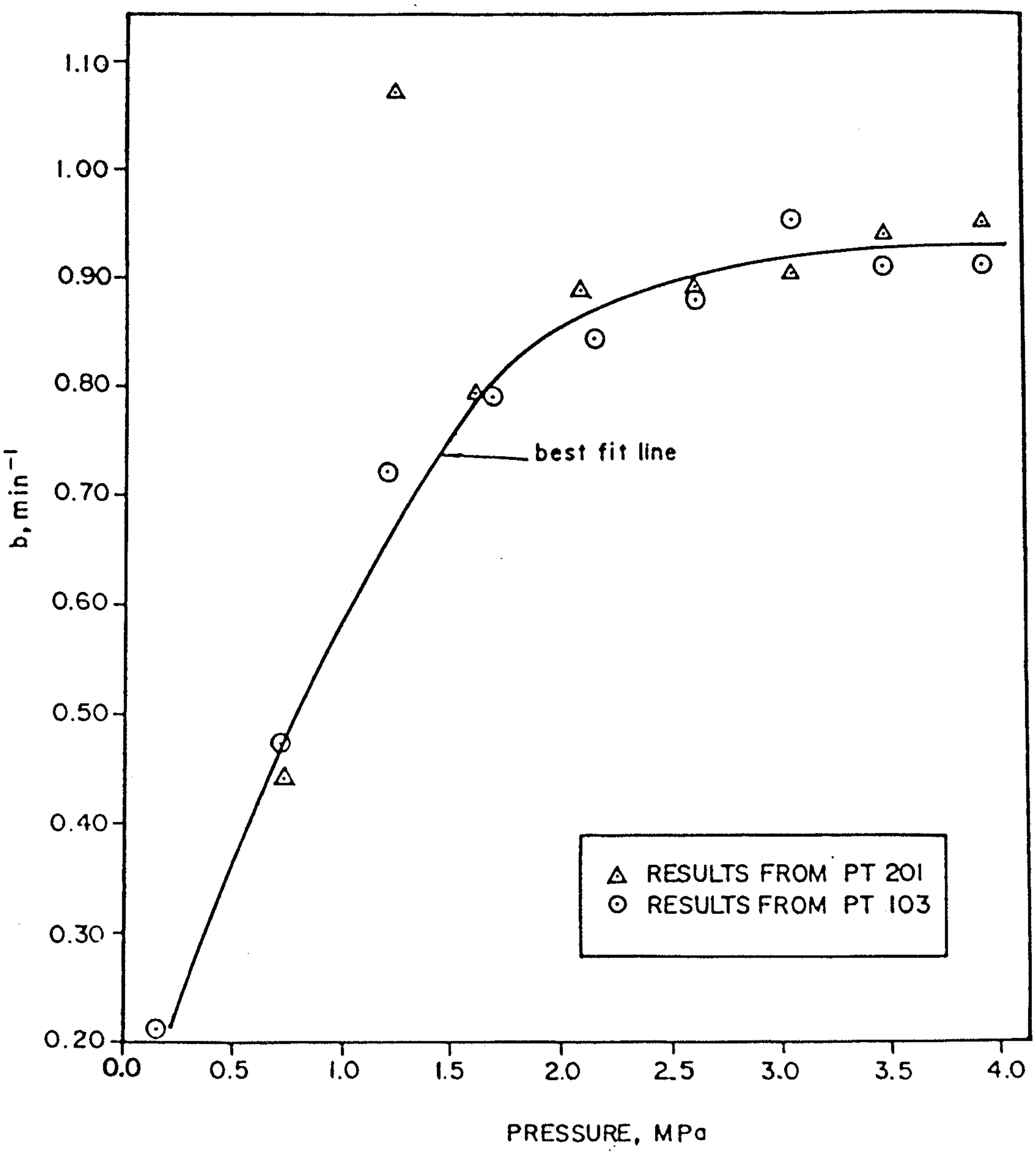


Figure 7. b values vs. pressure

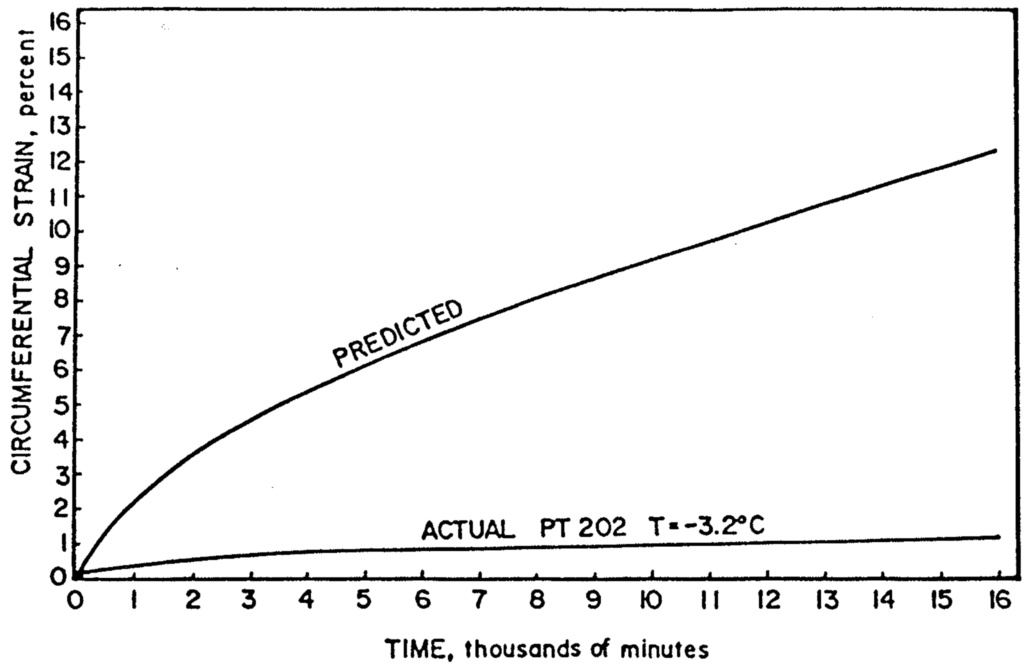


Figure 8. Actual vs. Predicted Strains at p = 1 MPa

