DISSERTATION

TIME AND SCALE EFFECTS IN LABORATORY PERMEABILITY TESTING OF COMPACTED CLAY SOIL

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WE HEREBY RECOMMENDED THAT THE DISSERTATION PREPARED UNDER OUR SUPERVISION BY FARHAT JAVED ENTITLED TIME AND SCALE EFFECTS IN LABORATORY PERMEABILITY TESTING OF COMPACTED CLAY SOIL BE ACCEPTED AS FULFILLING IN PART REQUIREMENT FOR THE DEGREE OF DOCTOR OF PHILOSOPHY.

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ABSTRACT OF DISSERTATION

TIME AND SCALE EFFECTS IN LABORATORY PERMEABILITY TESTING OF COMPACTED CLAY SOIL

Permeability (hydraulic conductivity) testing of clays in the laboratory typically requires a significant amount of time. It is hypothesized that the time required for clay permeability test can be reduced substantially through a statistical modelling technique known as "time series analysis". In order to test this hypothesis, permeability tests were performed on compacted samples of a silty clay soil in a standard Proctor mold (9.4×10^{-4} m^3). The soil was separated into five different fractions representing five ranges in precompaction clod sizes. Constant-head permeability tests were performed on each of these five fractions. Tests were replicated five times for the time series analysis. The results of analysis indicate that time series modelling can significantly reduce statistical error associated with permeability data. It is demonstrated that the time required for clay

permeability test can be reduced appreciably through time series modelling. Permeability tests also were performed on four soil fractions in a large-scale (0.914 m x 0.914 m x 0.457 m) double-ring, rigid-wall permeameter. The results of small-scale (Proctor mold) permeability tests indicate that the soil permeability does not vary much with a change in the precompaction clod size. Presence of large clods (> 25 mm), however, may result in side-wall leakage. The large-scale tests indicated that permeability is strongly related to the precompaction clod sizes. Permeability of the soil increased more than two orders-of-magnitude as the maximum precompaction clod size increased from 4.75 mm to 75 mm. Comparison of the results from the small-scale and the large-scale tests indicated that, for all soil fractions, the large-scale permeability was higher by more than an order-of-magnitude. As a result, there appears to be a scale-effect associated with laboratory permeability testing. This scale effect is more significant when soil contains considerable quantity of clods that are large relative to the size of permeameter. These results imply that the large-scale test is more capable of accounting for the hydraulic defects resulting from large clods. A more realistic evaluation of the field permeability of a compacted clay, therefore, may be possible in the laboratory if

the permeameter is fairly large relative to the maximum precompaction size of clods present under field conditions.

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Chapter 1

INTRODUCTION

1.1 BACKGROUND

Major problems in geotechnical engineering pertain to drainage associated with design and construction of structures, therefore, the permeability (hydraulic conductivity) of soil is an important property. In addition, the evaluation of permeability of fine-grained soils used as lining material for the containment of wastes has generated a great deal of interest during the last few years.

Permeability of compacted fine-grained soils is determined routinely in the laboratory using rigid-wall permeameters (Daniel, 1981; Daniel et al., 1985). The test typically is performed on the portion of the soil that passes a No. 4 (4.75 mm) sieve. The soil is placed in a standard Proctor mold and typically is compacted under standard procedures (e.g., ASTM D 698). For clays, the time required for testing may become very long (generally more than a month). High hydraulic gradients usually may be applied to achieve results within a reasonable period, but application of high hydraulic gradients is questionable since, in the field, such gradients generally are relatively low (i.e., about one) (Dunn and Mitchell, 1984).

Some studies (Daniel, 1981,1984; Day and Daniel, 1985; Elsbury and Sraders, 1989; and Olson and Daniel, 1981) have indicated that in-situ permeability of compacted clay soils can be as much as two to three orders-of-magnitude higher than permeability predicted by laboratory tests. Two possible reasons for this discrepancy are evident. First, since only the portion of the soil passing the No. 4 sieve is used in the laboratory permeability test, the size of all soil particles or aggregates of soil particles (clods) are less than 4.7 mm. However, in the field the size of clods associated with compacted soils may be as much as 0.3 m (1 ft) in diameter (Daniel, 1984). Second, the test specimen in the standard Proctor mold is only 0.1 m (4 in) in diameter. As a result, the distribution of voids in the laboratory sample typically does not represent the hydraulic defects that may be present in the field soil.

The available literature on clay permeability indicates that use of statistical modelling for predicting permeability is scanty. In the present study an attempt has been made to demonstrate that the time to determine the clay permeability can be reduced through statistical modelling. A dynamic transition model was used to reduce the time of testing and to improve statistical interpretation of permeability data. Predictions from a simple time series model were combined with laboratory measurements using a linear filter to provide a better estimate of permeability.

It was hypothesized that the time for permeability testing could be reduced appreciably through the time series modelling. The reduction in time would reduce the cost of permeability testing and allow the project to commence earlier. In order to test this hypothesis, permeability tests were performed on compacted samples of a silty clay soil in a standard Proctor mold (9.4×10^{-4} m^3). The soil was separated into five different fractions representing five ranges in precompaction clod sizes. Constant-head permeability tests were performed on each of these five fractions.

The effect of precompaction clod size on laboratory-permeability of a natural soil also has been evaluated as a part of this study. A large-scale, double-ring, rigid-wall permeameter was constructed to study the relationship between hydraulic defects and precompaction size of clods. Comparison of results from the small-scale and the large-scale tests indicated that, for all soil fractions, the large-scale permeability was higher by a more than an order-of-magnitude. As a result, there appears to be a scale-effect associated with laboratory permeability testing. This scale effect is more significant when soil contains considerable quantity of clods that are large relative to the size of permeameter.

1.2 OBJECTIVES OF RESEARCH

The objectives of the research were:

(1) to test the hypothesis that time series modelling can be used to reduce the time required for clay permeability testing, and

(2) to study the effect of precompaction clod size on clay permeability,

The dissertation consists of six chapters. Chapter 2 includes the literature review. The time series analysis is presented in Chapter 3 along with an example of its application to clay permeability data. Materials and methods are discussed in Chapter 4. Chapter 5 covers the results and discussion. Conclusions and recommendations are presented in Chapter 6.

Chapter 2

LITERATURE REVIEW

2.1 INTRODUCTION

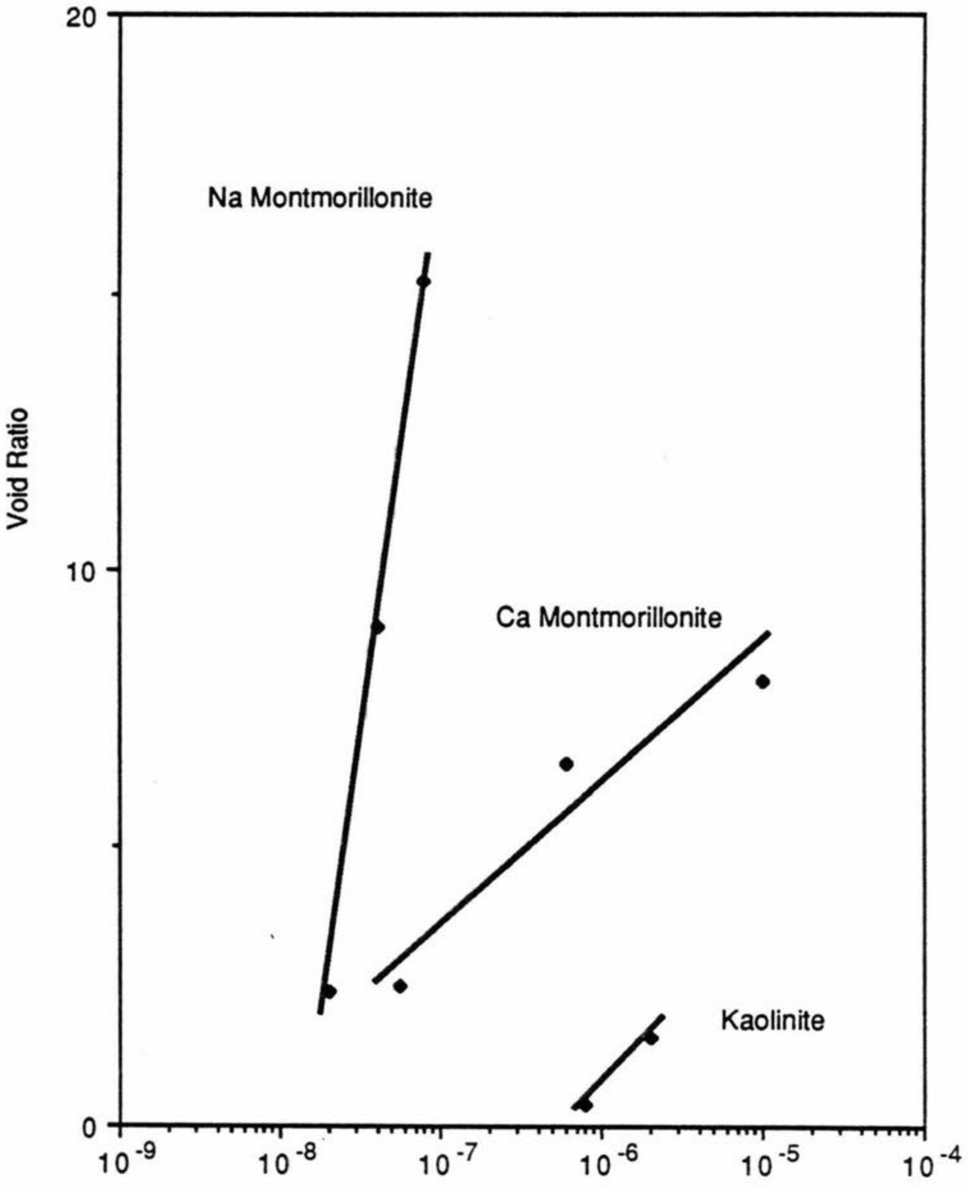
Darcy's law is the starting point for the solution of nearly all steady-state ground water problems involving saturated media (Darcy, 1856). This law, which is empirical, states that the velocity of flow in a saturated porous media, V, is proportional to the hydraulic gradient, i,

$$V = Ki \qquad (1)$$

where K is the coefficient of permeability or hydraulic conductivity. The hydraulic conductivity represents the slope of a straight line which passes through the origin on a plot of hydraulic gradient versus velocity of flow. Darcy's empirical relationship has been tested numerous times and has been found to be valid for steady-state, laminar flow in a saturated porous medium (i.e., the law does not apply to turbulent flow) (Mitchell, 1976). Although some researchers have indicated that Darcy's law is not valid for fine-grained soils at low hydraulic gradients (e.g., King, 1898; Englehardt and Tunn, 1955; Hansbo, 1960; Miller and low, 1963), there is a plethora of data supporting the validity of Darcy's law, even for clays (Fireman, 1944; Olsen, 1966; Gray, 1966; Mitchell and Younger, 1981; Matyas, 1967; Dematricopoulos et al., 1987; among others).

Permeability of soils can be determined in the laboratory or in the field. Laboratory measurements are relatively cheaper and faster to perform and, therefore, usually are preferred over field measurements. For coarse-grained soils, the permeability primarily is affected by the void ratio and grain-size distribution of the soil (Mitchell, 1976). However, the permeability of fine-grained soils is a function not only of the void ratio and grain-size distribution of the soil, but also the physico-chemical properties of the soil, such as composition, fabric, and structure (Lambe, 1954). Considerable literature is available concerning the effects of these factors (e.g., Mitchell et al., 1965; Lambe, 1954; Olson, 1971). The structure of the soil is taken to mean both the geometric arrangement of particles as well as the interparticle forces which may act between them. Soil fabric refers to the geometric arrangement of particles.

Lambe (1954) demonstrated the effect of soil composition on permeability of fine-grained soils. For the same void ratio, he found that sodium montmorillonite has a considerably lower permeability than the value for kaolinite (Fig. 2.1). Mitchell et al. (1965) demonstrated that permeability of compacted silty clay is function of



Permeability (cm/s)

Fig. 2.1 Effect of Soil Composition on Permeability

(data from Lambe, 1954)

compaction water content. Their data indicate that permeability decreases drastically when the soil is compacted wet of optimum water content (water content corresponding to the maximum dry density on the moisture-density curve). They attributed the decrease to a change in soil structure, from a flocculated structure at water contents dry of optimum water content to a dispersed structure at water contents wet of optimum water content. A dispersed structure has much smaller flow channels than a flocculated structure and also a lower permeability (Fig. 2.2).

The effect of compaction method on permeability (Fig. 2.3) was also studied by Mitchell et al. (1965). For the same dry density, kneading compaction results in a lower value of hydraulic conductivity than does static compaction, the difference being greater at water contents wet of optimum water content. The effect of permeant fluid on the permeability of fine-grained soils may be evaluated with reference to the Guoy-Chapman theory (Mitchell, 1976), which approximates the thickness of a diffuse double layer (DDL) as:

$$1 / K = (D\ k\ T / 8 - n_o\ e^2\ v^2)^{1/2} \qquad (2)$$

where 1/K is the diffused double layer (DDL) thickness, D is the dielectric constant of permeant, k is the Boltzman constant, e is a unit electronic charge, v is the cation valance, n_o is the electrolyte concentration, and T is the temperature. As the thickness of the DDL decreases, the

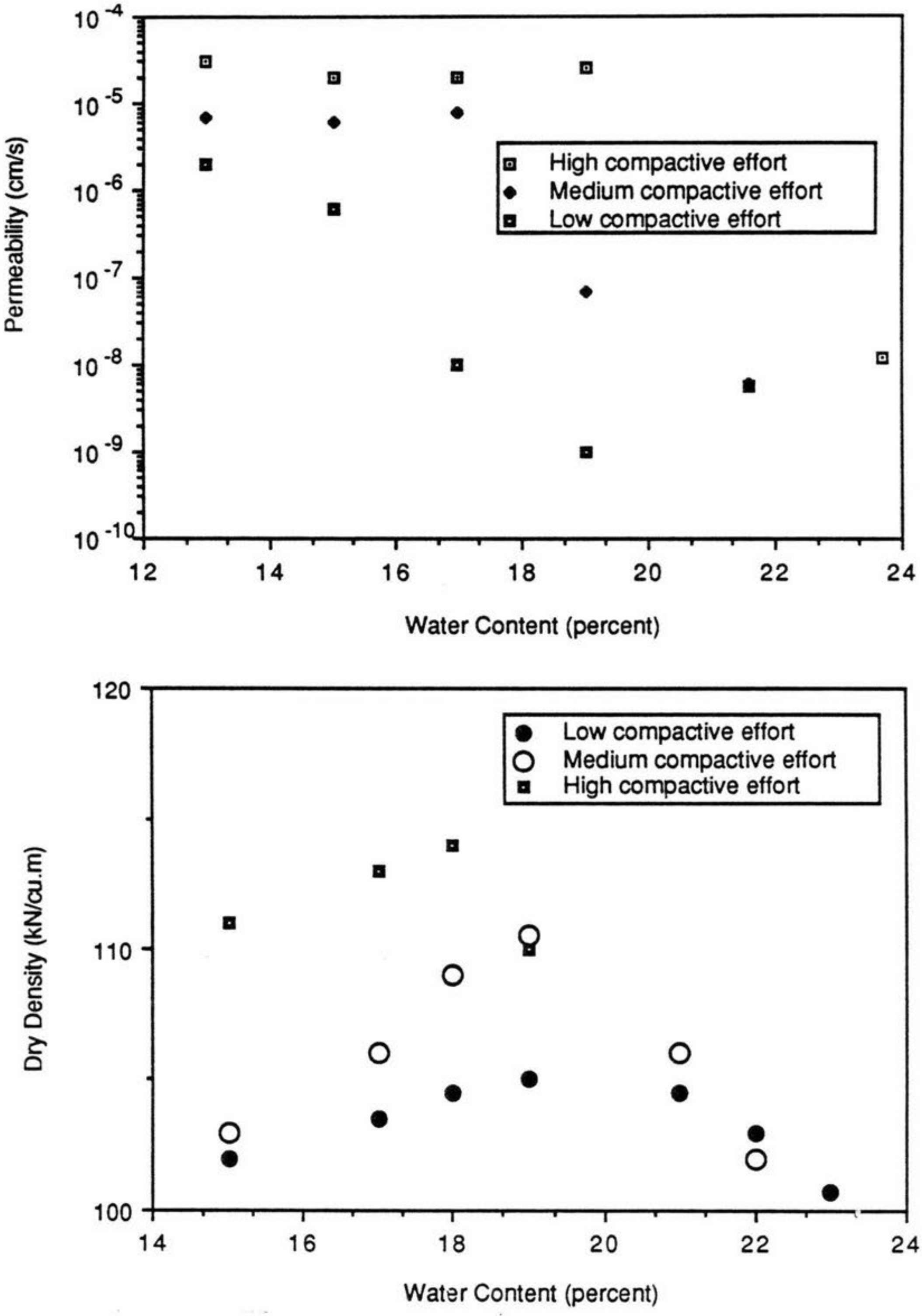


Figure 2.2 Effect of Water Content on Permeability for Three Compactive Efforts (data from Mitchell et al., 1965)

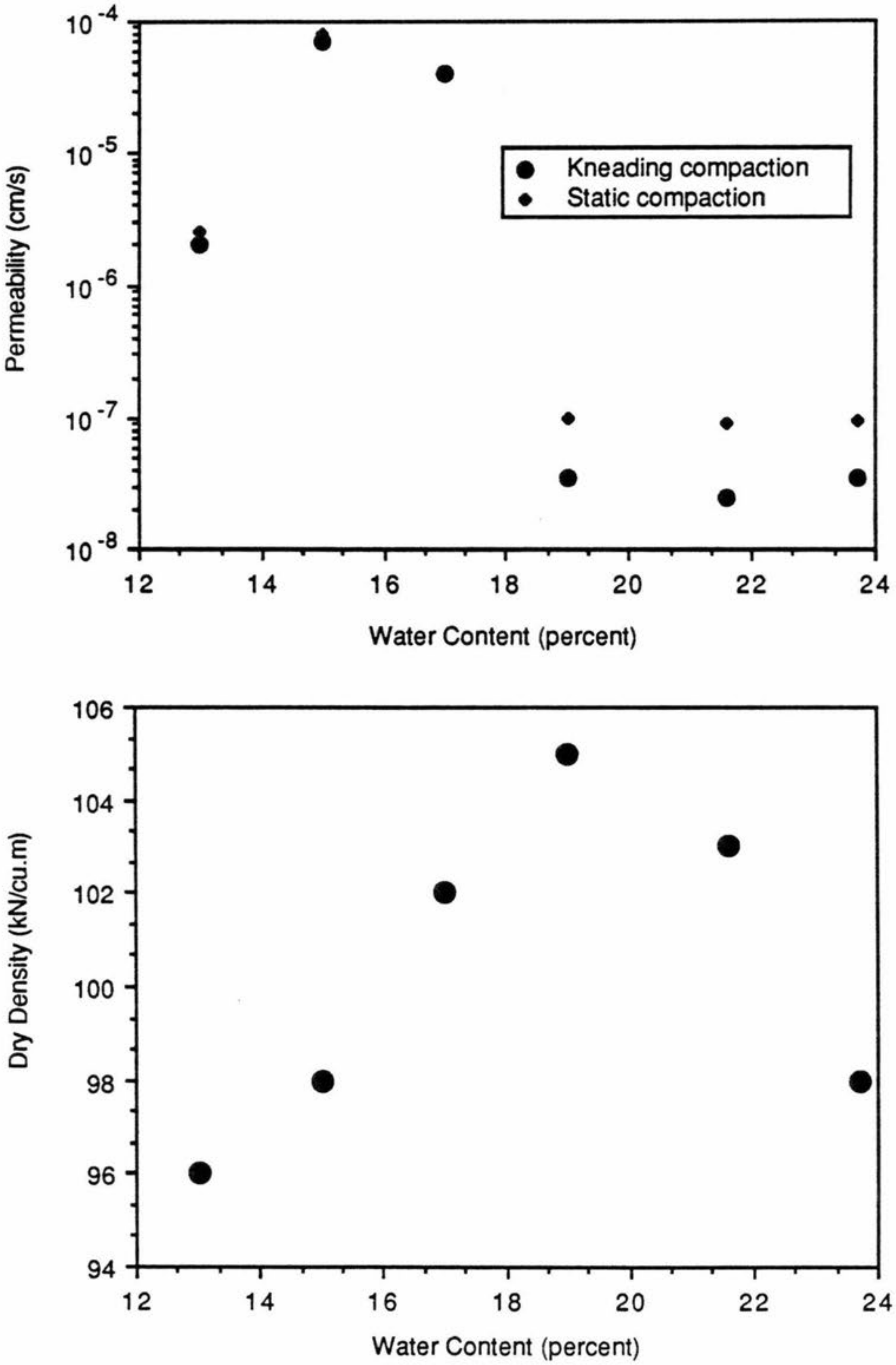


Figure. 2.3. Influence of Method of Compaction on Clay Permeability

(data from Mitchell et al., 1965)

soil structure becomes more flocculated and the permeability increases. Based on Equation 2, the factors that would cause a decrease in the DDL thickness include a decrease in the dielectric constant, an increase in the electrolyte concentration, and/or an increase in ionic valence. In addition, pH can have a marked effect on the structure of soil, with a lower pH promoting a flocculated structure (Mitchell, 1976). Acids tend to cause flocculation, whereas bases tend to disperse the soil structure (Mitchell and Madsen, 1987).

2.2 LABORATORY TESTING FOR PERMEABILITY

Different laboratory procedures for determining hydraulic conductivity include:

(1) rigid-wall test in a compaction mold;
(2) flexible-wall test in a triaxial-type cell;
(3) rigid-wall test in a consolidation cell; and
(4) flow pump method.

In addition, permeability can be determined indirectly from results of a consolidation test, but such determinations generally are considered to be relatively unreliable (Tavenas et al., 1983). The permeant in any of these tests should be a fluid similar to that encountered in the field (Olson and Daniel, 1981). Considerable difference in opinion exists regarding selection of the method for proper evaluation of permeability (Daniel et al., 1985). A rigid-wall (fixed-wall) cell is preferred by many laboratories for its simplicity and low cost. However, there may be imperfect contact between the soil and the inside of the fixed-wall cell, which can lead to side-wall leakage and to erroneously high values for permeability. Side-wall leakage may be particularly important when the soil is permeated with a concentrated organic chemical because the chemical may cause the soil to shrink and pull away from the walls of the permeameter (Foreman and Daniel, 1986). A consolidation cell permeameter is useful because a relationship between void ratio and permeability can be established. Mitchell and Madsen (1987) and Tavenas et al. (1983) favor its use. However, at low applied stresses side-wall leakage also can occur in this apparatus. Flexible-wall devices not only tend to minimize side-wall leakage but also are convenient for testing with back pressures, for measuring volume change within the specimen, and for controlling both horizontal and vertical effective stresses. However, if the effective stress applied to the soil in a flexible-wall apparatus exceeds the effective stress in the field, the measured permeability may be too low (Daniel et al., 1985). Olsen (1966) proposed that a flow-pump system be used to measure permeability. Among the reported advantages of the flow-pump system are that low hydraulic gradient tests ($i < 10$) can be performed accurately and that testing times are relatively short. However, the flow pump system apparently is in limited use since there are only a few published results of permeability tests performed with the flow-pump permeameter. As a result, the claims of Olsen are yet to be verified independently. Data presented by Daniel et. al. (1985) indicate that the type of permeater used has little effect on permeability of a laboratory-compacted clay permeated with water, but can have a major effect on compacted clays permeated with concentrated organic chemicals (Daniel et al., 1985). In their opinion, fixed-wall cells are perhaps best suited for testing laboratory-compacted clays that will be subjected to little or no effective overburden pressure in the field. Flexible-wall cells are better suited for testing undisturbed samples of soil (to minimize boundary leakage) and testing soil that will be subjected to significant effective stress in the field. Two American Society for Testing and Materials (ASTM) test methods (D18.04.02 and D18.04.85.03) are presently under development and are in draft form (Mitchell and Madsen, 1987).

Laboratory permeability tests are typically terminated once the following three criteria are met (Daniel et al., 1984):

(a) outflow is equal to inflow;

(b) two pore volumes of effluent are collected; and

(c) steady state permeability values are obtained.

The time required to perform a permeability test is another consideration associated with the selection of the permeameter. For fine-grained materials tested at low hydraulic gradients, the time required for obtaining measurable flow becomes prohibitive. To circumvent this problem, the soil sample normally is subjected to hydraulic gradients much higher than those expected in the field.

In the field, hydraulic gradients are probably on the order of one or two (Dunn and Mitchell, 1984) whereas values of 100 or more typically are utilized in the laboratory (Mitchell and Younger, 1967; Edil and Erickson, 1983). High gradients produce substantial seepage forces within the clay that can result in particle migration and permeability values that are too low (Mitchell and Younger, 1967; Olson and Daniel, 1981). Dunn and Mitchell (1984), and Mitchell and Younger (1967) observed that particle migration is relatively unimportant in dense soil specimens because only particles not involved in the load carrying framework of the soil mass are susceptible to migration. Particle migration, however, may become important for less dense specimens. Martin (1962), Korfiatis et al. (1987), Olsen (1966) and Demetracopoulos et al. (1987) report similar observations.

2.3 FIELD PERMEABILITY TESTS

In the laboratory, every effort should be made to subject the soil to conditions as close as possible to those encountered in the field. The effective stresses applied should be comparable to those expected in the field, and the permeant fluid should be the same as that expected in the field. The specimen should be compacted to the same dry density and at the same water content as the one specified for field compaction. In spite of all these precautions, field permeability value often exceed laboratory value by orders-of-magnitude (Daniel, 1984; Day and Daniel, 1985; and Elsbury and Sraders, 1989). Daniel (1984) cites four case histories in which actual values of the hydraulic conductivity of clay liners used to retain fresh water or salt water were approximately 10 to 1000 times higher than those measured in the laboratory. Daniel attributes this discrepancy to the problem of obtaining a representative sample of soil for laboratory testing. Recompacted specimens may be unrepresentative if the compaction water content, method of compaction, compactive effort, size of clay clods, and various other parameters do not match conditions in the field. Neither recompacted samples nor small, undisturbed samples are likely to contain a representative distribution of desiccation cracks, fissures, slickensides or other hydraulic defects that may be present in a compacted clay liner. The term hydraulic defects refers to a localized zone of significantly higher permeability embedded within a matrix of low permeability (Stewart and Nolan, 1987). A hydraulic defect might, therefore, be a crack or a pocket of poorly compacted soil.

The overall performance of an earthen liner is controlled by macropermeability and not micropermeability of the soil. Micropermeability refers to permeability associated with flow through pore spaces between soil particles, whereas macropermeability refers to permeability of a soil on a much larger scale. Secondary features such as cracks, root holes, fissures, slickensides, sand or silt partings, etc., control the macropermeability. Field hydraulic conductivity tests seem to be able to account for the macropermeability which may contribute to much of the flow through a compacted clay soil if hydraulic defects are present. Therefore, field permeability tests are more likely to yield accurate estimates of permeability than laboratory tests and, for this reason, are recommended as part of the final design process and/or quality control procedures (Daniel, 1984).

Some of the more popular types of in-situ permeability measurement techniques include:

(1) bore hole tests;
(2) porous probes;
(3) air entry permeameters;
(4) lysimeter pans; and
(5) infiltration tests.

Daniel et al. (1986) and Daniel (1987b) have discussed these tests and their associated advantages and disadvantages in detail. They conclude that infiltration tests yield the most realistic results since the large rings used in these tests permeate a relatively large volume of soil, enhancing the chance that the macropermeability of the compacted soil will be measured accurately.

The two commonly used infiltration tests are the single-ring infiltrometer test and the Double-ring infiltrometer test. The single-ring test is fairly straight forward to perform, but the possibility of lateral flow is a problem with this equipment. The double-ring permeameter has an advantage in that lateral flow occuring in the single-ring test can be minimized. Both of these tests, however, are fairly time consuming and are not quite suitable for clays with relatively low permeability (< 1 X 10^{-7} cm/sec). Daniel, et al. (1986) have developed a new version of double ring infiltrometer which they call the "Sealed Double Ring Infiltrometer" or SDRI (Fig. 2.4). Daniel (1987b) presents information on this equipment and Chen and Yamamoto (1987) describe a case history where SDRI was used successfully to predict in situ hydraulic conductivity of a clay liner.

2.4 CLOD THEORY

As stated earlier, permeability of compacted soil experiences a drastic decline when the soil is compacted wet of optimum water content (Lambe, 1958; and Mitchell et al., 1965). Olsen (1962) explained the decrease in permeability through a "clod" or "cluster" theory. In his theory, the uncompacted soil is considered to consist of aggregates or groups of soil particles called clods. Soil scientists refer to clods as peds. Prior to compaction, soil particles are grouped in agglomerations or clods whose size and strength characteristics are influenced by the compaction water content. Clods have a high strength and are better

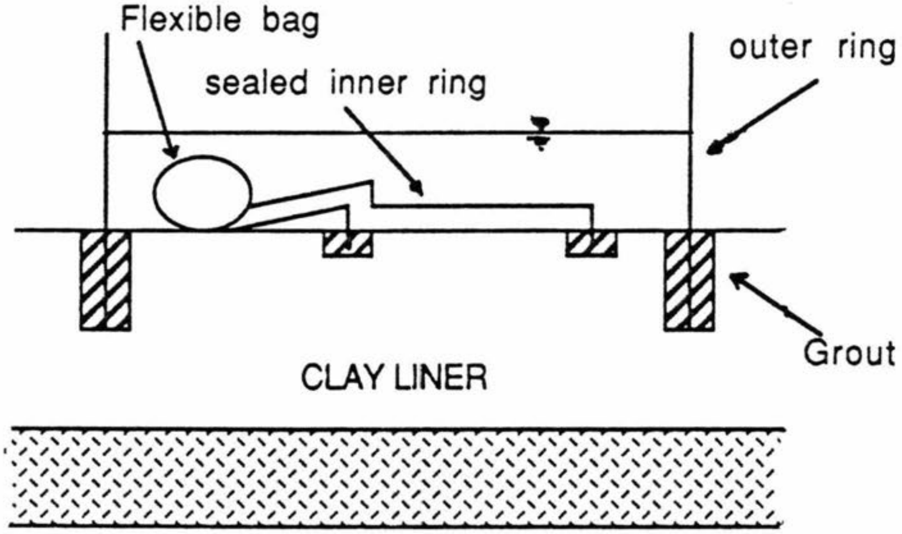


Fig. 2.4 Sealed Double Ring. Infiltrometer (From Daniel,1987)

able to resist compaction pressures without much distortion during compaction below optimum water content (Garcia-Bengochea et al., 1979). After a soil is compacted, interclod or macropores exist such that most of the permeating liquid flows around, rather than through, the clods. Compaction on the wet side of optimum water content results in a lower permeability because wet clods are remolded more easily during compaction and the volume and continuity of interclod pores is minimized (Daniel, 1987a). The effect of clod size can be significant in introducing spatial variability on permeability both in aerial extent and in depth. This is particularly true when hydration of clods is not complete and clods are not fully broken up and remolded during compaction. The clod-to-clod interface can then provide a macropore structure that will affect the hydraulic behavior of the soil mass (Korfiatis et al., 1987). Daniel (1987a) favors the clod theory and states that the ideal situation for achieving low permeability of a clay liner is small, soft, weak clods of clay that are easily molded and, when compacted with a heavy roller, can be effectively remolded and melded together. Heavy, footed rollers, with fully-penetrating feet, used on thin lifts of soil with a sufficient number of passes, are ideal. Reades et al. (1986) present a case history in which a low permeability value (2 x 10^{-8} cm/s) was demonstrated by in-situ measurements involving clay that was compacted by extremely heavy (more than 66,000 lbs or 293 kN) rollers.

Their tests indicated that lighter rollers would not produce such low permeabilities. If water is to be added to the clay, time must be allowed for the soil to absorb water and hydrate fully; otherwise, the clods will be wet only on the outside. The inside of the clods will remain dry and hard, and the clods will not be fully destroyed resulting in a higher permeability. In order to achieve a low permeability the size of the clods should be minimized by pulverizing the soil prior to compaction (Daniel, 1987a).

2.5 SUMMARY

Permeability of a soil is one of the most important and fundamental property. Permeability of a coarse-grained soil primarily is effected by void ratio and grain size distribution. However, the permeability of fine-grained soil is a function not only of void ratio and grain-size distribution of soil, but also the physico-chemical properties of soil, such as composition, fabric, and structure. The soil permeability can be determined in the laboratory or in the field. Laboratory measurements are relatively less expensive and faster to perform. Field permeability tests are expensive but they are more likely to yield a better estimate of permeability than the laboratory results. The soil used for constructing clay liners contains clods upto 30 cm (one foot) in size. These large clods may result in hydraulic defects that lead to higher permeability. Field permeability tests can account for the hydraulic defects whereas laboratory tests performed on a portion of the soil passing 4.75 mm seive size in a standard Proctor mold can not account for these defects.

Chapter 3

TIME SERIES ANALYSIS

3.1 INTRODUCTION

The basic linear regression model is:

$$y = a + bx + e \tag{3.1}$$

where y is a dependent variable, x is an independent variable, a is the intercept or value of y when $x = 0$, and b is the slope of the regression line. The symbol e indicates a residual error that is supposed to be normally distributed with zero mean, and the variance of e is that portion of the variance of y not explained by regression. The variance of e is minimized by the choice of a and b. The model:

$$y = bx \tag{3.2}$$

is interpreted as a linear equation with zero intercept. A simple time series regression results when the numerical values of the dependent variable y are the numerical values for the system at one time step later than values of the system indicated by the independent variable x, that is:

$$X_{k+1} = bX_k \tag{3.3}$$

This equation is a simple linear regression, calculated numerically like the previous example $y = bx$. If we plot the results of $X_{k+1} = bX_k$ over time k, $b = 1$ will produce a straight line with constant value. Values of $0 < b < 1$ will produce a line that asymptotically declines to zero, and values of $b > 1$ will produce a line that increases over time. The coefficient b may be dependent on time, but the system is nevertheless linear in the parameters for any time period k to k+1. Thus we can use all of the statistical procedures appropriate to linear dynamic systems for any series of intervals for which b_k can be mathematically specified.

In the time series literature (Box and Jenkins, 1976; Chatfield, 1984), the coefficient b of conventional regression is commonly indicated by the Greek letter α. In the literature on linear dynamic systems, b is commonly indicated by the Greek letter ϕ, and the letter W is often used for random error instead of the letter e.

3.2 LINEAR DYNAMIC SYSTEMS AND THE KALMAN FILTER

A time series is a familiar linear regression with somewhat different symbols:

$$X_{k+1} = \phi X_k + W_k,\ W \text{ is } N(0,q) \qquad (3.4)$$

where X is the variable of the system whose dynamics are indicated by the equation, ϕ is the time series regression coefficient or state transition multiplier, and W_k is a random error from a population that is normally distributed with zero mean and variance q (Jazwinski, 1970; Gelb, 1974; Maybeck, 1979; Anderson and Moore, 1979; Jameson, 1989). Recall that q is that portion of the variance of X_{k+1} not explained by regression. For any time period, an observation is:

$$Y_{k+1} = X_{k+1} + V_{k+1}, \quad \text{where V is N (0, r)} \qquad (3.5)$$

where Y is the observed value, X is the true state of the system, and V is a random error of observation. For unbiased samples, the random variable V_{k+1} comes from a population that is normally distributed with zero mean and variance r. Thus, even though the sample is unbiased, the state of the system is uncertain because of random sampling effects indicated by V and r.

At this point let us introduce the following notation:

Y_k = measured values at time k,

X_k = true value at time k,

$X_{k/k}$ = best estimate of X given information at time k (with variance $P_{k/k}$),

$X_{k+1/k}$ = predicted value of X for time k+1 given information at time k (with variance $P_{k+1/k}$), and

$X_{k+1/k+1}$ = updated best estimate of X for time k+1 given information at time k+1 (with variance $P_{k+1/k+1}$)

Assume that we have collected a chronological series of data and developed the time series equation

$$X_{k+1/k} = \phi X_k \qquad (3.6)$$

Through this equation we can predict X_{k+1} if ϕ is known. Even if the variance q is small, the sample value Y_{k+1} may be different than the predicted value X_{k+1}. It is possible to combine the sample value and the predicted value, and produce a weighted average that has a lower variance than either the prediction or the sample. This can be accomplished by Kalman Filter. To combine subsamples with unequal standard errors, we should devise weighting factors so that a subsample with a high standard error has a small weighting factor and a subsample with a low standard error has a large weighting factor. The appropriate weighting factor g_1 for Y_1 is

$$g_1 = r_2/(r_1+r_2) \tag{3.7}$$

and the weighting factor g_2 for Y_2 is

$$g_2 = r_1/(r_1+r_2) \tag{3.8}$$

It can be shown that $g_2 = (1-g_1)$. Therefore, if we want to combine a prediction with a sample, we could do so if we knew the variance of the prediction and of the sample. We certainly can determine the variance r (square of the standard error of the mean) of a sample, and the variance q of the departures from regression (Cochran, 1977). The variance of the difference between the observation and the prediction from time series is q. The variance of prediction can be given as:

$$p_{k+1/k} = \phi^2 p_{k/k} + q \tag{3.10}$$

where $p_{k+1/k}$ is the variance appropriate for the prediction of X at time k+1.

We can calculate the weighting factor g by

$$g = p_{k+1/k}/(p_{k+1/k} + r) \tag{3.11}$$

where g is the weighting factor for the sample, and (1-g) is the weighting factor for the prediction. Thus:

combined or best estimate at time k+1 = g(sample) + (1-g)(prediction).

The prediction for time k+1 uses only information available at time k; thus we indicate the prediction by $X_{k+1/k}$, which is read as X_{k+1} given k. When we update the information at time k+1 and combine the sample and prediction, we then have $X_{k+1/k+1}$, which is read as X_{k+1} given k+1. Thus the equation for the updated best estimate is:

$$X_{k+1/k+1} = gY_{k+1} + (1-g)\ X_{k+1/k} \qquad (3.12)$$

With this information, we can make a prediction for time k+2 based on knowledge of the state transition multiplier ϕ and the best available information for time k+1. However, in order to evaluate the prediction, we need to calculate a variance of combined information at time k+1 i.e., $p_{k+1/k+1}$. When we have incorporated the results of a new sample, variance p at time k+1 will be less than either variance q or variance r; thus we have achieved a reduction in statistical error only by combining two sources of information. In fact, we have combined knowledge of the past dynamic behavior of the system with knowledge of the current sample. If we indicate the variance of the prediction as $p_{k+1/k}$, then the variance appropriate for $X_{k+1/k+1}$ is:

$$p_{k+1/k+1} = (1-g)\ p_{k+1/k} \qquad (3.13)$$

The above equations can be summarized by the "Kalman filter":

Identify the time series or linear dynamic system as

$$X_{k+1} = \phi X_k + W_k, \text{ W is N(0,q)} \qquad (3.4)$$

the measurements as

$$Y_{k+1} = X_{k+1} + V_{k+1}, \text{ V is N(0,r)} \qquad (3.5)$$

and the prediction as

$$X_{k+1/k} = \phi X_k \qquad (3.6)$$

The variance of the prediction is

$$p_{k+1/k} = \phi^2 p_{k/k} + q \qquad (3.10)$$

and the weighting factor for the measurement is

$$g = p_{k+1/k}/(p_{k+1/k} + r) \qquad (3.11)$$

The best estimate at time k+1 is

$$X_{k+1/k+1} = gY_{k+1} + (1-g)\ X_{k+1/k} \qquad (3.12)$$

and the variance of the best estimate is

$$p_{k+1/k+1} = (1-g)\ p_{k+1/k} \qquad (3.13)$$

At time k = 0, take a sample and assume $p_{k/k} = r$. Solve for $X_{k+1/k+1}$ and $p_{k+1/k+1}$. However, if no measurement is taken at a time step, $p_{k+1/k+1} = p_{k+1/k}$ and $X_{k+1/k+1} = X_{k+1/k}$. For the next time step, in either case, set $p_{k/k} = p_{k+1/k+1}$, $X_{k/k} = X_{k+1/k+1}$, and repeat the calculations.

3.3 APPLICATION OF TIME SERIES TO CLAY PERMEABILITY

Permeability values for clays are generally very low and the time required for testing such soils in the laboratory is quite long. In traditional testing the following three conditions should be met before a permeability test can be terminated:

1. steady state flow
2. inflow is equal to outflow
3. two pore volumes of permeant is collected.

Because replicate samples and variances are not usually considered in traditional testing, the termination conditions do not consider variance of the results. Clays used for liners should have permeability less than 10^{-7} cm/sec. Therefore, to satisfy the above conditions may require testing time of more than two months. This means that the project is delayed and also the cost of laboratory testing is high. An effort has been made in this research to reduce the time of clay permeability testing through statistical inferences. A powerful statistical technique for prediction is time series modelling. Calculation of the appropriate variances was developed for aerospace research predictions in the early 60's, but has since been extensively used in various fields of science and engineering. Time series predictions are combined with observations to reach a better estimate through a filtering process known as the Kalman filter.

Consider a hypothetical case of permeability tests on five replicates of soil compacted to the same maximum dry density and at the same water content. After a few time steps each sample attained a steady state (Fig. 3.1) but it is highly unlikely that all of these samples will have the same permeability and for any time k there will be a

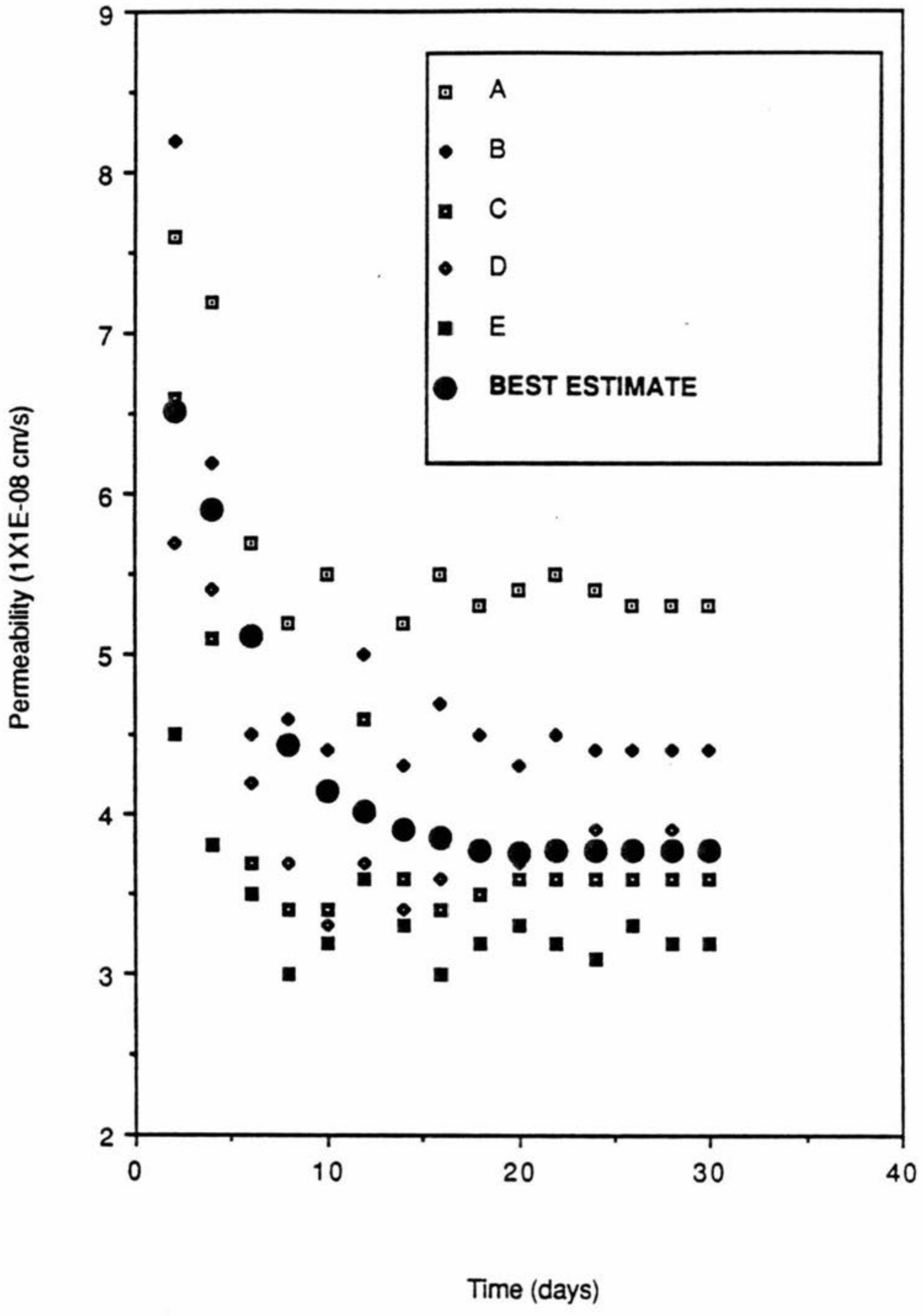


Figure 3.1 Time Series Analysis for Clay Permeability of Five Samples (A to E)

variance denoted by r that is associated with the samples. If only one specimen was tested it might be concluded that steady state has been reached. However, when all five replicates are considered there is still variation in permeability. This sample variance exists even if the test is performed for a long time. So, in spite of performing the test for a long time the confidence in the test results does not improve. By using time series modelling and the Kalman filter, it is possible to achieve a given variance at a much earlier time. To illustrate the procedure, consider the analysis shown in Table 3.1. The sample variance is listed in column seven of Table 3.1 and the average of five permeabilities is used in column eight for analysis. These observations are used to determine ϕ (time series regression coefficient) which will be used in the time series model: $X_{k+1/k} = \phi X_{k/k}$ to predict permeability one time step later. These predictions are further updated through the Kalman gain, g; the Kalman gain is a function of sample variance and the prediction variance ($p_{k+1/k}$). If the sample variance is large, g decreases and more weight is given to the value calculated from the prediction model during the updating process, or vice versa. The values are updated by the following equation:

$$X_{k+1/k+1} = g\, Y_{k+1} + (1-g)\, X_{k+1/k} \qquad (3.12)$$

The variance of these updated estimate is :

$$p_{k+1/k+1} = (1-g)\, p_{k+1/k} \qquad (3.13)$$

These updated values become starting values for $X_{k/k}$ and

Table 3.1. Example of Time Series Analysis

	permeability of five samples (1X1E-08 cm/s)															
(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 -φYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	7.6	8.2	6.6	5.7	4.5	2.19	6.52			2.19	2.15	6.52	6.26	0.50	5.90	1.08
4	7.2	6.2	5.1	5.4	3.8	1.61	5.54	6.26	-0.72	1.08	1.13	5.90	5.66	0.41	5.11	0.67
6	5.7	4.5	3.7	4.2	3.5	0.75	4.32	5.32	-1.00	0.67	0.75	5.11	4.90	0.50	4.44	0.38
8	5.2	4.6	3.4	3.7	3	0.81	3.98	4.15	-0.17	0.38	0.48	4.44	4.26	0.37	4.15	0.30
10	5.5	4.4	3.4	3.3	3.2	0.97	3.96	3.82	0.14	0.30	0.41	4.15	3.98	0.30	4.02	0.29
12	5	4.6	3.7	3.6	3.6	0.43	4.10	3.80	0.30	0.29	0.40	4.02	3.85	0.48	3.91	0.21
14	5.2	4.3	3.6	3.4	3.3	0.63	3.96	3.93	0.03	0.21	0.33	3.91	3.75	0.34	3.85	0.22
16	5.5	4.7	3.4	3.6	3	1.06	4.04	3.80	0.24	0.22	0.34	3.85	3.69	0.24	3.77	0.25
18	5.3	4.5	3.5	3.5	3.2	0.77	4.00	3.88	0.12	0.25	0.37	3.77	3.61	0.33	3.76	0.25
20	5.4	4.3	3.6	3.7	3.3	0.69	4.06	3.84	0.22	0.25	0.37	3.76	3.61	0.35	3.78	0.24
22	5.5	4.5	3.6	3.8	3.2	0.82	4.12	3.90	0.22	0.24	0.36	3.78	3.63	0.30	3.77	0.25
24	5.4	4.4	3.6	3.9	3.1	0.77	4.08	3.95	0.13	0.25	0.36	3.77	3.62	0.32	3.77	0.25
26	5.3	4.4	3.6	3.8	3.3	0.63	4.08	3.92	0.16	0.25	0.36	3.77	3.61	0.37	3.78	0.23
28	5.3	4.4	3.6	3.9	3.2	0.66	4.08	3.92	0.16	0.23	0.35	3.78	3.63	0.35	3.78	0.23
30	5.3	4.4	3.6	3.8	3.2	0.67	4.06	3.92	0.14	0.23	0.35	3.78	3.63	0.34	3.78	0.23

Sum Yk = 60.84 q = 0.14

Sum Yk+1 = 58.38

Regression Coefficient = 0.96

$p_{k/k}$ respectively for the next time step. Consider the variance of the sample (column 7) and the variance of the estimate $p_{k/k}$ at time k, (column 11). The variance of the sample after 30 days is 0.67 whereas the variance of the estimate drops to 0.3 in 10 days. This indicates that the prediction on the day 10 is as good as the observation on the day 30. On day 30 the variance of the estimate (0.23) is one third of the sample variance (0.67). Also the variance of the estimate on day 16 is 0.22, which is less than half of observation (0.67) on day 30. These observations are summarized below:

Day	Sample variance	Variance of estimate
10	0.97	0.3
16	1.06	0.22
30	0.67	0.22

From the results it is clear that the best estimate of permeability calculated through the model on day 16 is statistically better than any of the five observations recorded on day 30. Sample variance, r, does not show a drop after day 20, and it is reasonable to conclude that the test can be terminated on day 16. Through a time series model and a Kalman filter it is possible to bring down the statistical error considerably and the results would be more reliable. At the same time if achieving a suitably low variance is a condition, the test can be terminated much earlier than time required by the conventional procedure.

Chapter 4

LABORATORY PROCEDURE

4.1. SOILS

A silty clay soil was selected for this research. Specific gravity, Atterberg limits, and grain-size distribution determinations were performed in accordance with the prescribed ASTM (American Society of Testing and Materials) standards. Results of these tests are summarized in Table 4.1. The soil classifies as clay of low plasticity (CL) according to Unified Soil Classification system (ASTM D2487). Gradation tests, including sieve and hydrometer analysis, were performed in accordance with ASTM D422. A gradation test also was performed on the soil in its air-dried state, i.e., the clods were left intact to determine percentage of various clod sizes in the soil. The results of these tests are presented in Fig. 4.1. The values of "percent finer" for the "natural soil" gradation curve shown in Fig. 4.1 represent average values of analysis performed on three separate samples of the air-dried natural soil. Differences between the two gradation curves shown in Fig. 4.1 can be attributed to the difference between the individual particles and aggregates of particles, or clods.

Table 4.1. Physical Properties of Soil Used In the Study.

Property	Method of Measurement	Value
Natural Water Content	ASTM D 2216	2.5%
Grain-Size Analysis	ASTM D 422	
Sand (g/g)		30%
Silt (g/g)		36%
Clay (g/g)		34%
Optimum Water Content (g/g)	ASTM D 698- Method A	18%
Max. Dry Unit Weight	ASTM D 698- Method A	16.90 kN/m^3 (107.7 pcf)
Specific Gravity, G_s	ASTM D 854	2.73
Liquid Limit (g/g)	ASTM D 4318	31%
Plasticity Index (g/g)	ASTM D 4318	10%
Classification	ASTM D 2487	CL

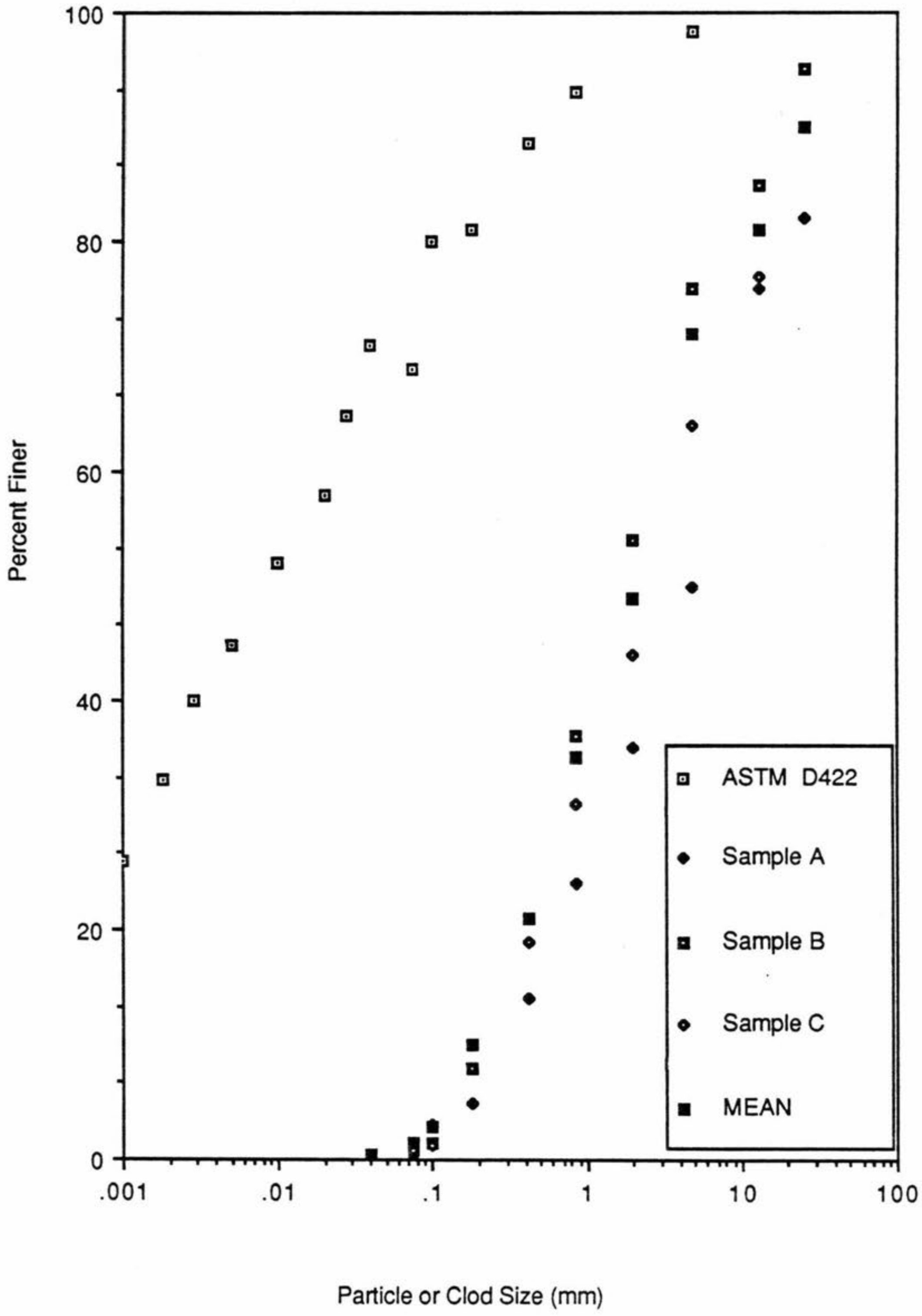


Figure. 4.1. Grain Size Distribution Curve

As a result, the five different categories of soil used for the test specimen can be thought of as representing soils with different ranges in clod sizes. Also, based on Fig. 4.1, about 92 percent of the natural soil passes the 75-mm sieve size. For the purposes of this study, the soil representing clod sizes less than 75 mm (3 in) in size is referred to as "natural soil". Test specimens of the soil were taken from the following five fractions of the natural soil:

(1) soil passing a No.10 (2-mm) sieve size;

(2) soil passing a No.4 (4.75-mm) sieve;

(3) soil passing a 25-mm sieve and retained on a 4.75-mm sieve (No.4);

(4) soil passing a 75-mm sieve and retained on a 25- mm sieve; and

(5) soil passing a 75-mm sieve.

4.2. MOISTURE-DENSITY RELATIONSHIPS

Standard Proctor tests were conducted on the soil in accordance with ASTM D698 Method A. In this method, soil is compacted into a 4-in. (10.16 cm) diameter mold with a volume of 1/30 cu. ft. (0.0009 m^3). The soil is compacted into three separate lifts. Each lift is compacted using 25 blows of a 5.5 lb (2.49 Kg) hammer which is dropped from a distance of 12 inches (0.3 m). The standard test is performed on the portion of soil that passes a No. 4 sieve corresponding to an opening of 4.75 mm. Five data points typically are generated for the standard Proctor curve (Fig. 4.2). This curve yields the maximum dry density and the optimum water content for the soil. Standard Proctor tests also were performed on the other four soil fractions to study the effect of clod size on maximum dry density and the optimum water content. Curves for soils with larger clod sizes indicate a higher maximum density at a lower optimum water content (Fig. 4.3). As indicated in Fig. 4.3, the compaction curve for the second catagory of soil, i.e. for soil passing the No. 4 (4.75-mm) sieve represents the compaction curve based on the standard Proctor procedure (ASTM D698, Method A). This standard Proctor curve was used as the reference compaction curve for control of the dry density and water content of all test specimens used for the permeability tests.

4.3. PERMEABILITY TESTS IN THE RIGID-WALL, PROCTOR-MOLD PERMEAMETER

Permeability tests in the rigid-wall permeameter are typically conducted on the fraction of a soil that passes a No. 4 sieve. The soil is wetted to a water content above the optimum water content and is compacted into a standard Proctor mold. The ends of the specimen are trimmed flush with the mold, the permeameter (Fig. 4.4) is assembled, and permeation of the sample is initiated.

Six series of tests were performed on the soil. In test series A, emphasis was placed on the study of the

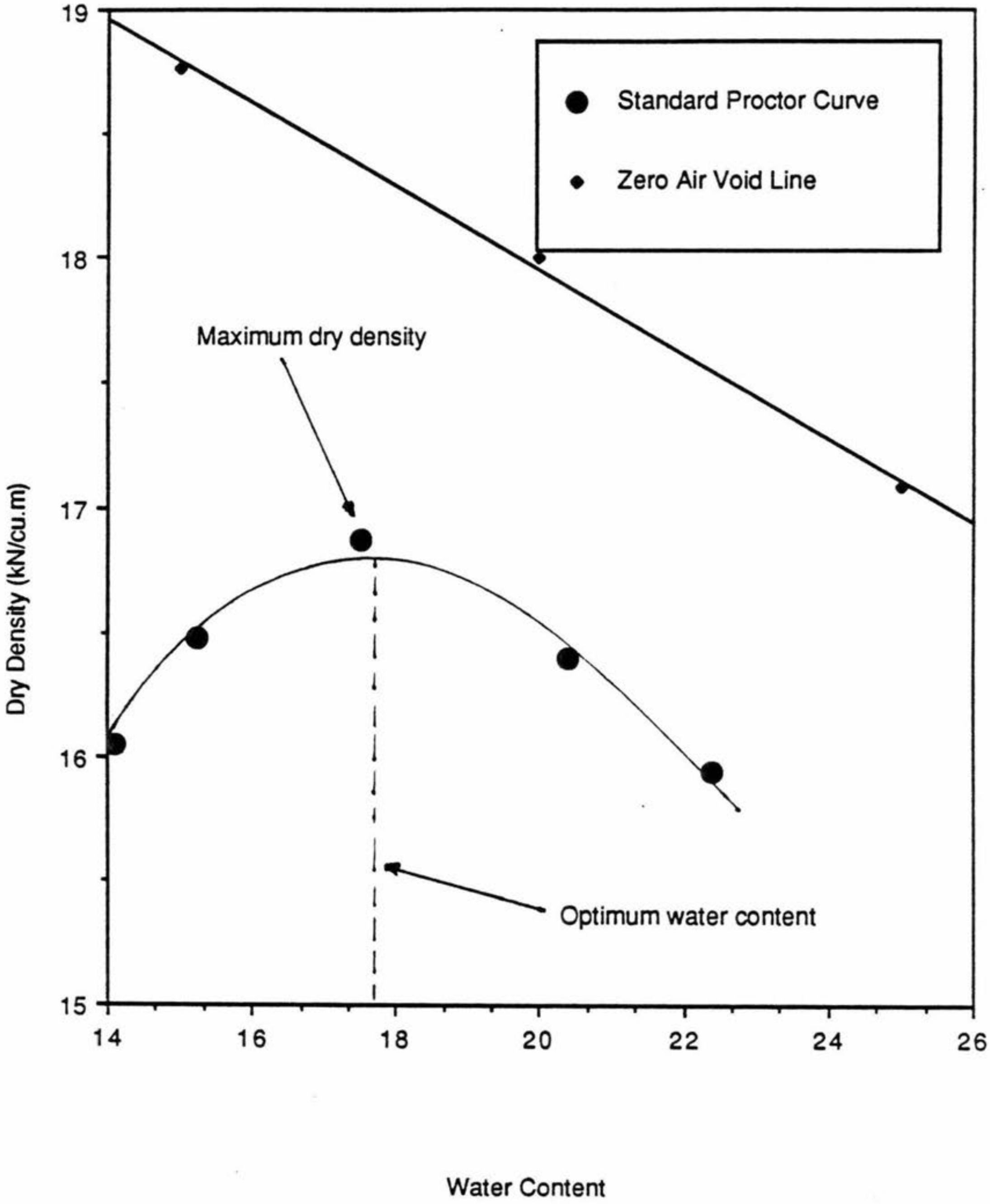


Figure. 4.2. Standard Proctor Curve (Soil Passing No.4 Sieve)

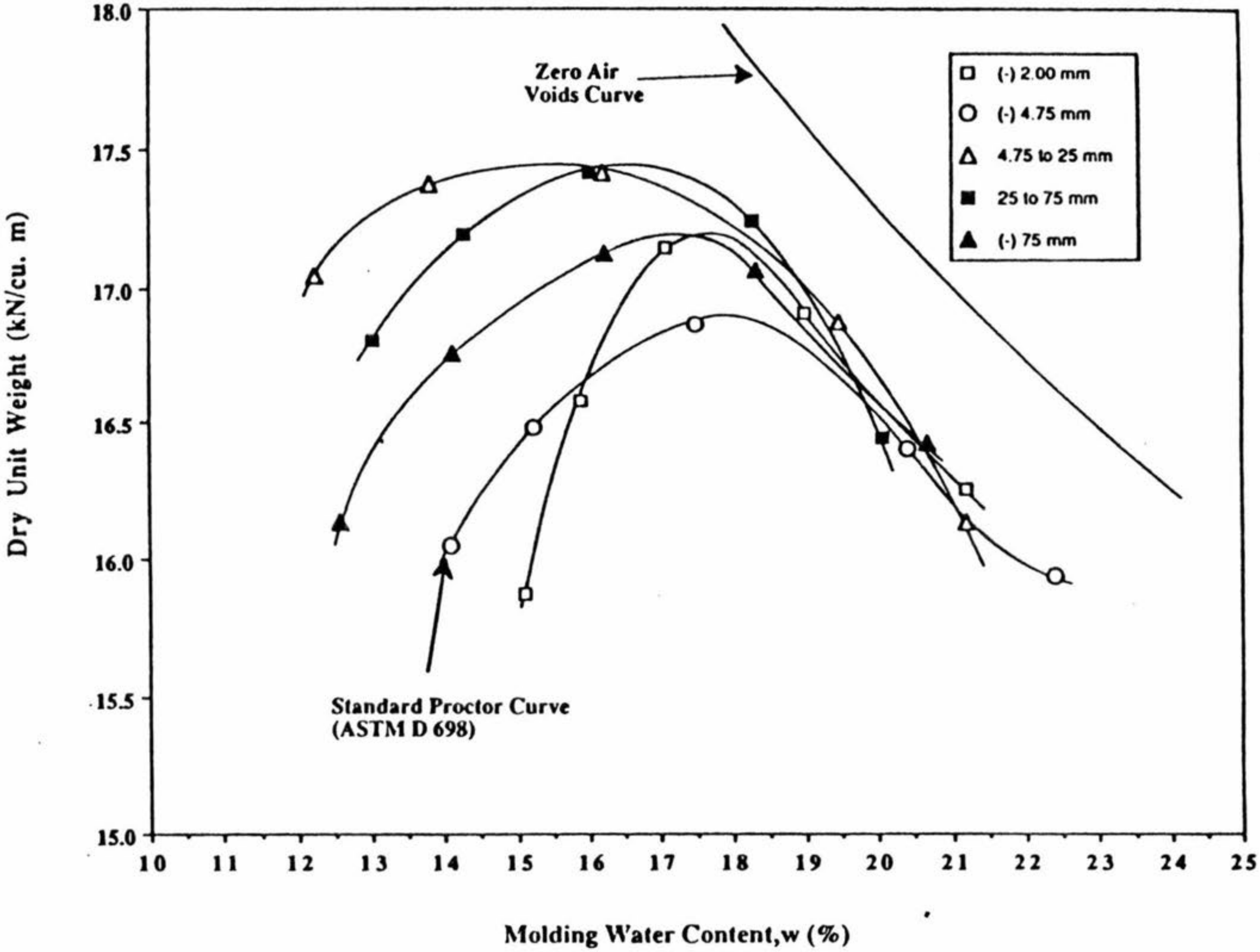


Figure. 4.3. Moisture Density Relationship for the Five Soil Fractions.

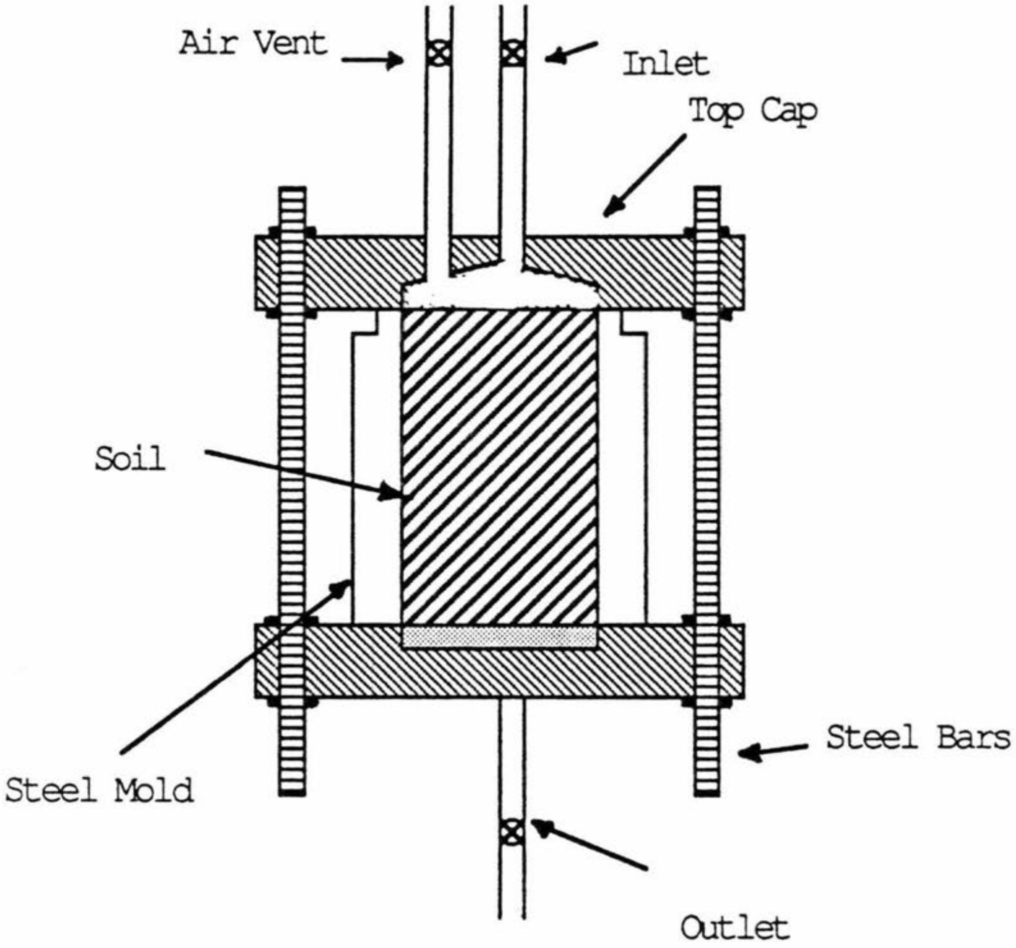


Figure 4.4 Rigid-wall Mold

effect of clod size on the permeability of compacted soil. The results from serires B to F were primarily used for time series analyses. Some of the tests from series A and B were used to determine the effect of compaction water content on the permeability of compacted soil. The dry density and water content for the specimens used in these test series are presented in Table 4.2 to 4.7.

4.3.1 SOIL PREPARATION

First, air-dried soil was sieved using a mechanical shaker and the appropriate nest of sieves, i.e. the 75-mm (3-in) 25-mm (1-in), No. 4 (4.75-mm), and No. 10 (2-mm) sieves. Second, the soil from the sieving procedure was separated into the five catagories outlined earlier. All specimens were compacted at a water content varying between one to three percent above optimum water content (19% to 21%) and a dry density of not more than ±2 percent of the values on a standard Proctor curve (Fig. 4.2). In other words, all the specimens fell within the shaded area as shown in Fig. 4.5.

4.3.2 SPECIMEN PREPARATION

First, the initial water content of the air-dried soil was determined. The weight of water required to raise the water content of soil to two percent above optimum water content was then calculated (Appendix 1). Water was added uniformly to 3000 g of soil through a spray bottle. The wet sample was placed into double polyethylene bags and allowed

Table 4.2. Water content and dry density for specimens in series A.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
A1	< 2.0	20.87	16.42
A2	< 4.75	19.95	16.78
A3	4.75 to 25	21.12	16.41
A4	25 to 75	20.91	16.27
A5	< 75	20.84	16.57
A6	< 4.75	17.0	16.87

Table 4.3. Water content and dry density for specimens in series B.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
B1	< 2.0	20.67	16.59
B2	< 4.75	20.71	16.64
B3	4.75 to 25	20.74	16.44
B4	25 to 75	20.82	16.41
B5	< 75	21.37	16.38
B6	< 4.75	21.45	16.71
B7	< 4.75	15.42	16.82

Table 4.4. Water content and dry density for specimens in series C.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
C1	< 2.0	19.86	16.47
C2	< 4.75	20.17	16.46
C3	4.75 to 25	20.72	16.53
C4	25 to 75	20.77	16.51
C5	< 75	20.47	16.46

Table 4.5. Water content and dry density for specimens in series D.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
D1	< 2.0	20.92	16.51
D2	< 4.75	20.86	16.53
D3	4.75 to 25	20.97	16.51
D4	25 to 75	21.13	16.38
D5	< 75	20.76	16.52

Table 4.6. Water content and dry density for specimens in series E.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
E1	< 2.0	20.31	16.49
E2	< 4.75	19.73	16.47
E3	4.75 to 25	19.82	16.48
E4	25 to 75	20.89	16.54
E5	< 75	20.19	16.49

Table 4.7. Water content and dry density for specimens in series F.

Test designation	Clod Sizes (mm)	Water Content (percent)	Dry Density (kN/cu.m)
F1	< 2.0	21.02	16.43
F2	< 4.75	20.04	16.51
F3	4.75 to 25	19.53	16.43
F4	25 to 75	20.37	16.47
F5	< 75	19.48	16.44

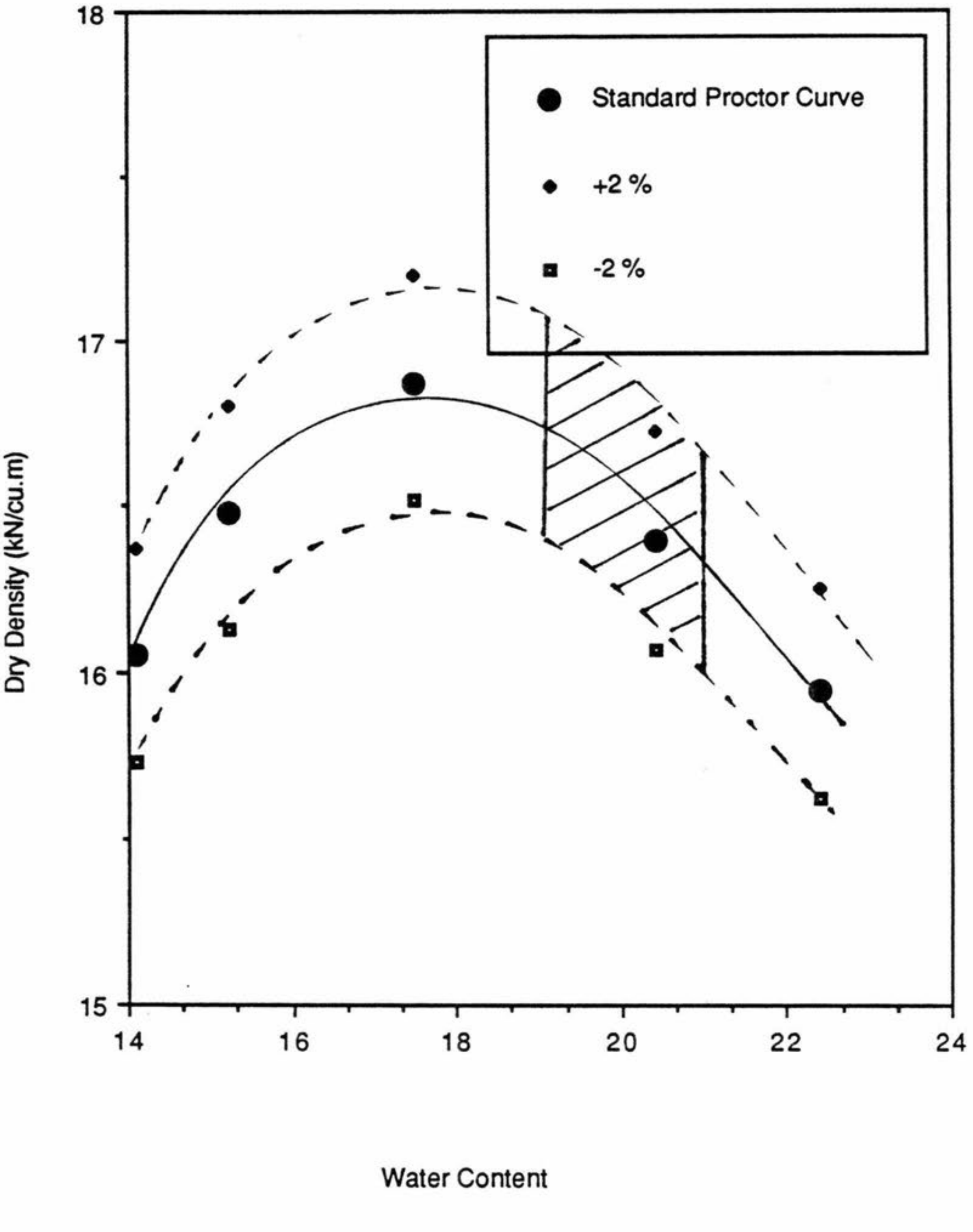


Figure 4.5 Compaction Curve Used for Accepting Specimen for Permeability Tests.

to hydrate for 48 hours. The soil was then compacted in the standard Proctor mold in accordance with the standard compaction procedure (ASTM D698, Method A). The top surface of specimen was trimmed and the dry density and water content of the specimen were determined. The specimen was discarded if the dry density and /or water content did not fall within the shaded area of Fig. 4.5. The specimen was placed immediately between end plates of the rigid-wall permeameter. The lower end plate contained a presoaked porous stone. The upper end plate allowed for swelling of the specimen. The specimen was allowed to saturate in water for 24 hours. The permeameter was then connected to the water pressure system. The test apparatus is illustrated schematically in Fig. 4.6. Water was pressurized in a separate reservoir and then forced through the test specimen. Tap water was used as the permeant fluid. Water was at a constant pressure at the top end of the specimen and atmospheric pressure at the effluent end of the sample. Hydrualic gradients varied from 30 to 180. The volume of water entering as well as leaving the specimen was monitored. In the begining inflow exceeded outflow but within two to four days inflow and outflow equalized. The average of these values was used to calculate the permeability from Darcy's law as:

$$K = V / Ait \qquad (4.1)$$

where V is the average of the volume of water entering and leaving the specimen in time t, A is the cross-sectional

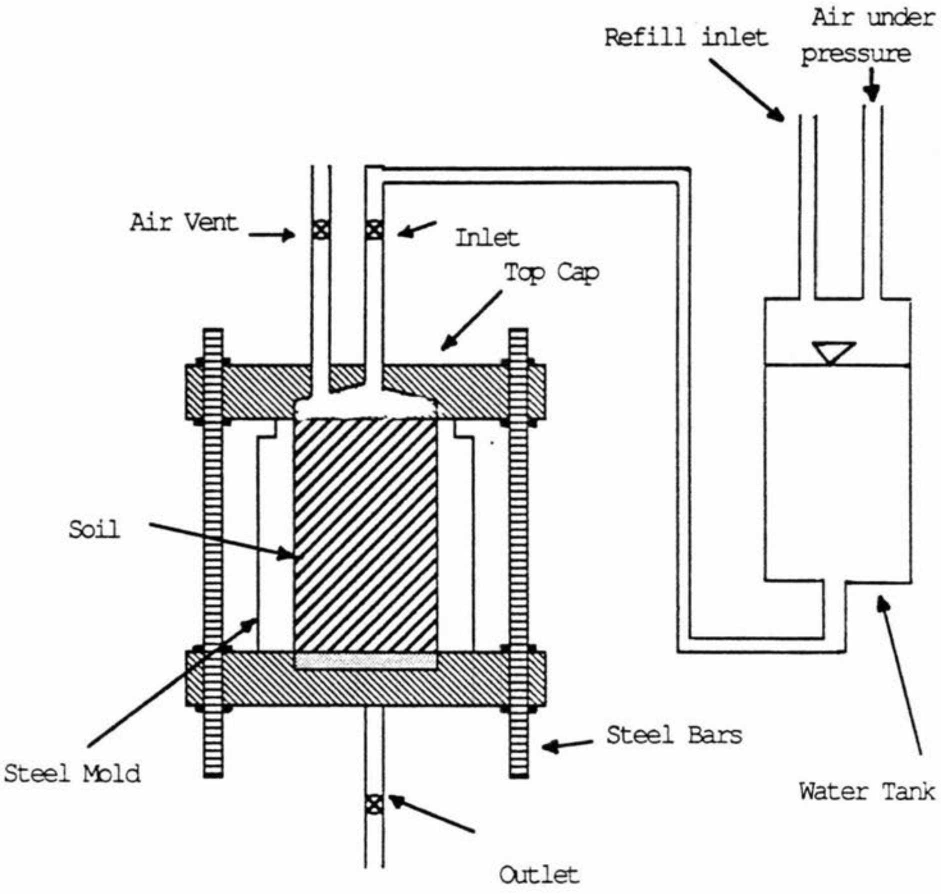
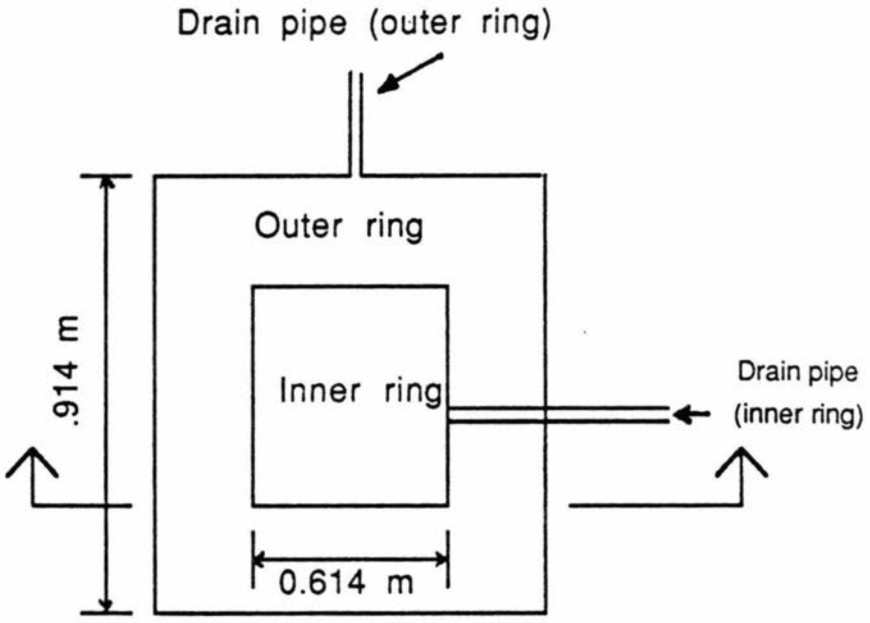


Fig. 4.6. Permeability Test Setup in a Rigid-wall Mold

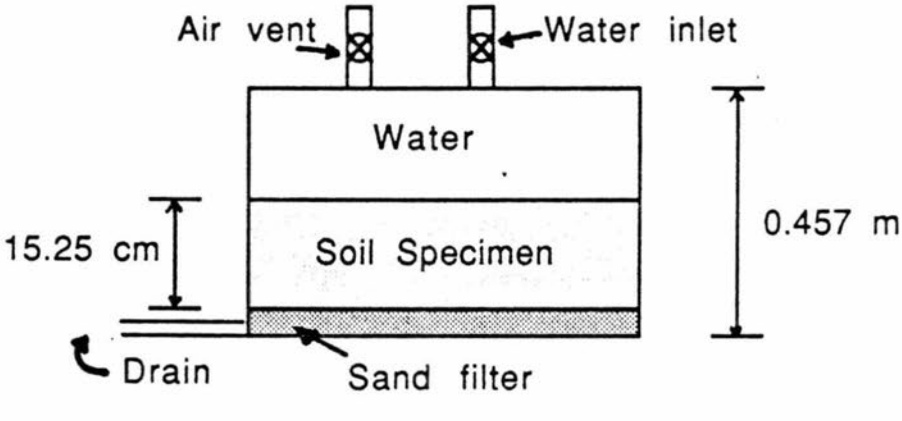
area of the specimen, and i is the hydraulic gradient. Tests in series A were continued for 2 1/2 months whereas tests in series B to F lasted for a month.

4.4 PERMEABILITY TESTS IN THE LARGE-SCALE PERMEAMETER

A large Permeater was constructed to study the effect of clod size on clay permeability. In principle the large-scale permeameter is similar to a double-ring, rigid-wall permeameter. The large-scale permeameter (Fig. 4.7) is a square steel tank supported on four wheels for ease of movement. The tank is 0.914 m (3-ft.) wide and 0.457 m (1.5-ft) high. The inner ring extends only 5.08 cm (2 in) into the permeameter. The outer ring has an area of 0.835 sq. m (9 sq. ft.) whereas the area of inner ring is 0.372 sq. m (4 sq. ft.). The entire permeameter, including the top cap, was constructed of 12.7 mm (0.5-in) thick steel plate. The top cap was sealed to the tank through a rubber gasket and a series of bolts. Preliminary tests indicated that the steel plate cap would bend under pressures exceeding approximately 160 KPa (25 psi) causing the seal between cap and permeameter to leak excessively. Steel I-beams were added to the cap plate to circumvent this problem. No leakage was observed for pressure upto 320 KPa (50 psi) after the reinforcement was added. The excessive weight of top cap required a portable hand crane to maneuver it. Fine sand was compacted in the bottom two inches (5 cm) of the Permeameter as a filter material. The gradation



PLAN VIEW



SECTION AA

Fig.4.7. Large-Scale Permeameter

curve for this sand is presented in Appendix 2. Whattman 60 filter paper was placed in front of outflow pipes to prevent the sand from being forced out of the permeameter.

4.4.1 SOIL PREPARATION

A six inch (15 cm) specimen was prepared by compacting wet soil in two 7.62 cm (3 inch) thick lifts. Since the volume of compacted specimen is known (4.5 cu. ft. or 0.125 cu. m.), the weight of soil required to achieve a desired wet density could be calculated (Appendix 3). Approximately 227 kg (500 lbs) of air-dried soil was used for each soil fraction. Soil was separated into 11.34 kg (25 lb) units for ease of handling. The procedure outlined in section 4.3.1 also was used for the large scale-test. After hydration the soil water content was determined for each bag of soil. Table 4.8 lists the average water content of soil prepared for compaction.

4.4.2. SPECIMEN PREPARATION

Half of the total soil required for each test (Appendix 3) was uniformaly spread in the permeameter and compacted with a 44.48-N (10 lb) rectangular (15.24 cm X 10.16 cm X 2.54 -cm) hammer. Soil was compacted in two 3-inches (7.5 cm) thick lifts. The lift thickness was measured using a ruler referenced to a network of strings tied across the top of the permeameter. The second 7.5 cm (3 in) layer was compacted in a similar way. The specimen was submerged in

Table 4.8. Test series in large Permeameter.

Test Designation	Clod size	Average water content (%)	Sample core	Sample core Water content (%)	Sample core Dry density (kN/m^3)	Average Dry density (kN/m^3)
T1	< 4.75 mm	20.72				16.56
			A	22.23	16.51	
			B	22.11	16.54	
			C	21.93	16.58	
			D	21.87	16.61	
T2	4.75 to 25 mm	20.93				16.44
			A	23.02	16.42	
			B	23.12	16.39	
			C	22.91	16.47	
			D	22.78	16.48	
T3	25 to 75 mm	20.74				16.61
			A	22.31	16.57	
			B	22.18	16.58	
			C	21.64	16.63	
			D	21.78	16.66	
T4	< 75 mm	20.87				16.74
			A	21.93	16.72	
			B	21.52	16.71	
			C	20.92	16.75	
			D	20.96	16.78	

water immediately after compaction to prevent any dessication cracks and was allowed to saturate for a week. The top lid was later secured in position and the permeameter was filled with water. Water pressure was applied at the top of the specimen whereas the bottom of the specimen was mantained at atmospheric pressure. Hydrualic gradients used during the permeability test varied from 10 to 50. This range of gradients was used to develop a relationship between the velocity and hydraulic gradient. The volume of water entering as well as leaving the permeameter was monitored. The volume of water collected from the inner ring and the outer ring was used to calculate the respective permeabilities. These permeabilities were compared to evaluate side-wall leakage (approximately equal permeability from outer and the inner ring indicates absence of side-wall leakage and a uniform specimen). The test was terminated when the three criteria outlined earlier in section 2.2 were achieved.

The dry density of test specimens was determined through core samples. Steel rings 10.2 cm (4-in) in diameter and either 6.35 cm (2.5-in) or 5.72 cm (2.25-in) in length were used. After termination of the test, two of these rings were inserted after removing 2.54 cm (1-in) thick layer of soil from top of the test specimen. The other two rings were inserted after removing the top 7.62 cm (3-in) of compacted soil. The core samples were weighed and then dried to determine water content and dry density. The dry densities determined through core samples (Table 4.8) are within two percent of the as-compacted dry density estimated from the weight of soil used for specimen preparation and the molding water content. A total of four tests on different ranges in clod sizes were performed in the large permeameter to study the effect of clod size on permeability. The test program for the large-scale permeameter tests is summarized in Table 4.8.

Chapter 5

RESULTS AND DISCUSSION

5.1. SMALL-SCALE PERMEABILITY TESTS

The results of the small-scale (Proctor mold) permeability tests for the five soil fractions are presented in Tables 5.1 through 5.5 and illustrated in Figs. 5.1 through 5.5. The plots for the relationship between permeability and pore volume, permeability and hydraulic gradient, hydraulic gradient and pore volume, and velocity and hydraulic gradient are shown in Appendix 5. Data for all the small-scale permeability tests is included in Appendix 6. Six specimens for each precompaction clod size were tested. The average permeability for each clod size is presented in Table 5.6. There was not much difference in permeability for specimens with maximum clod size less than 25 mm (Table 5.6). A slight increase in permeability was observed for the specimens that had precompaction clod sizes greater than 25 mm. On the average, there is about one order-of-magnitude increase in permeability as the range of precompaction clod sizes for the soil increases from less than 2 mm to less than 75 mm. However, Table 5.4 (clod sizes 25 to 75 mm) and Table 5.5 (clod sizes < 75 mm)

Table 5.1. Permeability Test Results (Precompaction Soil Clod Size < 2 mm) for Small-Scale Permeameter (Proctor Mold).

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
A1	20.9	16.42	1.5×10^{-8}
B1	20.7	16.59	2.1×10^{-8}
C1	19.86	16.47	1.8×10^{-8}
D1	20.92	16.51	1.9×10^{-8}
E1	20.31	16.49	4.4×10^{-8}
F1	21.02	16.43	1.9×10^{-8}
Average			2.3×10^{-8}

Table 5.2. Permeability Test Results (Precompaction Soil Clod Size < 4.75 mm) for Small-Scale Permeameter (Proctor Mold).

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
A2	20.0	16.78	1.5×10^{-8}
B2	20.7	16.64	1.5×10^{-8}
C2	20.17	16.46	2.7×10^{-8}
D2	20.86	16.53	5.6×10^{-8}
E2	19.73	16.47	2.5×10^{-8}
F2	21.04	16.51	2.9×10^{-8}
Average			1.9×10^{-8}

Table 5.3. Permeability Test Results (Precompaction Soil Clod Size 4.75 to 25 mm) for Small-Scale Permeameter (Proctor Mold).

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
A3	21.1	16.41	2.5×10^{-8}
B3	20.74	16.44	2.1×10^{-8}
C3	20.72	16.53	2.1×10^{-8}
D3	20.97	16.51	1.1×10^{-8}
E3	19.82	16.48	6.1×10^{-9}
F_3	19.53	16.43	4.1×10^{-8}
Average			2.1×10^{-8}

Table 5.4. Permeability Test Results (Precompaction Soil Clod Size 25 to 75 mm) for Small-Scale Permeameter (Proctor Mold).

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
A4	20.9	16.27	3.0×10^{-8}
B4	20.82	16.41	7.0×10^{-8}
C4	20.77	16.51	1.3×10^{-8}
D4	21.13	16.38	3.9×10^{-8}
E4	20.89	16.54	1.9×10^{-8}
F4	20.37	16.49	5.4×10^{-7}
Average (six samples)			1.2×10^{-7}
Average (neglecting sample F4)			3.4×10^{-8}

Table 5.5. Permeability Test Results (Precompaction Soil Clod Size < 75 mm) for Small-Scale Permeameter (Proctor Mold).

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
A5	20.8	16.57	7.5×10^{-8}
B5	21.37	16.38	2.5×10^{-7}
C5	20.47	16.46	1.4×10^{-8}
D5	20.76	16.52	3.1×10^{-8}
E5	20.19	16.49	6.9×10^{-8}
F5	19.48	16.44	6.0×10^{-8}
Average (six samples)			8.3×10^{-8}
Average (neglecting sample B5)			5.0×10^{-8}

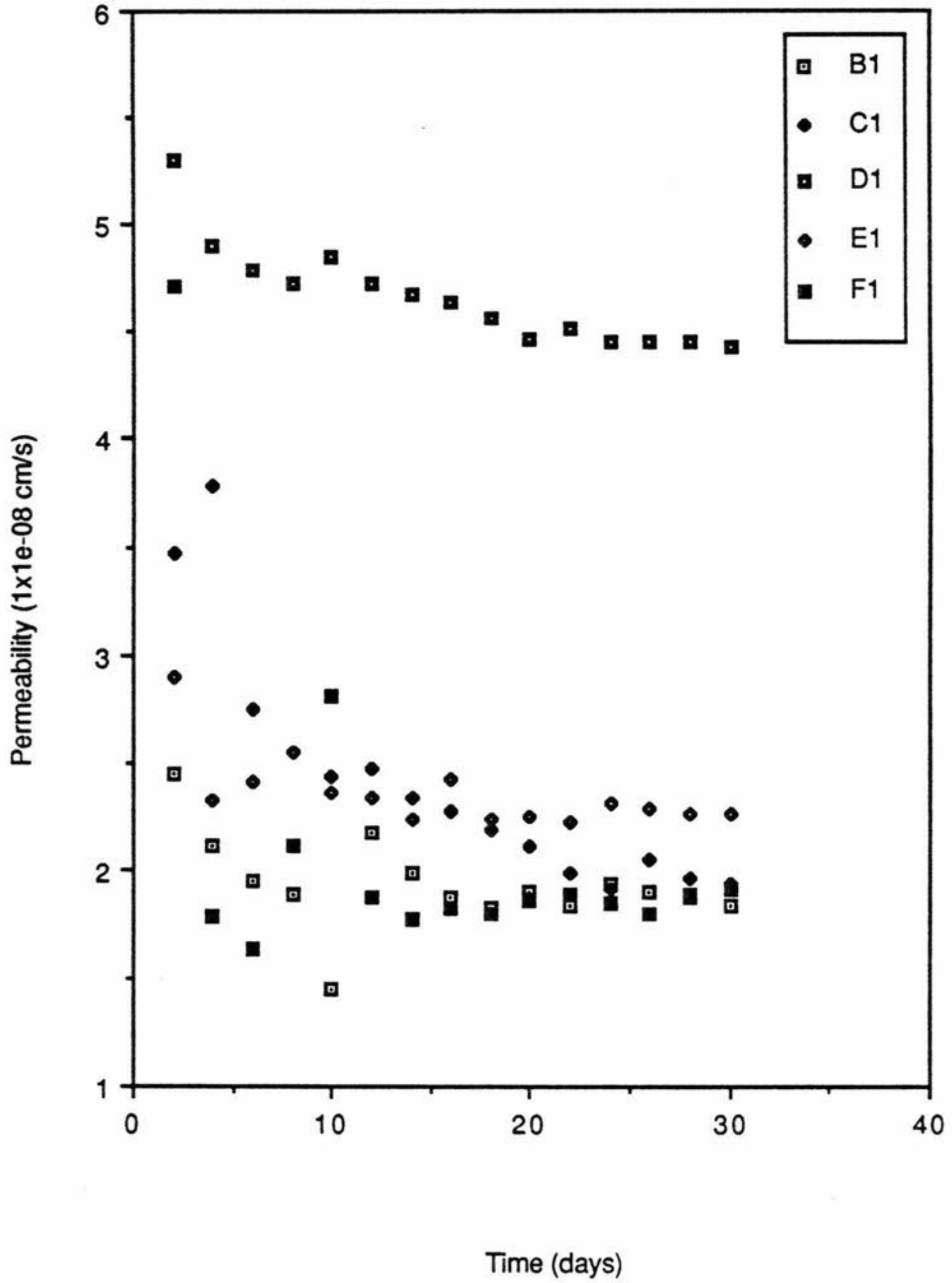


Figure 5.1. Permeability vs Time for Five Samples (clod sizes < 2 mm)

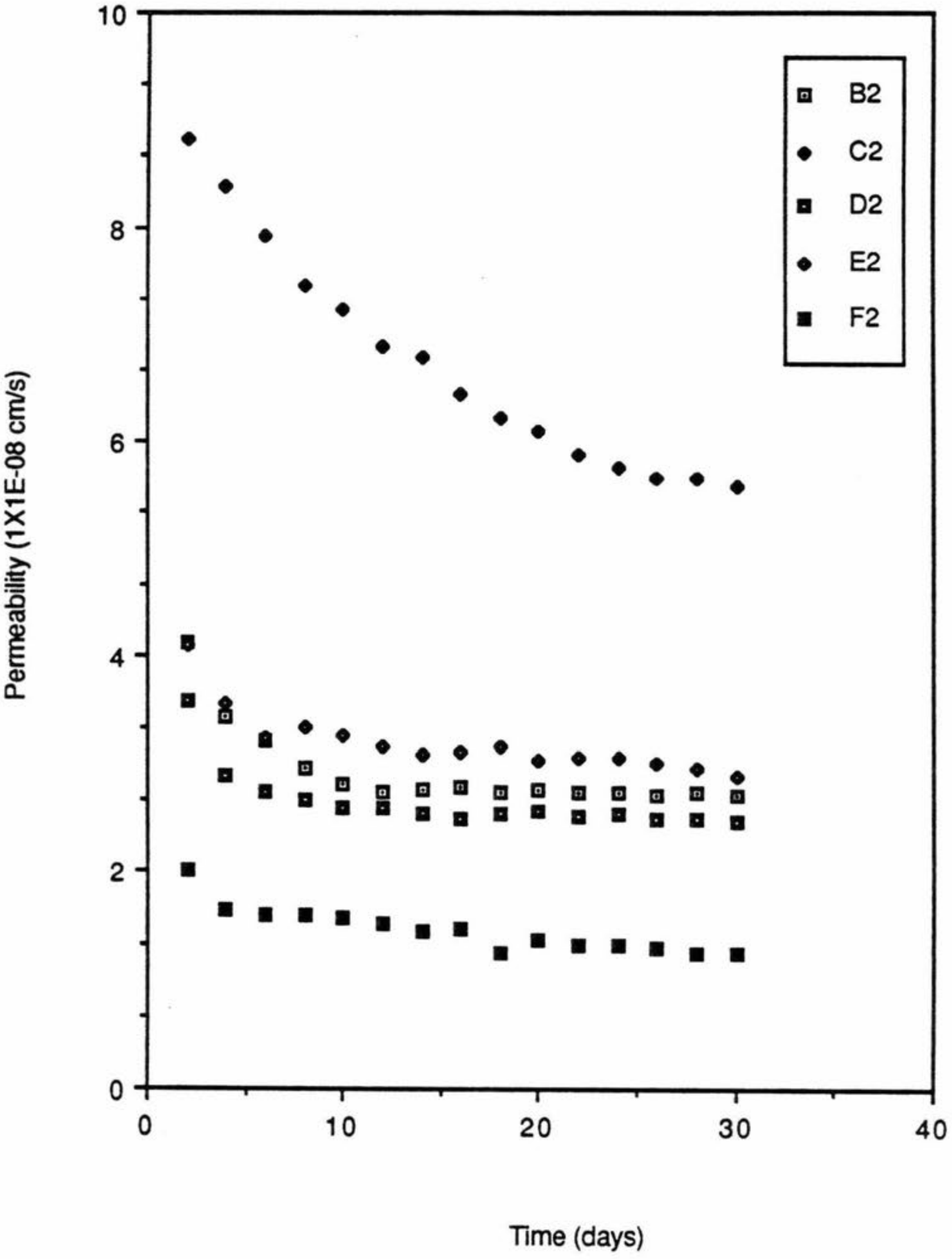


Figure 5.2. Permeability vs Time for Five Samples (clod sizes < 4.75 mm)

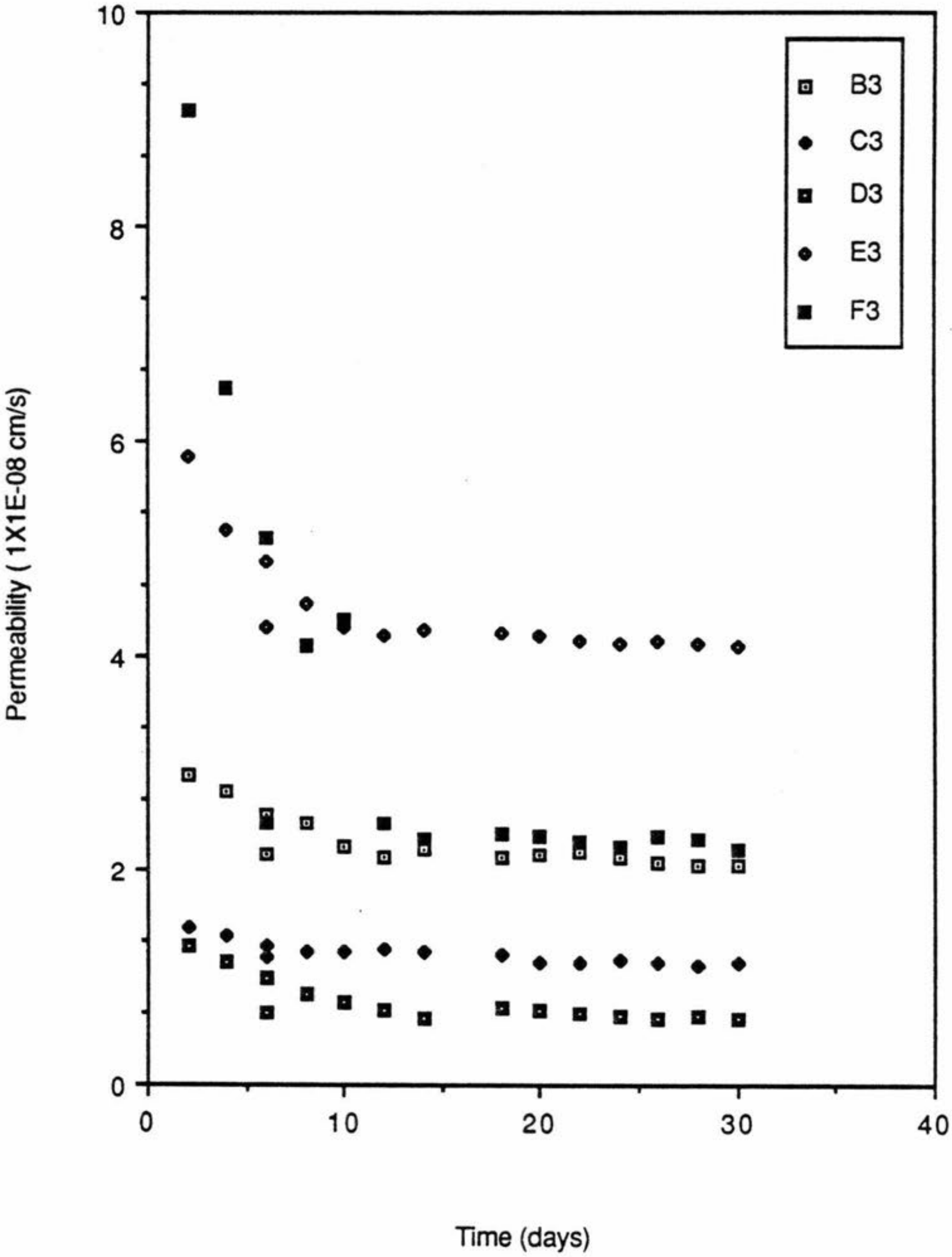


Figure 5.3. Permeability vs Time for Five Samples (clod size range 4.75 to 25 mm)

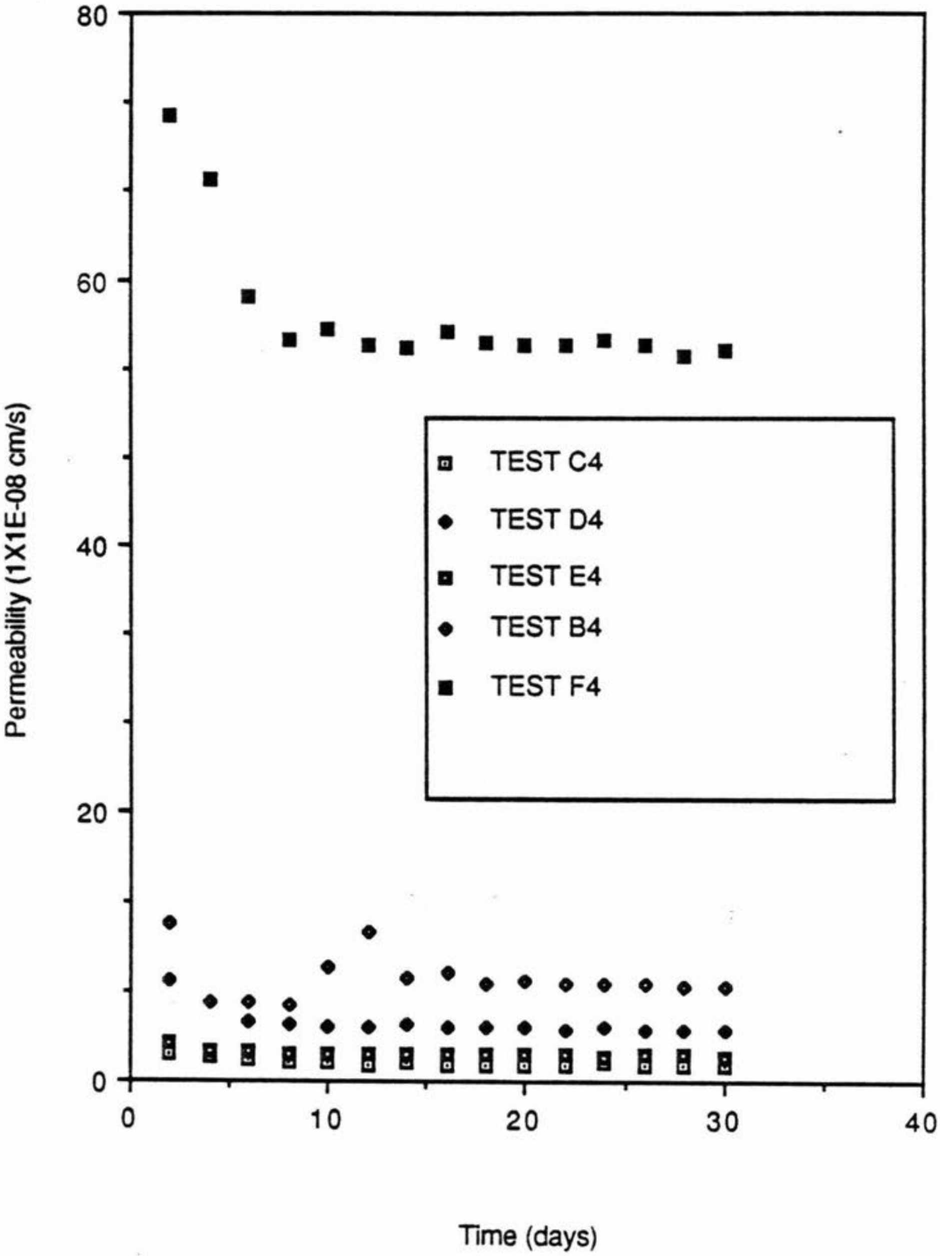


Figure 5.4. Permeability vs Time for Five Samples (clod size range 25 to 75 mm)

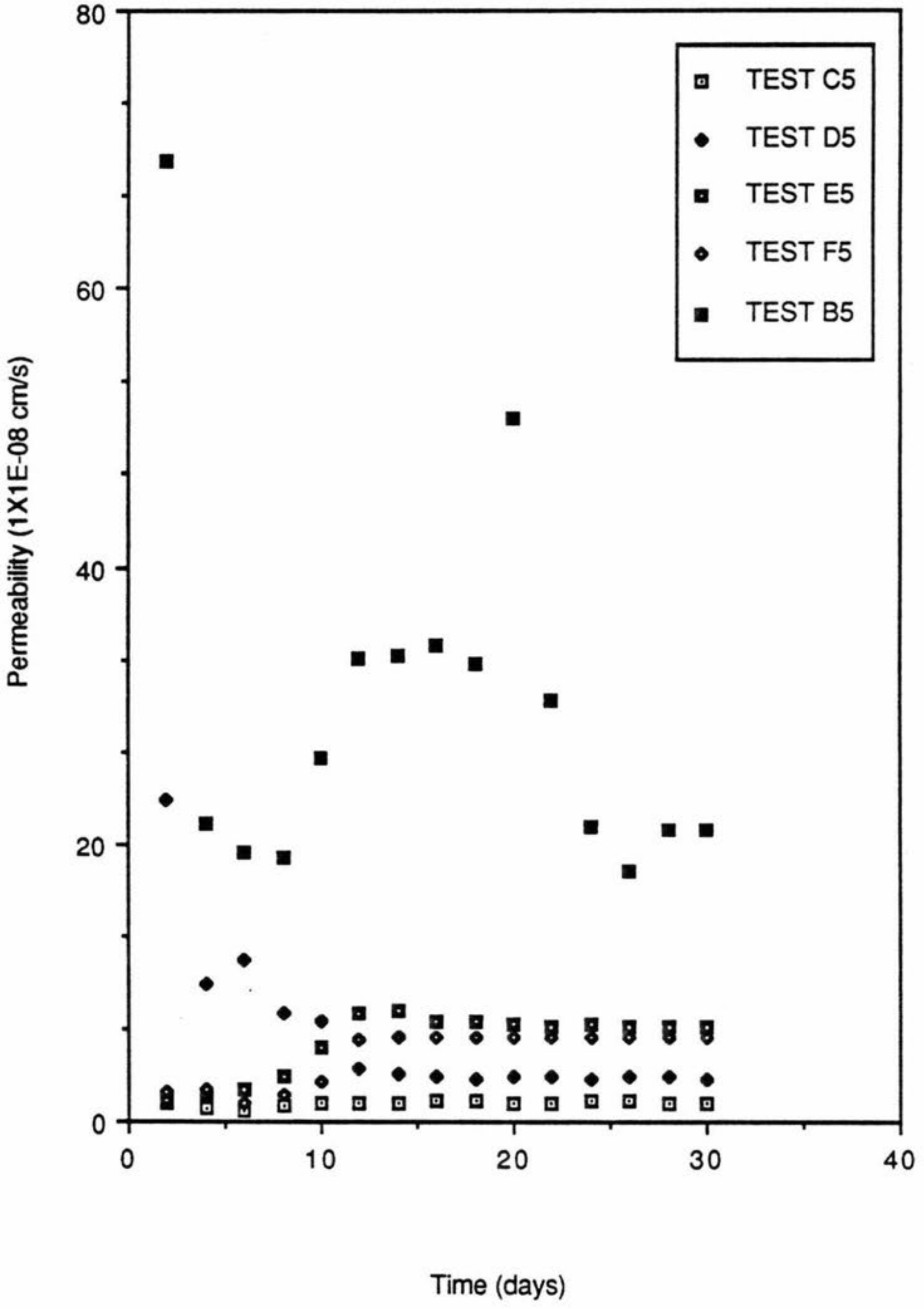


Figure 5.5. Permeability vs Time for Five Samples (clod sizes < 75 mm)

Table 5.6. Average permeability for the five soil fractions.