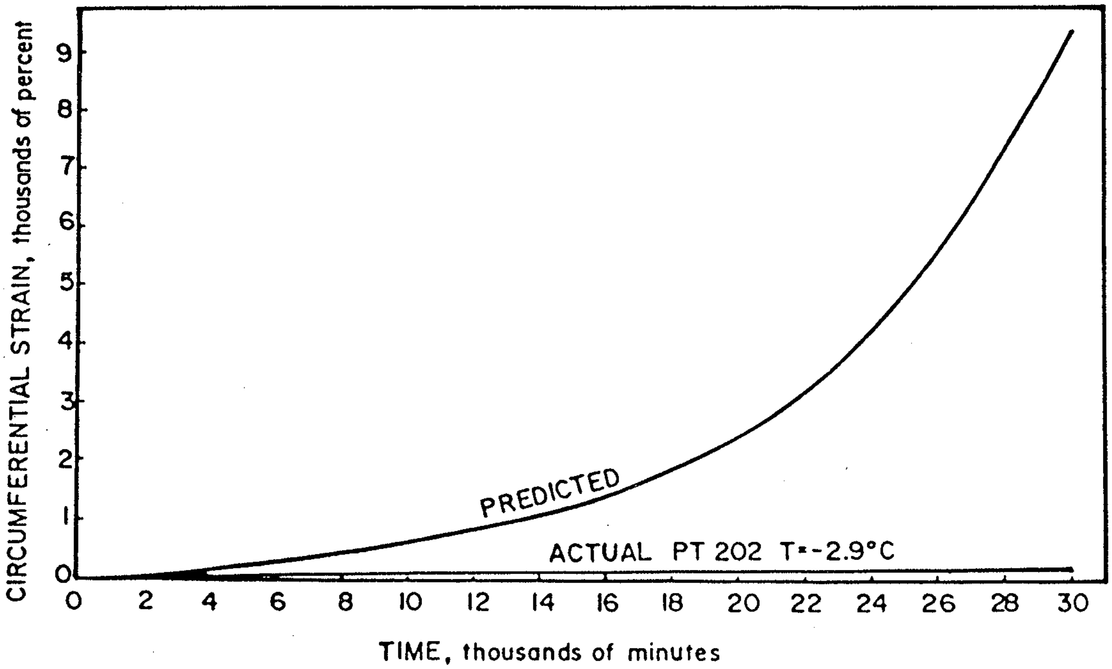


Figure 9. Actual vs. Predicted Strains at p = 2 MPa

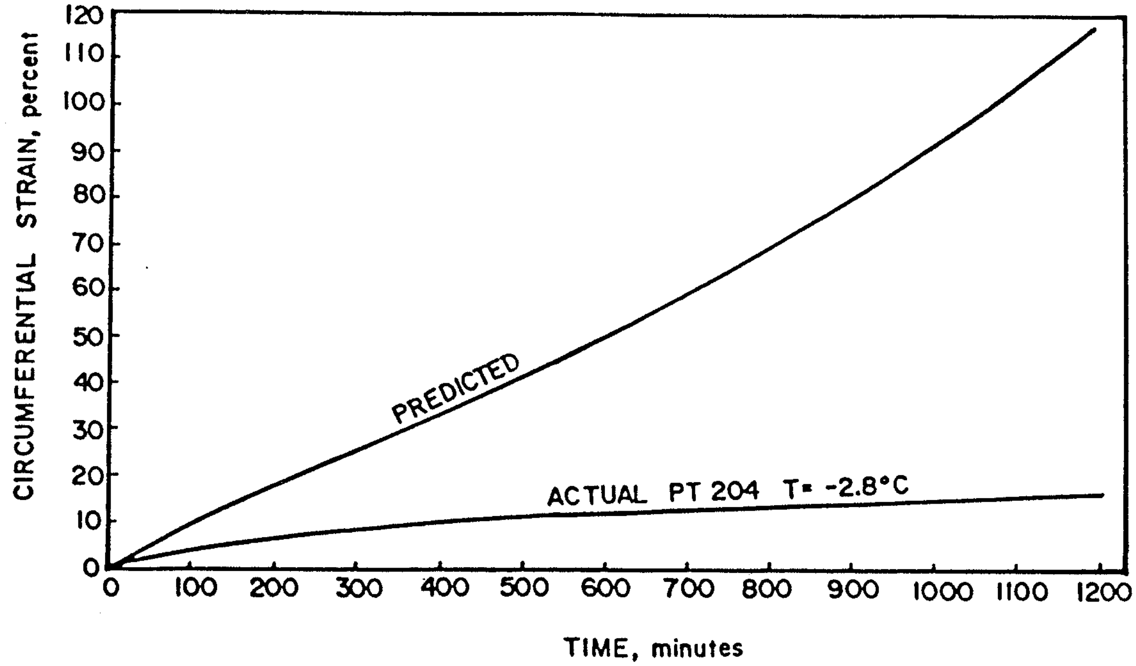