Precompaction clod Size (mm)	Average permeability (6 specimen)
< 2.0	2.3×10^{-8}
< 4.75	1.9×10^{-8}
4.75 to 25	2.1×10^{-8}
25 to 75	1.2×10^{-7} (3.4×10^{-8})*
< 75	8.3×10^{-8} (5.0×10^{-8})*

* Average permeability of five specimens.

indicate that only one specimen for either of the precompaction clod sizes has higher permeability. The presences of larger clods probably caused improper bonding between the rigid-wall of the small-scale permeameter and the soil specimen, resulting in side-wall leakage. If these two specimens are not considered, then the average permeability for clod sizes ranging between 25 and 75 mm is 3.4×10^{-8} cm/s and for clod sizes less than 75 mm is 5.0×10^{-8} cm/s. These results suggest that the soil permeability in small-scale (Proctor mold) tests is independent of the precompaction clod size.

The proportions of various ranges in precompaction clod sizes of natural soil can be used to determine a weighted-mean permeability of the compacted natural soil. From the gradation curve for natural soil (Fig. 4.1), the proportion of clods with maximum sizes less than 4.75 mm is 53 percent. Similarly the proportion of clods 4.75 mm to 25 mm in size is 35 percent. Only 12 percent of soil is composed of clods 25 to 75 mm in size. Using the average permeability values reported in Table 5.2, 5.3, and 5.4, the small-scale permeability is given as:

$$\begin{aligned} K_{ss} &= 0.53\ (1.94 \times 10^{-8}) + 0.35\ (2.08 \times 10^{-8}) + \\ &\qquad 0.12\ (3.4 \times 10^{-8})\ \text{cm/s} \\ &= 2.2 \times 10^{-8}\ \text{cm/s} \end{aligned}$$

This value is slightly less than the average permeability for specimens of soil in natural state (Table 5.6), suggesting that the permeability test results will be the same whether the soil in natural state (precompaction clod size < 75 mm) or soil sieved through a No. 4 sieve (precompaction clod size < 4.74 mm) is used for the specimen preparation in the Proctor mold. However, the possibility of side-wall leakage increases if the soil has precompaction clod size greater than 25 mm as indicated by tests B5 and F4.

The results for test B6, B7, A2, and A6 are summarized in Table 5.7 and illustrated in Fig. 5.6. Although the permeability for sample B7 (compacted at water content three percent dry of optimum water content) is higher than the other samples, the drastic decline (i.e., two to three orders-of-magnitude) in permeability wet of optimum water content reported by Mitchell et al. (1965) is not evident. An erratic behavior was observed for sample B7. The permeability for this sample stabilized at the reported value of 6.0 x 10^{-8} cm/s only after a flow of more than 15 pore volumes. If the test had been terminated before 5 pore volumes of flow, as were the other tests, then the permeability for sample B7 would have been reported as about 6.0 x 10^{-7} cm/s (Fig. 5.6) which is one order-of-magnitude higher.

5.2. LARGE-SCALE PERMEABILITY TESTS

The results of permeability tests using the large-scale permeameter are listed in Table 5.8 and illustrated in Fig. 5.7. The plots for the relationship between permeability

Table 5.7. Effect of compaction water content on the permeability of soil passing the No. 4 sieve.

Test	Molding water content (%)	Dry density kN/m^3	Permeability cm/s
B7	15.4	16.82	6.0×10^{-8}
A6	17.0	16.87	2.0×10^{-8}
A2	20.0	16.78	1.5×10^{-8}
B6	21.5	16.71	1.0×10^{-8}

Note: 1 kN/m^3 = 6.371 lb/ft^{t3}

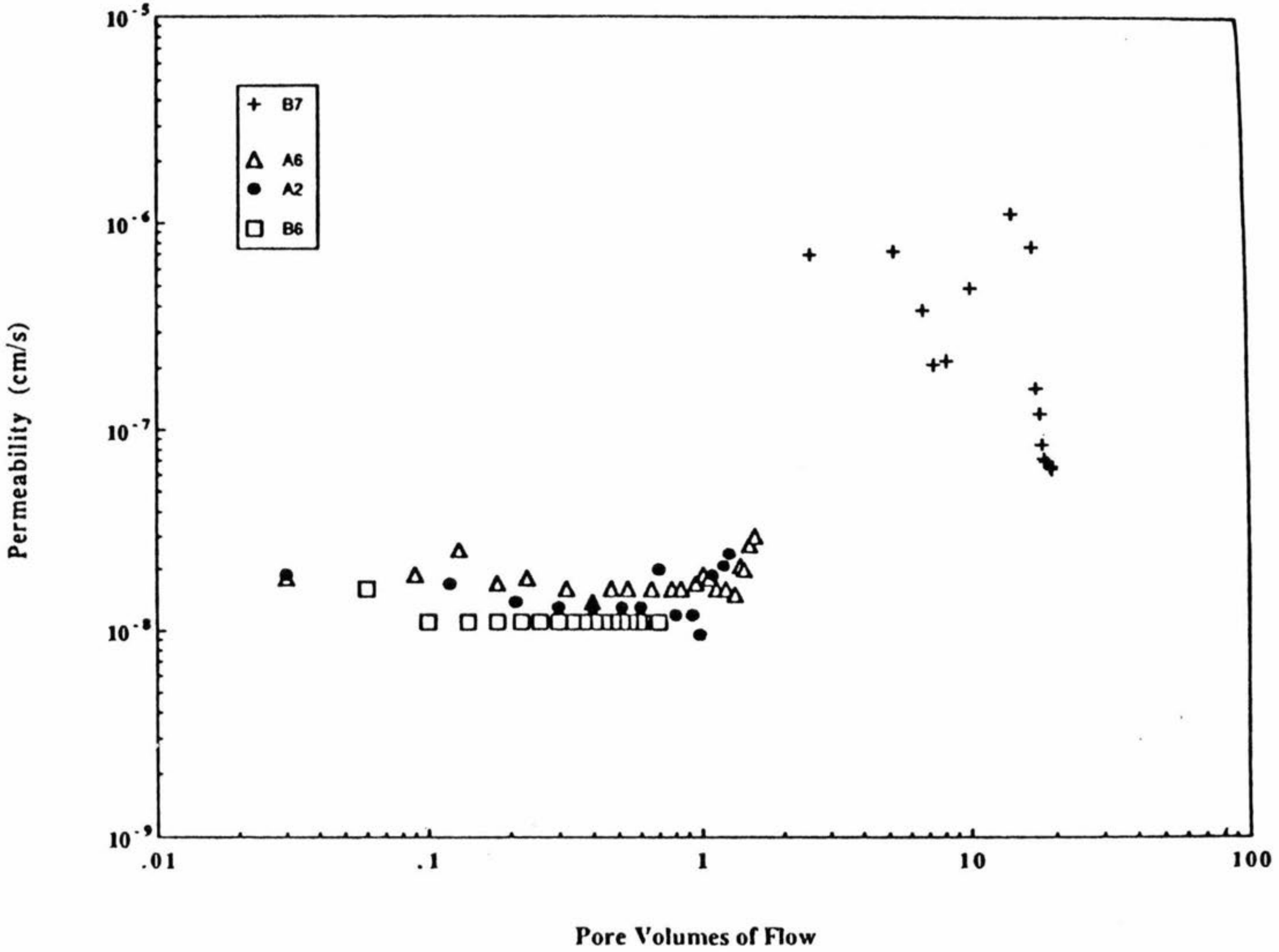


Figure 5.6. Variation in Permeability with Change in Compaction Water Content.

Table 5.8. Results of large-scale permeability tests.

Test	Precompaction soil clods size (mm)	Molding water content, %	Permeability, cm/s Outer ring	 Inner ring	 Average
T1	< 4.75	20.7	2.0×10^{-7}	2.5×10^{-7}	2.3×10^{-7}
T2	4.75 to 25	20.9	6.5×10^{-6}	6.5×10^{-6}	6.5×10^{-6}
T3	25 to 75	20.7	9.0×10^{-6}	1.5×10^{-5}	1.2×10^{-5}
T4	< 75	20.9	9.5×10^{-7}	9.0×10^{-7}	9.3×10^{-7}

Note: As-compacted dry density 16.70 kN/m^3

(1 kn/m^3 = 6.371 lb/ft^3)

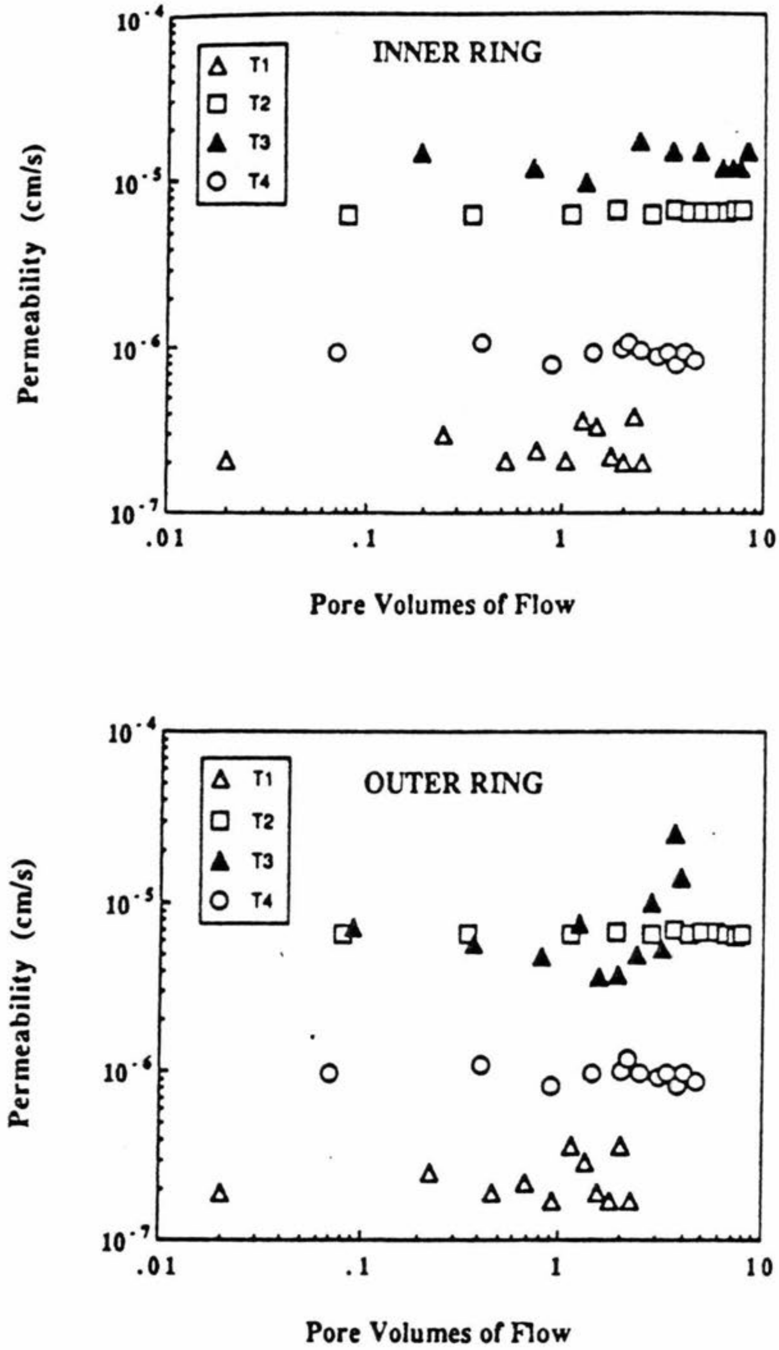


Figure 5.7. Results of Permeability Tests in the Large-scale Permeameter.

and pore volume, permeability and hydraulic gradient, hydraulic gradient and pore volume, and hydraulic gradient and velocity are presented in Appendix 5. Data for all the large-scale permeability tests is shown in Appendix 6. The results indicate that soil permeability is a function of the precompaction clod sizes. Soil permeability increases more than two orders-of-magnitude as the range of precompaction clod sizes for test specimens increases from less than 4.75 mm to a range between 25 and 75 mm. In the large-scale tests, the lowest permeability was observed for the specimen that had precompaction clod sizes less than 4.75 mm and the highest for the specimen having precompaction clod size range 25 to 75 mm. Permeability of compacted natural soil (sample T4) is about four times higher than that of specimen with precompaction clod sizes less than 4.75 mm (sample T1). Large-scale permeability for the sample with precompaction clod sizes ranging from 25 to 75 mm is about three orders-of-magnitude higher than small-scale permeability for precompaction clod sizes less than 4.75 mm (i.e., the standard permeability test).

The weighted-mean permeability of compacted natural soil also can be determined for the large-scale permeability test. The proportions of various clod sizes (section 5.1) and corresponding permeability values listed in Table 5.8 were used to determine the weighted mean permeability as:

$$K_{LS} = 0.53\ (2.25 \times 10^{-7}) + 0.35\ (6.5 \times 10^{-6}) + 0.12\ (1.2 \times 10^{-5})$$

$= 3.83 \times 10^{-6}$ cm/s

Thus, the weighted-mean permeability for the compacted natural soil is about one order-of-magnitude higher than the measured value of 9.25×10^{-7} cm/s for the soil in natural state (sample T4). As expected the large-scale permeability of the compacted natural soil, therefore, is not proportional to the percentage of the large clod sizes present in the natural soil.

5.3. COMPARISON BETWEEN LARGE-SCALE AND SMALL-SCALE PERMEABILITY TESTS.

The small-scale and the large-scale permeability values for each range of precompaction clod sizes presented in Table 5.6 and 5.8 are compared in Table 5.9. For all precompaction clod size ranges, the large-scale permeability exceeded the small-scale permeability by at least an order-of-magnitude. Since the permeability values for both the inner and outer ring of the large-scale permeameter essentially are the same (Table 5.8), these high large-scale permeability values can not be attributed to the side-wall leakage.

The highest increase in permeability was observed for the sample in which the precompaction range of clod sizes was 25 to 75 mm. For this range, the large-scale permeability is 2.8 orders-of-magnitude higher than the small-scale permeability. For the specimen of precompaction clod size range 4.75 to 25 mm an increase in permeability of

Table 5.9. Comparison of large-scale and small-scale (Proctor mold) permeability results.

Precompaction Clod sizes (mm)	Average permeability cm/s		K_{LS}/K_{ss}	
	Small scale K_{SS}	large scale K_{LS}	Arithmetic ratio	Orders-of-magnitude
< 4.75	1.9×10^{-8}	2.2×10^{-7}	12	1.0
4.75 to 25	2.1×10^{-8}	6.5×10^{-6}	310	2.4
25 to 75	3.4×10^{-8}	1.2×10^{-5}	360	2.8
< 75	5.0×10^{-8}	9.2×10^{-7}	18.6	1.4

2.4 orders-of magnitude was observed for the large-scale test. The samples of other two ranges of precompaction clod sizes (i.e., < 4.75 and < 75 mm) demonstrated smaller (about one order-of-magnitude) increase in permeability in the large-scale test. For these two ranges the void spaces between larger clods probably were filled with clods of smaller size and therefore, the effect of the larger clod sizes on the permeability was reduced.

5.4. TIME SERIES ANALYSIS

Application of time series analysis to permeability studies requires that the readings be taken at a fixed time interval. Also the test conditions should not change during the course of test, i.e., the gradient should stay constant. Observations were recorded at a fixed time interval of two days and the gradient was maintained at 92 for test series B to F of small-scale permeability tests. Five replicate samples were used for each soil fraction. For application of time series analysis to clay permeability, a computer program was written using the software Lotus 123. Details of this program are included in Appendix 4.

5.4.1. ANALYSES OF TESTS WITH PRECOMPACTION CLOD SIZE LESS THAN 2 mm.

The results of small-scale permeability tests B1, C1, D1, E1, and F1 were used for the analyses. The results are presented in Table 5.10 and illustrated in Fig. 5.8. The variance of the sample after 30 days is 1.22 where as variance of estimate drops to 0.31 on day 10. Therefore, the prediction on day 10 is far better than the observations on day 30. On day 30 the variance of estimate (0.18) is less than 1/5 the sample variance on the same day. Also on day 14 the variance of estimate is 0.24 which is more than four times smaller than that of observation (1.22) on day 30. This indicates that the prediction made on day 14 is much better than the observed permeability of five replicates recorded after 30 days of testing.

5.4.2 ANALYSES OF TESTS WITH PRECOMPACTION CLOD SIZE LESS THAN 4.75 mm.

This analysis was performed on the results of small-scale permeability tests B2, C2, D2, E2, and F2. The results of time series analysis for these samples are presented in Table 5.11 and illustrated in Fig. 5.9. The analysis considers the observations of all samples for a time step and includes a predicted value. The variance of observation, r, and of the prediction, $P_{k/k}$, are compared to find which is better. The analyses indicate that the prediction is consistently better than the five observed values. The variance of the sample after 30 days is 2.51, whereas the variance of estimate drops to a value of 1.08 only after 10 days suggesting that the prediction from a time series model on day 10 is better than the five

Table 5.10. Time Series Analysis (clod size < 2 mm)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 -φYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	2.45	3.47	5.30	2.90	4.71	1.45	3.77			1.45	1.40	3.77	3.64	0.49	3.32	0.71
4	2.11	3.78	4.90	2.32	1.79	1.73	2.98	3.64	-0.66	0.71	0.70	3.32	3.20	0.29	3.06	0.50
6	1.95	2.74	4.79	2.41	1.63	1.54	2.70	2.88	-0.17	0.50	0.51	3.06	2.95	0.25	2.89	0.38
8	1.88	2.11	4.73	2.55	2.11	1.38	2.68	2.61	0.06	0.38	0.40	2.89	2.79	0.22	2.79	0.31
10	1.45	2.44	4.85	2.36	2.81	1.59	2.78	2.58	0.20	0.31	0.33	2.79	2.69	0.17	2.69	0.27
12	2.17	2.47	4.73	2.33	1.87	1.32	2.71	2.69	0.03	0.27	0.29	2.69	2.60	0.18	2.60	0.24
14	1.98	2.34	4.68	2.23	1.77	1.40	2.60	2.62	-0.02	0.24	0.26	2.60	2.51	0.16	2.53	0.22
16	1.87	2.27	4.64	2.42	1.82	1.36	2.60	2.51	0.09	0.22	0.25	2.53	2.44	0.15	2.45	0.21
18	1.82	2.19	4.56	2.23	1.80	1.34	2.52	2.52	0.00	0.21	0.23	2.45	2.37	0.15	2.39	0.20
20	1.90	2.11	4.47	2.25	1.86	1.22	2.52	2.43	0.08	0.20	0.23	2.39	2.31	0.16	2.34	0.19
22	1.83	1.98	4.52	2.22	1.89	1.31	2.49	2.43	0.06	0.19	0.22	2.34	2.26	0.14	2.29	0.19
24	1.93	1.91	4.46	2.31	1.85	1.24	2.49	2.40	0.09	0.19	0.21	2.29	2.21	0.15	2.26	0.18
26	1.90	2.05	4.45	2.29	1.80	1.22	2.50	2.41	0.09	0.18	0.21	2.26	2.18	0.15	2.22	0.18
28	1.89	1.96	4.46	2.26	1.87	1.24	2.49	2.41	0.08	0.18	0.21	2.22	2.15	0.14	2.19	0.18
30	1.84	1.94	4.43	2.26	1.91	1.22	2.48	2.40	0.07	0.18	0.20	2.19	2.12	0.14	3.78	0.18

Sum Yk = 37.83   q = 0.04
Sum Yk+1 = 36.54
Regression Coefficient = 0.97

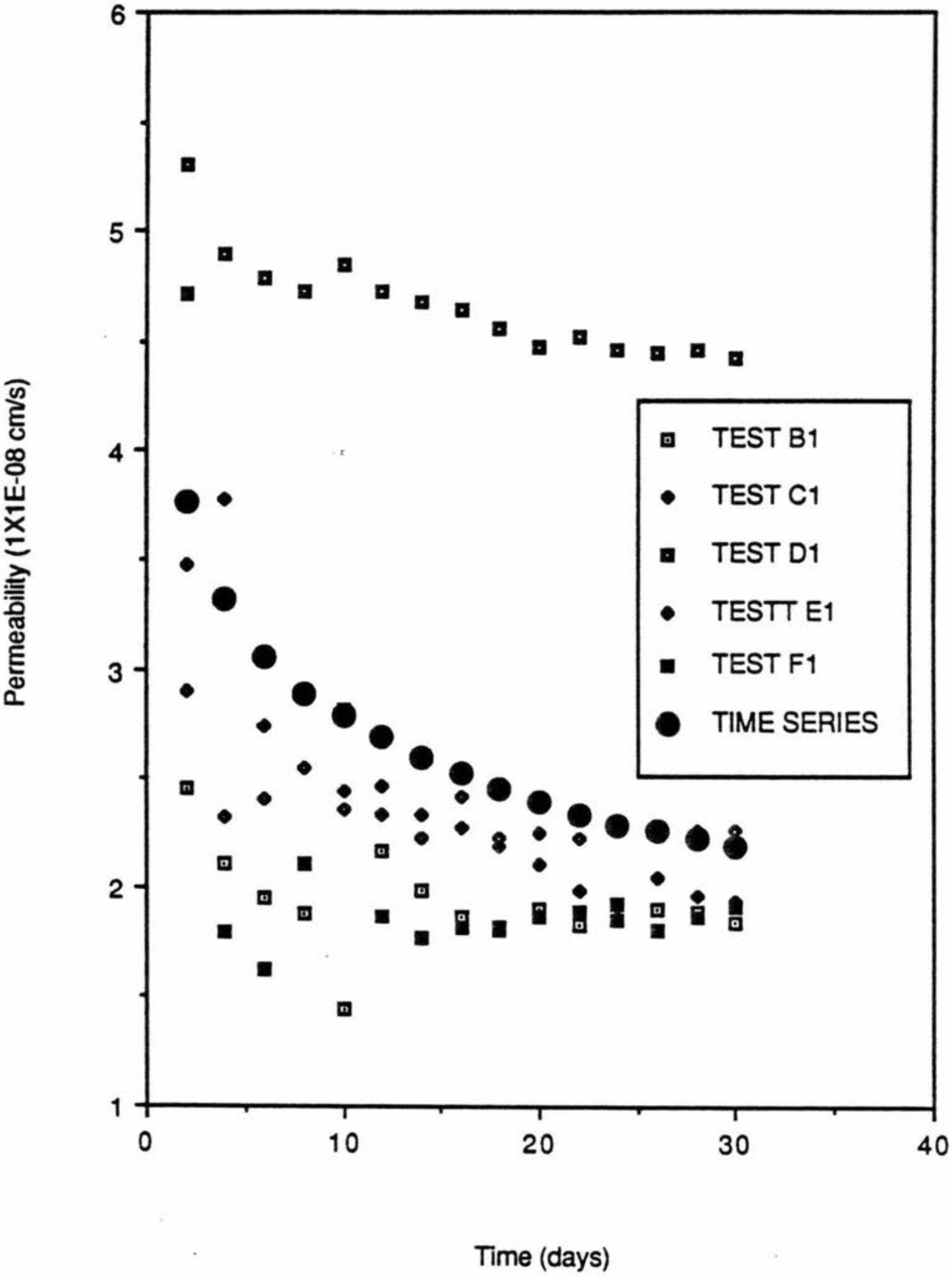


Figure 5.8. Time Series Modelling of Clay Permeability (clod sizes < 2mm)

Table 5.11. Time Series Analysis(clod size < 4.75 mm)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 -ΦYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	4.11	8.83	3.58	4.09	2.02	6.52	4.53			6.52	6.13	4.53	4.38	0.48	4.19	3.16
4	3.43	8.38	2.89	3.56	1.64	6.62	3.98	4.38	-0.40	3.16	2.97	4.19	4.05	0.31	3.95	2.05
6	3.20	7.92	2.74	3.23	1.60	5.90	3.74	3.85	-0.11	2.05	1.94	3.95	3.83	0.25	3.77	1.46
8	2.97	7.46	2.67	3.34	1.60	5.06	3.61	3.62	-0.01	1.46	1.38	3.77	3.65	0.21	3.62	1.08
10	2.82	7.23	2.59	3.26	1.56	4.77	3.49	3.49	0.00	1.08	1.03	3.62	3.50	0.18	3.48	0.85
12	2.74	6.89	2.59	3.15	1.52	4.22	3.38	3.38	0.00	0.85	0.81	3.48	3.37	0.16	3.36	0.68
14	2.76	6.78	2.56	3.09	1.45	4.10	3.33	3.27	0.06	0.68	0.65	3.36	3.25	0.14	3.25	0.56
16	2.79	6.45	2.51	3.11	1.48	3.54	3.27	3.22	0.05	0.56	0.54	3.25	3.15	0.13	3.16	0.47
18	2.75	6.23	2.54	3.16	1.26	3.40	3.19	3.16	0.02	0.47	0.45	3.16	3.05	0.12	3.07	0.40
20	2.77	6.11	2.58	3.04	1.37	3.10	3.17	3.09	0.09	0.40	0.39	3.07	2.97	0.11	2.98	0.35
22	2.74	5.88	2.53	3.07	1.33	2.83	3.11	3.07	0.04	0.35	0.34	2.98	2.89	0.11	2.91	0.30
24	2.74	5.76	2.55	3.07	1.33	2.66	3.09	3.01	0.08	0.30	0.30	2.91	2.82	0.10	2.84	0.27
26	2.71	5.65	2.49	3.02	1.29	2.57	3.03	2.99	0.04	0.27	0.27	2.84	2.75	0.09	2.77	0.24
28	2.75	5.65	2.51	2.96	1.26	2.59	3.03	2.93	0.09	0.24	0.24	2.77	2.68	0.09	2.71	0.22
30	2.72	5.58	2.47	2.89	1.26	2.51	2.98	2.93	0.05	0.22	0.22	2.71	2.62	0.08	3.78	0.20

Sum Yk = 47.94 q = 0.01
Sum Yk+1 = 46.40
Regression Coefficient = 0.97

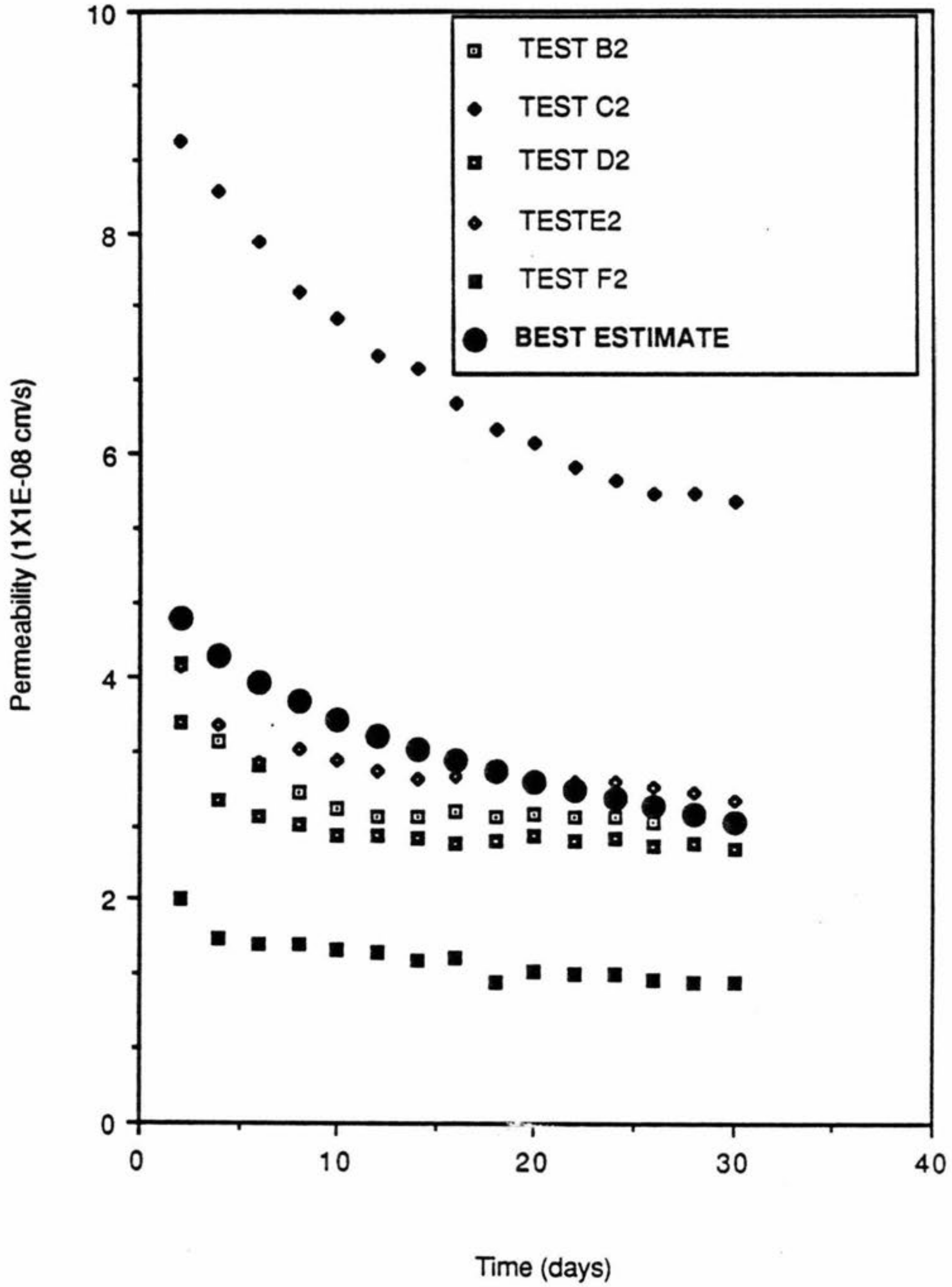


Figure 5.9. Time Series Modelling of Clay Permeability (clod sizes < 4.75mm)

observations recorded on day 30. The variance of estimate on day 14 is 0.68 which is less than 1/3 the variance of the sample on day 30. The variance of the estimate on day 30 (0.22) is 1/10 the variance of observations on the same day indicating that the predicted value from time series model on day 30 is far more reliable than the observation on the same day.

5.4.3 ANALYSES OF TESTS WITH PRECOMPACTION CLOD SIZE RANGE 4.75 TO 25 mm.

These analyses were performed on the results of permeability tests B3, C3, D3, E3, and F3. The results of time series analysis for these samples are presented in Table 5.12 and illustrated in Fig. 5.10. For this range of clod sizes the prediction is also better than the observed values. The variance of observation on day 30 is 1.78 which is ten times that of estimate (0.18) on the same day. The variance of estimate on day 10 is 0.87 which is about one half the variance of observations on day 30. This suggests that the prediction on day 10 is at least 50 percent better than the observed values on day 30. The variance of estimate on day 14 (0.44) is also about 1/4 the variance of observation on day 30 suggesting that the test may be terminated on day 14.

Table 5.12. Time Series Analysis(clod size 4.75 to 25 mm)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 =ϕYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	2.89	1.45	1.29	5.86	9.10	11.12	4.12			11.12	9.84	4.12	3.87	0.47	3.64	5.22
4	2.74	1.37	1.14	5.18	6.50	5.61	3.39	3.87	-0.48	5.22	4.64	3.64	3.42	0.45	3.21	2.54
6	2.51	1.29	0.99	4.87	5.10	3.77	2.95	3.18	-0.23	2.54	2.27	3.21	3.01	0.38	2.86	1.42
8	2.44	1.22	0.84	4.49	4.09	2.71	2.62	2.77	-0.16	1.42	1.29	2.86	2.69	0.32	2.65	0.87
10	2.21	1.24	0.76	4.26	4.33	2.78	2.56	2.46	0.11	0.87	0.81	2.65	2.49	0.22	2.41	0.63
12	2.13	1.26	0.69	4.19	2.45	1.80	2.14	2.40	-0.26	0.63	0.59	2.41	2.26	0.25	2.22	0.44
14	2.18	1.22	0.61	4.23	2.29	1.90	2.11	2.01	0.09	0.44	0.43	2.22	2.09	0.18	2.10	0.35
16	2.14	1.17	0.67	4.25	2.43	1.91	2.13	1.98	0.15	0.35	0.34	2.10	1.97	0.15	1.99	0.29
18	2.11	1.21	0.71	4.20	2.34	1.80	2.11	2.00	0.11	0.29	0.29	1.99	1.87	0.14	1.90	0.25
20	2.14	1.14	0.68	4.19	2.31	1.84	2.09	1.99	0.11	0.25	0.26	1.90	1.78	0.12	1.82	0.23
22	2.16	1.13	0.66	4.15	2.27	1.81	2.07	1.96	0.11	0.23	0.24	1.82	1.71	0.12	1.75	0.21
24	2.13	1.16	0.65	4.12	2.22	1.77	2.06	1.95	0.11	0.21	0.22	1.75	1.64	0.11	1.69	0.20
26	2.08	1.14	0.61	4.14	2.31	1.84	2.06	1.93	0.12	0.20	0.21	1.69	1.59	0.10	1.63	0.19
28	2.05	1.12	0.63	4.12	2.28	1.80	2.04	1.93	0.11	0.19	0.20	1.63	1.53	0.10	1.58	0.18
30	2.05	1.14	0.61	4.10	2.20	1.78	2.02	1.92	0.10	0.18	0.20	1.58	1.49	0.10	3.78	0.18

Sum Yk = 34.45

Sum Yk+1 = 32.35

Regression Coefficient = 0.94

q = 0.04

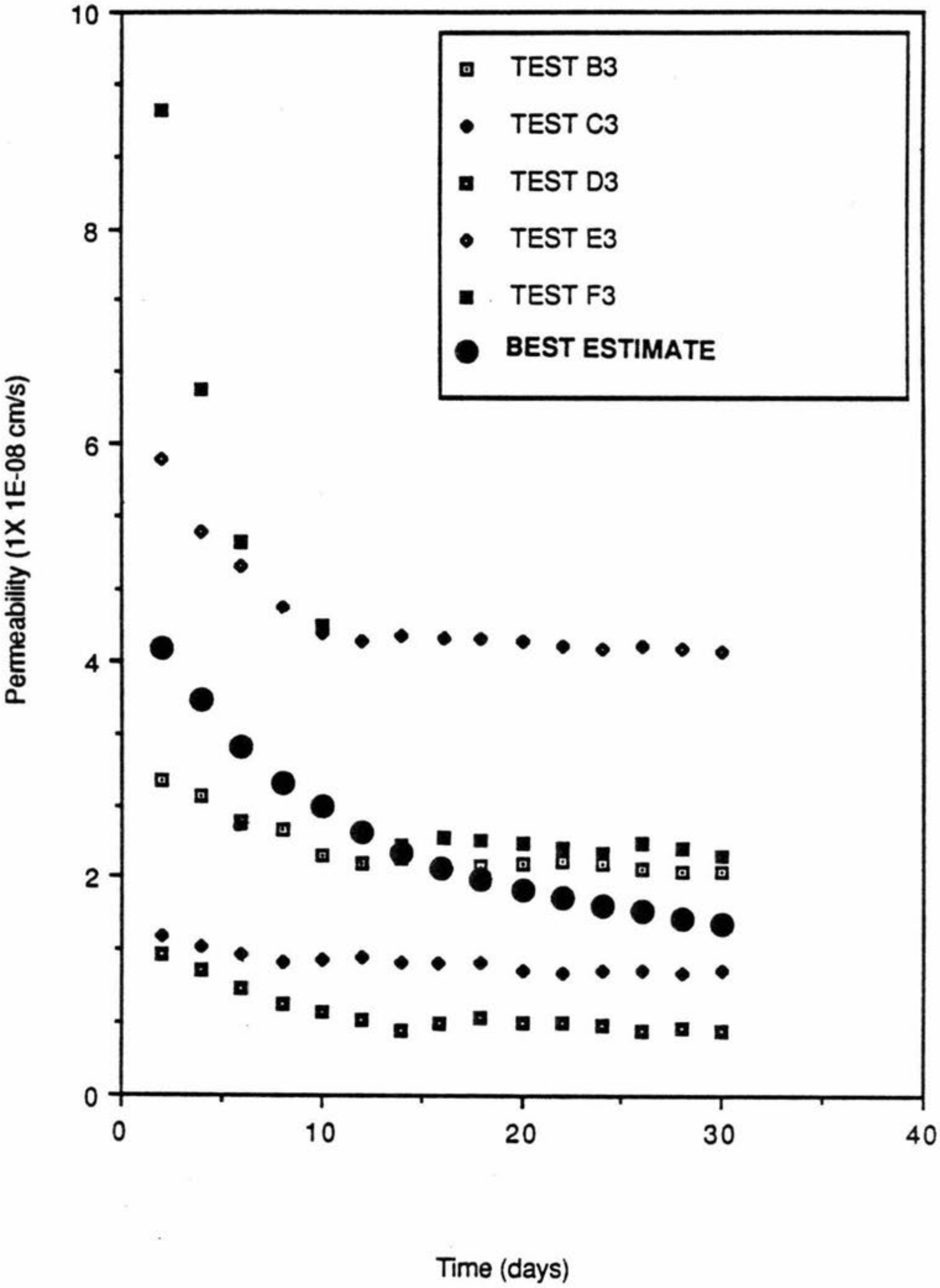


Figure 5.10. Time Series Modelling of Clay Permeability (clod size range 4.75 to 25 mm)

5.4.4. ANALYSIS OF TESTS WITH PRECOMPACTION CLOD SIZE RANGE 25 TO 75 mm.

Results of permeability tests on small-scale Proctor mold samples B4, C4, D4, E4, and F4 were used for this analyses. Results are included in Tables 5.13 and 5.14, and Fig. 5.11 and 5.12. These results indicate that one of the specimen (F4) had higher permeability compared to the others. This higher permeability can be due to different properties of this sample or slight leakage along the rigid-wall of the Permeameter. Analysis was performed for the permeability results of five samples and the results (Table 5.13) indicate very high variances. The variance of observations is quite large (527) even after 30 days. The variance of estimate (82) on day 10 is less than 1/5 the variance of observation on day 30 but still it is too high compared to the variance for other soil fractions. Another analysis was performed by ignoring the results of test F4 (Table 5.14). The results of this analysis are more reliable but in practice it is questionable whether unusual results should be ignored. The variance of observations drops to 6.9 in 30 days and the variance of estimate is only 1.22 on the same day. Variance of estimate on day 10 (1.28) is about 1/4 that of observation on day 30 suggesting that the predicted value on day 10 is far better than the observation on day 30. Since the variance for these four tests is fairly small, it can be implied that there was some problem with test F4. Probably some side-wall leakage

Table 5.13. Time Series Analysis(clod size 25 to 75 mm)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 =ΦYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	2.06	7.39	2.74	11.59	72.44	899.19	19.24			899.19	852.38	19.24	18.73	0.49	17.73	437.58
4	1.90	5.79	2.21	5.90	67.59	813.61	16.68	18.73	-2.05	437.58	415.17	17.73	17.26	0.34	16.33	274.90
6	1.60	4.34	2.13	5.80	58.77	614.53	14.53	16.23	-1.70	274.90	261.09	16.33	15.90	0.30	15.26	183.24
8	1.45	4.19	2.06	5.60	55.45	546.21	13.75	14.14	-0.39	183.24	174.28	15.26	14.85	0.24	14.75	132.12
10	1.37	4.04	2.06	8.40	56.33	555.92	14.44	13.38	1.06	132.12	125.86	14.75	14.35	0.18	14.42	102.63
12	1.29	4.12	1.98	11.06	55.12	525.12	14.71	14.05	0.66	102.63	97.93	14.42	14.03	0.16	14.03	82.54
14	1.33	4.18	2.03	7.60	54.87	527.89	14.00	14.32	-0.32	82.54	78.90	14.03	13.65	0.13	13.74	68.64
16	1.30	4.09	2.11	8.04	56.09	551.86	14.33	13.63	0.70	68.64	65.74	13.74	13.37	0.11	13.44	58.74
18	1.29	4.03	2.04	7.23	55.23	537.40	13.96	13.94	0.02	58.74	56.36	13.44	13.08	0.09	13.16	51.01
20	1.27	3.97	1.97	7.40	55.12	535.44	13.95	13.59	0.36	51.01	49.04	13.16	12.81	0.08	12.89	44.92
22	1.26	3.88	1.91	7.20	54.98	534.07	13.85	13.57	0.27	44.92	43.27	12.89	12.55	0.07	12.65	40.03
24	1.32	3.93	1.89	7.20	55.45	543.29	13.96	13.48	0.48	40.03	38.64	12.65	12.31	0.07	12.42	36.07
26	1.28	3.90	1.94	7.20	55.13	536.78	13.89	13.58	0.31	36.07	34.89	12.42	12.09	0.06	12.18	32.76
28	1.29	3.88	1.93	7.10	54.24	518.96	13.69	13.52	0.17	32.76	31.75	12.18	11.86	0.06	11.97	29.92
30	1.26	3.85	1.90	7.10	54.65	527.87	13.75	13.32	0.43	29.92	29.07	11.97	11.65	0.05	3.78	27.55

Sum Yk = 204.97   q = 0.72

Sum Yk+1 = 199.48

Regression Coefficient = 0.97

Table 5.14. Time Series Analysis(clod size 25 to 75 mm,neglecting results of test F4)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 -ΦYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	2.06	7.39	2.74	11.59	72.44	19.78	5.94			858.05	727.43	19.46	17.78	0.46	12.97	393.68
4	1.90	5.79	2.21	5.90	67.59	4.80	3.95	5.68	-1.73	393.68	339.75	12.97	11.85	0.82	7.96	61.56
6	1.60	4.34	2.13	5.80	58.77	3.83	3.47	3.77	-0.31	61.56	62.47	7.96	7.28	0.48	6.96	32.33
8	1.45	4.19	2.06	5.60	55.45	3.69	3.32	3.31	0.01	32.33	38.07	6.96	6.36	0.41	7.27	22.46
10	1.37	4.04	2.06	8.40	56.33	10.02	3.97	3.18	0.79	22.46	29.83	7.27	6.65	0.23	7.49	23.11
12	1.29	4.12	1.98	11.06	55.12	19.92	4.61	3.79	0.82	23.11	30.38	7.49	6.85	0.15	7.39	25.80
14	1.33	4.18	2.03	7.60	54.87	7.94	3.79	4.41	-0.62	25.80	32.62	7.39	6.75	0.16	7.34	27.45
16	1.30	4.09	2.11	8.04	56.09	9.05	3.89	3.62	0.27	27.45	33.99	7.34	6.71	0.16	7.26	28.68
18	1.29	4.03	2.04	7.23	55.23	7.03	3.65	3.71	-0.06	28.68	35.02	7.26	6.63	0.17	7.83	29.02
20	1.27	3.97	1.97	7.40	55.12	7.55	3.65	3.49	0.17	29.02	35.31	7.83	7.16	0.08	7.34	32.65
22	1.26	3.88	1.91	7.20	54.98	7.12	3.56	3.49	0.07	32.65	38.33	7.34	6.71	0.22	6.94	30.08
24	1.32	3.93	1.89	7.20	55.45	7.06	3.59	3.41	0.18	30.08	36.20	6.94	6.34	0.37	6.63	22.79
26	1.28	3.90	1.94	7.20	55.13	7.06	3.58	3.43	0.15	22.79	30.11	6.63	6.06	0.42	6.77	17.47
28	1.29	3.88	1.93	7.10	54.24	6.81	3.55	3.42	0.13	17.47	25.67	6.77	6.18	0.30	6.63	18.07
30	1.26	3.85	1.90	7.10	54.65	6.89	3.53	3.39	0.13	18.07	26.16	6.63	6.05	0.30	3.78	18.26

Sum Yk = 54.52 q = 0.36
Sum Yk+1 = 52.10
Regression Coefficient = 0.96

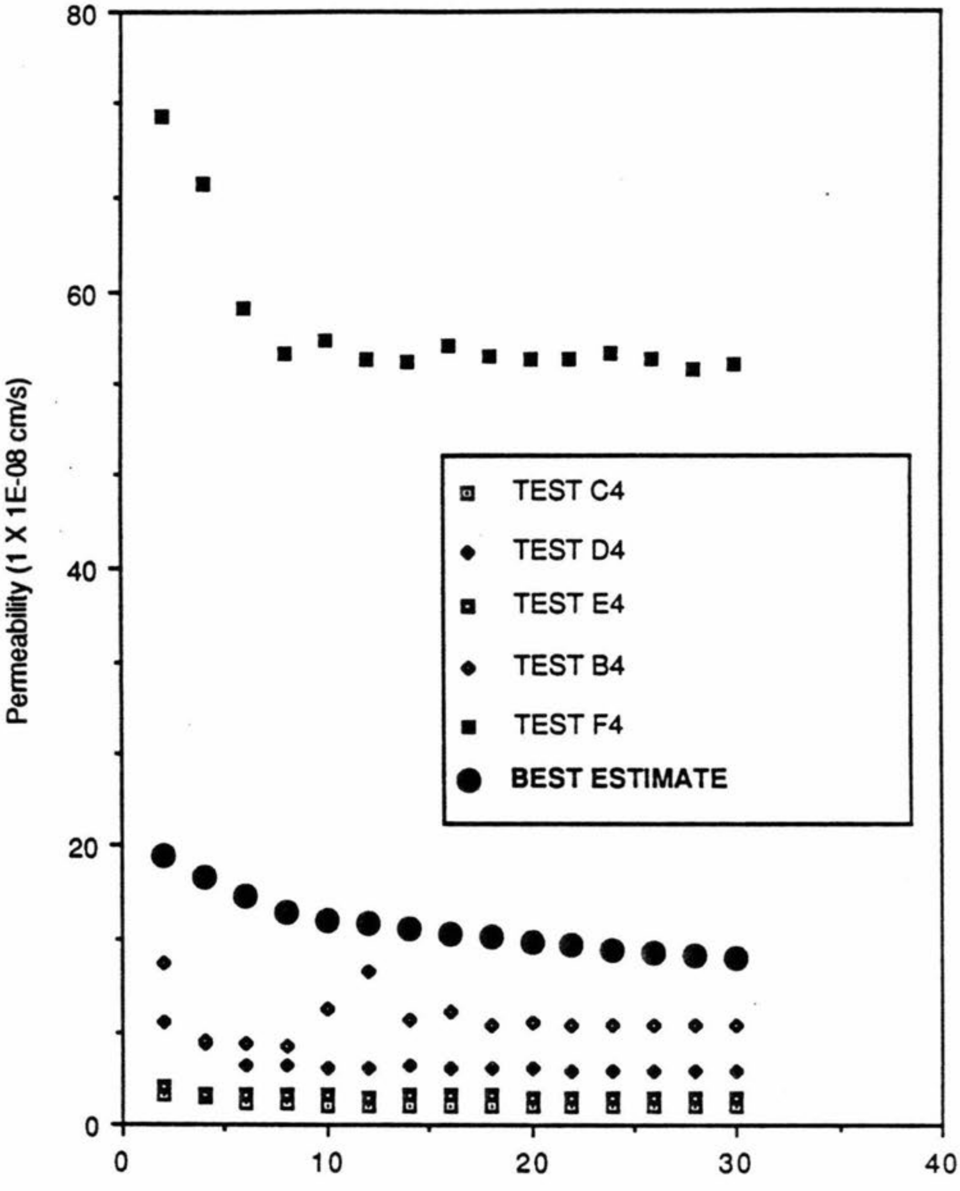


Figure 5.11. Permeability vs Time for five samples (clod size range 25 to 75 mm)

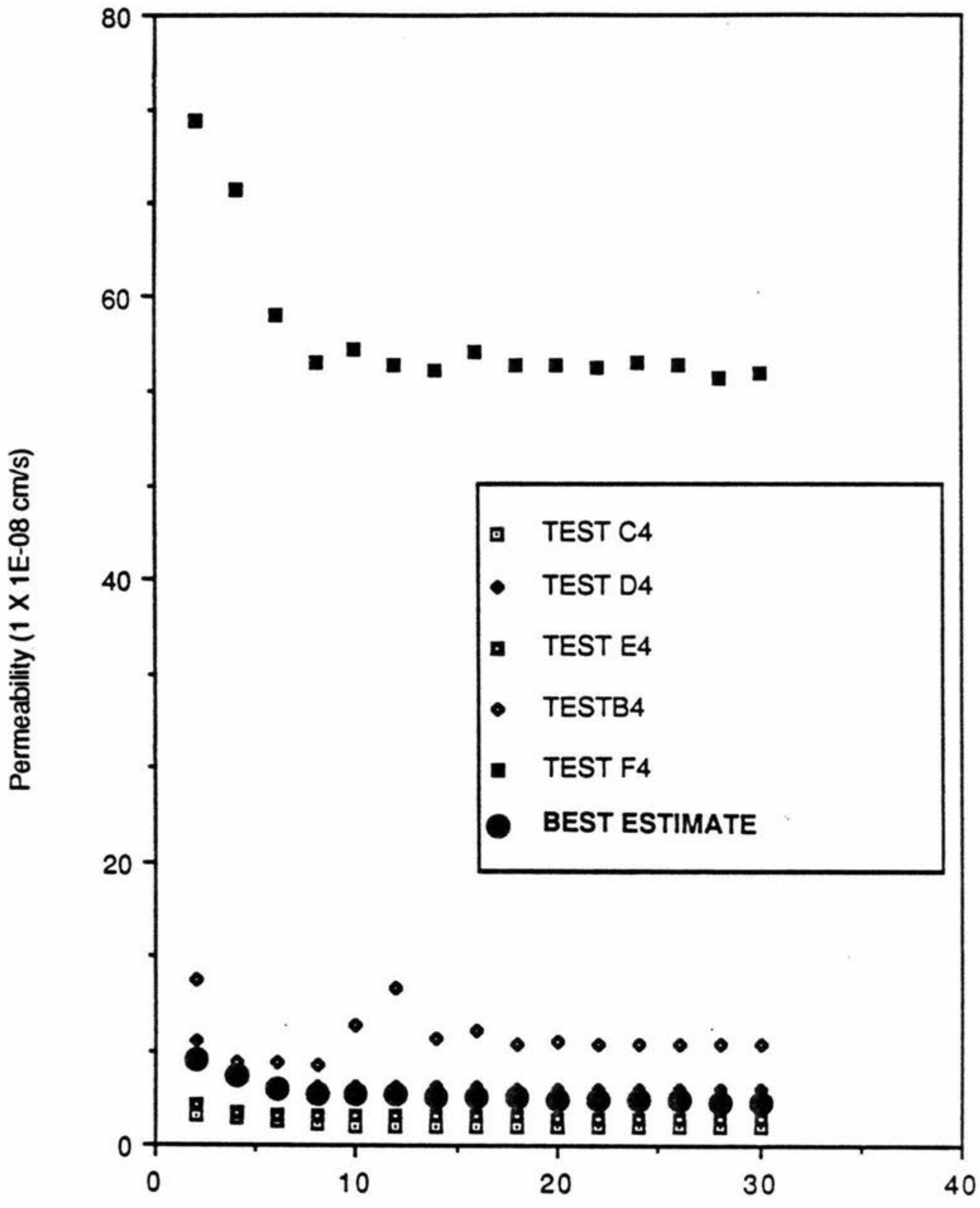


Figure 5.12. Time Series Modelling of Clay Permeability (clod size range 25 to 75 mm, neglecting test F4)

occured for specimen F4 resulting in high permeability values.

5.4.5. ANALYSES OF TESTS WITH PRECOMPACTION CLOD SIZES LESS THAN 75 mm.

This analysis was performed on the results of permeability tests B5, C5, D5, E5, and F5. The results are presented in Tables 5.15 and 5.16, and illustrated in Fig. 5.13 and 5.14. The results of test B5 are not consistent with other tests, resulting in large variances. The variance of sample after 30 days is 60.5, whereas the variance of estimate on the same day is 18.07. The variance of estimate on day 10 is 22.46, which is about 1/3 the variance of sample on day 30, but it is still higher than the variance of estimate for the samples of relatively smaller precompaction clod sizes.

Another analysis was performed by ignoring the results of test B5 and it was observed that the variances came down to reasonable values. The variance of sample after 30 days for four samples is 6.48 where as that of estimate after 10 days is 4.29. The variance of estimate on day 14 however, is 2.23 which is about 1/3 that of sample on day 30. The variances in this analysis are approximately 1/10 the variances associated with analysis of five samples. Therefore, it is concluded that the behavior of sample B5 is not representative of permeability tests on this range of clod sizes. Probably some side-wall leakage occured in test

Table 5.15. Time Series Analysis(clod size < 75 mm)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 =ΦYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	1.29	23.23	1.60	2.06	69.12	858.05	19.46			858.05	727.43	19.46	17.78	0.46	12.97	393.68
4	0.91	9.90	1.90	2.36	21.43	75.18	7.30	17.78	-10.48	393.68	339.75	12.97	11.85	0.82	7.96	61.56
6	0.76	11.58	2.36	1.37	19.45	67.00	7.10	6.67	0.43	61.56	62.47	7.96	7.28	0.48	6.96	32.33
8	1.22	7.77	3.20	1.90	19.06	54.80	6.63	6.49	0.14	32.33	38.07	6.96	6.36	0.41	7.27	22.46
10	1.29	7.31	5.25	2.82	26.23	102.62	8.58	6.06	2.52	22.46	29.83	7.27	6.65	0.23	7.49	23.11
12	1.29	3.73	7.77	5.86	33.43	171.32	10.42	7.84	2.58	23.11	30.38	7.49	6.85	0.15	7.39	25.80
14	1.37	3.43	7.92	6.02	33.56	172.97	10.46	9.52	0.94	25.80	32.62	7.39	6.75	0.16	7.34	27.45
16	1.45	3.20	7.23	6.09	34.34	183.43	10.46	9.56	0.91	27.45	33.99	7.34	6.71	0.16	7.26	28.68
18	1.45	3.12	7.16	6.17	33.12	169.39	10.20	9.56	0.64	28.68	35.02	7.26	6.63	0.17	7.83	29.02
20	1.37	3.20	7.01	6.09	50.65	432.57	13.66	9.32	4.34	29.02	35.31	7.83	7.16	0.08	7.34	32.65
22	1.37	3.20	6.93	6.17	30.37	139.75	9.61	12.48	-2.88	32.65	38.33	7.34	6.71	0.22	6.94	30.08
24	1.45	3.12	7.01	6.09	21.23	61.54	7.78	8.78	-1.00	30.08	36.20	6.94	6.34	0.37	6.63	22.79
26	1.45	3.20	6.85	6.17	17.98	41.62	7.13	7.11	0.02	22.79	30.11	6.63	6.06	0.42	6.77	17.47
28	1.37	3.20	6.93	6.09	21.14	61.03	7.75	6.51	1.23	17.47	25.67	6.77	6.18	0.30	6.63	18.07
30	1.37	3.12	6.85	6.02	21.02	60.50	7.68	7.08	0.60	18.07	26.16	6.63	6.05	0.30	3.78	18.26

Sum Yk = 136.54　　q = 11.08
Sum Yk+1 = 124.76
Regression Coefficient = 0.91

Table 5.16. Time Series Analysis (clod size < 75 mm,neglecting results of test B5)

permeability of five samples
(1X1E-08 cm/s)

(1) Time (Days)	(2) Y1	(3) Y2	(4) Y3	(5) Y4	(6) Y5	(7) r	(8) Average (Y)	(9) Yk+1 =ϕYk	(10) W	(11) pk|k	(12) pk+1|k	(13) Xk|k	(14) Xk+1|k	(15) g	(16) Xk+1|k+1	(17) pk+1|k+1
2	1.29	23.23	1.60	2.06	69.12	116.48	7.04			116.48	107.43	7.04	6.74	0.48	5.32	55.89
4	0.91	9.90	1.90	2.36	21.43	17.07	3.77	6.74	-2.97	55.89	51.93	5.32	5.09	0.75	4.28	12.85
6	0.76	11.58	2.36	1.37	19.45	25.82	4.02	3.61	0.41	12.85	12.51	4.28	4.10	0.33	3.91	8.43
8	1.22	7.77	3.20	1.90	19.06	8.68	3.52	3.84	-0.32	8.43	8.47	3.91	3.74	0.49	3.95	4.29
10	1.29	7.31	5.25	2.82	26.23	7.05	4.17	3.37	0.80	4.29	4.67	3.95	3.78	0.40	4.13	2.81
12	1.29	3.73	7.77	5.86	33.43	7.76	4.66	3.99	0.67	2.81	3.32	4.13	3.96	0.30	4.17	2.33
14	1.37	3.43	7.92	6.02	33.56	8.27	4.68	4.46	0.22	2.33	2.88	4.17	3.99	0.26	4.12	2.13
16	1.45	3.20	7.23	6.09	34.34	7.01	4.49	4.48	0.01	2.13	2.70	4.12	3.95	0.28	4.09	1.95
18	1.45	3.12	7.16	6.17	33.12	7.02	4.47	4.30	0.17	1.95	2.53	4.09	3.92	0.26	4.05	1.86
20	1.37	3.20	7.01	6.09	50.65	6.76	4.42	4.28	0.14	1.86	2.45	4.05	3.88	0.27	4.02	1.80
22	1.37	3.20	6.93	6.17	30.37	6.72	4.42	4.23	0.19	1.80	2.39	4.02	3.85	0.26	4.00	1.76
24	1.45	3.12	7.01	6.09	21.23	6.67	4.42	4.23	0.19	1.76	2.36	4.00	3.82	0.26	3.98	1.74
26	1.45	3.20	6.85	6.17	17.98	6.44	4.42	4.23	0.19	1.74	2.34	3.98	3.81	0.27	3.97	1.72
28	1.37	3.20	6.93	6.09	21.14	6.63	4.40	4.23	0.17	1.72	2.32	3.97	3.80	0.26	3.94	1.72
30	1.37	3.12	6.85	6.02	21.02	6.48	4.34	4.21	0.13	1.72	2.32	3.94	3.77	0.26	3.78	1.71

Sum Yk = 62.90

Sum Yk+1 = 60.20

Regression Coefficient = 0.96

q = 0.75

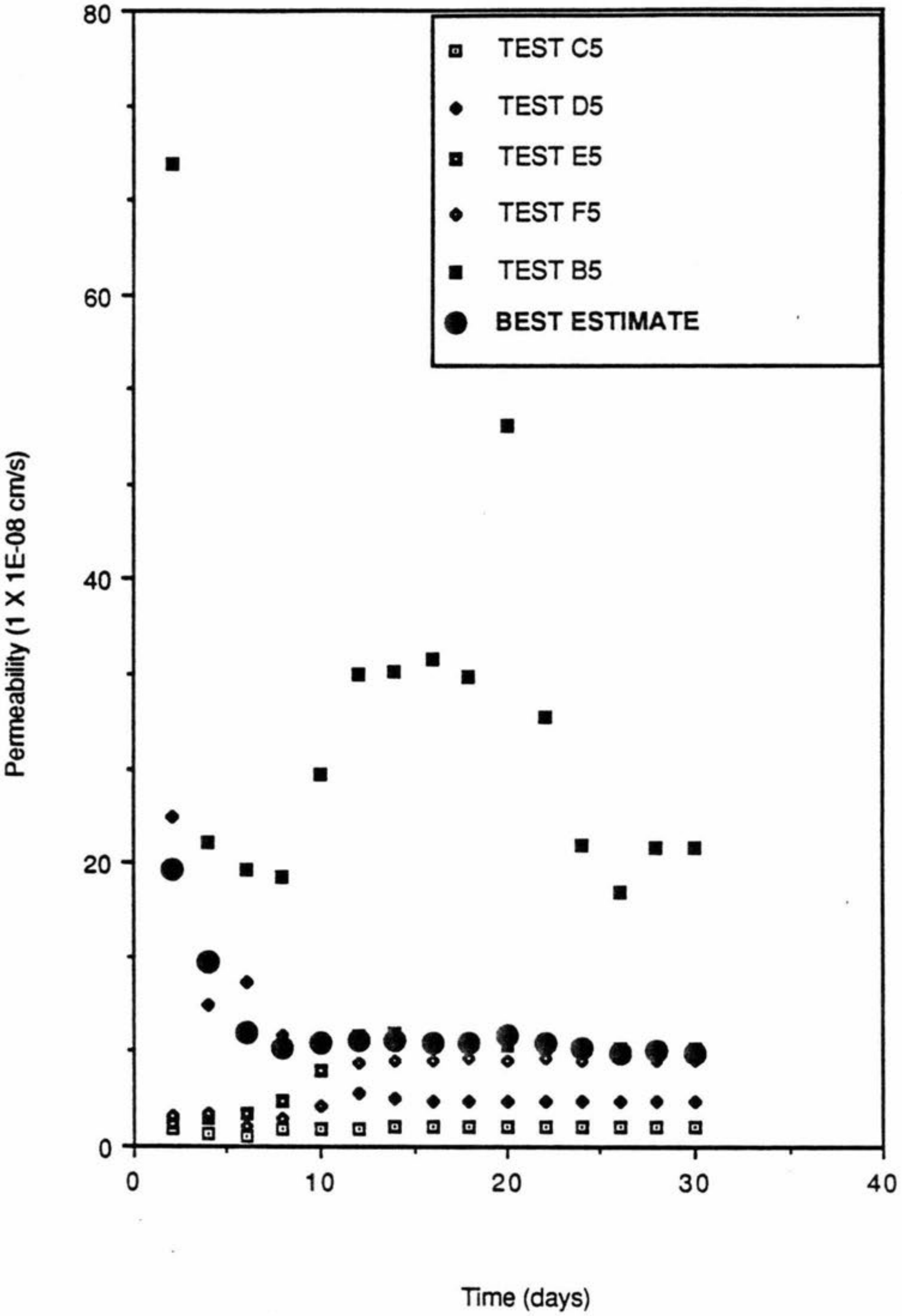


Figure 5.13. Time Series Modelling of Clay Permeability (clod sizes < 75mm)

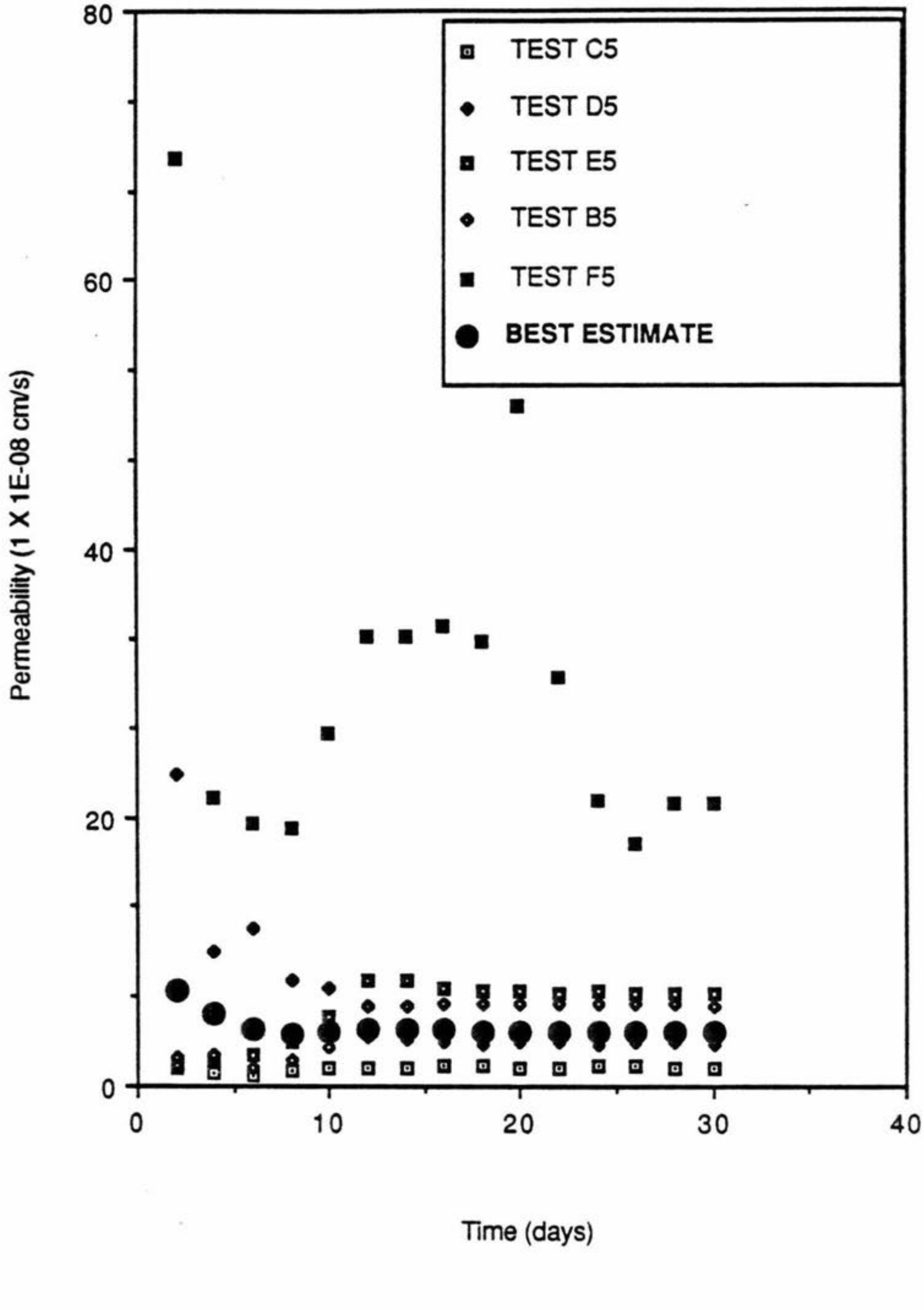


Figure 5.14. Time Series Model of Clay Permeability(clod sizes < 75mm, neglecting test B5)

B5 that resulted in high permeability.

5.5. DISCUSSION

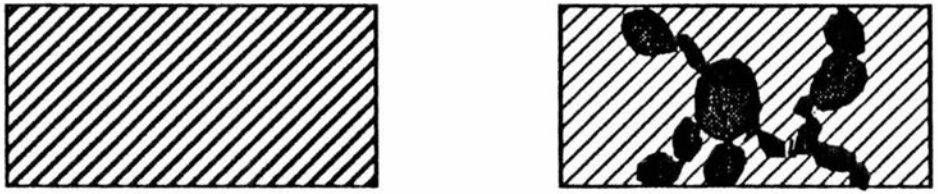
5.5.1. CLOD SIZE EFFECT

The results of the permeability tests for the small-scale (Proctor mold) permeameter indicate that the permeability of the soil increases only slightly with an increase in the precompaction clod sizes associated with the soil. Results of the tests using the large-scale permeameter, on the contrary, indicate that the permeability is related strongly to the precompaction clod sizes of the soil, with a higher permeability value being associated with larger precompaction clod sizes. Test specimens in both types of permeameters were compacted at essentially the same water content and dry density, so the void ratio of the compacted soil in either case should be about the same. However, the distribution of the voids for large-scale samples is probably quite different from that of small-scale samples. There are two probable causes for this difference in void ratio distribution.

In the Proctor mold, horizontal displacements of the soil during compaction are less than those experienced in the large-scale permeameter due to the greater degree of confinement in the Proctor mold. As a result, the applied energy during compaction is more capable of breaking the clods apart in the Proctor mold, thereby eliminating large voids between clods. In the large-scale permeameter, the lateral displacements of the soil are greater during compaction and, therefore, more of the applied energy is expended in displacing the soil laterally. Consequently, the compactive effort used for preparation of the large-scale samples probably was not sufficient to destroy all the clods.

Another factor that may be responsible for the difference between the distribution of void ratio of small-scale and large-scale sample is the cross-sectional area of the hammer used for soil compaction. The cross-sectional area of the hammer used for large-scale tests is almost eight times that used for small-scale tests. The large-scale hammer is probably less capable of destroying the clods than is the small scale hammer.

The flow model depicted in Fig. 5.15 is suggested to explain the discrepancy between large-scale and small-scale permeability test results. In the standard Proctor mold the larger clods get destroyed and the sample has a relatively uniform void ratio (Fig. 5.15a). Therefore, a uniform vertical flow through the soil is more likely to occur in the small-scale test. For the large-scale test, sections of different void ratio are created within the specimen due to the reasons mentioned earlier. For example let e_1 be the void ratio corresponding to the maximum dry density and optimum water content for the soil passing 4.75 mm sieve, and also for small-scale test specimens, e_2 the void ratio



(a)
Section of small-scale compacted Soil sample

(b)
Section of Large-scale compacted soil sample

▨ Void ratio e1

▨ Void ratio e2

■ Void ratio e3

e1= Void Ratio Corresponding to Maximum Dry Density

$e2 > e1$

$e3 < e1$

Fig. 5.15. Explanation for Possible Distribution of Void Ratio for the Compacted Soil.

for well compacted soil surrounding intact clods, and e_3 the void ratio of the intact clods. The overall void ratio of the large-scale sample can be equal to e_1 provided that the denser soil matrix (e_2) balances out the smaller void ratio of the intact clods (e_3). It is speculated that the intact clods are embedded in a dense soil matrix. The boundry between the dense soil matrix and the intact clods may act as a flow channel resulting in a higher permeability. Flow may also occur through the less compacted intact clods resulting in high permeability for the large-scale tests.

The above concept is similar to the "clod theory" presented by Olsen (1962) for flow through saturated clays and to the explanation given by Daniel (1984) for the discrepancy between the laboratory and field measured permeabilities of compacted clay soils. The test results indicate that there is a scale effect associated with laboratory permeability testing of clay soils. A higher permeability is associated with large-scale permeability tests. The effect is more pronounced if the soil used for sample preparation has a significant proportion of relatively large precompaction clod sizes. The ratio of large-scale to small-scale permeability was also found to range from 1.0 to 2.8 orders-of-magnitude, which is consistent with the relationship reported for the ratio of field-measured to laboratory-measured permeability (Daniel, 1981; 1984; and Elsbury and Sraders, 1989). From the results of this study, it appears that a more realistic evaluation of the field-measured permeability of a compacted clay soil can be made in the laboratory if the permeameter is sufficiently large to account for the possibility of hydraulic defects of the soil. Since in laboratory specimens are prepared through impact type of compaction whereas, in the field kneading compaction is used, a correlation between compaction effort (compaction energy and type of compaction) used in the laboratory for specimen preparation and in the field for construction needs to be established. Also, field permeability tests are required for verification of large-scale, laboratory-measured permeability values to determine if the large-scale permeameter can yield better estimates of the field permeability.

5.5.2. TIME SERIES ANALYSES

The results of time series analyses on five different soil fractions are summarized in Table 5.17. These results indicate that for permeability tests on compacted soil composed of smaller than 25 mm precompaction clod size, the variance of estimate on day 10 is less than one-half the variance of sample on day 30. Therefore, the estimate of permeability on day 10 is statistically much better than the five observed values on day 30. If the permeability test is prolonged for 30 days then the estimate of permeability given by time series on day 30 is significantly more accurate than the observations on this day since the

Table 5.17. Comparison of variance of sample and the prediction for five soil segments.

Precompaction clod size (mm)	Replicate test No.	Elapsed time (Days)	Variance of sample (r)	Variance of best estimate ($P_{k/k}$)
< 2	B1, C1, D1, E1, F1	10	1.59	0.31
		14	1.4	0.24
		30	1.22	0.18
< 4.75	B2, C2, D2, E2, F2	10	4.77	1.08
		14	4.1	0.68
		30	2.51	0.22
4.75 to 25	B3, C3, D3, E3, F3	10	2.78	0.87
		14	1.9	0.44
		30	1.78	0.18
25 to 75	B4, C4, D4, E4, F4	10	555	132
		14	527	82
		30	527	30
25 to 75*	B4, C4, D4, E4	10	10.02	1.28
		14	7.94	1.45
		30	6.9	1.22
< 75	B5, C5, D5, E5, F5	10	102.6	22.46
		14	173	25.8
		30	60.5	18.07
< 75*	C5, D5, E5, F5	10	7.05	4.29
		14	8.27	2.23
		30	6.48	1.72

* Variances of four samples.

variance of estimate on day 30 is 1/5 the variance of sample. The variance of estimate on day 14 for small clod size (precompaction clod sizes less than 25 mm) tests is about 1/5 the sample variance on day 30. Therefore, the estimate of permeability given by time series model on day 14 is more accurate than the observations made even after 30 days of testing. Values of Kalman gain after day 10 in these three cases is less than 0.3, which is related to a better confidence in the model than in the observed values. If the values from test results are fairly erractic, then the value of g will be closer to one and more weight is given to the observation. However, it is not the case here. Since the variance of the estimate is much smaller than that of sample on day 14, it is concluded that there is no need for continuing the test up to 30 days or more. The permeability predicted by time series on day 14 is more accurate than the observations recorded for five samples on day 30 and therefore, the test can be terminated on day 14.

The results of time series analyses on soil composed of precompaction clod sizes greater than 25 mm indicate a more erratic behavior. The variances of sample and prediction are much higher than the corresponding values for the three cases discussed earlier. The erractic behavior is caused by higher permeability of one of the samples in either case. The variances came down appreciably when analyses were performed by ignoring the samples with high permeability.

The variances, however, are still higher than the corresponding values for the samples of less than 25 mm precompaction clod sizes. The variance of sample on day 30 is approximately 7.0 for two analysis with precompaction clod sizes greater than 25 mm whereas the corresponding variance for three analysis with precompaction clod sizes less than 25 mm is less than 2.0. On day 30 the variance of estimate for two analyses with precompaction clod sizes greater than 25 mm is approximately 1.5 whereas the variance of estimate of three analyses with precompaction clod sizes less than 25 mm is about 0.2 which is ten times smaller. These observations imply that the soil behavior changes as clods greater than 25 mm in size are incorporated in the precompacted soil.

The results of small-scale tests, especially, are difficult to interpret without statistical analysis. The average permeability (small-scale tests) determined for various clod size ranges is almost the same (Table 5.6), and it could be concluded that there is not much change in the permeability of compacted soil with a change in precompaction clod size in the small-scale permeability tests. The results of time series analyses discussed earlier, however, indicate that the behavior of soil with respect to permeability changes as large clods are introduced in the precompacted soil. The behavior becomes rather erratic as the size of precompaction clods used for sample preparation exceeds 25 mm. Statistical analysis, therefore, is not only useful in reducing the time of testing but also provide a check on the quality of results.

Although, no field tests were conducted in this study, the statistical procedures could also be applied to field data. The major expense of field test is the physical preparation of the liner; use of infiltrometers to determine permeability is a lesser cost. Replicated infiltrometers in field tests could provide a check on quality of data. In addition, field tests typically have low hydraulic gradients and thus take a much longer time than laboratory tests. The possible reduction of time demonstrated by use of Kalman filter would therefore be even more important for field tests.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 CONCLUSIONS

1. The time series model and Kalman filter significantly reduced the variance associated with the laboratory permeability data collected in this study. Also the variation in permeability behavior was more apparent when the data was analyzed using time series analysis.

2. In this study, it was shown That the time series model could reduce the testing time when applied to laboratory permeability data.

3. A slight increase (less than an order-of-magnitude) in permeability with increase in precompaction clod sizes was observed for the tests in the small-scale permeameter. This finding does not agree with that of Daniel (1981) who found up to 1.5 orders-of-magnitude increase in permeability with increased clod sizes of the sample.

4. The permeability of the soil tested in the large permeameter increased by about three orders-of-magnitude as the precompaction clod sizes of the soil samples increased up to 75 mm in size.

5. The large-scale permeability for all soil fractions tested was approximately 1.0 to 2.5 orders-of-magnitude higher than the value measured in the small-scale permeameter. As a result, there was a scale effect associated with laboratory permeability testing of the low-plasticity clay soil used in this study. The apparent scale effect was more prominent when a significant portion of the soil being tested consisted of precompaction clod sizes that were large relative to the size of permeameter.

6.2 LIMITATIONS OF STUDY

1. In this study clods up to 75 mm in size were used. Soils with larger clods may exibit a different behavior.

2. A silty clay of low plasticity was used in this study. The results may be different for other types of soils.

3. Only two different scales of permeameters were used for this study. Other scales may be more appropriate.

6.2 RECOMMENDATIONS FOR FURTHER STUDY

1. A field test using replicated infiltrometers and time series analysis is needed to determine the statistical advantages of time series analysis under field conditions.

2. Criteria for accepting the results of permeability testing should include a statement of acceptable variances. Additional permeability tests are required on a variety of

soils to establish a catalog of variances associated with specific soil conditions and different types of soils.

3. Field permeability tests are required for verification of large-scale, laboratory measured values. A comparison of field and large-scale permeability tests will determine whether large-scale permeameter is a better device for approximating the field permeability.

4. Work needs to be done to correlate the compaction energy used in sample preparation for the small-scale and the large-scale laboratory permeability tests.

5. There is a need for a study that can correlate the compaction effort (compaction energy and type of compaction) in the field construction and the compactive effort used in the laboratory for specimen preparation.

REFERENCES

Anderson, B.D. and Moore, J.B. (1979), Optimal filtering, Prentice-Hall, New York, pp 399.

Box, G.E. and Jenkins, G.M. (1976), Time series analysis: forecasting and control, Holden-Day, San Francisco, pp. 575.

Chatfield, C. (1984), The analysis of time series, Chapman and Hall, New York, pp. 286.

Chen, H.W. and Yamamoto, L.O. (1987), "Permeability tests for hazardous waste management unit clay liners". Geotechnical and Geohydrological aspects of waste management, D. J. A. Van Zyl, J. D. Nelson, S. R. Abt, and T. A. Shapherd, Eds. pp. 229-244.

Cochran, W. G. (1977). Sampling techniques. John Wiley & Sons, New York, pp. 428.

Daniel, D.E. (1981), "Problems in predicting the permeability of compacted clay liners", Symp. on Uranium Mill Tailings Management, Fort Collins, Colorado, Oct. 26-27, pp. 665-673.

Daniel, D.E. (1984), "Predicting hydraulic conductivity of clay liners", Journal of Geotechnical Engineering, ASCE, Vol. 110, No. 2, 285-300.

Daniel, D.E. (1987a), "Earthen liners for land disposal facilities", Geotechnical Practice for Waste Disposal Practice, Proceedings of a Speciality Conference, University of Michigan, Ann Arbor, Michigan, Ed. R. D. Woods, 21-39.

Daniel, D.E. (1987b), "Hydraulic conductivity tests for clay liners", Geotechnical and Geohydrological aspects of waste management. D. J. Van Zyl, J. D. Nelson, S. R. Abt, and T. A. Shapherd, Eds., pp.15-34.

Daniel, D.E., Anderson, D.C., and Boynton, S.S. (1985), "Fixed-wall versus Flexible-wall permeameters", Hydraulic barriers in soil and rock, ASTM, STP 874, A.I. Johnson, R.K. Frobel, N.J. Cavalli, and C.B. Petterson, Eds., American Society for Testing and Materials, Philadelphia, 107-126.

Daniel, D.E., Trautwein, S.J., Boynton, S.S., and Foreman, D.E. (1984), "Permeability testing with flexible-wall permeameters, Geotechnical Testing Journal, GTJODJ, Vol. 7, No. 3, pp. 113-122.

Daniel, D.E., Trautwein, S.J., and McMurtry, D.(1986), "A case history of leakage from a surface impoundment", *Proceeding of Seepage and leakage from dams impoundments, ASCE*, 220-235.

Darcy, H. (1856), *Histoire Des Foundatataines Publique de Dijon*, Dalmont, Paris, 590-594.

Day, S.R. and Daniel, D.E. (1985), "Hydraulic conductivity of two prototype clay liners", *Journal of Geotechnical Engineering, ASCE*, Vol. 111, No. 8, 957-970.

Demetracopoulos, A.C. and Dharmapal, A.P. (1987), "Flow and mass transport for hazardous waste liners", Geotechnical Practice for Waste Disposal, *Proceedings of a Speciality Conference*, University of Michigan, Ann Arbor, Michigan, Ed. R. D. Woods. 392-405.

Dunn, R.J. and Mitchell, J.K. (1984), "Fluid conductivity testing of fine-grained soils", *Journal of Geotechnical Engineering*. Vol. 110, No. 11, 1648-1665.

Edil, T. B. and Erickson, A. E. (1985), "Procedure and equipment factors affecting permeability testing of a Bentonite-sand liner material", *Hydraulic Barriers in Soil and Rock, ASTM STP 874*, A. I. Johnson, R. K. Frobel, N. J. Cavalli, and C. B. Petterson, eds., American Society for Testing and Materials, Philadelphia, pp. 155-170.

Elsbury, B.R. and Sraders, G.A. (1989), "Buliding a better landfill liner", *Civil Engineering*, 57-59.

Fireman, M. (1944), "Permeability measurements on disturbed soil sample", *Soil Science*. Vol. 58, 337-355.

Foreman, D. E. and Daniel, D. E. (1986), "Permeation of compacted clay with organic chemicals. *Journal of Geotechnical Engineering*, Vol. 112, No. 7, 669-681.

Gelb, A. (1974), *Applied optimal estimation*, MIT Press, Cambridge, Massachusettes, pp. 374.

Garcia-Bengochea, I., ASCE, A.M., Lovell, C. W., and Altschaeffl, A.G. (1979), "Pore distribution and permeability of silty clays", *Journal of Geotechnical Engineering, ASCE*, Vol. 105, No. GT7, 839-855.

Gray, D.H. (1966), "Coupled flow phenomena in clay-water systems", Thesis presented to the University of California, at Berkeley, California, in partial fulfillment of the requirements of the degree of Doctor of Philosophy.

Hansbo, S. (1960), "Consolidation of Clay with special reference to the influence of vertical sand drains", Proceedings of Swedish Geotechnical Inst., Stockholm, No. 18.

Jameson, D.A. (1985), "A priori analysis of allowable interval between measurements as a test of model validity", Applied Math and Computation, Vol. 17, 93-105.

Jameson, D.A. (1986), "Sampling intensity for monitoring of environmental systems", Applied Math and Computation, Vol. 18, 71-75.

Jameson, D.A. (1989), Adaptive management and monitoring of natural resources; Introduction to statistical and control analysis, John Wiley and Sons Inc., New York, N.Y., In press.

Jazwinski, A.H. (1970),. Stochastic processes and filtering theory, Academic Press, New York, N.Y., 269-272.

King, F.H. (1899), "Principles and conditions of the movement of ground water", U. S. Geo. Survey Ann. Rpt. 19, pp. 61-294.

Korfiatis, G.P., Rabah, N., and Lekmine, D. (1987), "Permeability of compacted clay liners in laboratory scale models", Geotechnical practice for waste disposal. Proceedings of a Speciality Conference, University of Michigan, Ann Arbor, Michigan. Ed. R. D. Woods, pp. 611-624.

Lambe, T.W. (1954), "The permeability of fine-grained soils", Proceedings of the Symposium on permeability of soils, ASTM #163, pp. 56-67.

Lambe, T.W. (1958), "The structure of compacted clay", Journal of Soil Mechanics and Foundation Division, ASCE, Vol. 84, 1-34.

Martin, R.T. (1962), Adsorbed Water on Clay: A Review. Clay and Clay Minerals, Vol. 9, Pergamon Press, New York, N.Y.

Matyas, E.L. (1967), "Air and water permeability of compacted soils", Permeability and capillarity of soils, ASTM STP, Am. Soc. Testing Mats. pp. 160.

Maybeck, P.S. (1979), Stochastic models, estimation, and control. Vol. 1. Academic Press, New York, N.Y. pp. 423.

Von Engelardt, W.V. and Tunn, W.L.M. (1955), " The flow of fluids through sandstones", translated by P.A. Witherspoon from *Heidelberger Beitraege Zur Mineralogie and Petrographie*, Vol. 2, pp. 12-25 (Illinois State Geologic Survey, Circular 194, 1955).

Appendix 1. Determination of weight of water required to increase water content to a desired level.

Let

W_T = total weight of the soil
w_i = initial water content
w_f = final water content
W_s = weight of solids in soil
W_w = weight of water in soil

then

$$W_T = W_w + W_S$$

or

$$\frac{W_T}{W_S} = 1 + w_i$$

or

$$W_S = \frac{W_T}{1+w_i} \qquad (1)$$

$$W_{wi} = \text{initial weight of water in soil} = W_T - W_S \qquad (2)$$

If we want to increase the moisture content to w_f %

then:

$$w_f = \text{final weight of water/weight of solids} = W_{wf}/W_S$$

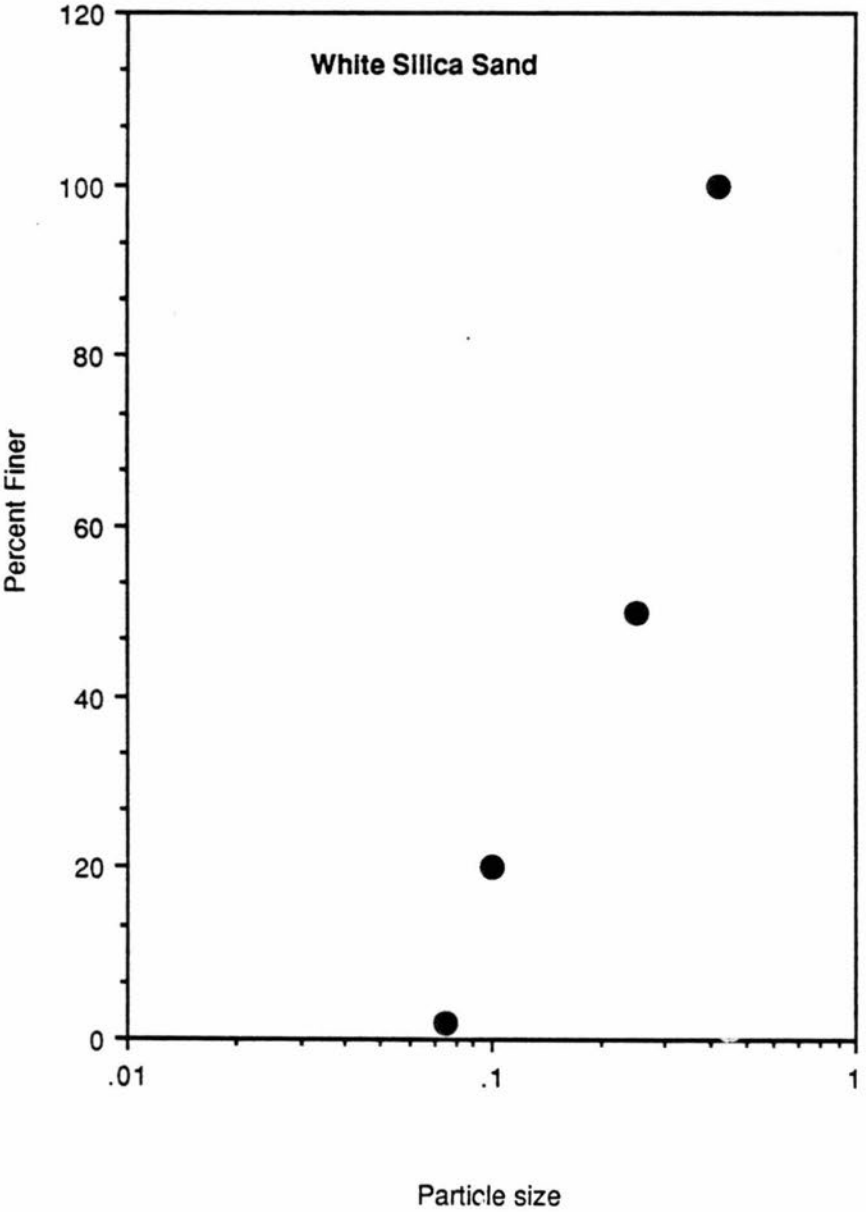
or

$$W_{wf} = w_f \times W_S \qquad (3)$$

and the weight of water required to increase water content to w_f can be calculated as:

$$DW_w = W_{wf} - W_{wi} \qquad (4)$$

Appendix 2. Gradation curve for the fine sand used as filter in the large-scale permeameter.


White Silica Sand
Percent Finer
120
100
80
60
40
20
0
.01
.1
1
Particle size

Appendix 3. Determination of weight of wet soil required for large-scale tests.

Volume of specimen = 6/12 x 9 = 4.5 cu.ft

Desired dry density = 107 lb/cu.ft

Optimum water content = 18%

2% wet of optimum = 20%

We know that

$$\gamma_{dry} = \gamma_{wet}/1+w$$

$$\gamma_{wet} = \gamma_{dry}(1+w) = 107(1+0.2) = 128.5 \text{ lb/cu.ft}$$

Since

γ_{wet} = weight of wet specimen/volume of specimen

Weight of wet soil used for preparing specimen =

128.5 x 4.5 = 578 lbs.

The water content of air dry soil can be adjusted to a value around optimum water content through the procedure outlined in Appendix A.

Appendix 4. Details of computer program used for time series analysis.

Application of time series analysis to permeability data was presented in chapter 3. A spread sheet of computer software Lotus 123 works very well for this type of analysis. Following is the details of the program used with reference to table 3.1.

Column 1. The day of observation with respect to the day the test started is listed in this column.

Column 2 to 6. These columns list the observed permeabilities for five replicates.

Column 7. This column lists the variance of five replicates.

Column 8. Listed in this column is the average permeability for five replicates.

Column 9. Her the predicted value of permeability is calculated by using column No. 8 and the time series regression coefficient. Equation 3.6 is used to generate this column.

Column 10. This column lists the difference between predicted value one time step later (column 9) and the observed value (column 8). The variance of these differences is the variance of error term W denoted by q in equation 3.4.

Column 11. This column lists the variance of estimate $p_{k/k}$. For the first time step variance of estimate (2.19) is equal to the variance of sample (r). The updated variance of prediction for first step (1.08 from column (16) becomes $p_{k/k}$ for the second time step.

Column 12. Here the variance of prediction is listed which si calculated by equation 3.10.

Column 13. This column lists the estimated value of the system at time k given the information at time k. The first value is the mean of permeabilities from the five replicates (6.52). The updated prediction from first time step (Column 15, 5.9) is the value for $X_{k/k}$ for the second time step and so on.

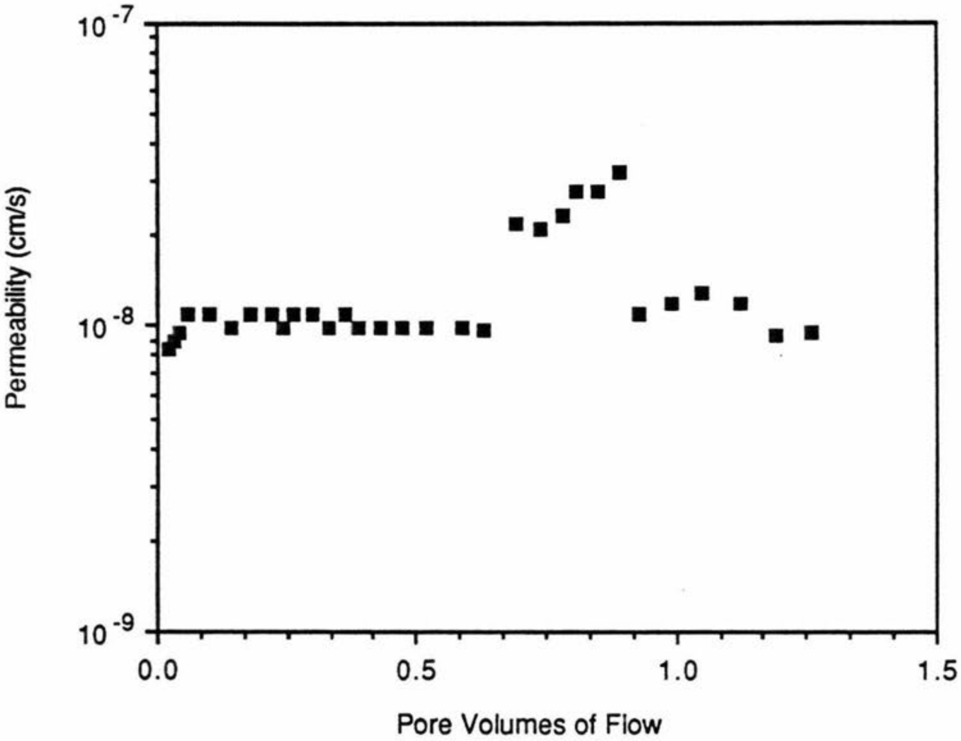
Column 14. The permeability predicted by time series model si calculated here. The best estimate for time k from column 13 is multiplied with time series regression coefficient to yield $X_{k+1/k}$.

Column 15. In this column the values for Kalman gain are calculated through equation 3.11. Variance of prediction (column 12) and variance of sample (column 7) are used here.

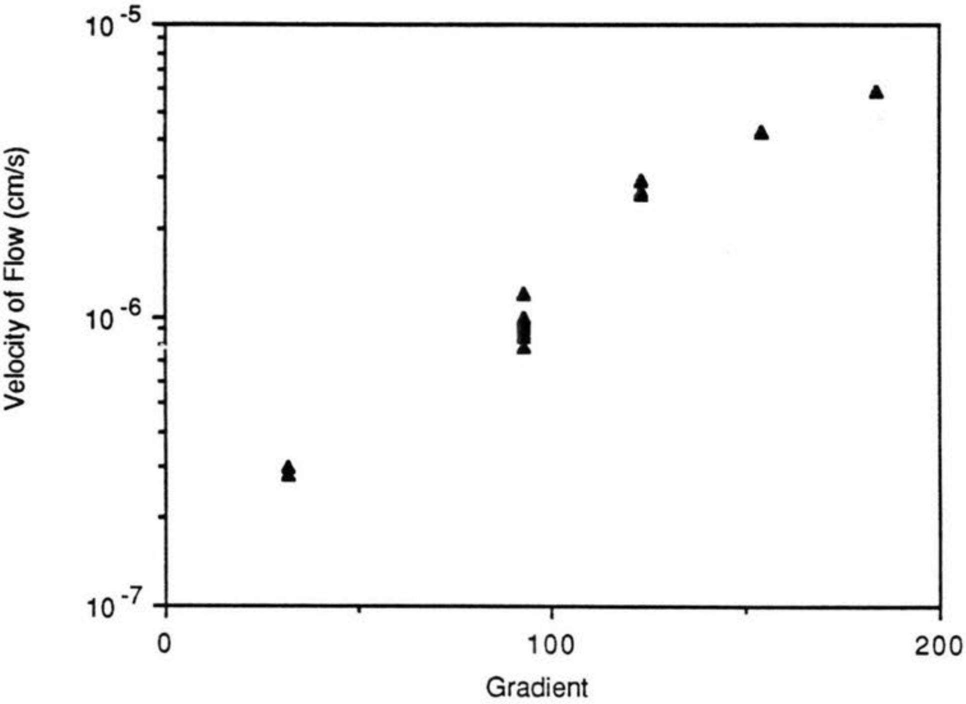
Column 16. Here the updated best estimate of permeability si listed making use of equation 3.12.

Column 17. Here the variance of updated best estimate is calculated through equation 3.13.

Appendix 5. Permeability test results (Figures).