Figure 10. Actual vs. Predicted Strains at p = 3 MPa

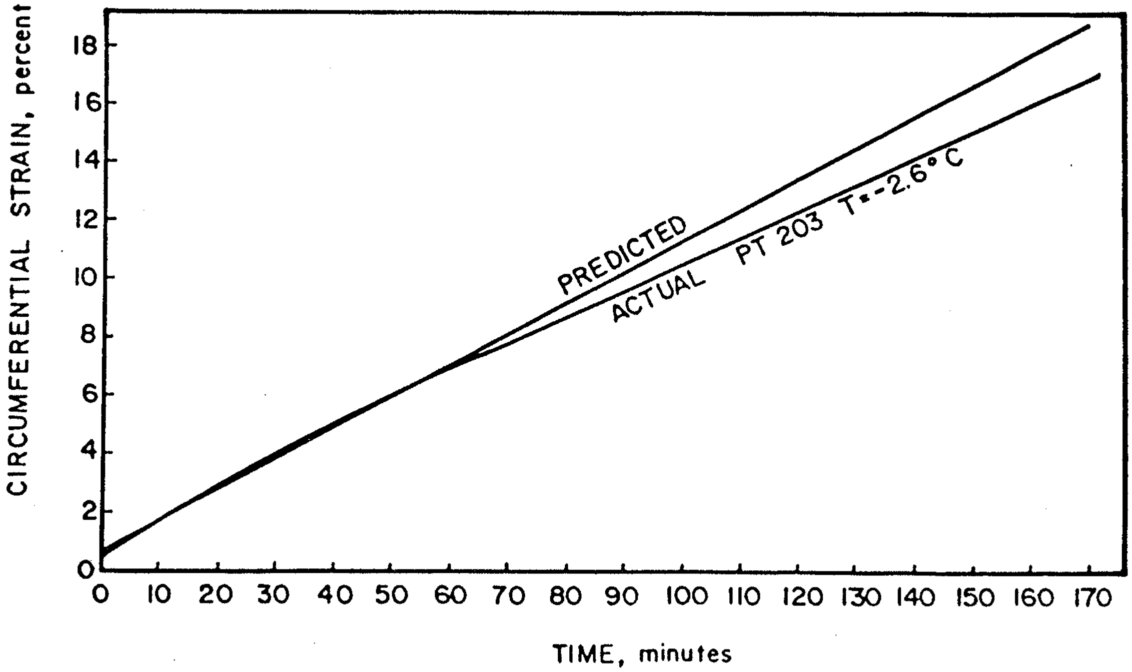


Figure 11. Actual vs. Predicted Strains at p = 4 MPa