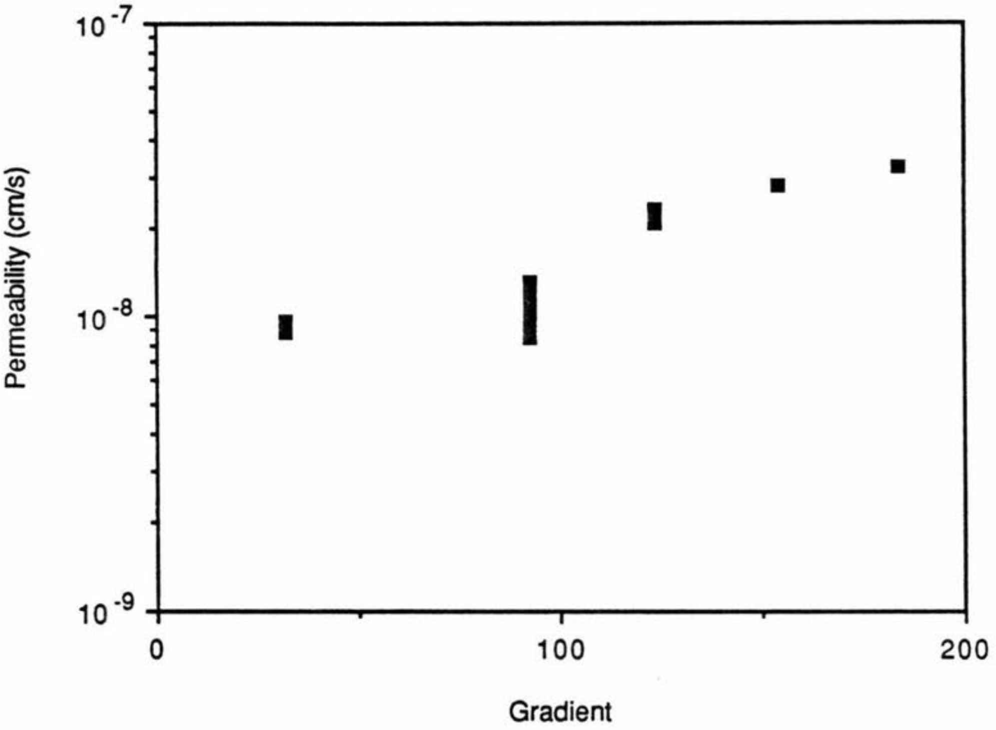


Permeability Versus Pore Volumes - Test A1

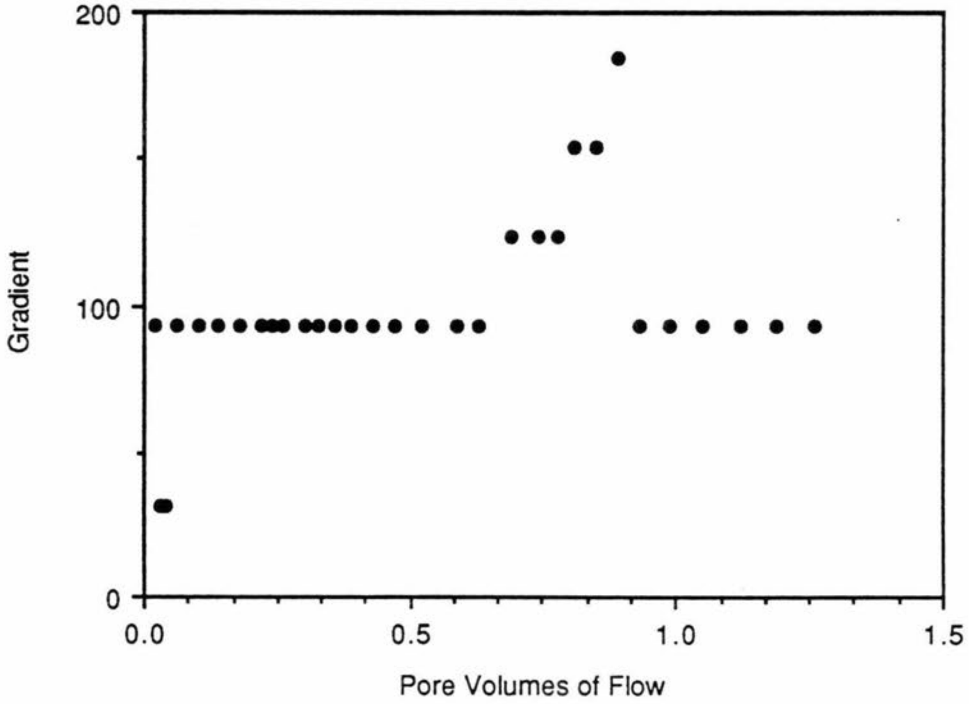


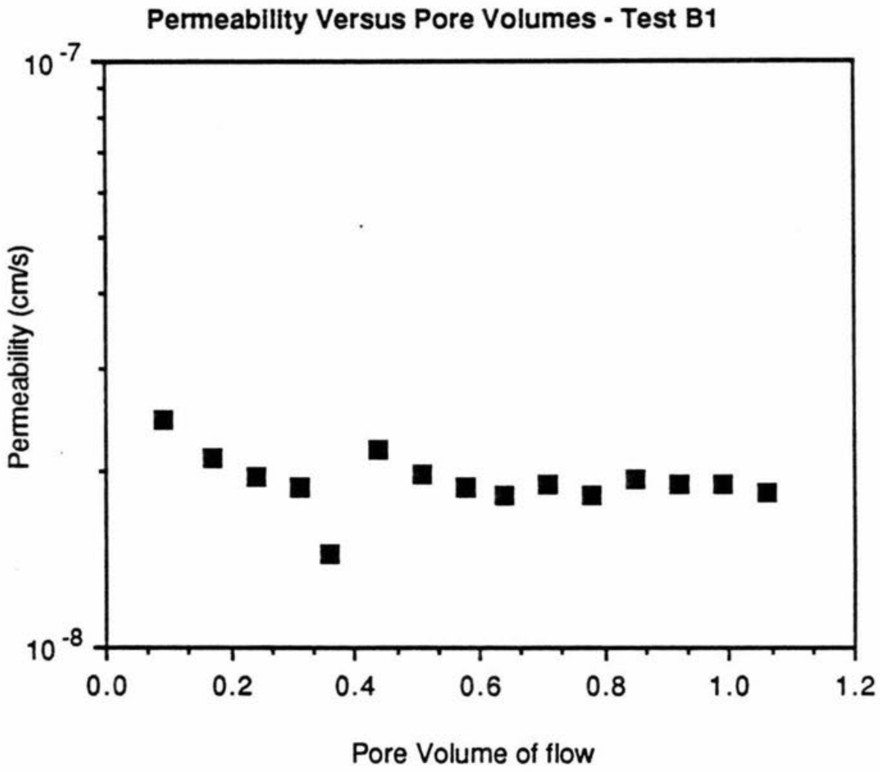
Velocity Versus Gradient -Test A1

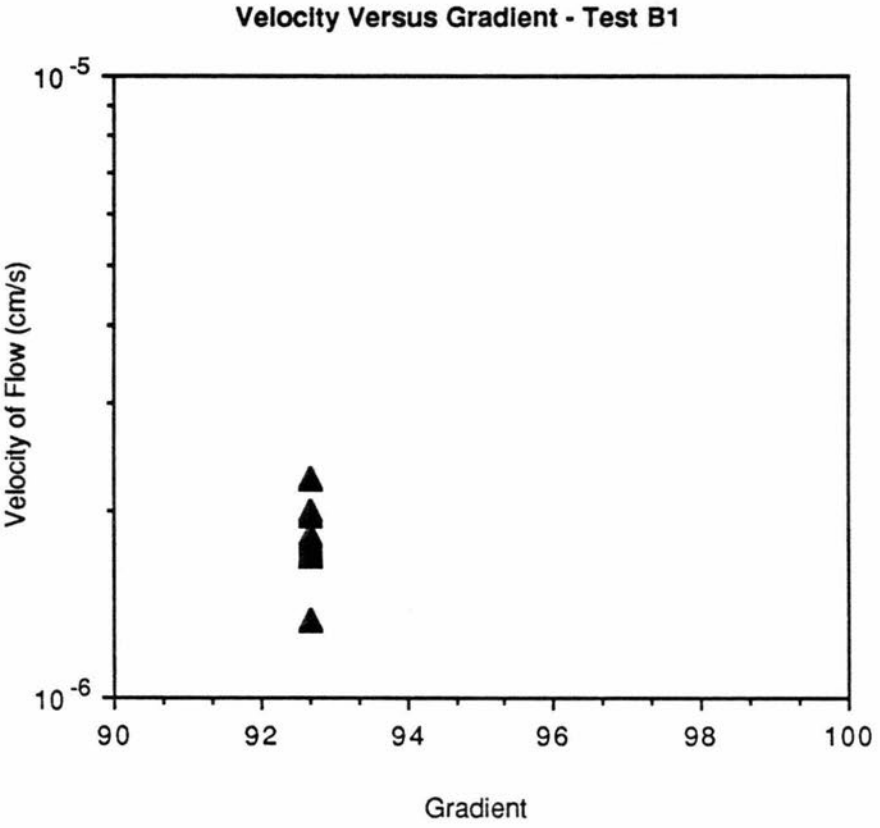
Permeability Versus Gradient - Test A1

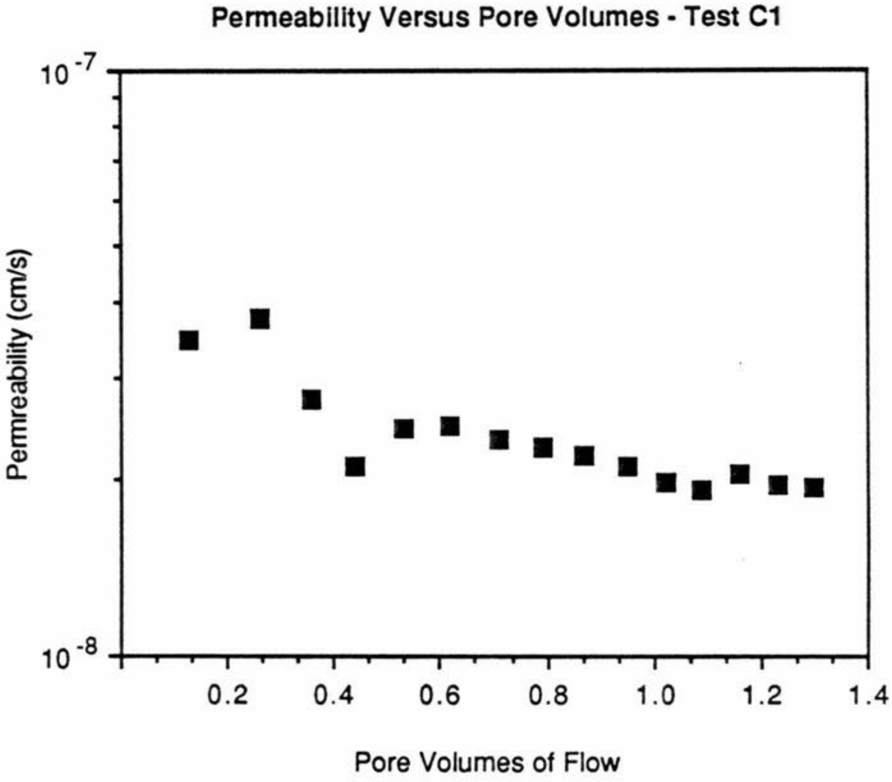


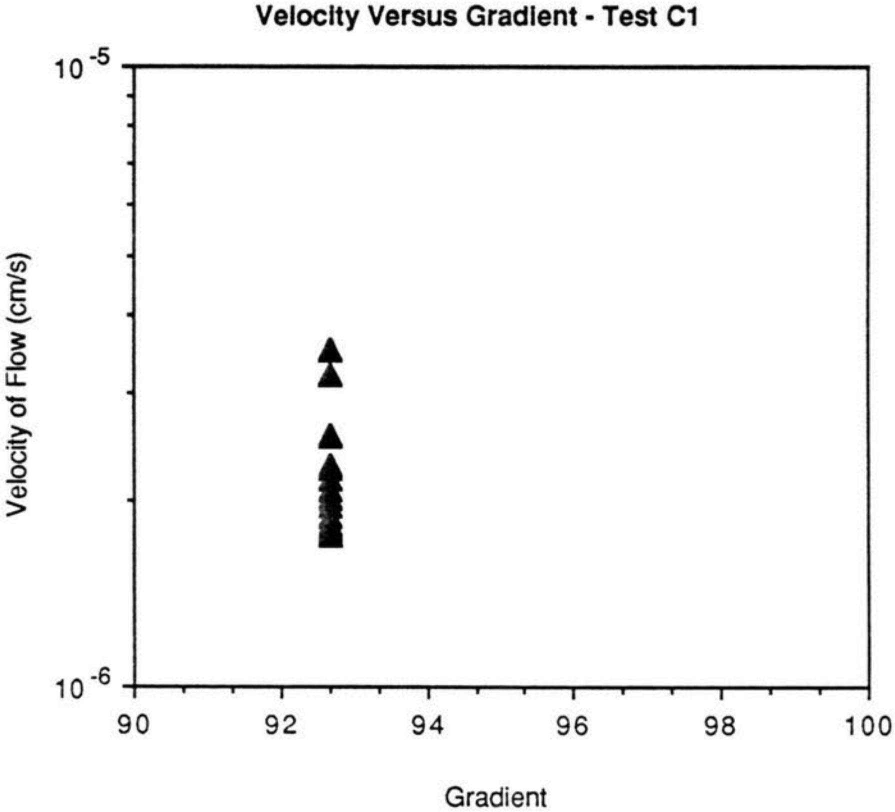
Gradient Versus Pore Volumes - Test A1



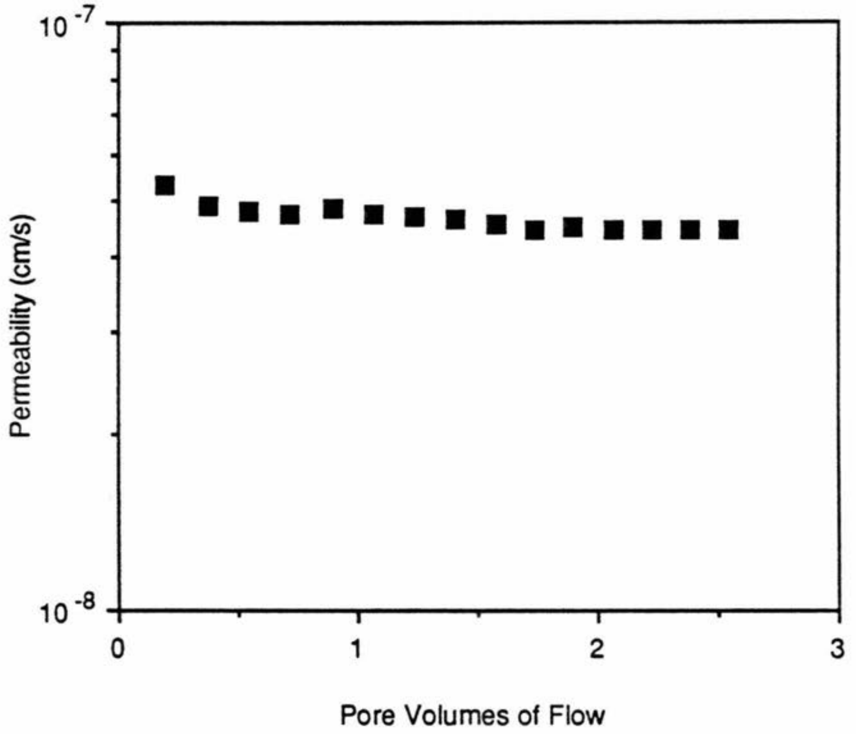

Permeability Versus Pore Volumes - Test B1
10^{-7}
10^{-8}
Permeability (cm/s)
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Pore Volume of flow


Velocity Versus Gradient - Test B1
10^{-5}
10^{-6}
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient

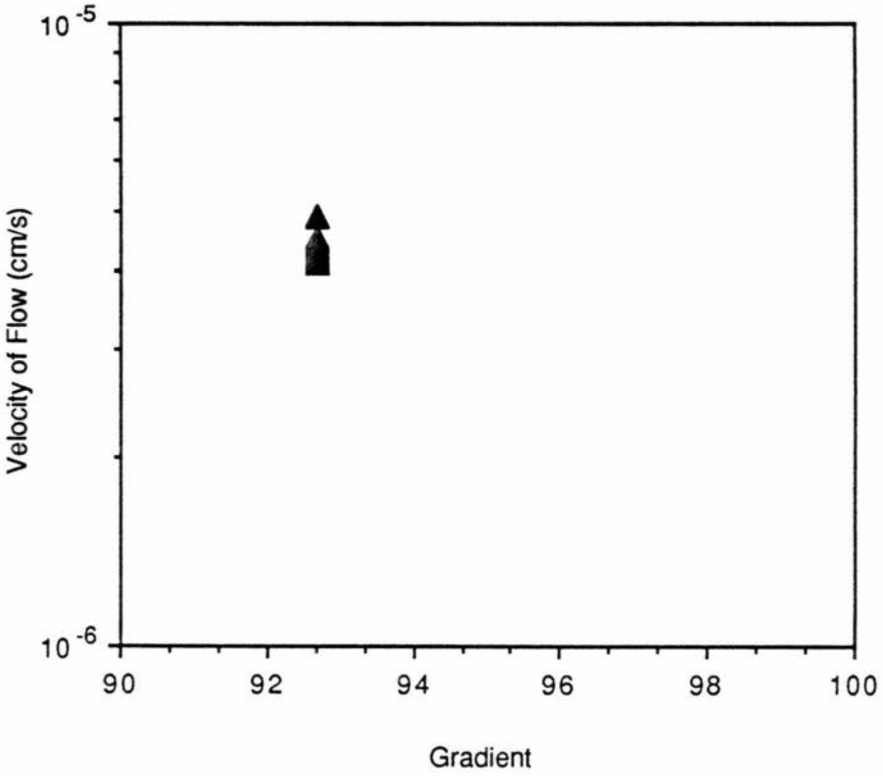

Permeability Versus Pore Volumes - Test C1
10^{-7}
10^{-8}
Permreability (cm/s)
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Pore Volumes of Flow


Velocity Versus Gradient - Test C1
10^{-5}
10^{-6}
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient

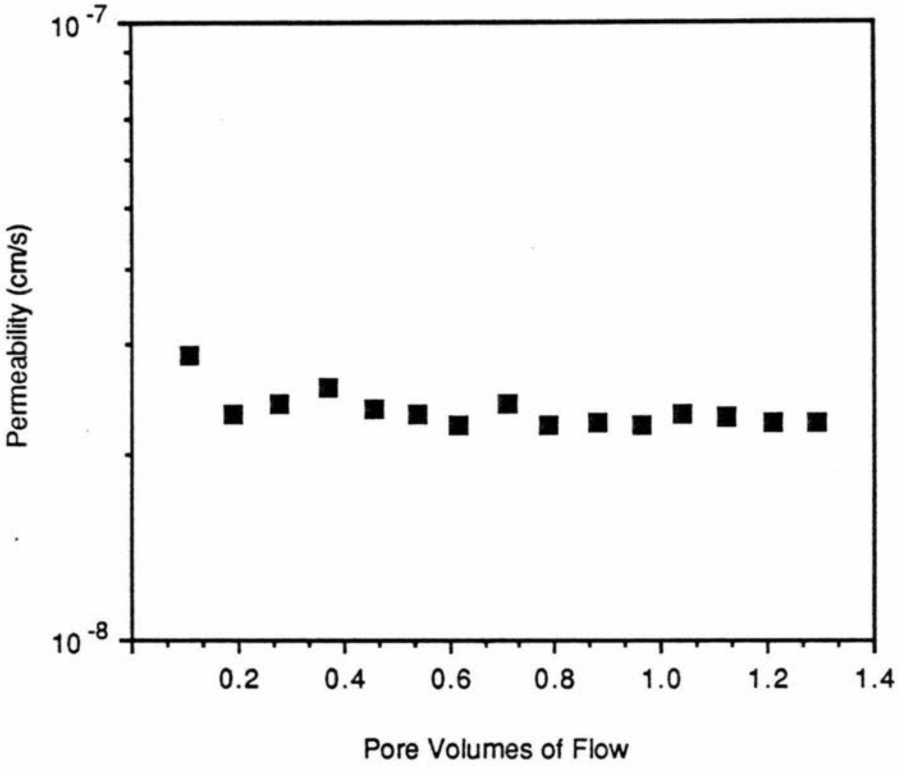
Permeability Versus Pore Volumes - Test D1



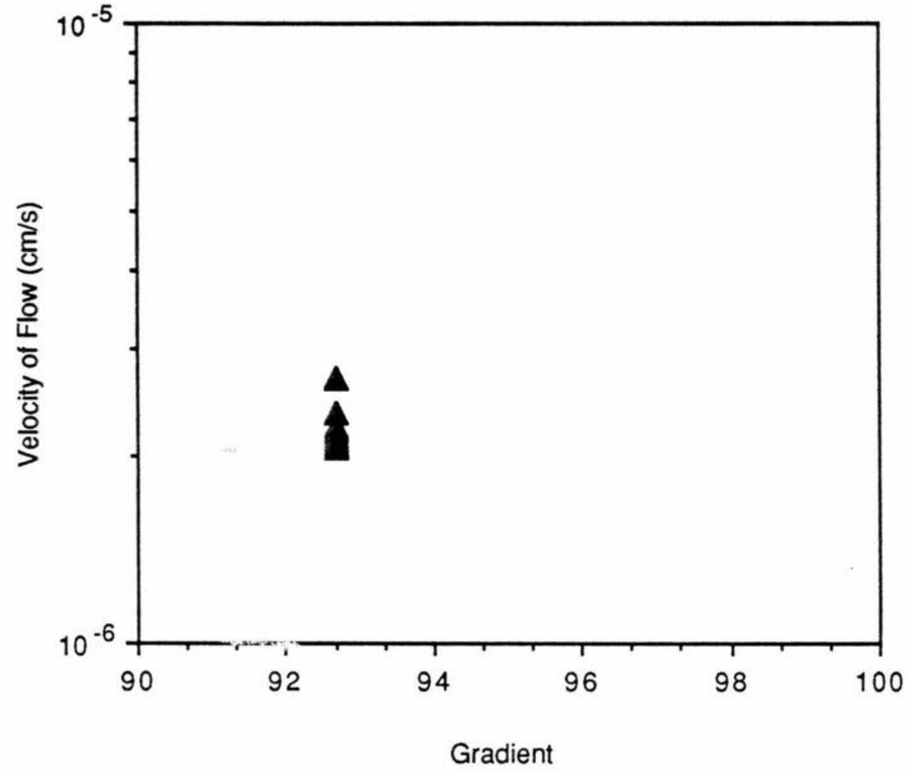
Velocity Versus Gradient - Test D1



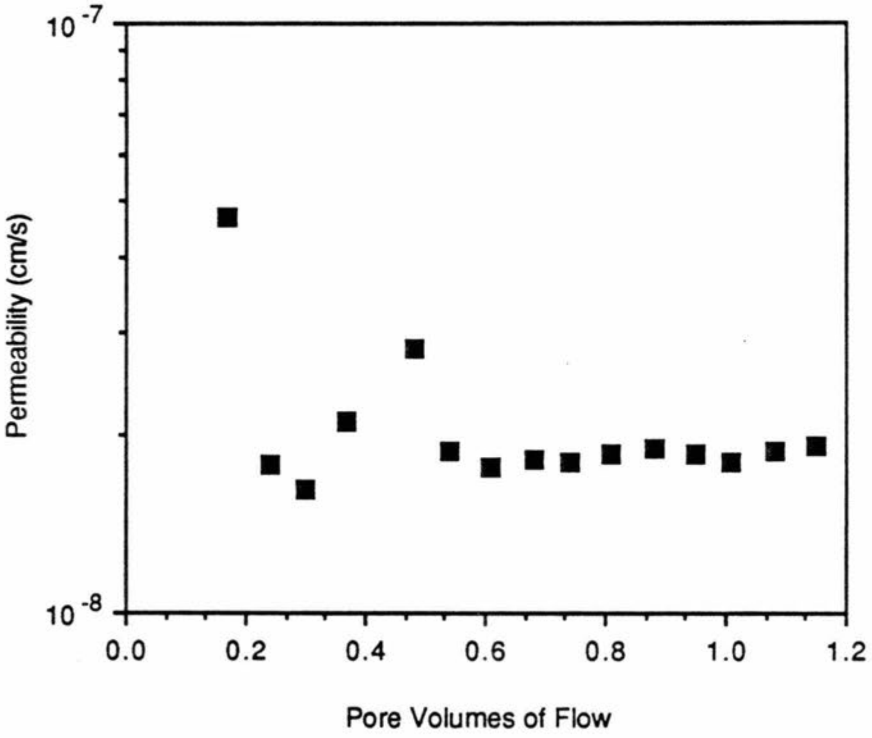
Permeability Versus Pore Volumes - Test E1



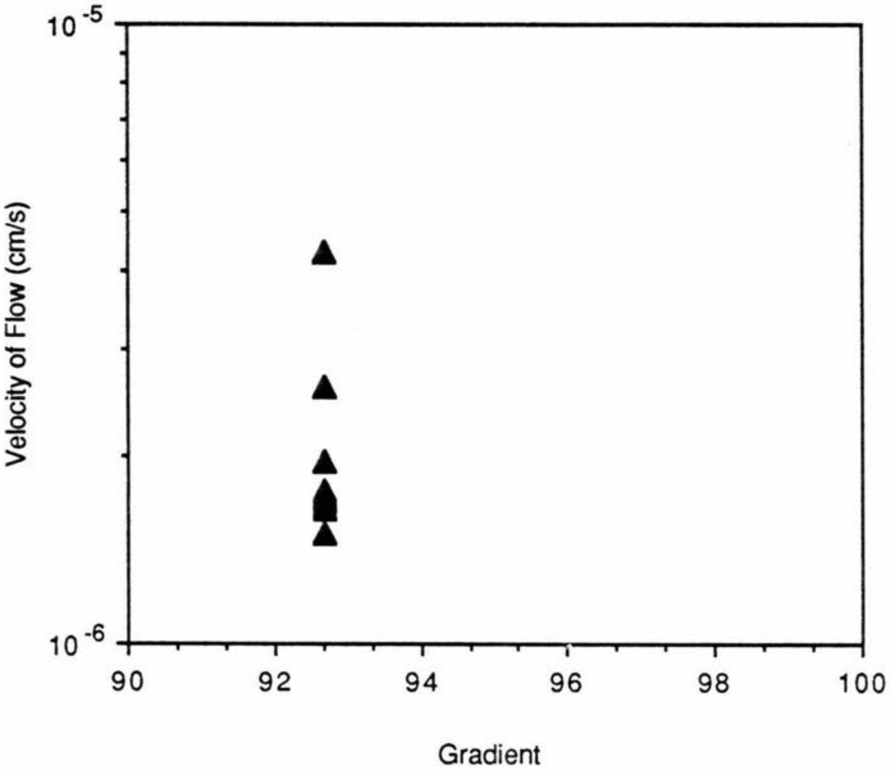
Velocity Versus Gradient - Test E1

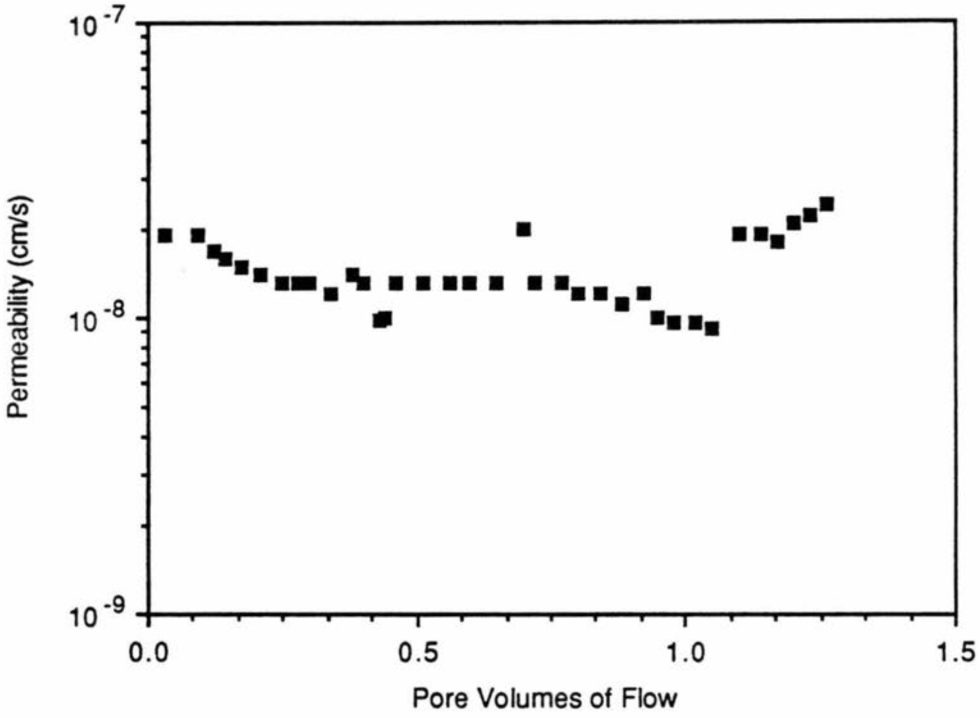


Permeability Versus Pore Volumes - Test F1

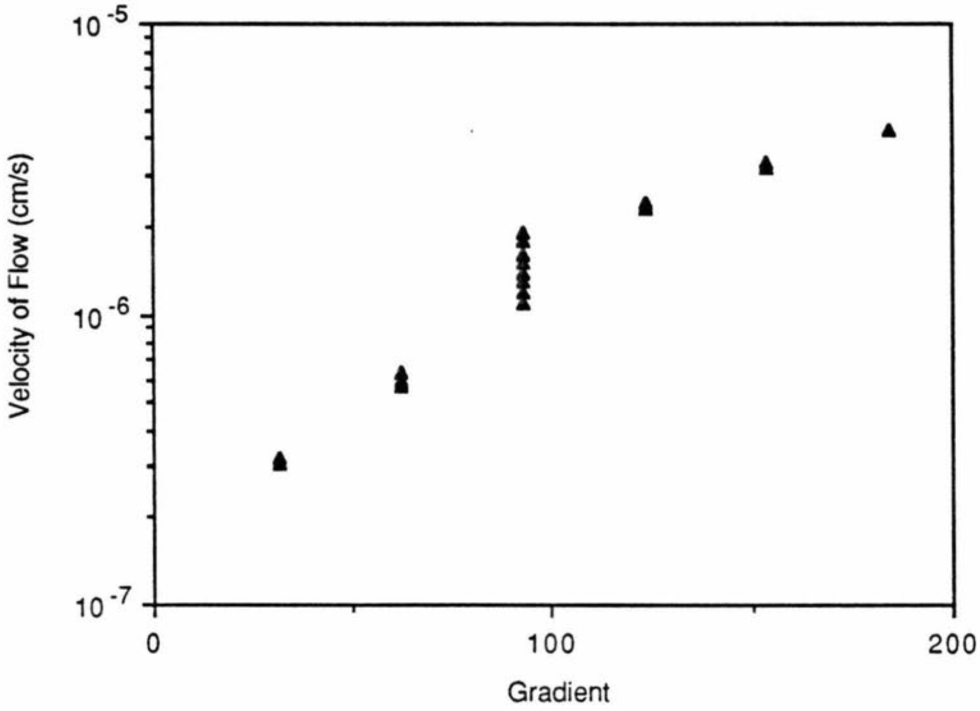


Velocity Versus Gradient - Test F1

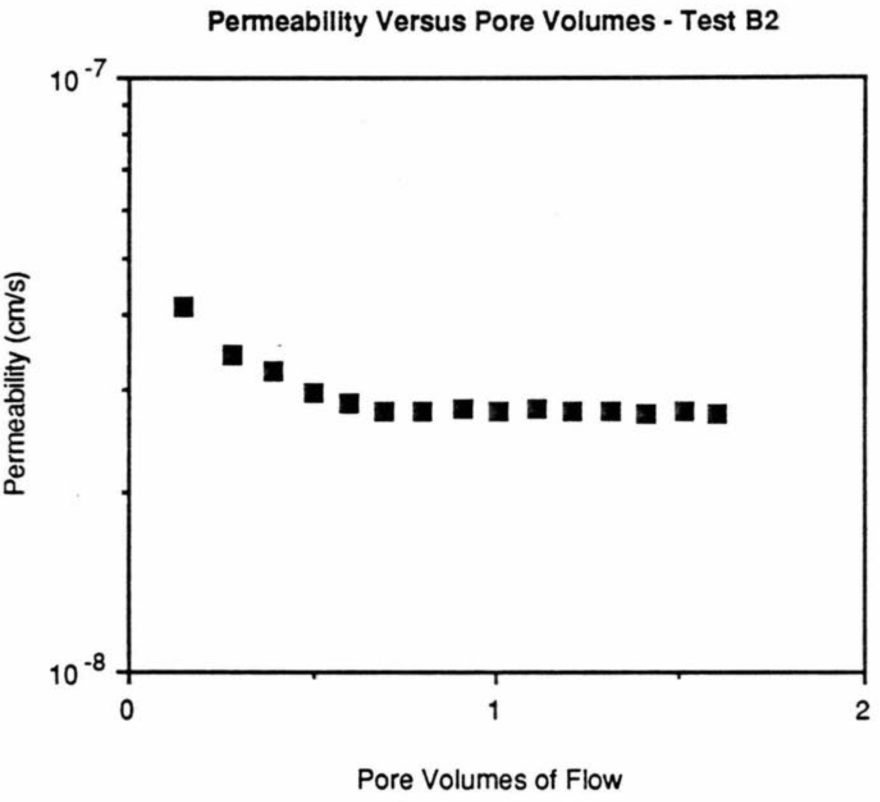


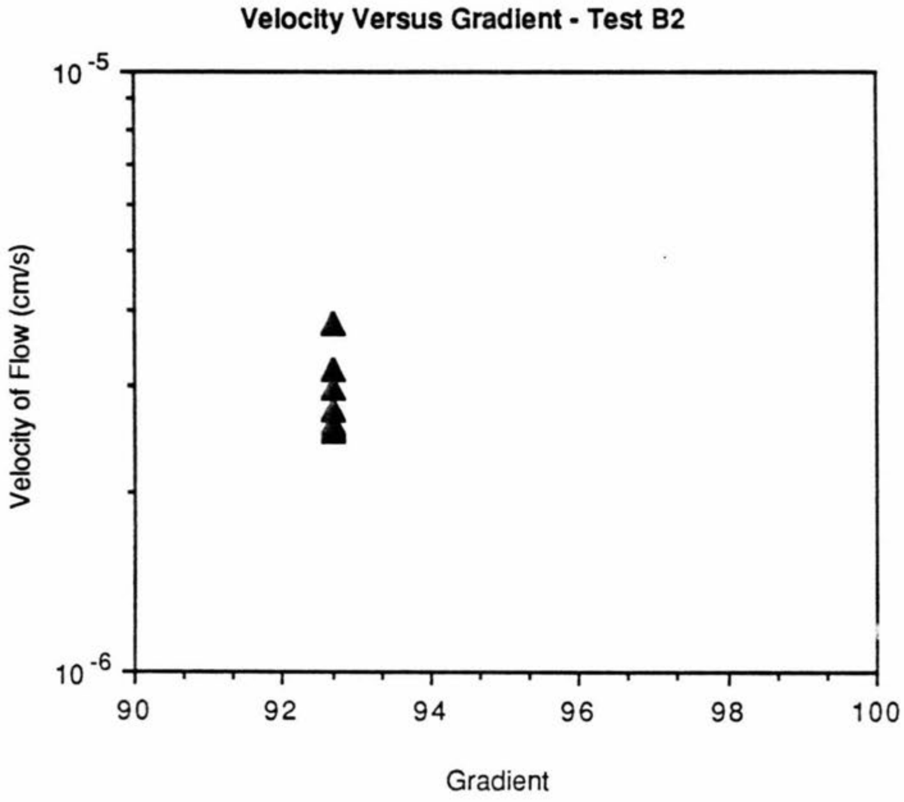


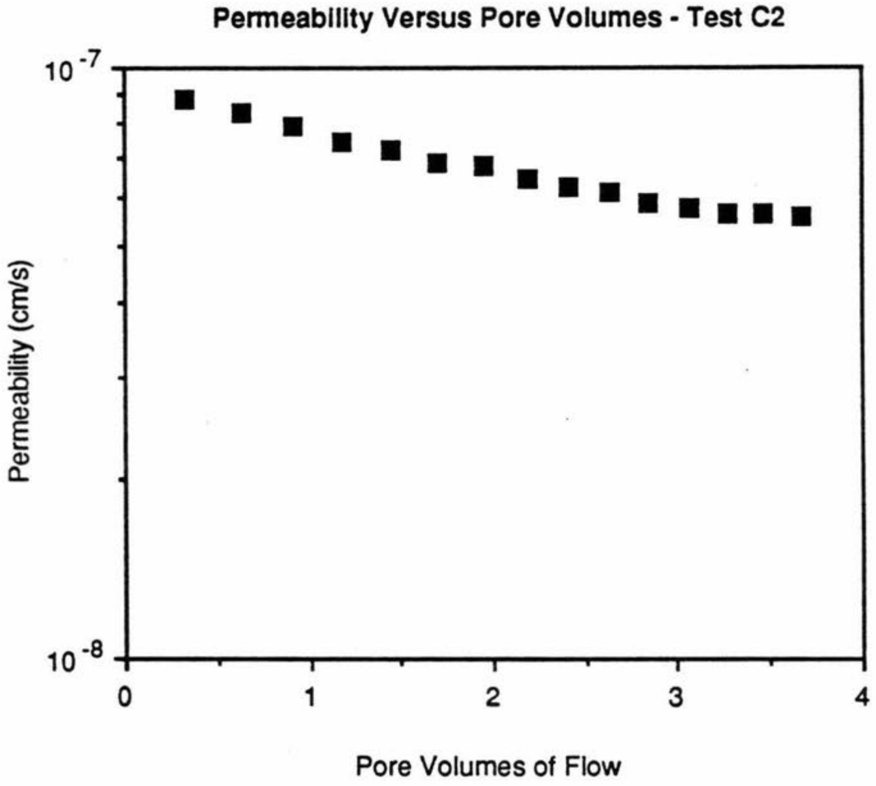
Permeability Versus Pore Volumes - Test A2

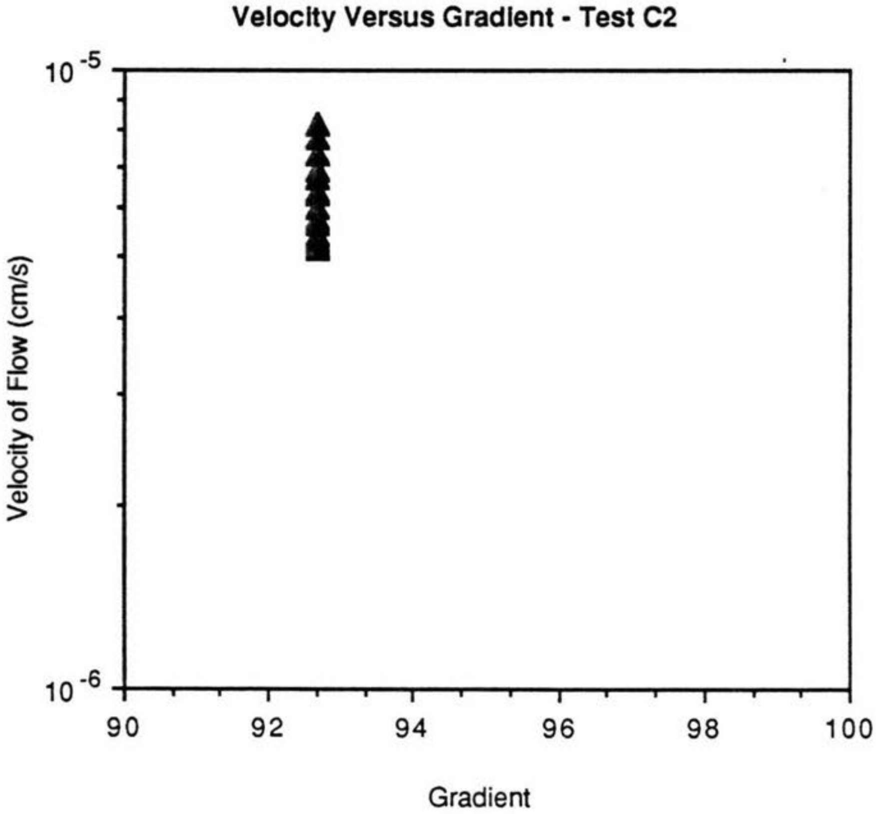


Velocity Versus Gradient - Test A2

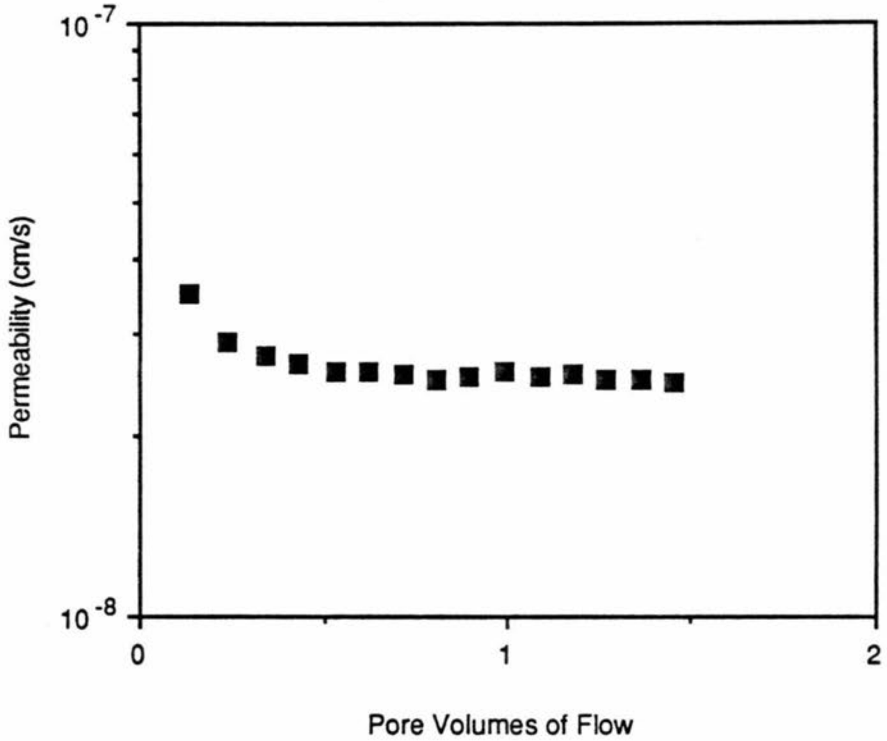

Permeability Versus Pore Volumes - Test B2
10 -7
10 -8
Permeability (cm/s)
0
1
2
Pore Volumes of Flow


Velocity Versus Gradient - Test B2
10 -5
10 -6
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient

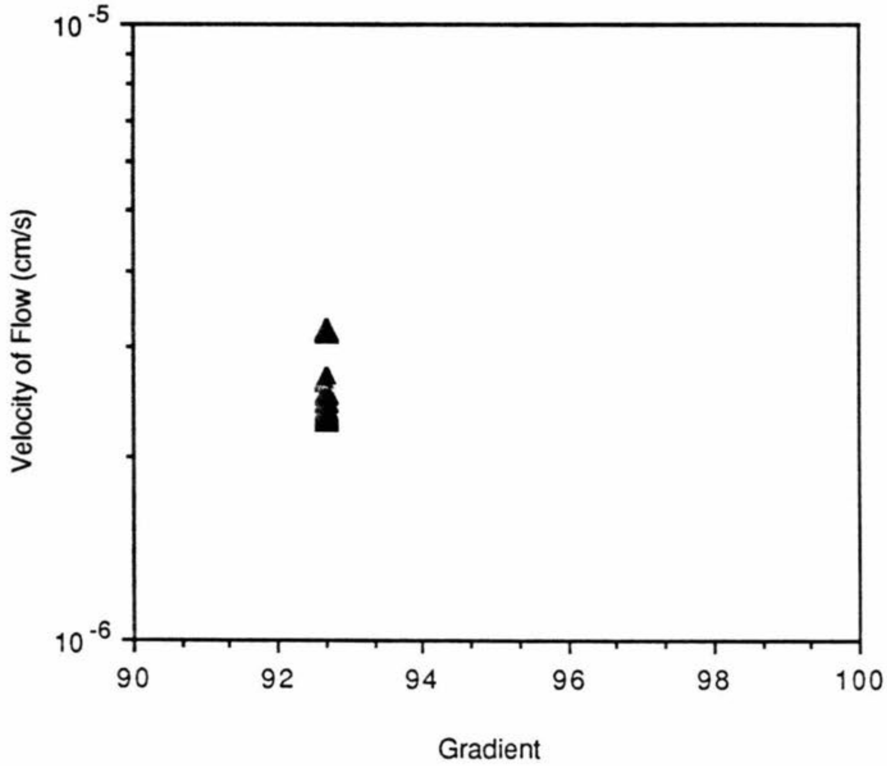

Permeability Versus Pore Volumes - Test C2
10 -7
10 -8
Permeability (cm/s)
0
1
2
3
4
Pore Volumes of Flow

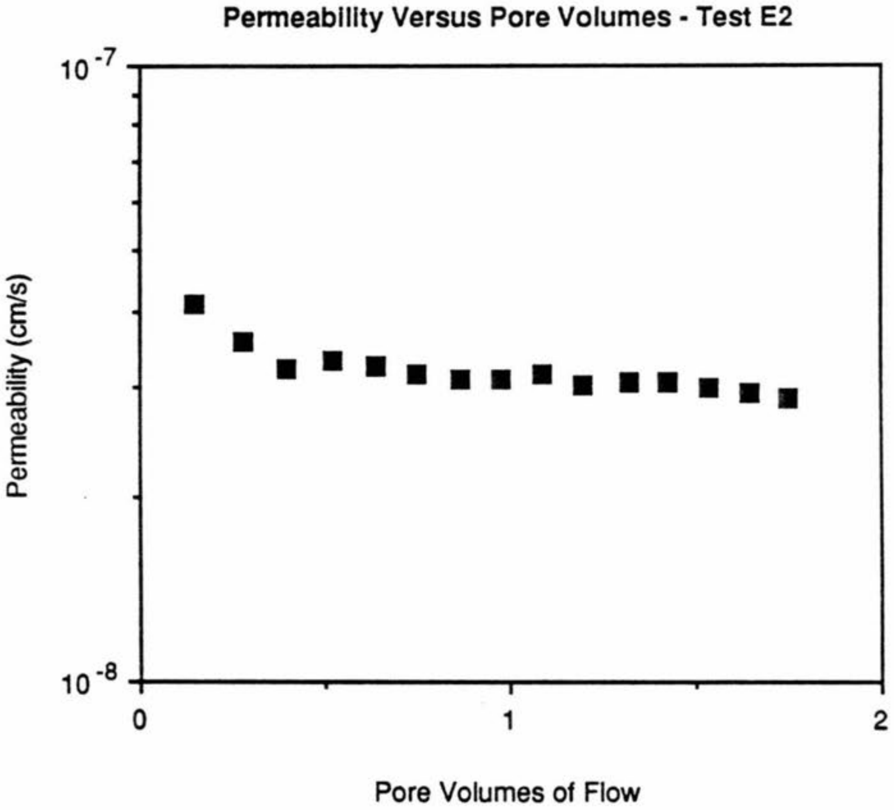

Velocity Versus Gradient - Test C2
10 -5
10 -6
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient

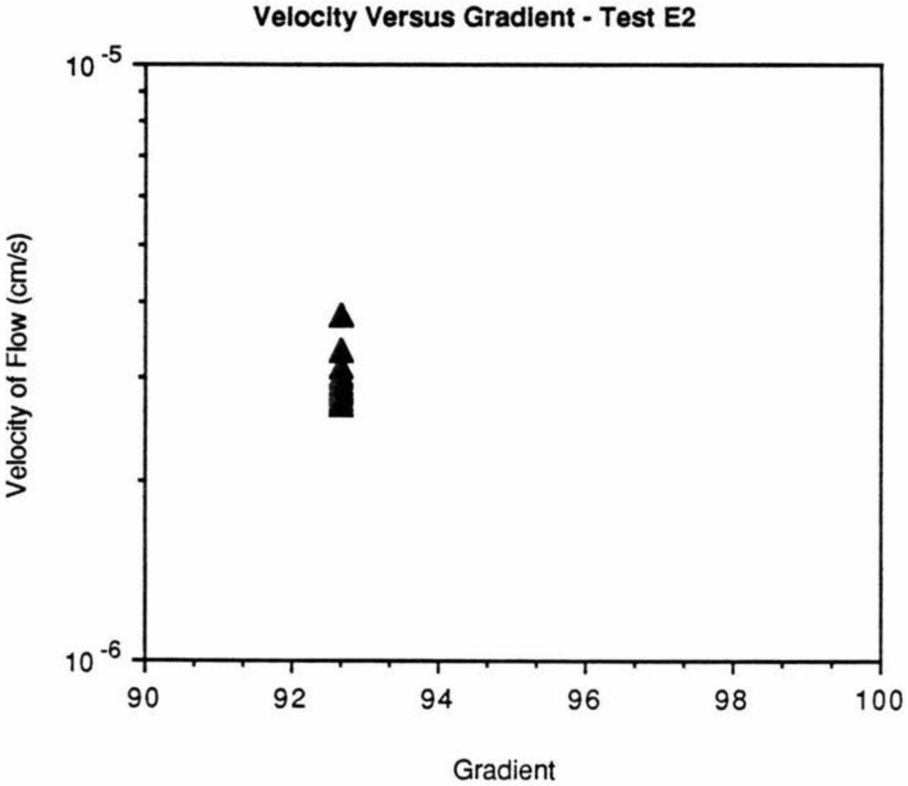
Permeability Versus Pore Volumes - Test D2

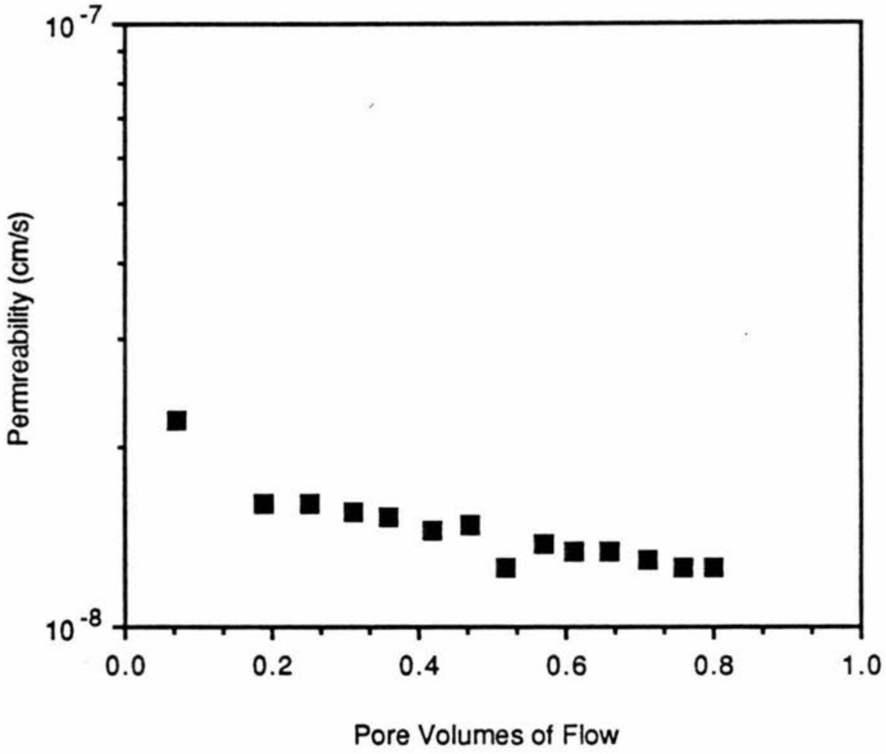


Velocity Versus Gradient - Test D2

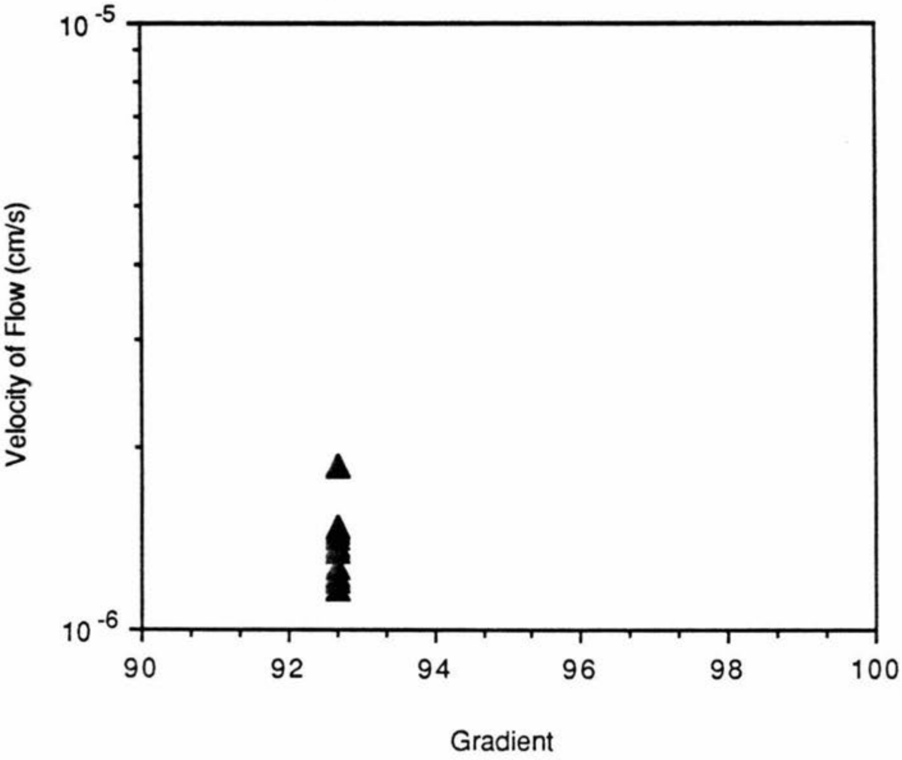



Permeability Versus Pore Volumes - Test E2
10 -7
10 -8
Permeability (cm/s)
0
1
2
Pore Volumes of Flow


Velocity Versus Gradient - Test E2
10 -5
10 -6
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient

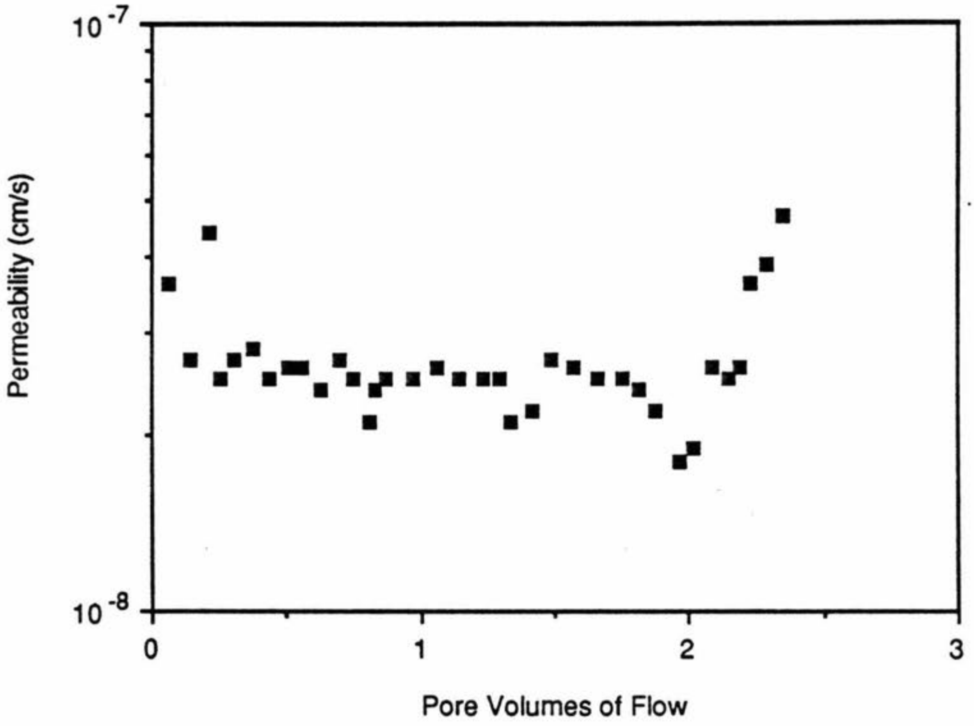


Permeability Versus Pore Volumes - Test F2

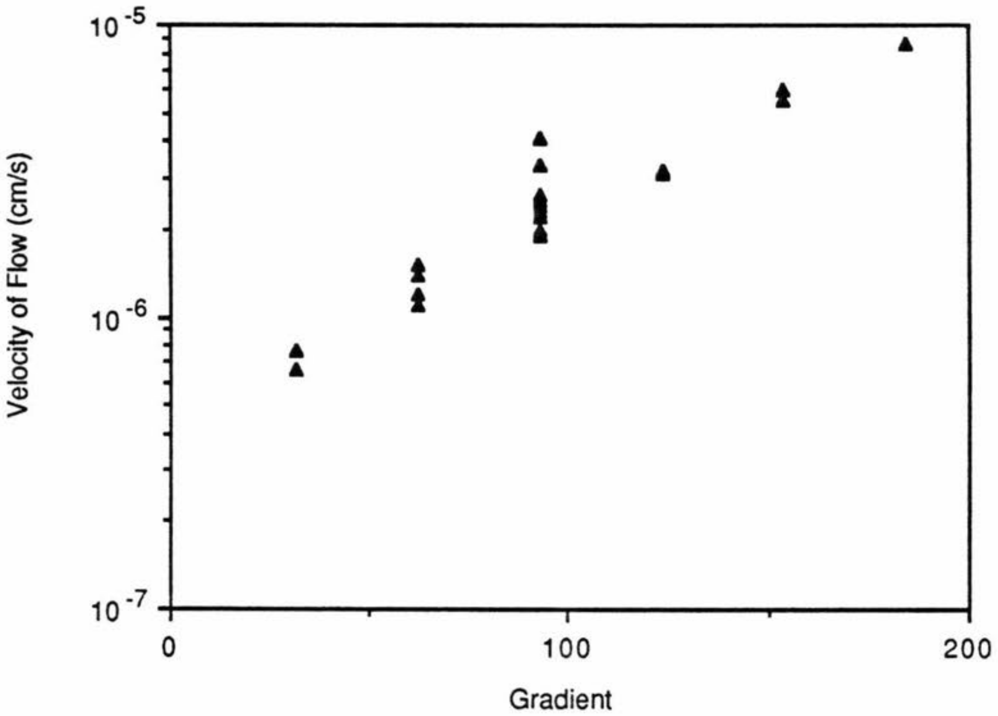


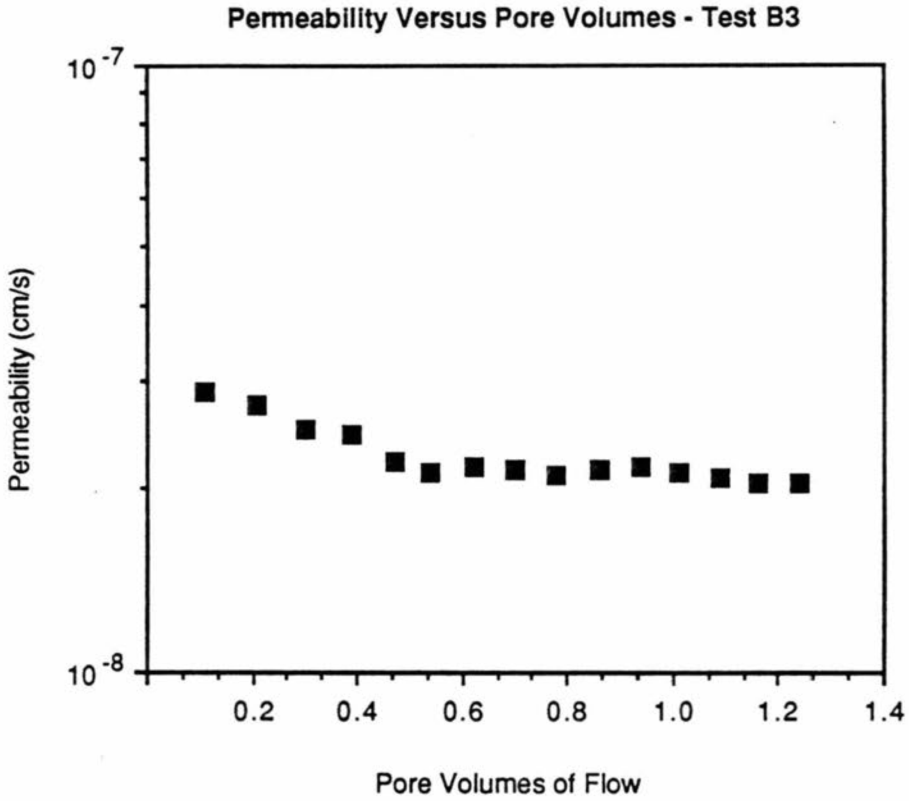
Velocity Versus Gradient - Test F2

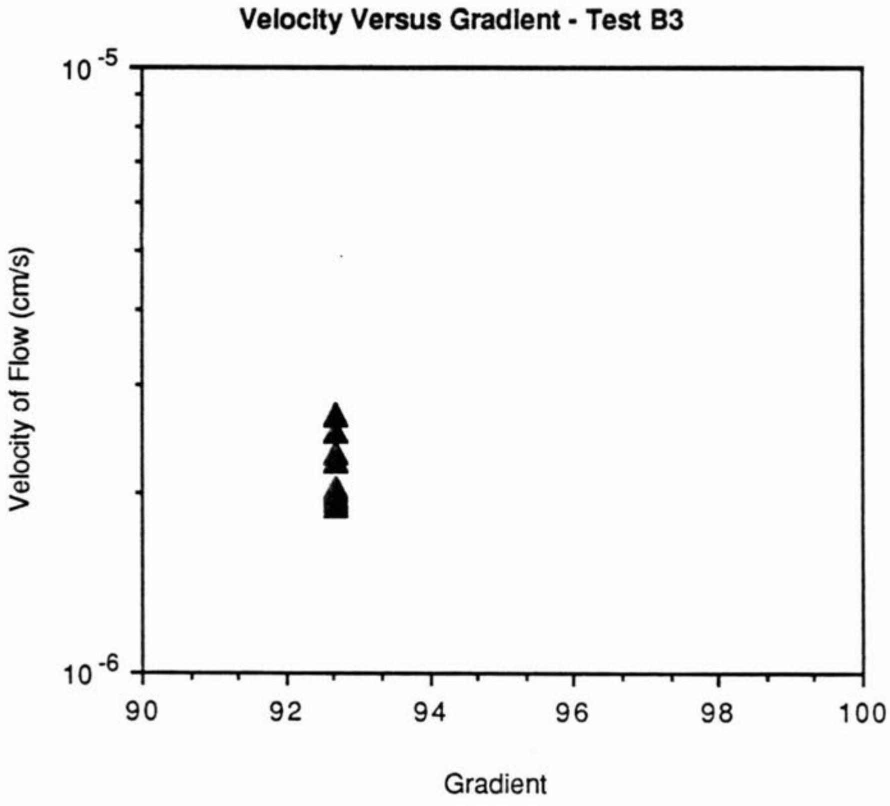
Permeability Versus Pore Volumes - Test A3

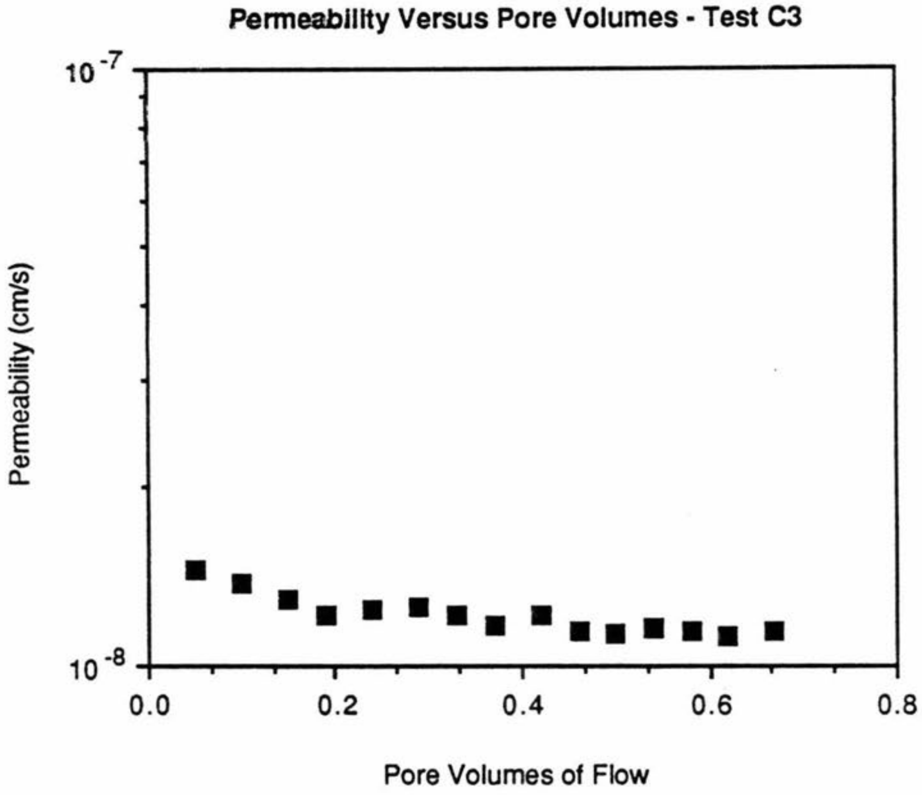


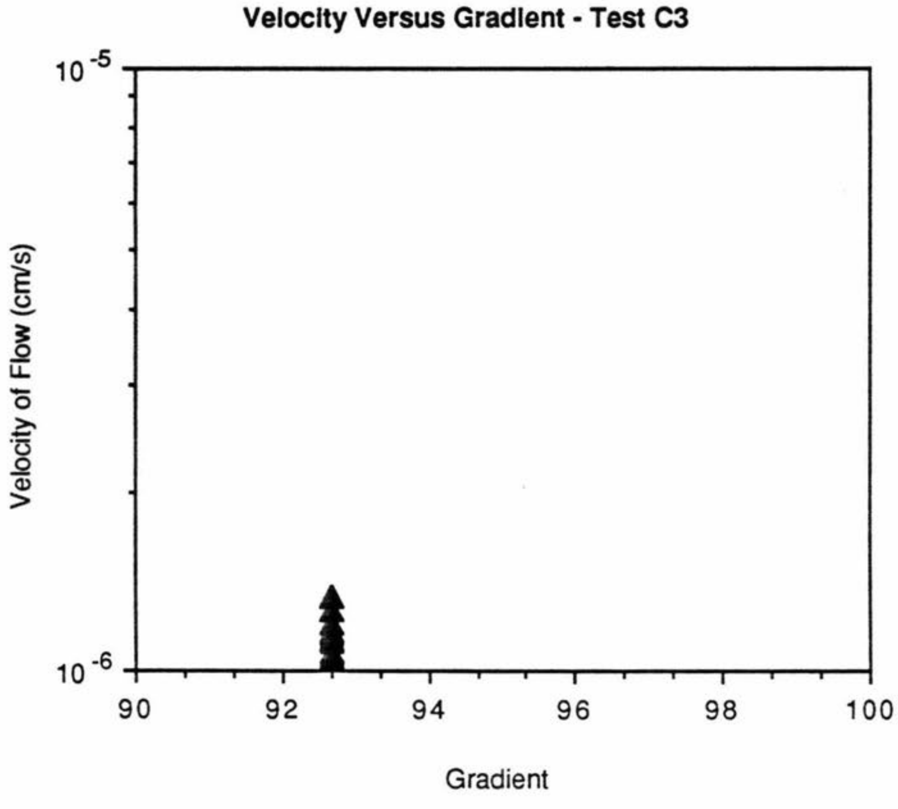
Velocity Versus Gradient - Test A3

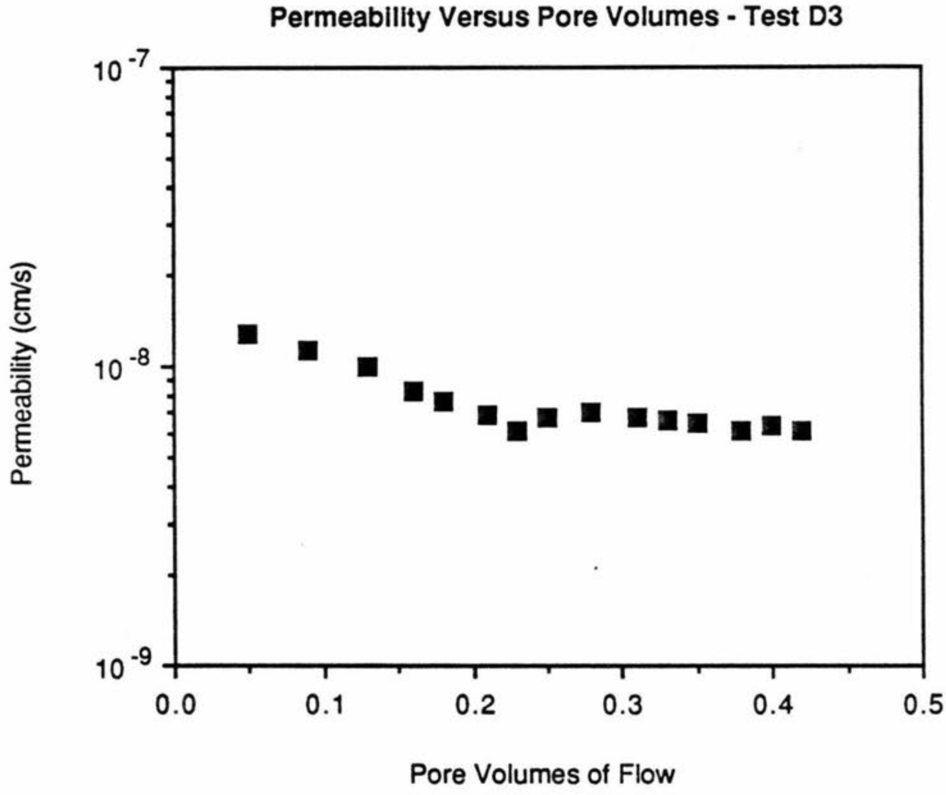


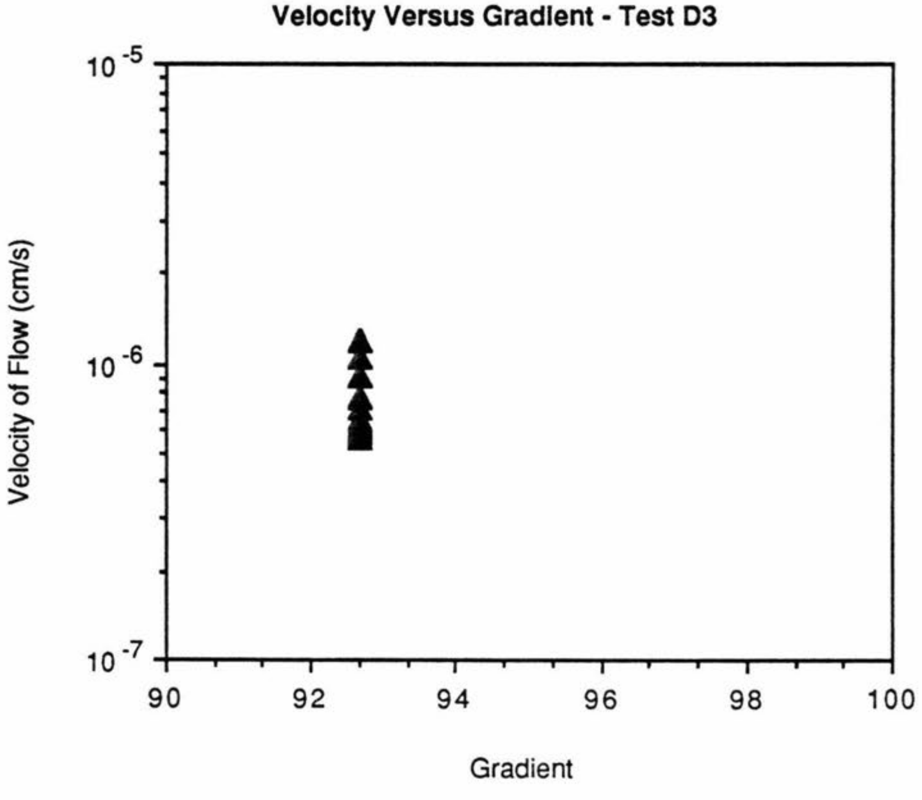

Permeability Versus Pore Volumes - Test B3
Permeability (cm/s)
10^{-7}
10^{-8}
0.2
0.4
0.6
0.8
1.0
1.2
1.4
Pore Volumes of Flow

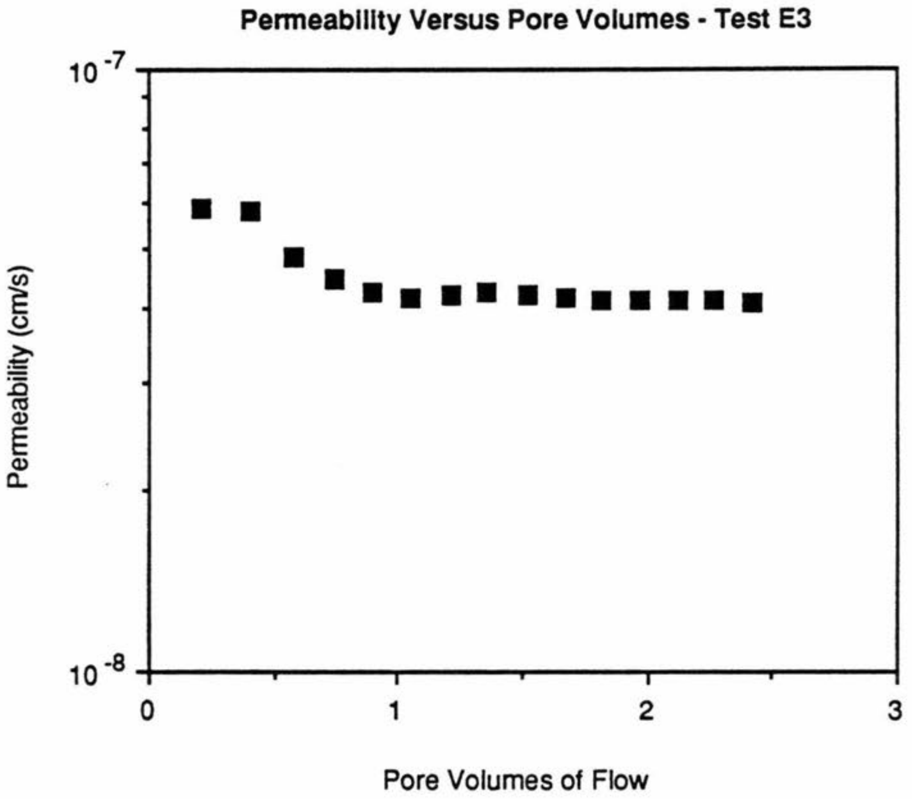

Velocity Versus Gradient - Test B3
Velocity of Flow (cm/s)
10^{-5}
10^{-6}
90
92
94
96
98
100
Gradient

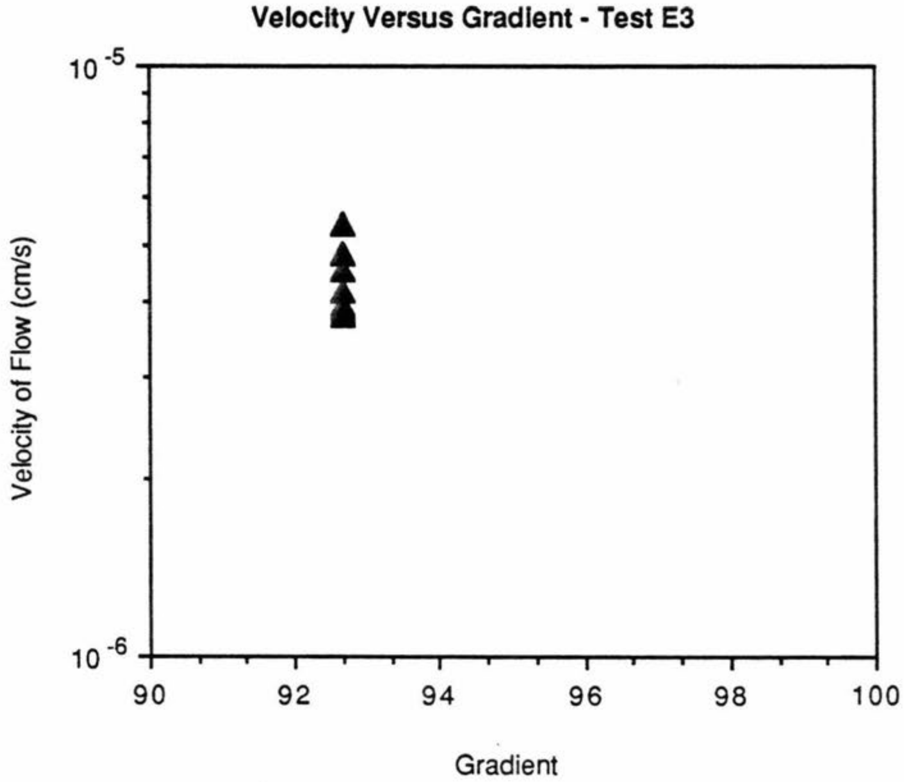

Permeability Versus Pore Volumes - Test C3
10 -7
10 -8
Permeability (cm/s)
0.0
0.2
0.4
0.6
0.8
Pore Volumes of Flow

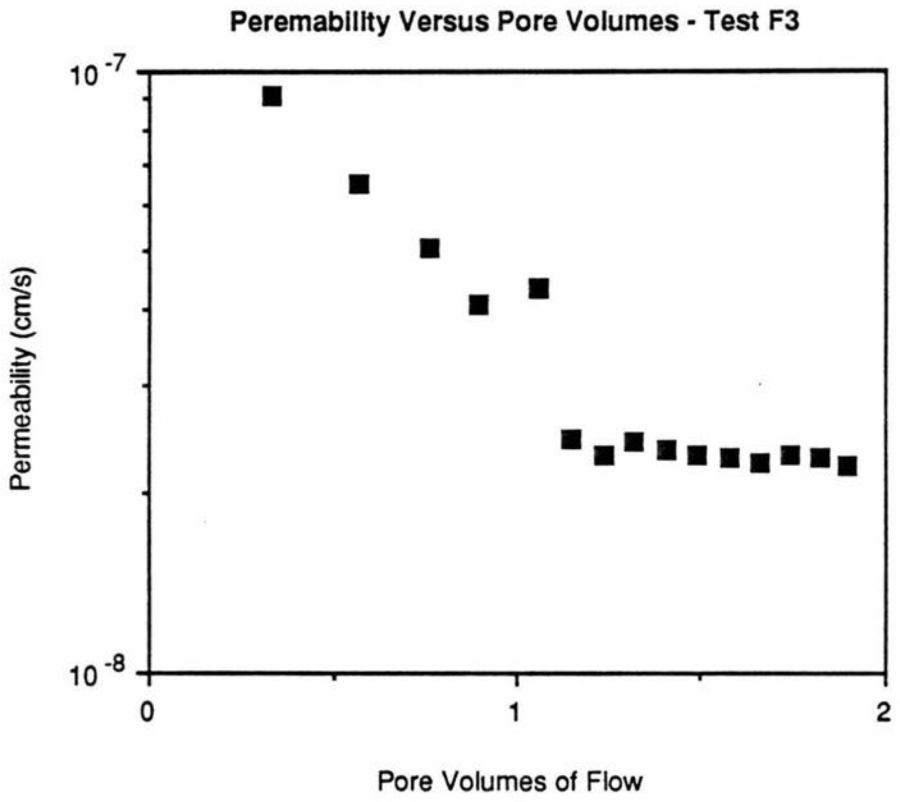

Velocity Versus Gradient - Test C3
10 -5
10 -6
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient


Permeability Versus Pore Volumes - Test D3
10 -7
10 -8
10 -9
Permeability (cm/s)
0.0
0.1
0.2
0.3
0.4
0.5
Pore Volumes of Flow

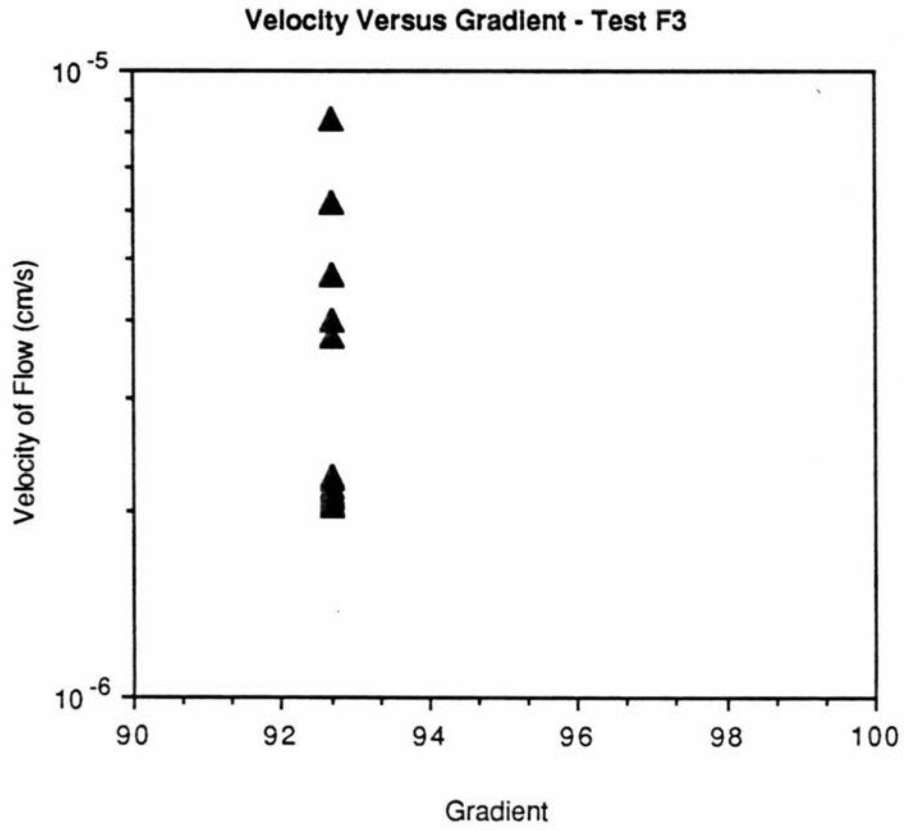

Velocity Versus Gradient - Test D3
10 -5
10 -6
10 -7
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient


Permeability Versus Pore Volumes - Test E3
10 -7
10 -8
Permeability (cm/s)
0
1
2
3
Pore Volumes of Flow

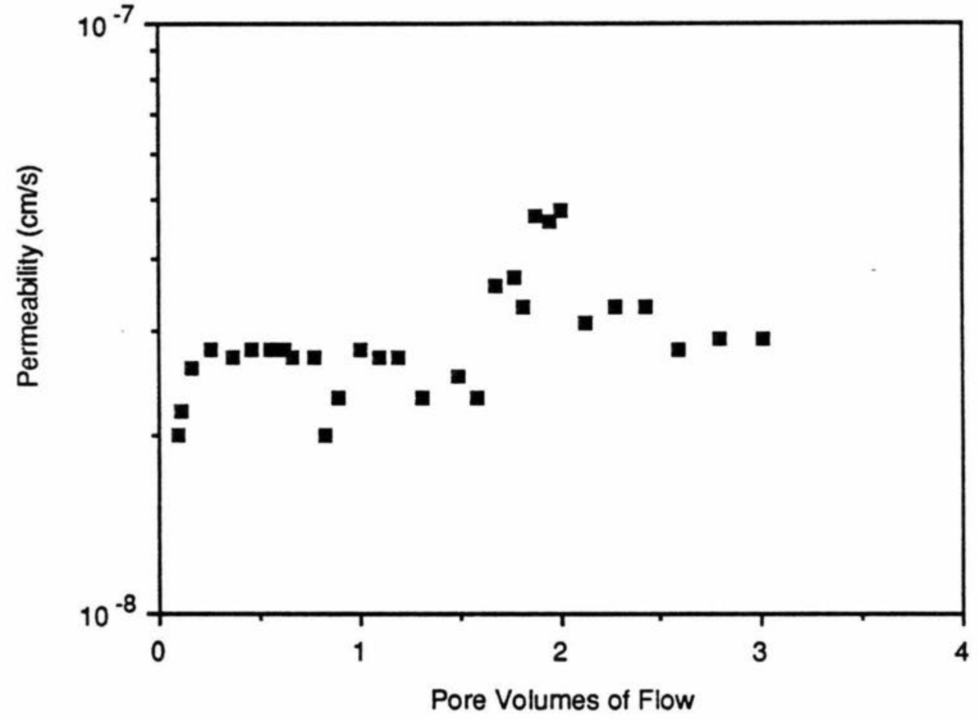

Velocity Versus Gradient - Test E3
10 -5
10 -6
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient



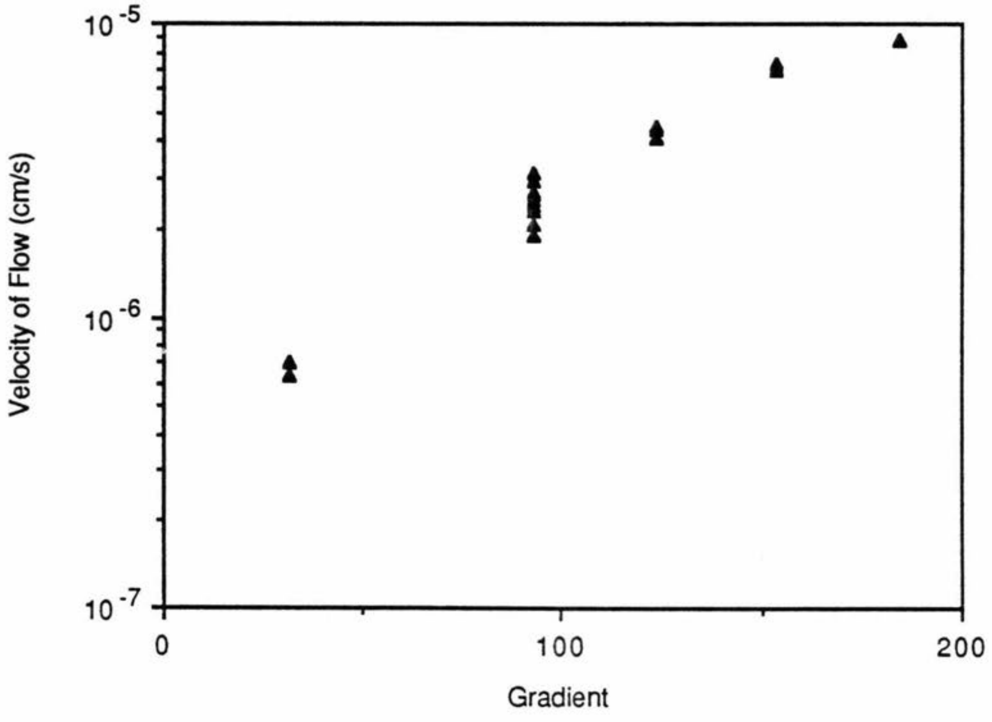
Peremability Versus Pore Volumes - Test F3



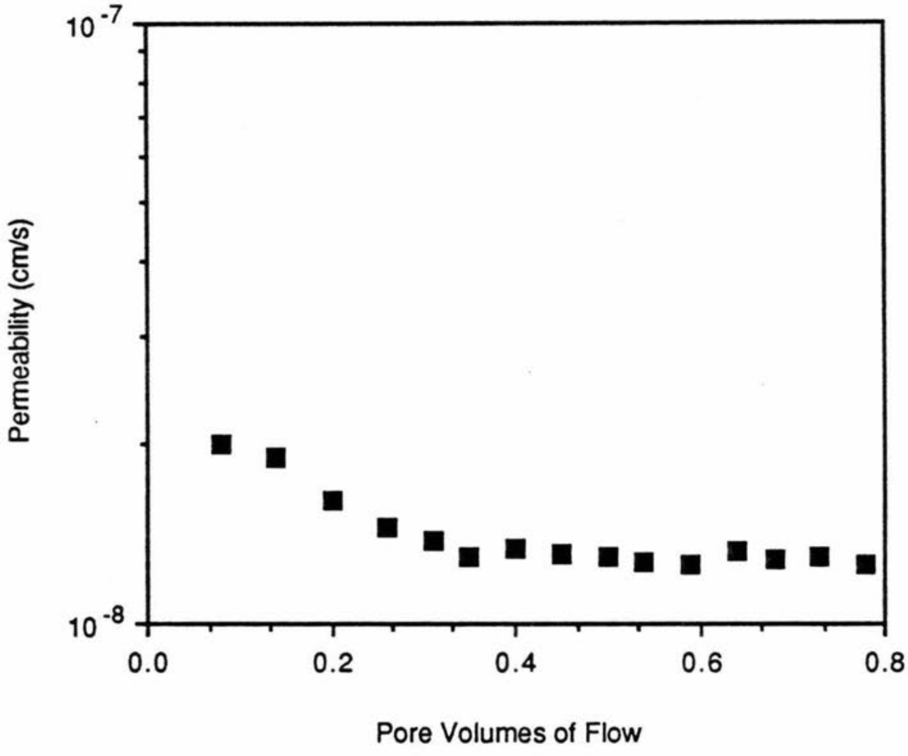
Velocity Versus Gradient - Test F3

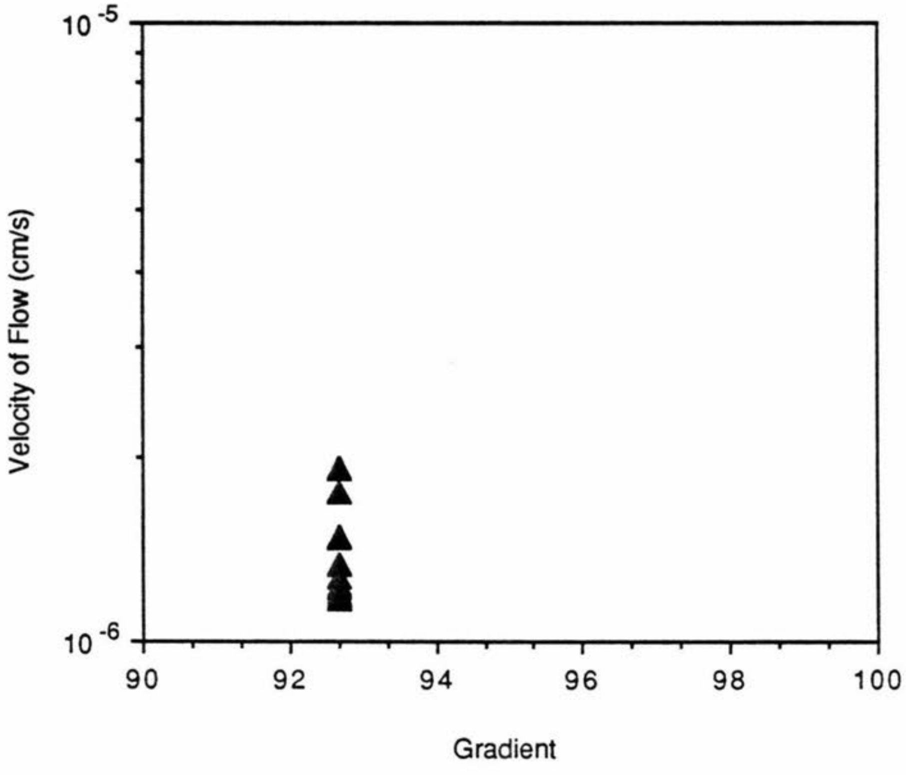


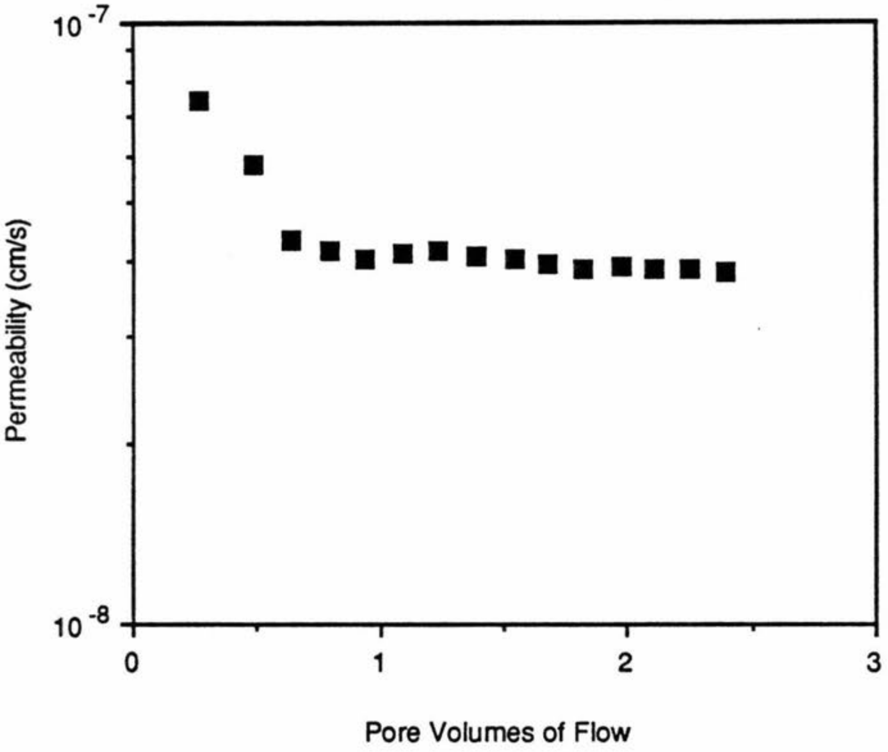
Permeability Versus Pore Volumes - Test A4



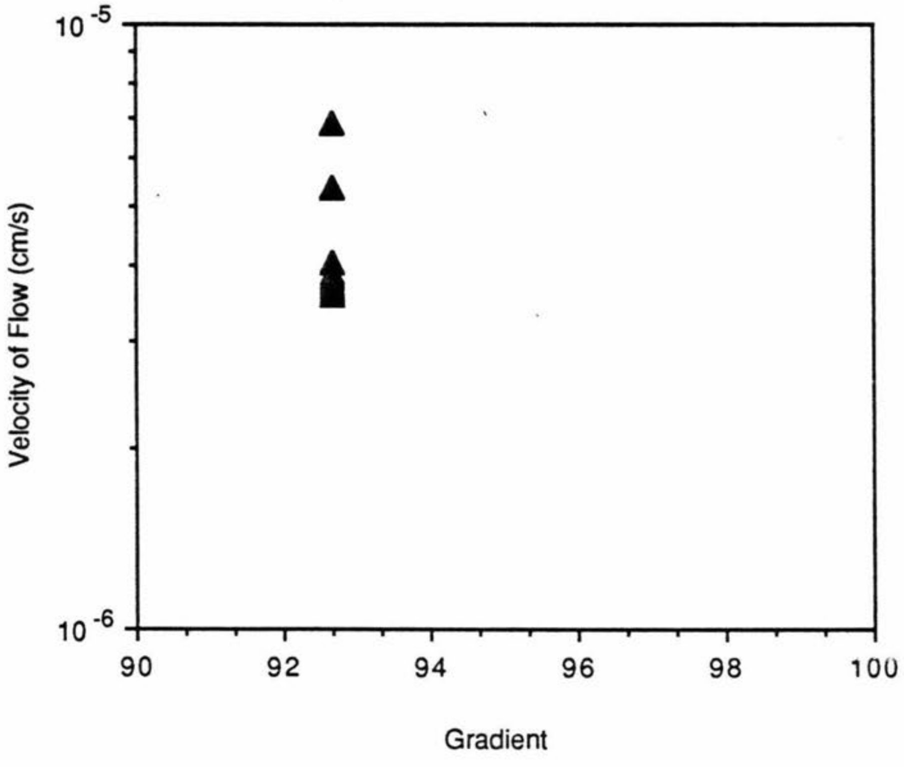
Velocity Vresus Gradient - test A4


Permeability Versus Pore Volumes - Test B4


Velocity Versus Gradient - Test B4

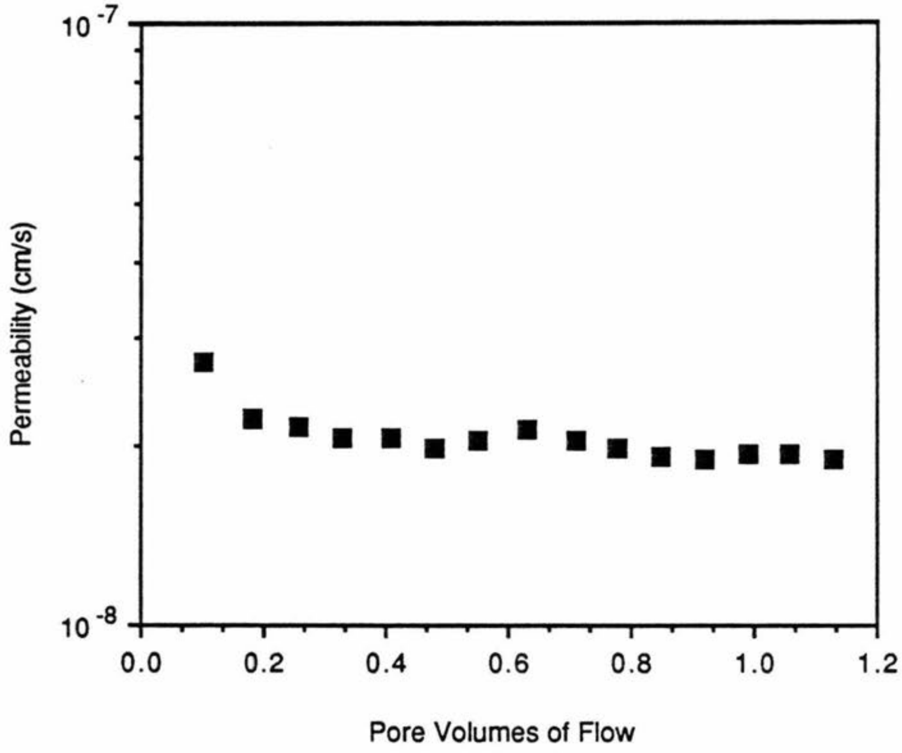


Permeability Versus Pore Volumes - Test C4

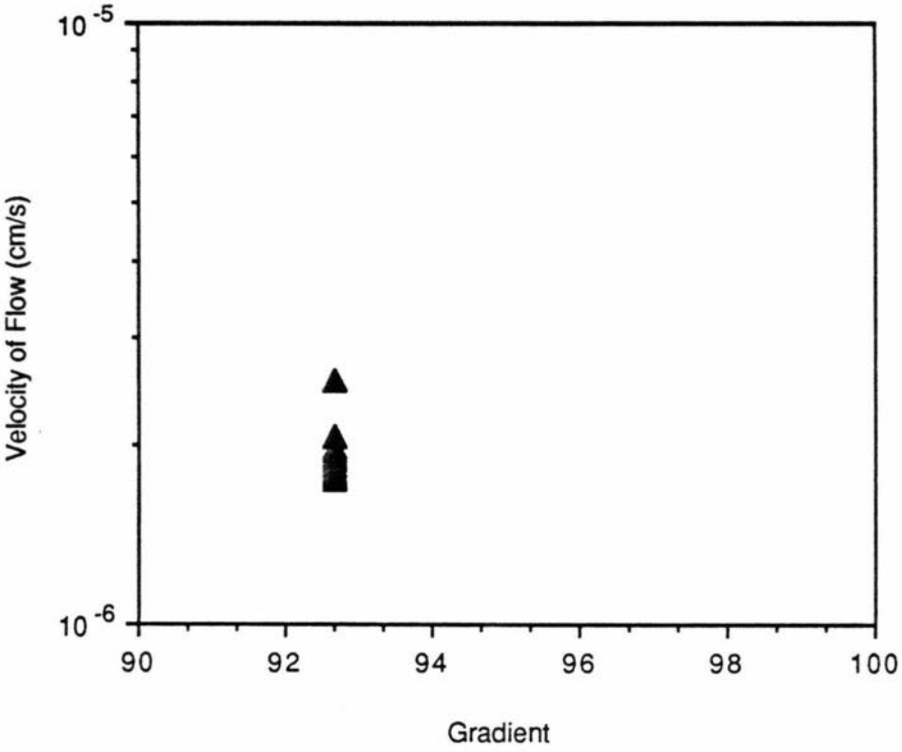


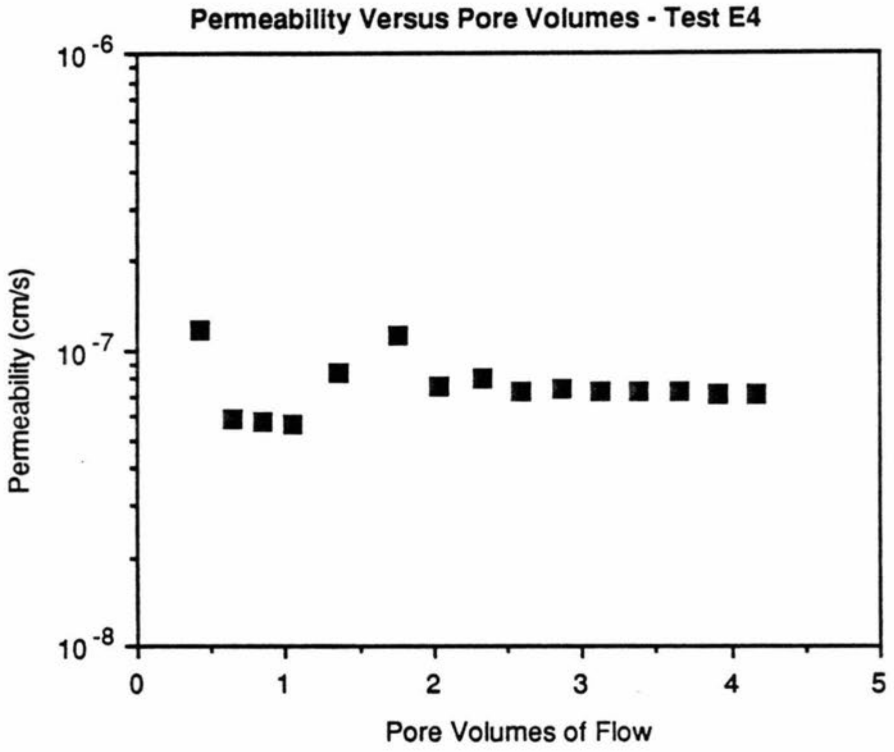
Velocity Versus Gradient - Test C4

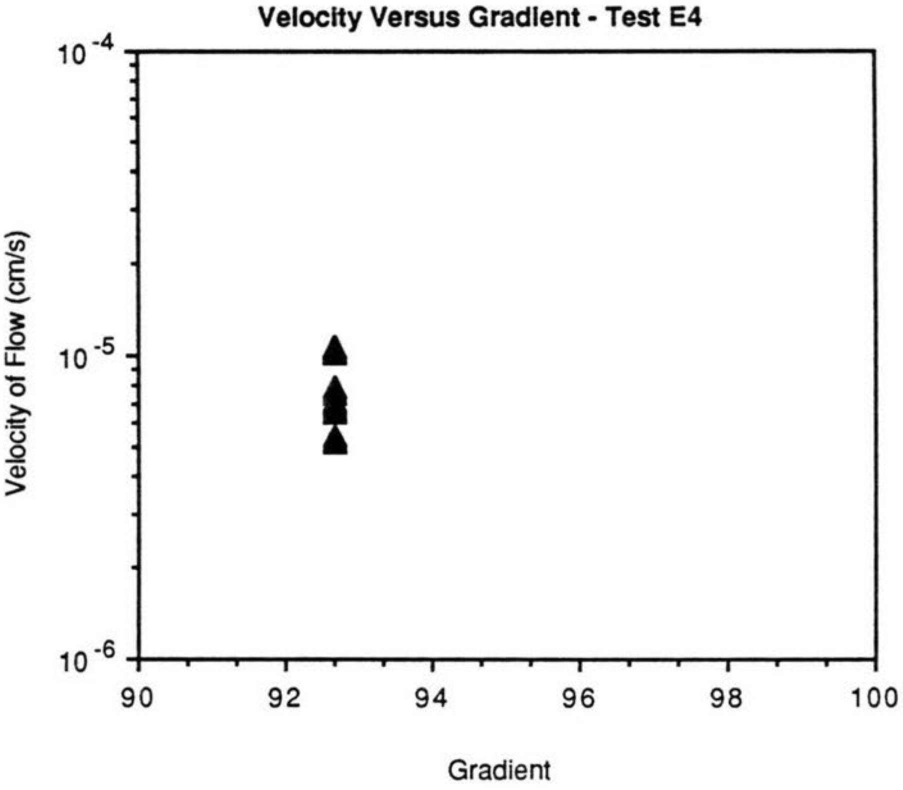
Permeability Versus Pore Volumes - Test D4

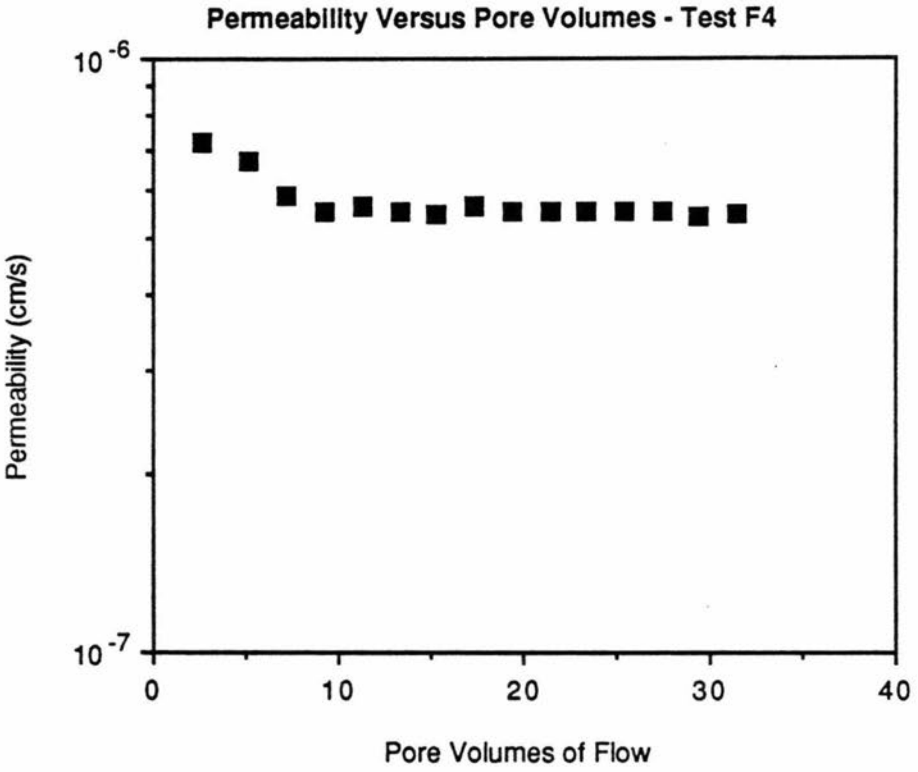


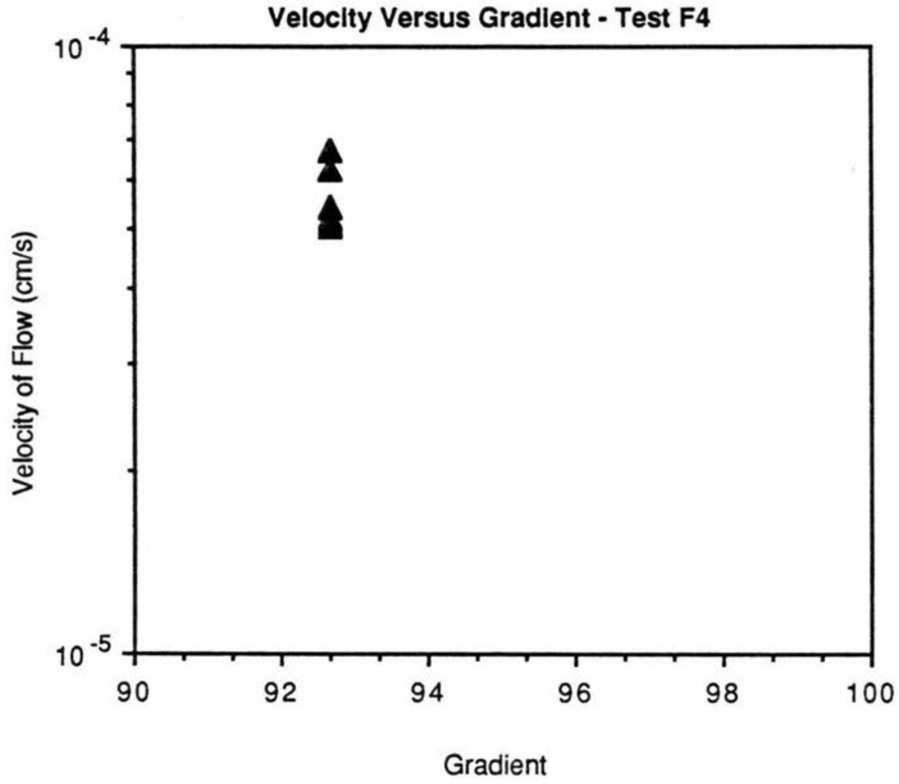
Velocity Versus Gradient - Test D4



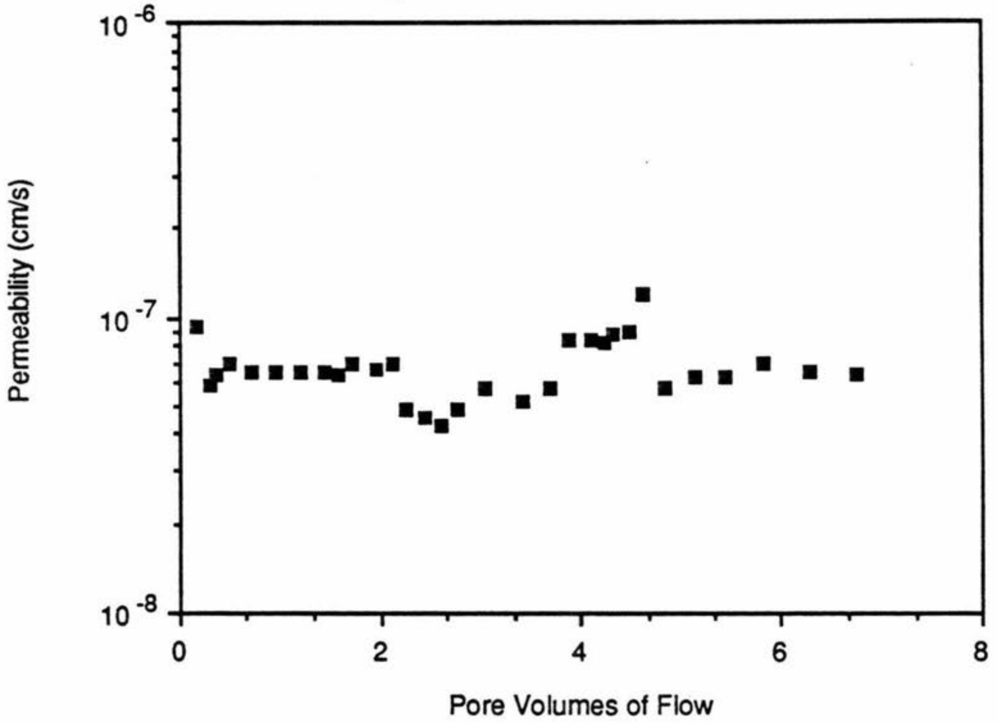

Permeability Versus Pore Volumes - Test E4
Permeability (cm/s)
10 -6
10 -7
10 -8
0
1
2
3
4
5
Pore Volumes of Flow


Velocity Versus Gradient - Test E4
Velocity of Flow (cm/s)
10 -4
10 -5
10 -6
90
92
94
96
98
100
Gradient

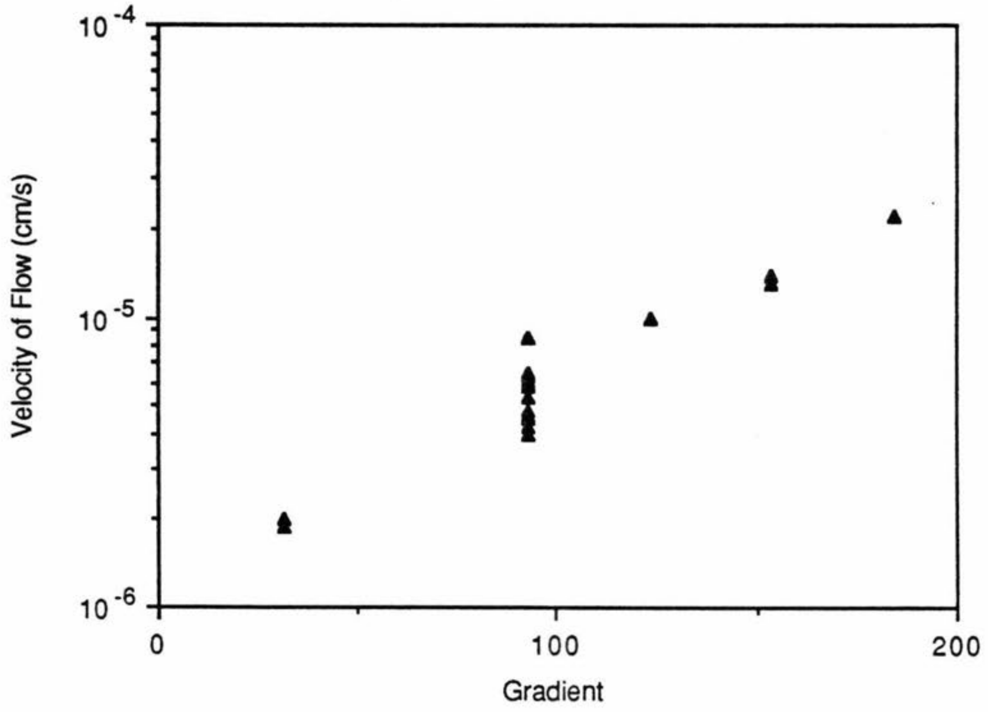

Permeability Versus Pore Volumes - Test F4
Permeability (cm/s)
10^{-6}
10^{-7}
0
10
20
30
40
Pore Volumes of Flow

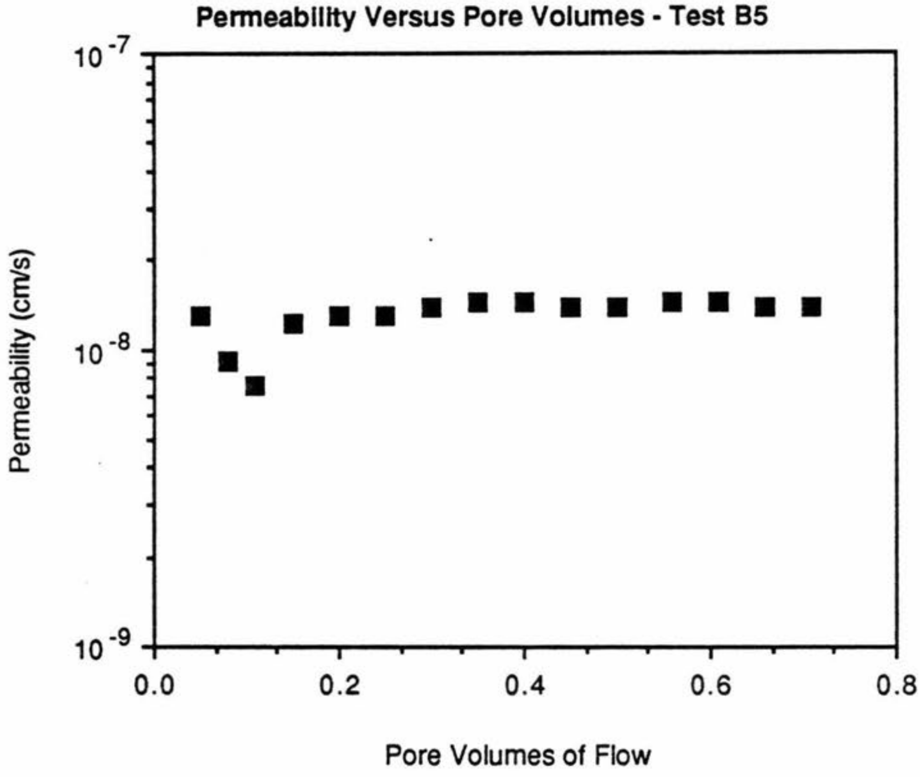

Velocity Versus Gradient - Test F4
Velocity of Flow (cm/s)
10^{-4}
10^{-5}
90
92
94
96
98
100
Gradient

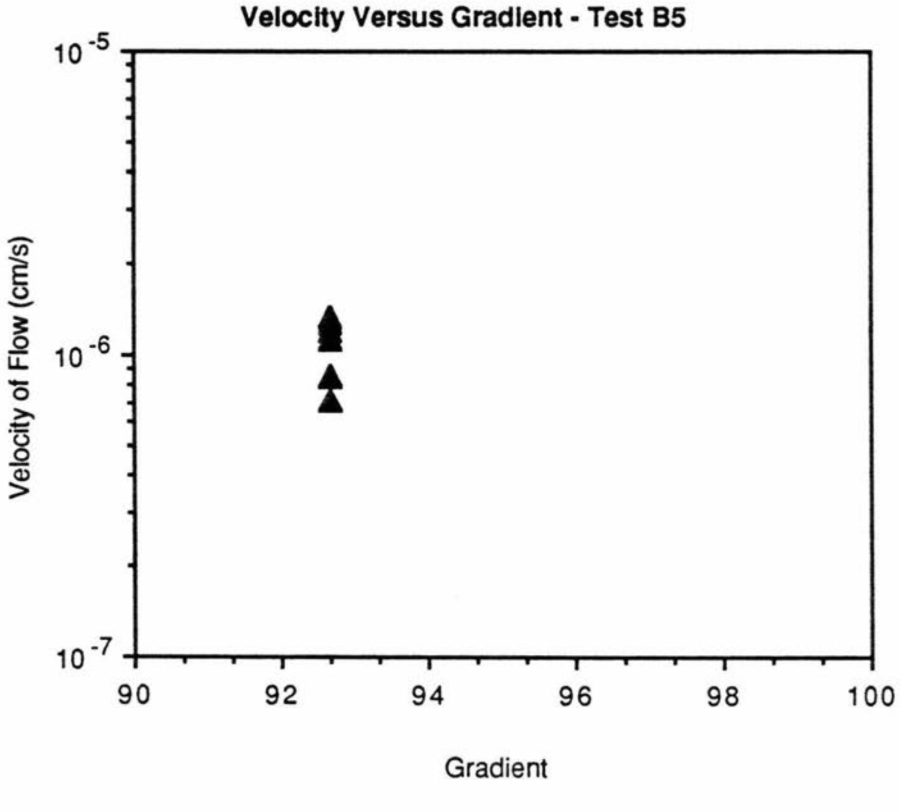
Permeability Versus Pore Volumes - Test A5

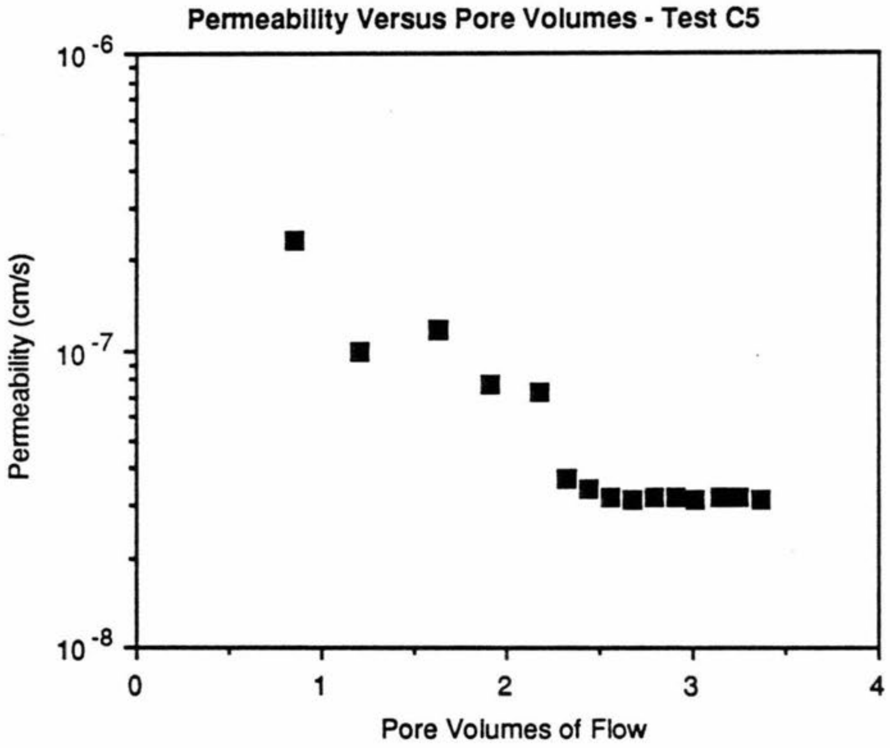


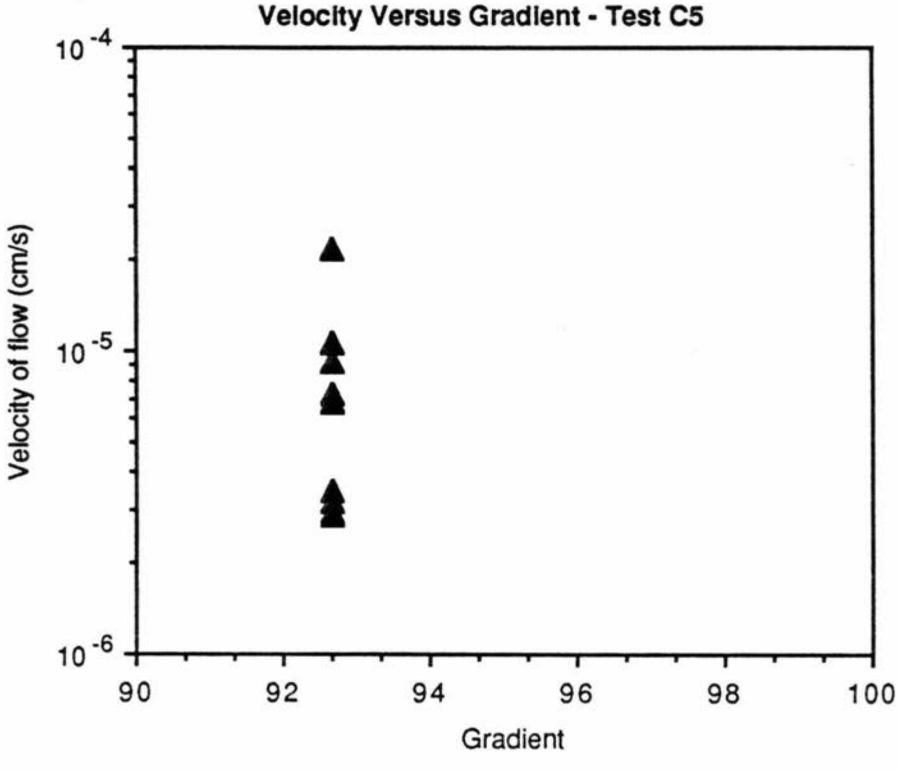
Velocity Versus Gradient - Test A5

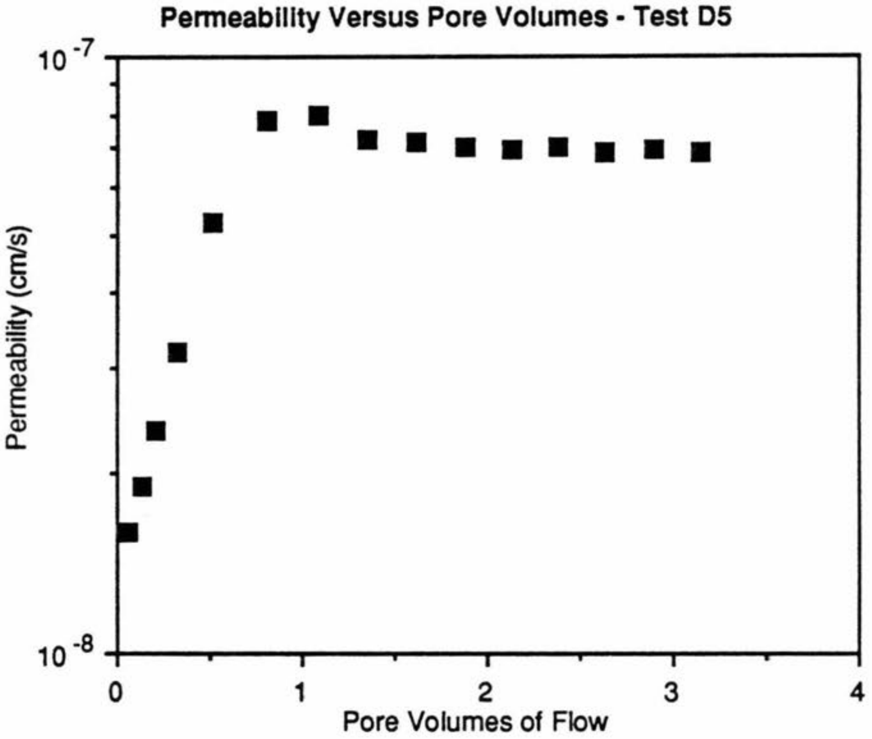


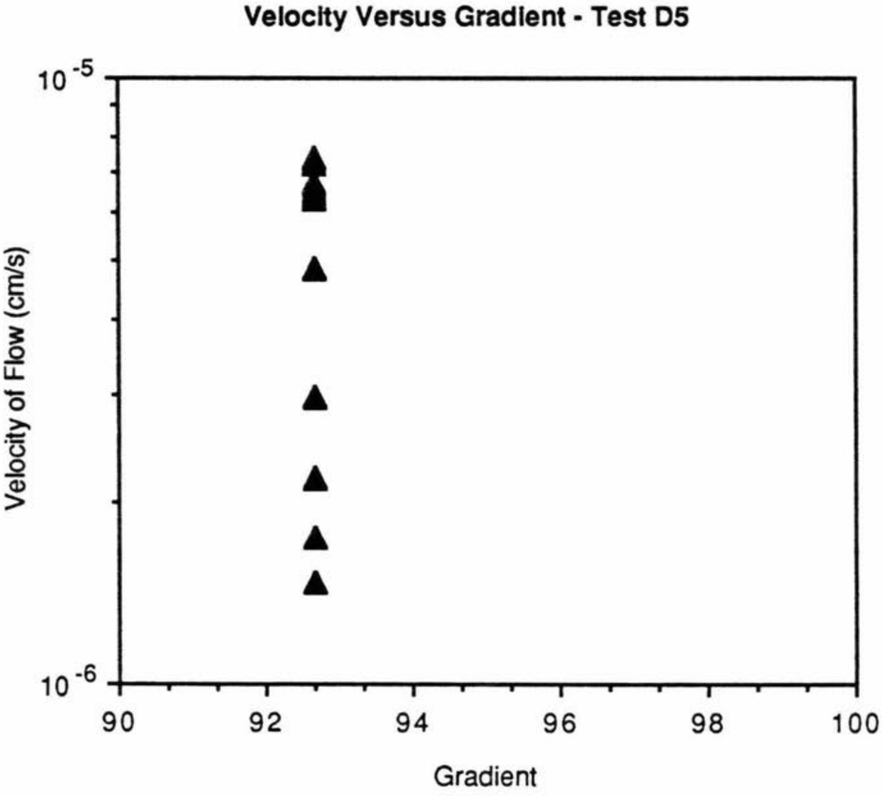

Permeability Versus Pore Volumes - Test B5
Permeability (cm/s)
10^{-7}
10^{-8}
10^{-9}
0.0
0.2
0.4
0.6
0.8
Pore Volumes of Flow

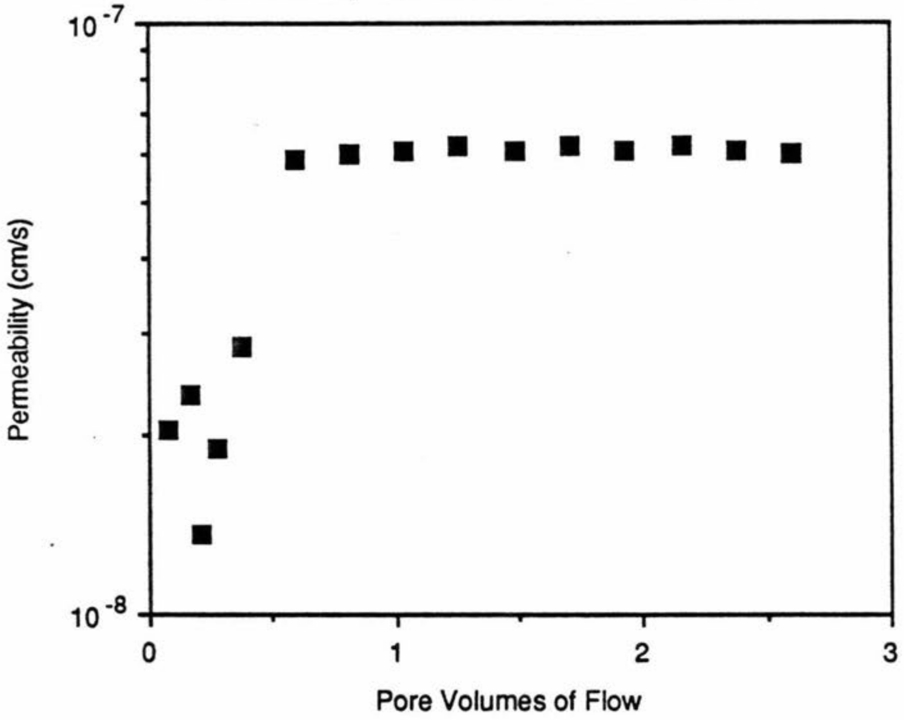

Velocity Versus Gradient - Test B5
Velocity of Flow (cm/s)
10^{-5}
10^{-6}
10^{-7}
90
92
94
96
98
100
Gradient


Permeability Versus Pore Volumes - Test C5
Permeability (cm/s)
10^{-6}
10^{-7}
10^{-8}
0
1
2
3
4
Pore Volumes of Flow

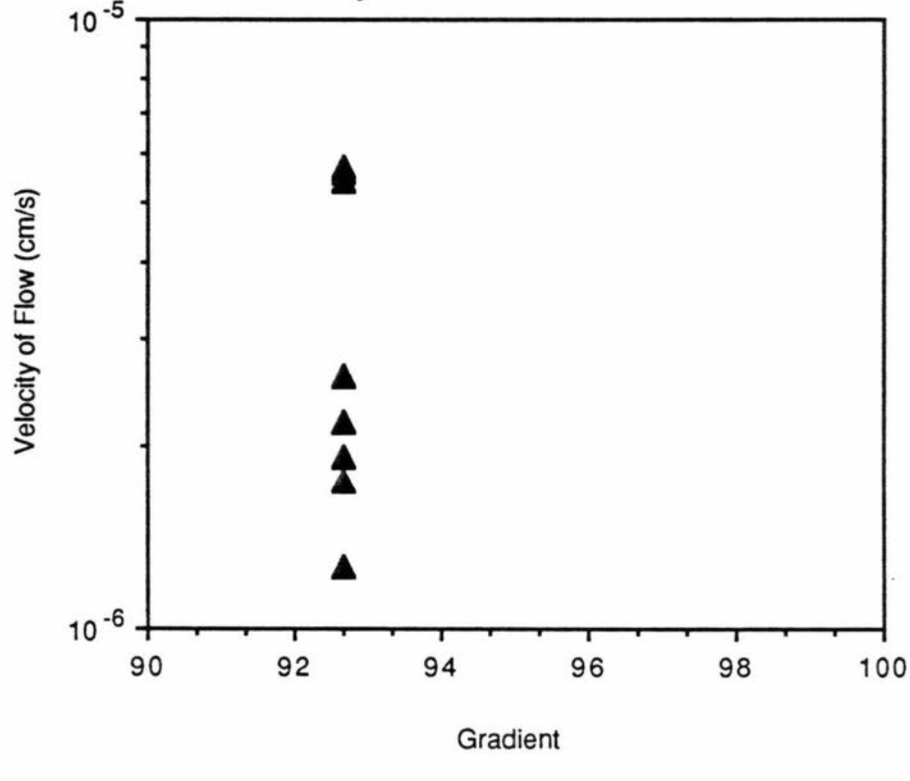

Velocity Versus Gradient - Test C5
Velocity of flow (cm/s)
10^{-4}
10^{-5}
10^{-6}
90
92
94
96
98
100
Gradient


Permeability Versus Pore Volumes - Test D5
Permeability (cm/s)
10 -7
10 -8
0
1
2
3
4
Pore Volumes of Flow

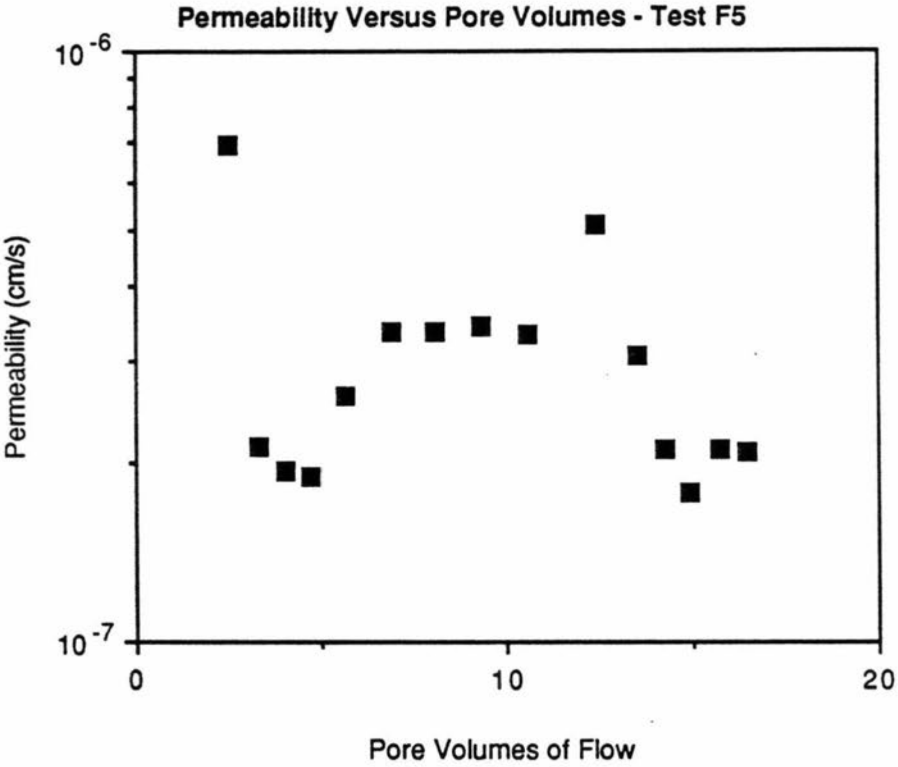

Velocity Versus Gradient - Test D5
Velocity of Flow (cm/s)
10 -5
10 -6
90
92
94
96
98
100
Gradient

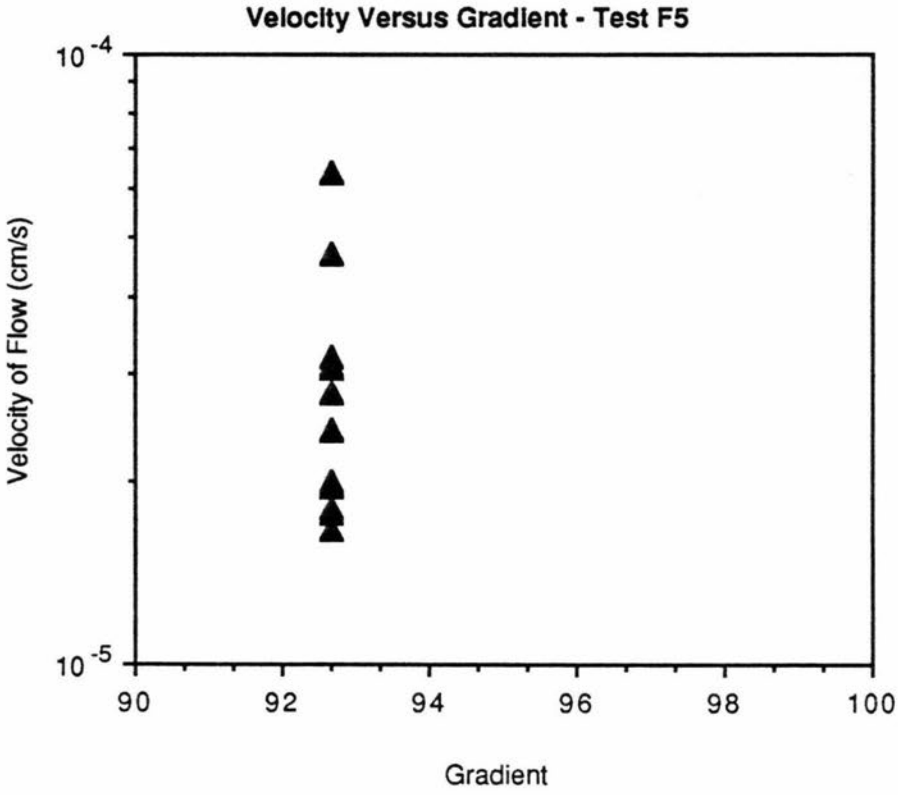


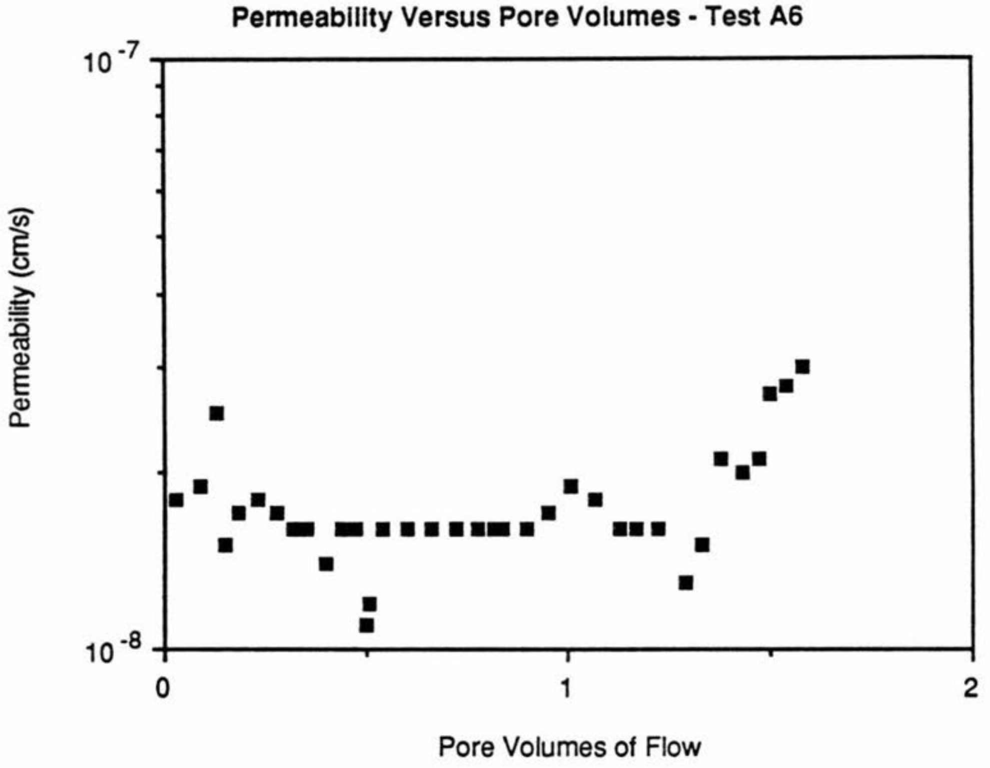
Permeability Versus Pore Volumes - Test E5

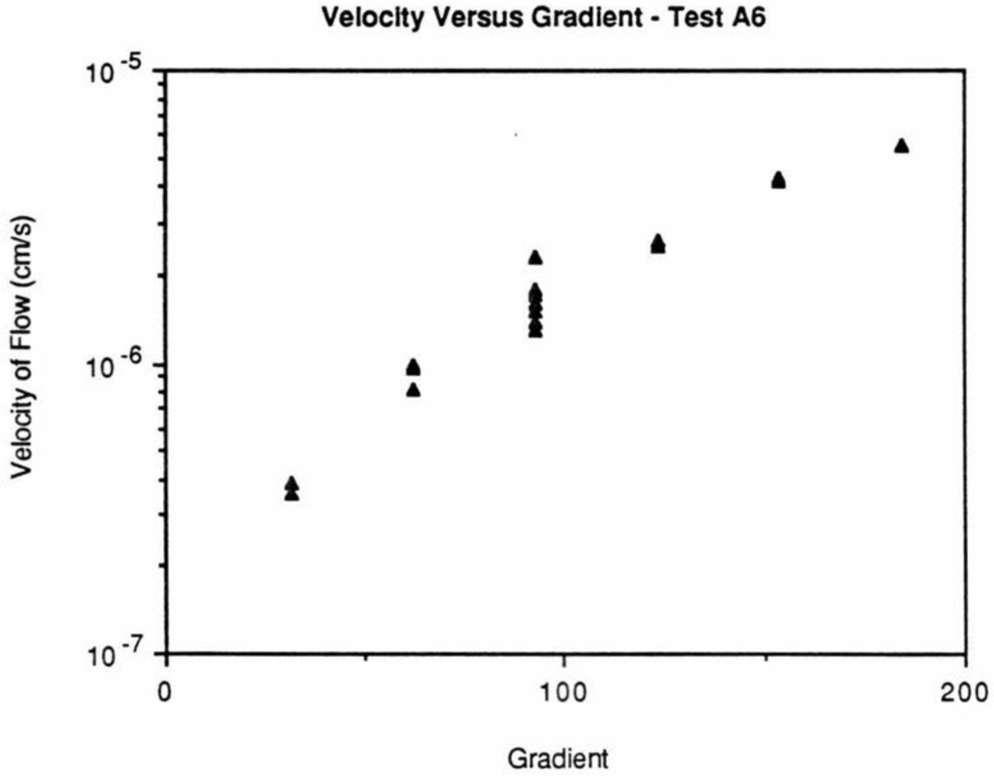


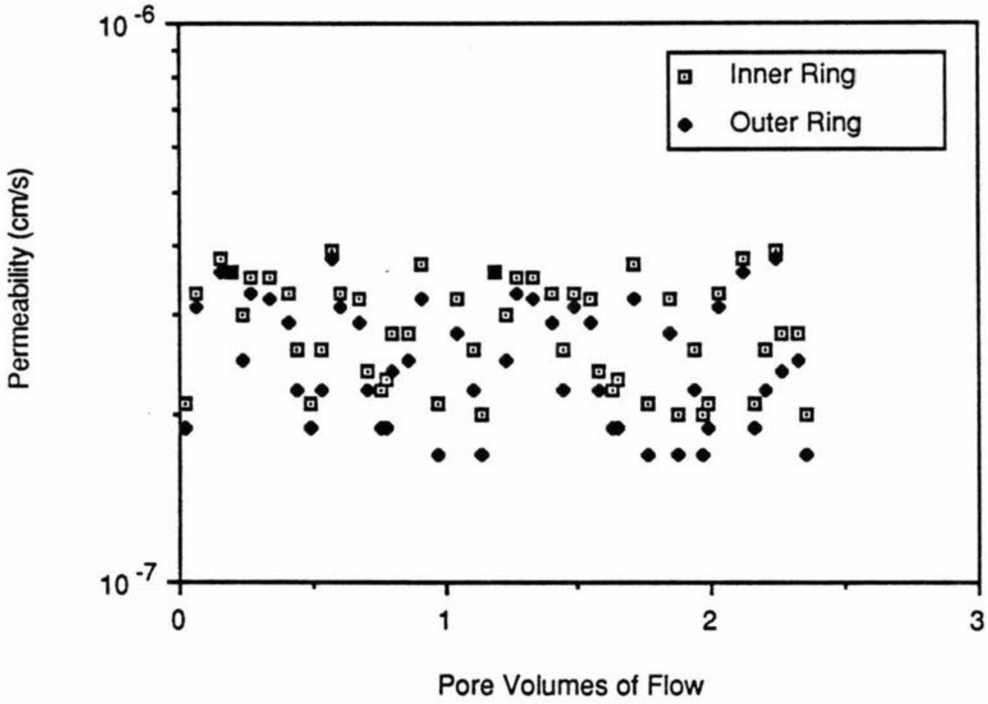
Velocity Versus Gradient - Test E5


Permeability Versus Pore Volumes - Test F5
10 -6
10 -7
Permeability (cm/s)
0
10
20
Pore Volumes of Flow

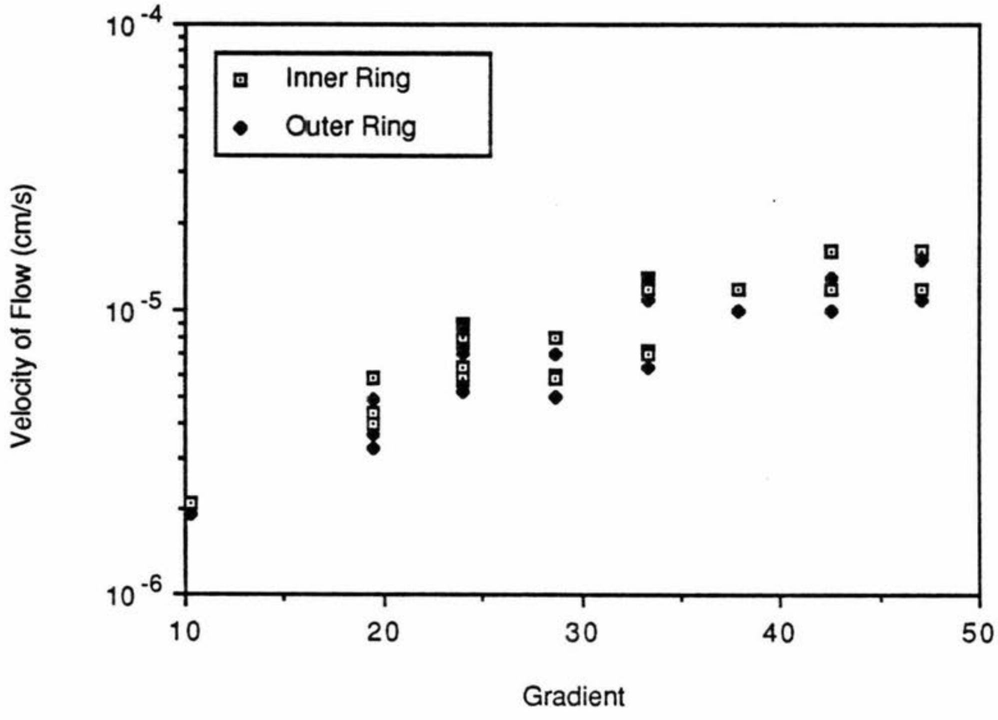

Velocity Versus Gradient - Test F5
10 -4
10 -5
Velocity of Flow (cm/s)
90
92
94
96
98
100
Gradient


Permeability Versus Pore Volumes - Test A6
Permeability (cm/s)
10 -7
10 -8
0
1
2
Pore Volumes of Flow

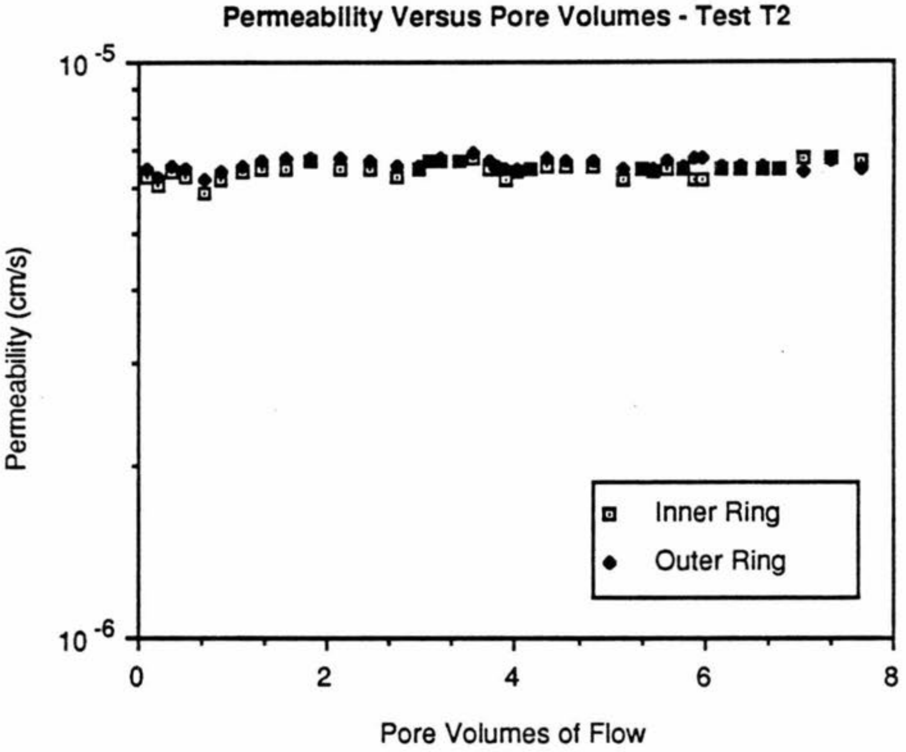

Velocity Versus Gradient - Test A6
Velocity of Flow (cm/s)
10 -5
10 -6
10 -7
0
100
200
Gradient

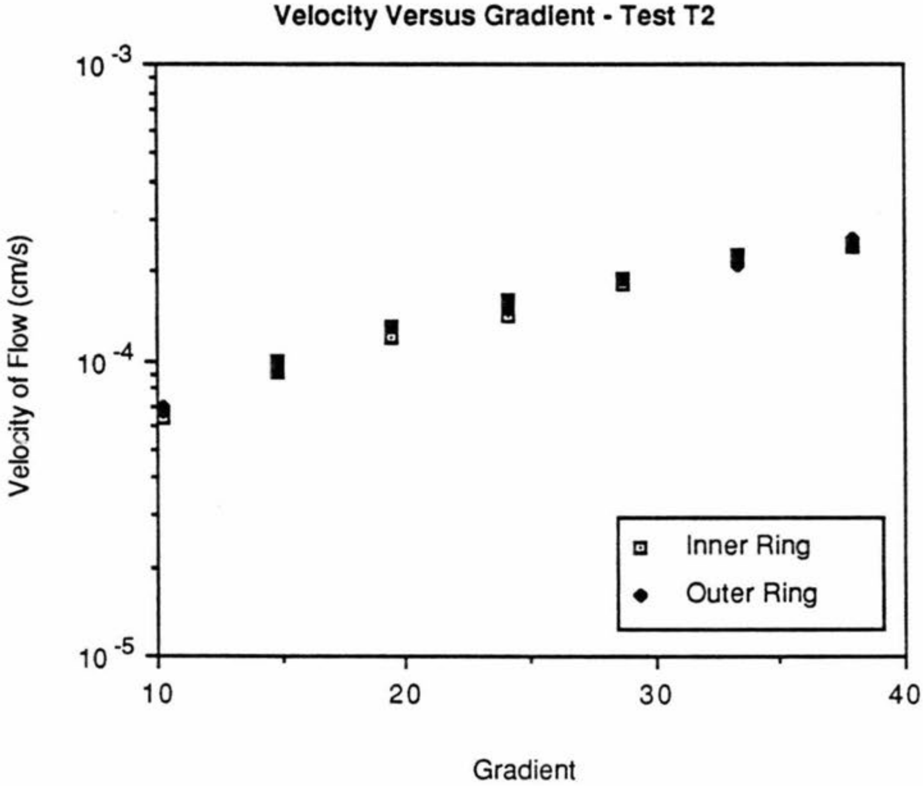


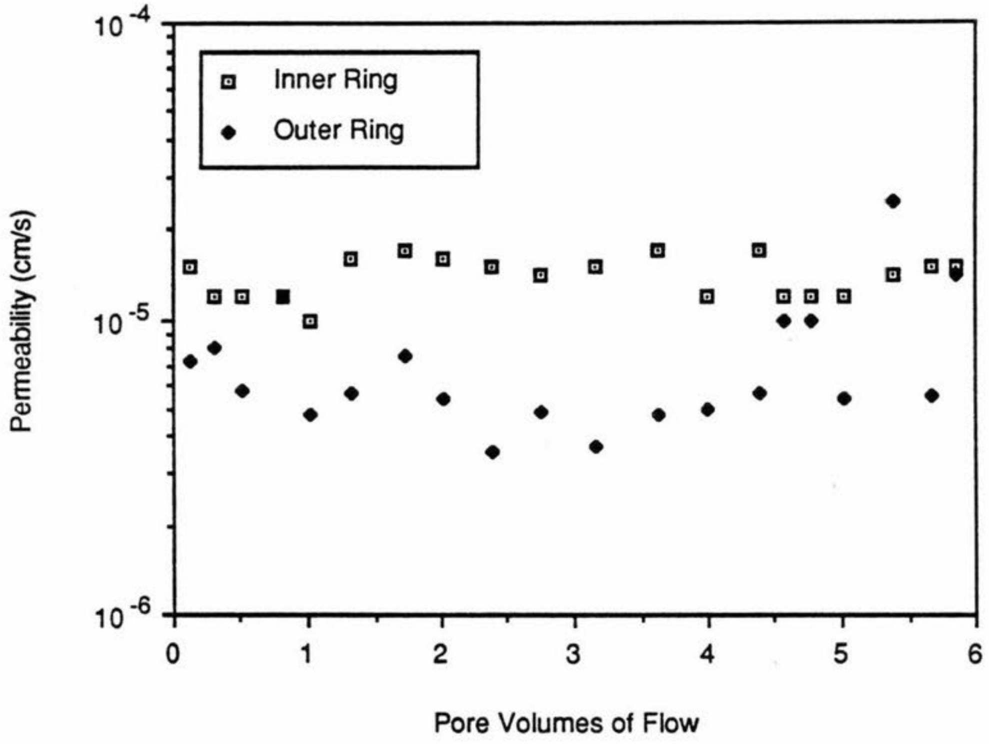
Permeability Versus Pore Volumes - Test T1



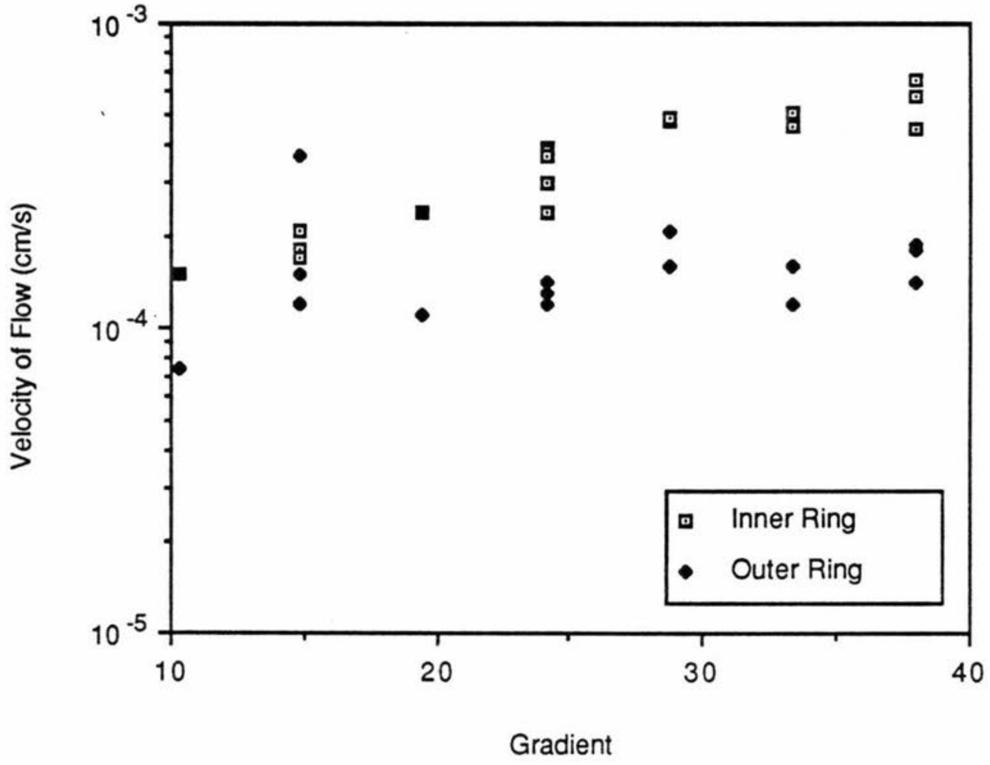
Velocity Versus Gradient - Test T1


Permeability Versus Pore Volumes - Test T2
Permeability (cm/s)
10 -5
10 -6
0
2
4
6
8
Pore Volumes of Flow
Inner Ring
Outer Ring


Velocity Versus Gradient - Test T2
Velocity of Flow (cm/s)
10 -3
10 -4
10 -5
10
20
30
40
Gradient
Inner Ring
Outer Ring

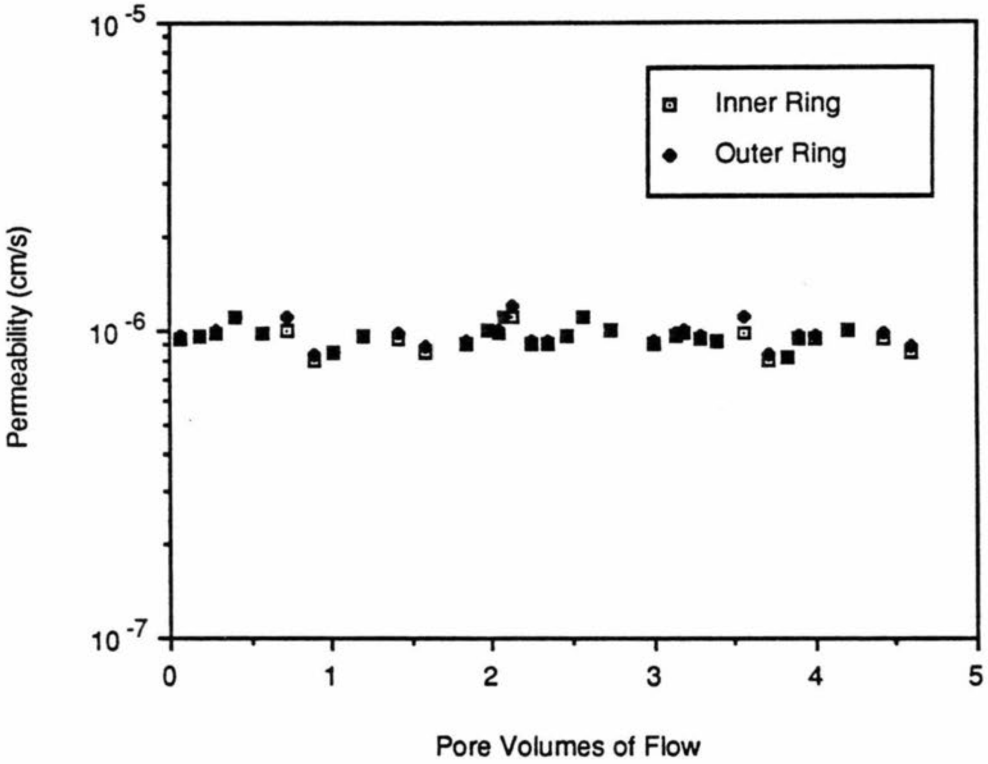


Permeability Versus Pore Volumes - Test T3

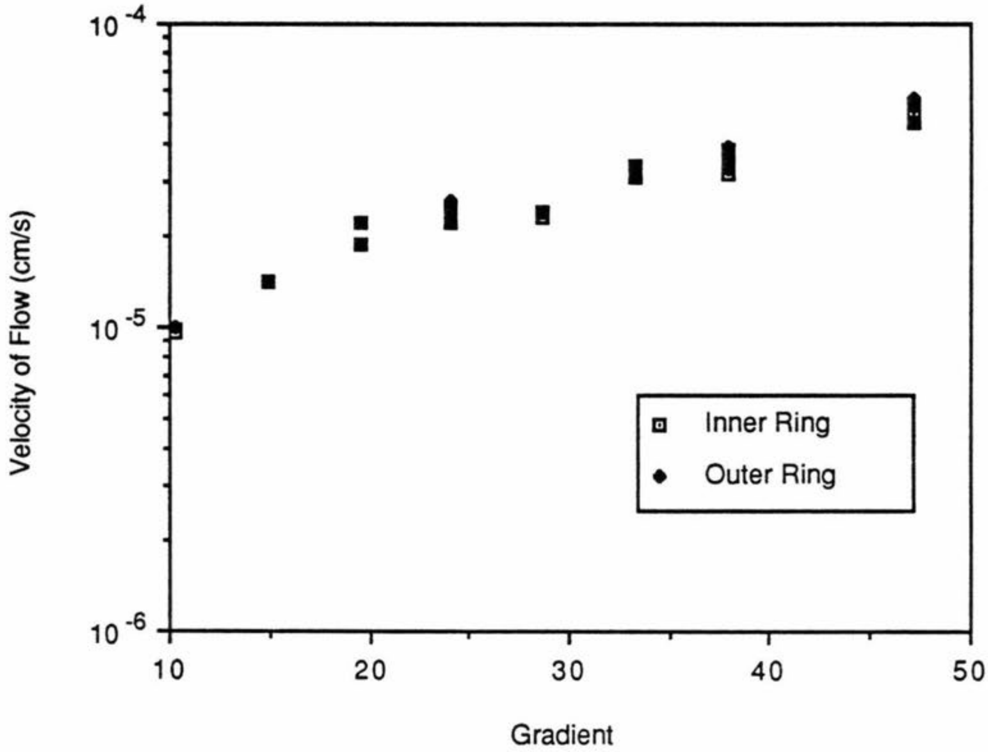


Velocity Versus Gradient - Test T3

Permeability Versus Pore Volumes Test T4



Velocity Versus Gradient - Test T4



Appendix 6. Permeability test results (Tables).

Permeability Test Results (Test A1)

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.02	8.4E-09	7.8E-07
31.58	0.03	8.9E-09	2.8E-07
31.58	0.04	9.5E-09	3.0E-07
92.68	0.06	1.1E-08	9.9E-07
92.68	0.10	1.1E-08	9.9E-07
92.68	0.14	1.0E-08	9.5E-07
92.68	0.18	1.1E-08	9.9E-07
92.68	0.22	1.1E-08	9.9E-07
92.68	0.24	1.0E-08	9.4E-07
92.68	0.26	1.1E-08	9.9E-07
92.68	0.30	1.1E-08	9.9E-07
92.68	0.33	1.0E-08	9.3E-07
92.68	0.36	1.1E-08	1.0E-06
92.68	0.39	1.0E-08	9.5E-07
92.68	0.43	9.9E-09	9.2E-07
92.68	0.47	9.9E-09	9.2E-07
92.68	0.52	1.0E-08	9.6E-07
92.68	0.59	9.9E-09	9.2E-07
92.68	0.63	9.7E-09	9.0E-07
123.33	0.69	2.2E-08	2.7E-06
123.33	0.74	2.1E-08	2.6E-06
123.33	0.78	2.3E-08	2.9E-06
153.90	0.81	2.8E-08	4.3E-06
153.90	0.85	2.8E-08	4.3E-06
184.00	0.89	3.2E-08	5.9E-06
92.68	0.93	1.1E-08	1.0E-06
92.68	0.99	1.2E-08	1.2E-06
92.68	1.05	1.3E-08	1.2E-06
92.68	1.12	1.2E-08	1.2E-06
92.68	1.19	9.3E-09	8.6E-07
92.68	1.26	9.5E-09	8.8E-07

Results of Permeability Test B1

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.09	2.45E-08	2.27E-06
92.68	0.17	2.11E-08	1.96E-06
92.68	0.24	1.95E-08	1.81E-06
92.68	0.31	1.88E-08	1.74E-06
92.68	0.36	1.45E-08	1.34E-06
92.68	0.44	2.17E-08	2.01E-06
92.68	0.51	1.98E-08	1.83E-06
92.68	0.58	1.87E-08	1.73E-06
92.68	0.64	1.82E-08	1.69E-06
92.68	0.71	1.90E-08	1.76E-06
92.68	0.78	1.83E-08	1.70E-06
92.68	0.85	1.93E-08	1.79E-06
92.68	0.92	1.90E-08	1.76E-06
92.68	0.99	1.89E-08	1.75E-06
92.68	1.06	1.84E-08	1.71E-06

Results of Permeability Test C1

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.675	0.13	3.47E-08	3.22E-06
92.675	0.26	3.78E-08	3.50E-06
92.675	0.36	2.74E-08	2.54E-06
92.675	0.44	2.11E-08	1.96E-06
92.675	0.53	2.44E-08	2.26E-06
92.675	0.62	2.47E-08	2.29E-06
92.675	0.71	2.34E-08	2.17E-06
92.675	0.79	2.27E-08	2.10E-06
92.675	0.87	2.19E-08	2.03E-06
92.675	0.95	2.11E-08	1.96E-06
92.675	1.02	1.98E-08	1.83E-06
92.675	1.09	1.91E-08	1.77E-06
92.675	1.16	2.05E-08	1.90E-06
92.675	1.23	1.96E-08	1.82E-06
92.675	1.30	1.94E-08	1.80E-06

Results of Permeability Test D1

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.675	0.19	5.30E-08	4.91E-06
92.675	0.37	4.90E-08	4.54E-06
92.675	0.55	4.79E-08	4.44E-06
92.675	0.72	4.73E-08	4.38E-06
92.675	0.90	4.85E-08	4.49E-06
92.675	1.07	4.73E-08	4.38E-06
92.675	1.24	4.68E-08	4.34E-06
92.675	1.41	4.64E-08	4.30E-06
92.675	1.58	4.56E-08	4.23E-06
92.675	1.74	4.47E-08	4.14E-06
92.675	1.90	4.52E-08	4.19E-06
92.675	2.07	4.46E-08	4.13E-06
92.675	2.23	4.45E-08	4.12E-06
92.675	2.39	4.46E-08	4.13E-06
92.675	2.55	4.43E-08	4.11E-06

Results of Permeability Test E1

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.11	2.90E-08	2.69E-06
92.68	0.19	2.32E-08	2.15E-06
92.68	0.28	2.41E-08	2.23E-06
92.68	0.37	2.55E-08	2.36E-06
92.68	0.46	2.36E-08	2.19E-06
92.68	0.54	2.33E-08	2.16E-06
92.68	0.62	2.23E-08	2.07E-06
92.68	0.71	2.42E-08	2.24E-06
92.68	0.79	2.23E-08	2.07E-06
92.68	0.88	2.25E-08	2.09E-06
92.68	0.96	2.22E-08	2.06E-06
92.68	1.04	2.31E-08	2.14E-06
92.68	1.12	2.29E-08	2.12E-06
92.68	1.21	2.26E-08	2.09E-06
92.68	1.29	2.26E-08	2.09E-06

Results of Permeability Test F1

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.17	4.71E-08	4.36E-06
92.68	0.24	1.79E-08	1.66E-06
92.68	0.30	1.63E-08	1.51E-06
92.68	0.37	2.11E-08	1.96E-06
92.68	0.48	2.81E-08	2.60E-06
92.68	0.54	1.87E-08	1.73E-06
92.68	0.61	1.77E-08	1.64E-06
92.68	0.68	1.82E-08	1.69E-06
92.68	0.74	1.80E-08	1.67E-06
92.68	0.81	1.86E-08	1.72E-06
92.68	0.88	1.89E-08	1.75E-06
92.68	0.95	1.85E-08	1.71E-06
92.68	1.01	1.80E-08	1.67E-06
92.68	1.08	1.87E-08	1.73E-06
92.68	1.15	1.91E-08	1.77E-06

Permeability Test Results (Test A2)

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.03	1.9E-08	1.8E-06
92.68	0.09	1.9E-08	1.8E-06
92.68	0.12	1.7E-08	1.6E-06
92.68	0.14	1.6E-08	1.5E-06
92.68	0.17	1.5E-08	1.4E-06
92.68	0.21	1.4E-08	1.3E-06
92.68	0.25	1.3E-08	1.2E-06
92.68	0.28	1.3E-08	1.2E-06
92.68	0.30	1.3E-08	1.2E-06
92.68	0.34	1.2E-08	1.1E-06
92.68	0.38	1.4E-08	1.3E-06
92.68	0.40	1.3E-08	1.2E-06
31.58	0.43	9.7E-09	3.1E-07
31.58	0.44	1.0E-08	3.2E-07
92.68	0.46	1.3E-08	1.2E-06
92.68	0.51	1.3E-08	1.2E-06
92.68	0.56	1.3E-08	1.2E-06
92.68	0.60	1.3E-08	1.2E-06
92.68	0.65	1.3E-08	1.2E-06
92.68	0.70	2.0E-08	1.9E-06
92.68	0.72	1.3E-08	1.2E-06
92.68	0.77	1.3E-08	1.2E-06
92.68	0.80	1.2E-08	1.2E-06
92.68	0.84	1.2E-08	1.1E-06
92.68	0.88	1.1E-08	1.1E-06
92.68	0.92	1.2E-08	1.1E-06
62.16	0.95	1.0E-08	6.3E-07
62.16	0.98	9.6E-09	6.0E-07
62.16	1.02	9.5E-09	5.9E-07
62.16	1.05	9.2E-09	5.7E-07
123.33	1.10	1.9E-08	2.3E-06
123.33	1.14	1.9E-08	2.4E-06
123.33	1.17	1.8E-08	2.3E-06
153.90	1.20	2.1E-08	3.2E-06
153.90	1.23	2.2E-08	3.3E-06
184.00	1.26	2.4E-08	4.3E-06

Permeability Test Result (Test B2)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.15	4.11E-08	3.81E-06
92.68	0.28	3.43E-08	3.18E-06
92.68	0.39	3.20E-08	2.96E-06
92.68	0.50	2.97E-08	2.75E-06
92.68	0.60	2.82E-08	2.61E-06
92.68	0.70	2.74E-08	2.54E-06
92.68	0.80	2.76E-08	2.56E-06
92.68	0.91	2.79E-08	2.59E-06
92.68	1.01	2.75E-08	2.55E-06
92.68	1.11	2.77E-08	2.57E-06
92.68	1.21	2.74E-08	2.54E-06
92.68	1.31	2.74E-08	2.54E-06
92.68	1.41	2.71E-08	2.51E-06
92.68	1.51	2.75E-08	2.55E-06
92.68	1.60	2.72E-08	2.52E-06

Permeability Test Result (Test C2)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.32	8.83E-08	8.19E-06
92.675	0.63	8.38E-08	7.76E-06
92.675	0.92	7.92E-08	7.34E-06
92.675	1.19	7.46E-08	6.92E-06
92.675	1.45	7.23E-08	6.70E-06
92.675	1.70	6.89E-08	6.39E-06
92.675	1.95	6.78E-08	6.28E-06
92.675	2.19	6.45E-08	5.98E-06
92.675	2.41	6.23E-08	5.77E-06
92.675	2.64	6.11E-08	5.66E-06
92.675	2.85	5.88E-08	5.45E-06
92.675	3.06	5.76E-08	5.34E-06
92.675	3.27	5.65E-08	5.24E-06
92.675	3.47	5.65E-08	5.24E-06
92.675	3.68	5.58E-08	5.17E-06

Permeability Test Result (Test D2)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.13	3.58E-08	3.32E-06
92.675	0.24	2.89E-08	2.68E-06
92.675	0.34	2.74E-08	2.54E-06
92.675	0.43	2.67E-08	2.47E-06
92.675	0.53	2.59E-08	2.40E-06
92.675	0.62	2.59E-08	2.40E-06
92.675	0.72	2.56E-08	2.37E-06
92.675	0.81	2.51E-08	2.33E-06
92.675	0.90	2.54E-08	2.35E-06
92.675	0.99	2.58E-08	2.39E-06
92.675	1.09	2.53E-08	2.34E-06
92.675	1.18	2.55E-08	2.36E-06
92.675	1.27	2.49E-08	2.31E-06
92.675	1.36	2.51E-08	2.33E-06
92.675	1.45	2.47E-08	2.29E-06

Permeability Test Result (Test E2)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.15	4.09E-08	3.79E-06
92.68	0.28	3.56E-08	3.30E-06
92.68	0.40	3.23E-08	2.99E-06
92.68	0.52	3.34E-08	3.10E-06
92.68	0.64	3.26E-08	3.02E-06
92.68	0.75	3.15E-08	2.92E-06
92.68	0.87	3.09E-08	2.86E-06
92.68	0.98	3.11E-08	2.88E-06
92.68	1.09	3.16E-08	2.93E-06
92.68	1.20	3.04E-08	2.82E-06
92.68	1.32	3.07E-08	2.85E-06
92.68	1.43	3.07E-08	2.85E-06
92.68	1.54	3.02E-08	2.80E-06
92.68	1.65	2.96E-08	2.74E-06
92.68	1.75	2.89E-08	2.68E-06

Permeability Test Result (Test F2)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.07	2.02E-08	1.87E-06
92.68	0.13	1.64E-08	1.52E-06
92.68	0.19	1.60E-08	1.48E-06
92.68	0.25	1.60E-08	1.48E-06
92.68	0.31	1.56E-08	1.45E-06
92.68	0.36	1.52E-08	1.41E-06
92.68	0.42	1.45E-08	1.34E-06
92.68	0.47	1.48E-08	1.37E-06
92.68	0.52	1.26E-08	1.17E-06
92.68	0.57	1.37E-08	1.27E-06
92.68	0.61	1.33E-08	1.23E-06
92.68	0.66	1.33E-08	1.23E-06
92.68	0.71	1.29E-08	1.20E-06
92.68	0.76	1.26E-08	1.17E-06
92.68	0.80	1.26E-08	1.17E-06

Permeability Test Results (Test A3)

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.06	3.6E-08	3.3E-06
92.68	0.14	2.7E-08	2.5E-06
92.68	0.21	4.4E-08	4.1E-06
92.68	0.25	2.5E-08	2.3E-06
92.68	0.30	2.7E-08	2.5E-06
92.68	0.38	2.8E-08	2.6E-06
92.68	0.44	2.5E-08	2.3E-06
92.68	0.51	2.6E-08	2.4E-06
92.68	0.56	2.6E-08	2.4E-06
92.68	0.63	2.4E-08	2.2E-06
92.68	0.70	2.7E-08	2.5E-06
92.68	0.75	2.5E-08	2.3E-06
31.58	0.81	2.1E-08	6.6E-07
31.58	0.83	2.4E-08	7.7E-07
92.68	0.87	2.5E-08	2.3E-06
92.68	0.97	2.5E-08	2.3E-06
92.68	1.06	2.6E-08	2.4E-06
92.68	1.15	2.5E-08	2.3E-06
92.68	1.24	2.5E-08	2.3E-06
92.68	1.30	2.5E-08	2.3E-06
92.68	1.34	2.1E-08	1.9E-06
92.68	1.42	2.2E-08	2.0E-06
92.68	1.49	2.7E-08	2.5E-06
92.68	1.57	2.6E-08	2.4E-06
92.68	1.66	2.5E-08	2.3E-06
92.68	1.75	2.5E-08	2.3E-06
62.16	1.81	2.4E-08	1.5E-06
62.16	1.88	2.2E-08	1.4E-06
62.16	1.97	1.8E-08	1.1E-06
62.16	2.02	1.9E-08	1.2E-06
123.33	2.09	2.6E-08	3.2E-06
123.33	2.15	2.5E-08	3.1E-06
123.33	2.19	2.6E-08	3.2E-06
153.90	2.23	3.6E-08	5.5E-06
153.90	2.29	3.9E-08	6.0E-06
184.00	2.35	4.7E-08	8.7E-06

Permeability Test Results (Test B3)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.11	2.89E-08	2.68E-06
92.68	0.21	2.74E-08	2.54E-06
92.68	0.30	2.51E-08	2.33E-06
92.68	0.39	2.44E-08	2.26E-06
92.68	0.47	2.21E-08	2.05E-06
92.68	0.54	2.13E-08	1.98E-06
92.68	0.62	2.18E-08	2.02E-06
92.68	0.70	2.14E-08	1.98E-06
92.68	0.78	2.11E-08	1.96E-06
92.68	0.86	2.14E-08	1.98E-06
92.68	0.94	2.16E-08	2.00E-06
92.68	1.01	2.13E-08	1.98E-06
92.68	1.09	2.08E-08	1.93E-06
92.68	1.16	2.05E-08	1.90E-06
92.68	1.24	2.05E-08	1.90E-06

Permeability Test Results (Test C3)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.05	1.45E-08	1.34E-06
92.675	0.10	1.37E-08	1.27E-06
92.675	0.15	1.29E-08	1.20E-06
92.675	0.19	1.22E-08	1.13E-06
92.675	0.24	1.24E-08	1.15E-06
92.675	0.29	1.26E-08	1.17E-06
92.675	0.33	1.22E-08	1.13E-06
92.675	0.37	1.17E-08	1.08E-06
92.675	0.42	1.21E-08	1.12E-06
92.675	0.46	1.14E-08	1.06E-06
92.675	0.50	1.13E-08	1.05E-06
92.675	0.54	1.16E-08	1.08E-06
92.675	0.58	1.14E-08	1.06E-06
92.675	0.62	1.12E-08	1.04E-06
92.675	0.67	1.14E-08	1.06E-06

Permeability Test Results (Test D3)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.05	1.29E-08	1.20E-06
92.675	0.09	1.14E-08	1.06E-06
92.675	0.13	9.90E-09	9.17E-07
92.675	0.16	8.38E-09	7.76E-07
92.675	0.18	7.62E-09	7.06E-07
92.675	0.21	6.85E-09	6.35E-07
92.675	0.23	6.09E-09	5.65E-07
92.675	0.25	6.70E-09	6.21E-07
92.675	0.28	7.10E-09	6.58E-07
92.675	0.31	6.80E-09	6.30E-07
92.675	0.33	6.60E-09	6.12E-07
92.675	0.35	6.50E-09	6.02E-07
92.675	0.38	6.09E-09	5.65E-07
92.675	0.40	6.30E-09	5.84E-07
92.675	0.42	6.09E-09	5.65E-07

Permeability Test Results (Test E3)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.21	5.86E-08	5.43E-06
92.68	0.40	5.18E-08	4.80E-06
92.68	0.58	4.87E-08	4.52E-06
92.68	0.74	4.49E-08	4.16E-06
92.68	0.90	4.26E-08	3.95E-06
92.68	1.05	4.19E-08	3.88E-06
92.68	1.21	4.23E-08	3.92E-06
92.68	1.36	4.25E-08	3.94E-06
92.68	1.52	4.20E-08	3.89E-06
92.68	1.67	4.19E-08	3.88E-06
92.68	1.82	4.15E-08	3.85E-06
92.68	1.97	4.12E-08	3.82E-06
92.68	2.12	4.14E-08	3.84E-06
92.68	2.27	4.12E-08	3.82E-06
92.68	2.42	4.10E-08	3.80E-06

Permeability Test Results (Test F3)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.33	9.10E-08	8.43E-06
92.68	0.57	6.50E-08	6.02E-06
92.68	0.76	5.10E-08	4.73E-06
92.68	0.90	4.09E-08	3.79E-06
92.68	1.06	4.33E-08	4.01E-06
92.68	1.15	2.45E-08	2.27E-06
92.68	1.24	2.29E-08	2.12E-06
92.68	1.32	2.43E-08	2.25E-06
92.68	1.41	2.34E-08	2.17E-06
92.68	1.49	2.31E-08	2.14E-06
92.68	1.58	2.27E-08	2.10E-06
92.68	1.66	2.22E-08	2.06E-06
92.68	1.74	2.31E-08	2.14E-06
92.68	1.82	2.28E-08	2.11E-06
92.68	1.90	2.20E-08	2.04E-06

Permeability Test Results (Test A4)

Gradient	Pore Volume	Permerability (cm/s)	Velocity (cm/s)
92.68	0.05	2.5E-08	2.3E-06
31.58	0.09	2.0E-08	6.3E-07
31.58	0.11	2.2E-08	7.0E-07
92.68	0.16	2.6E-08	2.4E-06
92.68	0.26	2.8E-08	2.6E-06
92.68	0.36	2.7E-08	2.5E-06
92.68	0.46	2.8E-08	2.6E-06
92.68	0.56	2.8E-08	2.6E-06
92.68	0.62	2.8E-08	2.6E-06
92.68	0.67	2.7E-08	2.5E-06
92.68	0.77	2.7E-08	2.5E-06
92.68	0.83	2.0E-08	1.9E-06
92.68	0.89	2.3E-08	2.1E-06
92.68	1.00	2.8E-08	2.6E-06
92.68	1.10	2.7E-08	2.5E-06
92.68	1.19	2.7E-08	2.5E-06
92.68	1.31	2.3E-08	2.1E-06
92.68	1.49	2.5E-08	2.3E-06
92.68	1.59	2.3E-08	2.1E-06
123.33	1.68	3.6E-08	4.4E-06
123.33	1.77	3.7E-08	4.5E-06
123.33	1.82	3.3E-08	4.1E-06
153.90	1.88	4.7E-08	7.3E-06
153.90	1.95	4.6E-08	7.0E-06
184.00	2.01	4.8E-08	8.8E-06
92.68	2.13	3.1E-08	2.9E-06
92.68	2.28	3.3E-08	3.1E-06
92.68	2.43	3.3E-08	3.1E-06
92.68	2.59	2.8E-08	2.6E-06
92.68	2.80	2.9E-08	2.7E-06
92.68	3.01	2.9E-08	2.7E-06

Permeability Test Results (Test B4)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.08	2.06E-08	1.91E-06
92.68	0.14	1.90E-08	1.76E-06
92.68	0.20	1.60E-08	1.48E-06
92.68	0.26	1.45E-08	1.34E-06
92.68	0.31	1.37E-08	1.27E-06
92.68	0.35	1.29E-08	1.20E-06
92.68	0.40	1.33E-08	1.23E-06
92.68	0.45	1.30E-08	1.20E-06
92.68	0.50	1.29E-08	1.20E-06
92.68	0.54	1.27E-08	1.18E-06
92.68	0.59	1.26E-08	1.17E-06
92.68	0.64	1.32E-08	1.22E-06
92.68	0.68	1.28E-08	1.19E-06
92.68	0.73	1.29E-08	1.20E-06
92.68	0.78	1.26E-08	1.17E-06

Permeability Test Results (Test C4)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.27	7.39E-08	6.85E-06
92.675	0.48	5.79E-08	5.36E-06
92.675	0.64	4.34E-08	4.02E-06
92.675	0.79	4.19E-08	3.88E-06
92.675	0.94	4.04E-08	3.74E-06
92.675	1.09	4.12E-08	3.82E-06
92.675	1.24	4.18E-08	3.87E-06
92.675	1.39	4.09E-08	3.79E-06
92.675	1.54	4.03E-08	3.73E-06
92.675	1.68	3.97E-08	3.68E-06
92.675	1.82	3.88E-08	3.60E-06
92.675	1.97	3.93E-08	3.64E-06
92.675	2.11	3.90E-08	3.61E-06
92.675	2.25	3.88E-08	3.60E-06
92.675	2.39	3.85E-08	3.57E-06

Permeability Test Results (Test D4)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.10	2.74E-08	2.54E-06
92.675	0.18	2.21E-08	2.05E-06
92.675	0.26	2.13E-08	1.98E-06
92.675	0.33	2.06E-08	1.91E-06
92.675	0.41	2.06E-08	1.91E-06
92.675	0.48	1.98E-08	1.83E-06
92.675	0.55	2.03E-08	1.88E-06
92.675	0.63	2.11E-08	1.96E-06
92.675	0.71	2.04E-08	1.89E-06
92.675	0.78	1.97E-08	1.83E-06
92.675	0.85	1.91E-08	1.77E-06
92.675	0.92	1.89E-08	1.75E-06
92.675	0.99	1.94E-08	1.80E-06
92.675	1.06	1.93E-08	1.79E-06
92.675	1.13	1.90E-08	1.76E-06

Permeability Test Results (Test E4)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.42	1.16E-07	1.07E-05
92.68	0.64	5.90E-08	5.47E-06
92.68	0.85	5.80E-08	5.38E-06
92.68	1.05	5.60E-08	5.19E-06
92.68	1.36	8.40E-08	7.78E-06
92.68	1.76	1.11E-07	1.02E-05
92.68	2.04	7.60E-08	7.04E-06
92.68	2.33	8.04E-08	7.45E-06
92.68	2.60	7.23E-08	6.70E-06
92.68	2.87	7.40E-08	6.86E-06
92.68	3.13	7.20E-08	6.67E-06
92.68	3.39	7.20E-08	6.67E-06
92.68	3.66	7.20E-08	6.67E-06
92.68	3.91	7.10E-08	6.58E-06
92.68	4.17	7.10E-08	6.58E-06

Permeability Test Results (Test F4)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	2.64	7.24E-07	6.71E-05
92.68	5.11	6.76E-07	6.26E-05
92.68	7.25	5.88E-07	5.45E-05
92.68	9.27	5.55E-07	5.14E-05
92.68	11.33	5.63E-07	5.22E-05
92.68	13.34	5.51E-07	5.11E-05
92.68	15.34	5.49E-07	5.09E-05
92.68	17.39	5.61E-07	5.20E-05
92.68	19.40	5.52E-07	5.12E-05
92.68	21.41	5.51E-07	5.11E-05
92.68	23.42	5.50E-07	5.10E-05
92.68	25.44	5.55E-07	5.14E-05
92.68	27.45	5.51E-07	5.11E-05
92.68	29.43	5.42E-07	5.03E-05
92.68	31.42	5.47E-07	5.06E-05

Permeability Test Results (Test A5)

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.17	9.3E-08	8.6E-06
31.58	0.30	5.9E-08	1.9E-06
31.58	0.35	6.4E-08	2.0E-06
92.68	0.48	7.0E-08	6.5E-06
92.68	0.72	6.5E-08	6.0E-06
92.68	0.96	6.5E-08	6.1E-06
92.68	1.19	6.5E-08	6.0E-06
92.68	1.43	6.5E-08	6.1E-06
92.68	1.58	6.4E-08	5.9E-06
92.68	1.71	7.0E-08	6.5E-06
92.68	1.95	6.6E-08	6.1E-06
92.68	2.13	6.9E-08	6.4E-06
92.68	2.27	4.9E-08	4.5E-06
92.68	2.44	4.6E-08	4.2E-06
92.68	2.60	4.3E-08	4.0E-06
92.68	2.78	4.9E-08	4.6E-06
92.68	3.06	5.7E-08	5.3E-06
92.68	3.44	5.2E-08	4.8E-06
92.68	3.70	5.7E-08	5.3E-06
123.33	3.90	8.3E-08	1.0E-05
123.33	4.11	8.4E-08	1.0E-05
123.33	4.24	8.2E-08	1.0E-05
153.90	4.34	8.7E-08	1.3E-05
153.90	4.48	9.0E-08	1.4E-05
184.00	4.63	1.2E-07	2.2E-05
92.68	4.85	5.7E-08	5.3E-06
92.68	5.13	6.2E-08	5.8E-06
92.68	5.43	6.3E-08	5.8E-06
92.68	5.81	7.0E-08	6.4E-06
92.68	6.28	6.5E-08	6.0E-06
92.68	6.75	6.4E-08	5.9E-06

Permeability Test Results (Test B5)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.05	1.29E-08	1.20E-06
92.68	0.08	9.14E-09	8.47E-07
92.68	0.11	7.62E-09	7.06E-07
92.68	0.15	1.22E-08	1.13E-06
92.68	0.20	1.29E-08	1.20E-06
92.68	0.25	1.29E-08	1.20E-06
92.68	0.30	1.37E-08	1.27E-06
92.68	0.35	1.45E-08	1.34E-06
92.68	0.40	1.45E-08	1.34E-06
92.68	0.45	1.37E-08	1.27E-06
92.68	0.50	1.37E-08	1.27E-06
92.68	0.56	1.45E-08	1.34E-06
92.68	0.61	1.45E-08	1.34E-06
92.68	0.66	1.37E-08	1.27E-06

Permeability Test Results (Test C5)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.85	2.32E-07	2.15E-05
92.675	1.21	9.90E-08	9.17E-06
92.675	1.63	1.16E-07	1.07E-05
92.675	1.91	7.77E-08	7.20E-06
92.675	2.18	7.31E-08	6.78E-06
92.675	2.32	3.73E-08	3.46E-06
92.675	2.44	3.43E-08	3.18E-06
92.675	2.56	3.20E-08	2.96E-06
92.675	2.67	3.12E-08	2.89E-06
92.675	2.79	3.20E-08	2.96E-06
92.675	2.91	3.20E-08	2.96E-06
92.675	3.02	3.12E-08	2.89E-06
92.675	3.14	3.20E-08	2.96E-06
92.675	3.25	3.20E-08	2.96E-06
92.675	3.37	3.12E-08	2.89E-06

Permeability Test Results (Test D5)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.675	0.06	1.60E-08	1.48E-06
92.675	0.13	1.90E-08	1.76E-06
92.675	0.21	2.36E-08	2.19E-06
92.675	0.33	3.20E-08	2.96E-06
92.675	0.52	5.25E-08	4.87E-06
92.675	0.81	7.77E-08	7.20E-06
92.675	1.09	7.92E-08	7.34E-06
92.675	1.36	7.23E-08	6.70E-06
92.675	1.62	7.16E-08	6.63E-06
92.675	1.88	7.01E-08	6.49E-06
92.675	2.13	6.93E-08	6.42E-06
92.675	2.38	7.01E-08	6.49E-06
92.675	2.63	6.85E-08	6.35E-06
92.675	2.89	6.93E-08	6.42E-06
92.675	3.14	6.85E-08	6.35E-06

Permeability Test Results (Test E5)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.08	2.06E-08	1.91E-06
92.68	0.16	2.36E-08	2.19E-06
92.68	0.21	1.37E-08	1.27E-06
92.68	0.28	1.90E-08	1.76E-06
92.68	0.38	2.82E-08	2.61E-06
92.68	0.60	5.86E-08	5.43E-06
92.68	0.82	6.02E-08	5.58E-06
92.68	1.04	6.09E-08	5.65E-06
92.68	1.26	6.17E-08	5.72E-06
92.68	1.49	6.09E-08	5.65E-06
92.68	1.71	6.17E-08	5.72E-06
92.68	1.93	6.09E-08	5.65E-06
92.68	2.16	6.17E-08	5.72E-06
92.68	2.38	6.09E-08	5.65E-06
92.68	2.60	6.02E-08	5.58E-06

Permeability Test Results (Test F5)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	2.52	6.91E-07	6.41E-05
92.68	3.30	2.14E-07	1.99E-05
92.68	4.01	1.95E-07	1.80E-05
92.68	4.71	1.91E-07	1.77E-05
92.68	5.66	2.62E-07	2.43E-05
92.68	6.88	3.34E-07	3.10E-05
92.68	8.11	3.36E-07	3.11E-05
92.68	9.36	3.43E-07	3.18E-05
92.68	10.57	3.31E-07	3.07E-05
92.68	12.42	5.07E-07	4.69E-05
92.68	13.52	3.04E-07	2.81E-05
92.68	14.30	2.12E-07	1.97E-05
92.68	14.95	1.80E-07	1.67E-05
92.68	15.73	2.11E-07	1.96E-05
92.68	16.49	2.10E-07	1.95E-05

Permeability Test Results (Test A6)

Gradient	Pore Volume	Permeability (cm/s)	Velocity (cm/s)
92.68	0.03	1.8E-08	1.7E-06
92.68	0.09	1.9E-08	1.8E-06
92.68	0.13	2.5E-08	2.3E-06
92.68	0.15	1.5E-08	1.4E-06
92.68	0.18	1.7E-08	1.6E-06
92.68	0.23	1.8E-08	1.7E-06
92.68	0.28	1.7E-08	1.6E-06
92.68	0.32	1.6E-08	1.5E-06
92.68	0.35	1.6E-08	1.5E-06
92.68	0.40	1.4E-08	1.3E-06
92.68	0.44	1.6E-08	1.5E-06
92.68	0.47	1.6E-08	1.5E-06
31.58	0.50	1.1E-08	3.6E-07
31.58	0.51	1.2E-08	3.9E-07
92.68	0.54	1.6E-08	1.5E-06
92.68	0.60	1.6E-08	1.5E-06
92.68	0.66	1.6E-08	1.5E-06
92.68	0.72	1.6E-08	1.5E-06
92.68	0.78	1.6E-08	1.5E-06
92.68	0.82	1.6E-08	1.5E-06
92.68	0.84	1.6E-08	1.5E-06
92.68	0.90	1.6E-08	1.5E-06
92.68	0.95	1.7E-08	1.6E-06
92.68	1.01	1.9E-08	1.7E-06
92.68	1.07	1.8E-08	1.7E-06
92.68	1.13	1.6E-08	1.5E-06
62.16	1.17	1.6E-08	1.0E-06
62.16	1.22	1.6E-08	9.6E-07
62.16	1.29	1.3E-08	8.1E-07
62.16	1.33	1.5E-08	9.6E-07
123.33	1.38	2.1E-08	2.5E-06
123.33	1.43	2.0E-08	2.5E-06
123.33	1.47	2.1E-08	2.6E-06
153.90	1.50	2.7E-08	4.2E-06
153.90	1.54	2.8E-08	4.3E-06
184.00	1.58	3.0E-08	5.5E-06

Permeability test Result (Test B6)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	0.06	1.6E-08	1.4E-06
92.68	0.10	1.1E-08	1.0E-06
92.68	0.14	1.1E-08	1.0E-06
92.68	0.18	1.1E-08	1.1E-06
92.68	0.22	1.1E-08	1.0E-06
92.68	0.26	1.1E-08	9.9E-07
92.68	0.30	1.1E-08	9.9E-07
92.68	0.34	1.1E-08	1.0E-06
92.68	0.38	1.1E-08	9.9E-07
92.68	0.42	1.1E-08	1.1E-06
92.68	0.46	1.1E-08	9.9E-07
92.68	0.50	1.1E-08	1.1E-06
92.68	0.54	1.1E-08	1.1E-06
92.68	0.58	1.1E-08	1.1E-06
92.68	0.62	1.1E-08	1.1E-06
92.68	0.67	1.1E-08	1.1E-06
31.58	0.67	1.1E-08	3.5E-07
62.16	0.69	1.1E-08	7.1E-07
123.33	0.70	1.1E-08	1.4E-06

Permeability Test Results (Test B7)

Gradient	Pore Vol	Permeability (cm/s)	Velocity (cm/s)
92.68	2.56	7.0E-07	6.5E-05
92.68	5.22	7.3E-07	6.8E-05
92.68	6.63	3.8E-07	3.6E-05
92.68	7.38	2.1E-07	1.9E-05
92.68	8.19	2.2E-07	2.1E-05
92.68	10.00	4.9E-07	4.6E-05
92.68	14.00	1.1E-06	1.0E-04
92.68	16.78	7.6E-07	7.1E-05
92.68	17.34	1.6E-07	1.4E-05
92.68	17.79	1.2E-07	1.1E-05
92.68	18.09	8.4E-08	7.8E-06
92.68	18.36	7.2E-08	6.7E-06
92.68	18.61	6.9E-08	6.4E-06
92.68	18.86	6.9E-08	6.4E-06
92.68	19.10	6.6E-08	6.1E-06
92.68	19.34	6.5E-08	6.0E-06
31.58	19.38	6.3E-08	2.0E-06
62.16	19.46	6.6E-08	4.1E-06
123.33	19.53	6.4E-08	7.9E-06

Permeability Test Results (Test T1)

Grad.	P.Vol	Perm(cm/s) (inner)	Perm(cm/s) (outer)	Vel(cm/s) (inner)	Vel(cm/s) (outer)
10.23	0.02	2.1E-07	1.9E-07	2.1E-06	1.9E-06
24.08	0.06	3.3E-07	3.1E-07	8.1E-06	7.4E-06
24.08	0.15	3.8E-07	3.6E-07	9.0E-06	8.7E-06
24.08	0.19	3.6E-07	3.6E-07	8.7E-06	8.6E-06
19.46	0.24	3.0E-07	2.5E-07	5.8E-06	4.9E-06
33.31	0.27	3.5E-07	3.3E-07	1.2E-05	1.1E-05
47.15	0.34	3.5E-07	3.2E-07	1.6E-05	1.5E-05
24.08	0.41	3.3E-07	2.9E-07	7.9E-06	7.0E-06
24.08	0.44	2.6E-07	2.2E-07	6.2E-06	5.2E-06
33.31	0.49	2.1E-07	1.9E-07	7.0E-06	6.4E-06
24.08	0.53	2.6E-07	2.2E-07	6.3E-06	5.4E-06
33.31	0.57	3.9E-07	3.8E-07	1.3E-05	1.3E-05
47.15	0.60	3.3E-07	3.1E-07	1.6E-05	1.5E-05
24.08	0.68	3.2E-07	2.9E-07	7.8E-06	7.0E-06
24.08	0.71	2.4E-07	2.2E-07	5.8E-06	5.2E-06
33.31	0.76	2.2E-07	1.9E-07	7.2E-06	6.4E-06
19.46	0.78	2.3E-07	1.9E-07	4.4E-06	3.7E-06
42.54	0.80	2.8E-07	2.4E-07	1.2E-05	1.0E-05
28.69	0.86	2.8E-07	2.5E-07	8.0E-06	7.1E-06
42.54	0.91	3.7E-07	3.2E-07	1.6E-05	1.3E-05
28.69	0.97	2.1E-07	1.7E-07	6.0E-06	5.0E-06
37.92	1.04	3.2E-07	2.8E-07	1.2E-05	1.0E-05
47.15	1.11	2.6E-07	2.2E-07	1.2E-05	1.1E-05
28.69	1.14	2.0E-07	1.7E-07	5.8E-06	5.0E-06
24.08	1.19	3.6E-07	3.6E-07	8.7E-06	8.6E-06
19.46	1.23	3.0E-07	2.5E-07	5.8E-06	4.9E-06
33.31	1.27	3.5E-07	3.3E-07	1.2E-05	1.1E-05
47.15	1.33	3.5E-07	3.2E-07	1.6E-05	1.5E-05
24.08	1.40	3.3E-07	2.9E-07	7.9E-06	7.0E-06
24.08	1.44	2.6E-07	2.2E-07	6.2E-06	5.2E-06
47.15	1.48	3.3E-07	3.1E-07	1.6E-05	1.5E-05
24.08	1.55	3.2E-07	2.9E-07	7.8E-06	7.0E-06
24.08	1.58	2.4E-07	2.2E-07	5.8E-06	5.2E-06
33.31	1.63	2.2E-07	1.9E-07	7.2E-06	6.4E-06
19.46	1.65	2.3E-07	1.9E-07	4.4E-06	3.7E-06
42.54	1.71	3.7E-07	3.2E-07	1.6E-05	1.3E-05
28.69	1.76	2.1E-07	1.7E-07	6.0E-06	5.0E-06
37.92	1.84	3.2E-07	2.8E-07	1.2E-05	1.0E-05
19.46	1.87	2.0E-07	1.7E-07	4.0E-06	3.3E-06
47.15	1.94	2.6E-07	2.2E-07	1.2E-05	1.1E-05
28.69	1.97	2.0E-07	1.7E-07	5.8E-06	5.0E-06
10.23	1.99	2.1E-07	1.9E-07	2.1E-06	1.9E-06
24.08	2.03	3.3E-07	3.1E-07	8.1E-06	7.4E-06
24.08	2.12	3.8E-07	3.6E-07	9.0E-06	8.7E-06
33.31	2.16	2.1E-07	1.9E-07	7.0E-06	6.4E-06
24.08	2.20	2.6E-07	2.2E-07	6.3E-06	5.4E-06
33.31	2.24	3.9E-07	3.8E-07	1.3E-05	1.3E-05
24.08	2.20	2.6E-07	2.2E-07	6.3E-06	5.4E-06
33.31	2.24	3.9E-07	3.8E-07	1.3E-05	1.3E-05
42.54	2.26	2.8E-07	2.4E-07	1.2E-05	1.0E-05
28.69	2.32	2.8E-07	2.5E-07	8.0E-06	7.1E-06
19.46	2.35	2.0E-07	1.7E-07	4.0E-06	3.3E-06

Permeability Test Results (Test T2)

Gradient	Pore Vol.	Perm(cm/s) (inner)	Perm(cm/s) (outer)	Vel(cm/s) (inner)	Vel(cm/s) (outer)
10.27	0.08	6.3E-06	6.5E-06	6.5E-05	6.7E-05
14.85	0.19	6.1E-06	6.3E-06	9.1E-05	9.4E-05
19.46	0.35	6.4E-06	6.6E-06	1.3E-04	1.3E-04
19.46	0.50	6.3E-06	6.5E-06	1.2E-04	1.3E-04
24.08	0.68	5.9E-06	6.2E-06	1.4E-04	1.5E-04
24.08	0.87	6.2E-06	6.4E-06	1.5E-04	1.5E-04
28.69	1.09	6.4E-06	6.6E-06	1.8E-04	1.9E-04
24.08	1.29	6.5E-06	6.7E-06	1.6E-04	1.6E-04
33.30	1.56	6.5E-06	6.8E-06	2.2E-04	2.3E-04
33.30	1.83	6.7E-06	6.8E-06	2.2E-04	2.3E-04
37.92	2.14	6.5E-06	6.8E-06	2.5E-04	2.6E-04
37.92	2.45	6.5E-06	6.7E-06	2.4E-04	2.5E-04
37.92	2.74	6.3E-06	6.6E-06	2.4E-04	2.5E-04
28.69	2.97	6.5E-06	6.6E-06	1.9E-04	1.9E-04
14.85	3.10	6.7E-06	6.7E-06	9.9E-05	1.0E-04
14.85	3.22	6.7E-06	6.8E-06	1.0E-04	1.0E-04
24.08	3.41	6.7E-06	6.7E-06	1.6E-04	1.6E-04
14.85	3.54	6.8E-06	6.9E-06	1.0E-04	1.0E-04
24.08	3.73	6.5E-06	6.7E-06	1.6E-04	1.6E-04
10.27	3.82	6.5E-06	6.6E-06	6.7E-05	6.8E-05
10.27	3.90	6.2E-06	6.5E-06	6.4E-05	6.7E-05
14.85	4.01	6.4E-06	6.5E-06	9.5E-05	9.7E-05
19.46	4.17	6.5E-06	6.5E-06	1.3E-04	1.3E-04
19.46	4.33	6.6E-06	6.8E-06	1.3E-04	1.3E-04
24.08	4.52	6.6E-06	6.7E-06	1.6E-04	1.6E-04
37.92	4.83	6.6E-06	6.7E-06	2.5E-04	2.5E-04
37.92	5.13	6.2E-06	6.5E-06	2.4E-04	2.5E-04
28.69	5.35	6.5E-06	6.5E-06	1.9E-04	1.9E-04
14.85	5.47	6.4E-06	6.5E-06	9.5E-05	9.7E-05
14.85	5.59	6.5E-06	6.7E-06	9.6E-05	1.0E-04
24.08	5.78	6.5E-06	6.6E-06	1.6E-04	1.6E-04
14.85	5.90	6.2E-06	6.8E-06	9.3E-05	1.0E-04
10.27	5.99	6.2E-06	6.8E-06	6.4E-05	7.0E-05
24.08	6.18	6.5E-06	6.6E-06	1.6E-04	1.6E-04
24.08	6.37	6.5E-06	6.6E-06	1.6E-04	1.6E-04
28.69	6.60	6.5E-06	6.6E-06	1.9E-04	1.9E-04
24.08	6.79	6.5E-06	6.5E-06	1.6E-04	1.6E-04
33.30	7.06	6.8E-06	6.4E-06	2.3E-04	2.1E-04
33.30	7.33	6.8E-06	6.7E-06	2.3E-04	2.2E-04
37.92	7.64	6.7E-06	6.5E-06	2.5E-04	2.5E-04

Permeability Test Results (Test T3)

Gradient	Pore Vol.	Perm(cm/s) (inner)	Perm(cm/s) (outer)	Vel(cm/s) (inner)	Vel(cm/s) (outer)
10.27	0.13	1.5E-05	7.2E-06	1.5E-04	7.4E-05
14.85	0.31	1.2E-05	8.1E-06	1.8E-04	1.2E-04
19.46	0.52	1.2E-05	5.7E-06	2.4E-04	1.1E-04
19.46	0.81	1.2E-05	1.2E-05	2.4E-04	2.4E-04
24.08	1.02	9.8E-06	4.8E-06	2.4E-04	1.2E-04
24.08	1.33	1.6E-05	5.6E-06	3.9E-04	1.4E-04
28.69	1.73	1.7E-05	7.5E-06	4.8E-04	2.1E-04
24.08	2.03	1.6E-05	5.4E-06	3.8E-04	1.3E-04
33.30	2.39	1.5E-05	3.6E-06	5.1E-04	1.2E-04
33.30	2.75	1.4E-05	4.9E-06	4.6E-04	1.6E-04
37.92	3.16	1.5E-05	3.7E-06	5.8E-04	1.4E-04
37.92	3.64	1.7E-05	4.8E-06	6.5E-04	1.8E-04
37.92	4.01	1.2E-05	5.0E-06	4.5E-04	1.9E-04
28.69	4.38	1.7E-05	5.6E-06	4.9E-04	1.6E-04
14.85	4.58	1.2E-05	1.0E-05	1.8E-04	1.5E-04
14.85	4.77	1.2E-05	1.0E-05	1.7E-04	1.5E-04
24.08	5.02	1.2E-05	5.4E-06	3.0E-04	1.3E-04
14.85	5.39	1.4E-05	2.5E-05	2.1E-04	3.7E-04
24.08	5.68	1.5E-05	5.5E-06	3.7E-04	1.3E-04
10.27	5.86	1.5E-05	1.4E-05	1.5E-04	1.5E-04

Permeability Test Results (Test T4)

Gradient	Pore Vol.	Perm(cm/s) (inner)	Perm(cm/s) (outer)	Vel(cm/s) (inner)	Vel(cm/s) (outer)
10.27	0.07	9.5E-07	9.6E-07	9.7E-06	9.9E-06
14.85	0.18	9.6E-07	9.7E-07	1.4E-05	1.4E-05
19.46	0.29	9.8E-07	1.0E-06	1.9E-05	1.9E-05
19.46	0.40	1.1E-06	1.1E-06	2.2E-05	2.2E-05
24.08	0.58	9.8E-07	9.9E-07	2.4E-05	2.4E-05
24.08	0.73	1.0E-06	1.1E-06	2.4E-05	2.6E-05
28.69	0.89	8.1E-07	8.3E-07	2.3E-05	2.4E-05
28.69	1.01	8.5E-07	8.5E-07	2.4E-05	2.4E-05
33.30	1.20	9.6E-07	9.7E-07	3.2E-05	3.2E-05
33.30	1.42	9.4E-07	9.8E-07	3.1E-05	3.3E-05
37.92	1.58	8.5E-07	8.8E-07	3.2E-05	3.3E-05
37.92	1.84	9.1E-07	9.3E-07	3.5E-05	3.5E-05
37.92	1.98	1.0E-06	1.0E-06	3.8E-05	3.9E-05
47.15	2.04	9.9E-07	1.0E-06	4.7E-05	4.7E-05
47.15	2.08	1.1E-06	1.1E-06	5.0E-05	5.3E-05
47.15	2.13	1.1E-06	1.2E-06	5.4E-05	5.6E-05
24.08	2.24	9.1E-07	9.3E-07	2.2E-05	2.2E-05
14.85	2.34	9.1E-07	9.2E-07	1.4E-05	1.4E-05
19.46	2.46	9.6E-07	9.7E-07	1.9E-05	1.9E-05
19.46	2.57	1.1E-06	1.1E-06	2.2E-05	2.2E-05
24.08	2.74	1.0E-06	1.0E-06	2.5E-05	2.5E-05
37.92	3.00	9.0E-07	9.3E-07	3.4E-05	3.5E-05
37.92	3.14	9.7E-07	9.8E-07	3.7E-05	3.7E-05
47.15	3.19	9.9E-07	1.0E-06	4.7E-05	4.7E-05
24.08	3.30	9.4E-07	9.6E-07	2.3E-05	2.3E-05
14.85	3.40	9.3E-07	9.2E-07	1.4E-05	1.4E-05
24.08	3.56	9.8E-07	1.1E-06	2.4E-05	2.6E-05
28.69	3.72	8.1E-07	8.3E-07	2.3E-05	2.4E-05
28.69	3.84	8.2E-07	8.2E-07	2.4E-05	2.4E-05
10.27	3.91	9.4E-07	9.6E-07	9.6E-06	9.9E-06
14.85	4.01	9.5E-07	9.7E-07	1.4E-05	1.4E-05
33.30	4.21	1.0E-06	1.0E-06	3.4E-05	3.4E-05
33.30	4.42	9.5E-07	9.8E-07	3.2E-05	3.3E-05
37.92	4.59	8.5E-07	8.8E-07	3.2E-05	3.3E-05