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Gregory W. Carpenter

Richard W. Stephenson
Missouri University of Science and Technology, rwstephenson@mst.edu

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Gregory W. Carpenter[1] *and Richard W. Stephenson*[2]

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ABSTRACT: It has been suggested that a triaxial shear test chamber can be used to measure the permeability of low permeability soils. To verify this, the influence of a number of test parameters on the measured coefficient of permeability was investigated. Results indicate such permeability tests should be performed on samples having a minimum diameter of 71.1 mm (2.8 in.) and a length to diameter ratio of 0.5 to 1.0. It was found that a permeant consisting of 1 g of magnesium sulfate heptahydrate (epsom salt) dissolved in 1 L of deaired, distilled water is adequate for general permeability testing. The triaxial, falling head permeability test should be conducted at a gradient that results in an applied effective stress at the outflow end of the sample less than the preconsolidation stress of the material. It was found that with very careful trimming, the influence of the smear zones created at the ends of the samples during the trimming process can be minimized.

KEYWORDS: soil tests, permeability, triaxial tests, clays

In conducting a falling head, permeability test, a soil sample is often confined in a rigid ring or cylinder. This method of confinement sometimes results in permeant flow along the interface between the ring and the sample. To correct this deficiency, it has been proposed that a triaxial cell be used as a permeameter [*1*]. In a triaxial cell, a flexible membrane replaces the rigid confining ring and is kept tightly compressed against the sides of the sample by pressure applied to the fluid in the cell. This minimizes the possibility of seepage along the interface. Another advantage is that the sample can be consolidated to its in-situ stress condition or other desired stress states before it is tested.

This technique, which incorporates back-pressure saturation, has been used to confirm that Darcy's law is valid for soil, if the soil is completely saturated [*2*]. The same technique has been used to test rock cores [*3*], which are not subject to testing with water but with natural gas, petroleum products, and grout mixtures. The conclusion is that the procedure can be a valuable evaluation tool for solving petroleum engineering problems and high-pressure rock grouting problems. This triaxial cell permeability testing technique has been used in conjunction with earlier work [*4,5*] to show that the coefficient of permeability can quickly be obtained by using a pressure-stressed metal diaphragm (small volume of flow).

This paper documents the use of a triaxial cell for hydraulic conductivity characteristics of fine grained soils. During the investigation, factors, which may influence the coefficient of permeability as determined by the triaxial, falling head, permeability testing technique, were evaluated.

Experimental Program

Several clay soils were investigated as possible choices for use in the testing program. The desired soil required a coefficient of permeability of approximately 10^{-8} cm/s in a reconstituted form. The clay finally chosen for testing was a clay obtained from an operating clay mine in Bloomfield, MO. This clay, which is being mined from the Porter Creek Formation, is composed of about 55 to 65% smectite, 10 to 20% illite, 10 to 20% kaolinite, 5 to 15% quartz, and less than 0.001% heavy minerals. A chemical analysis of the material by the Southern Clay Company indicates the major constituents are potassium and magnesium with very small amounts of calcium and sodium.

Specimen Preparation

A static consolidation technique was used to prepare the specimens for study [*6*]. The clay was pulverized in a mortar with a pestle until it could be passed through a 425-μm (No. 40) sieve. The sieved clay for each specimen was mixed by hand with enough of the epsom salt permeant chosen for the study to result in a moisture content of 105%. This is well above the soil's liquid limit of 98 evaluated using the epsom salt solution. This mixture was then allowed to stand covered for a period of 48 h. Each sample was then placed in a 101.6-mm (4.0-in.) diameter consolidation cell. As the sample was placed in the consolidation cell, air was trapped between the particles of clay. To remove as much of this air as possible, a 74.6-W (0.1-hp) vibratory motor attached to a 762-mm (30-in.) piece of 25.4- by 25.4-mm (1- by 1-in.) aluminum angle section was inserted into the sample. The vibration of the angle section densified the clay and helped to remove the air. A piston with a porous stone and filter paper was then inserted, and the rest of the consolidation cell was assembled. The specimen was then loaded sequentially with 13.4, 26.8, 41.2, 68.0, 94.8, and 177.2 kPa (1 kPa = 0.0104 tons/ft^2). Small increments of stress were employed to prevent any clay from being extruded past the piston.

Each sample was X-rayed on two perpendicular planes after being removed from the consolidation cell to determine if it was suitable for use. Some of the specimens were rejected when the X-ray results indicated that they contained large voids.

All specimens used for testing were trimmed from these 101.6-mm samples. Specimens prepared in this manner exhibited uniform grain size distribution and unit weight characteristics. The

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[1] Civil engineer, Dawe Engineers, Ankorage, AK.

[2] Professor, Department of Civil Engineering, University of Missouri—Rolla, Rolla, MO 65401. Member of ASTM.

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dry unit weights of the specimen varied between 13.0 to 13.7 kN/m^3 (85.9 to 87.3 lb/ft^3).

Permeant Used for Testing

Because of a concern about the variations in permeability testing caused by changes in the permeant used, a standardized permeant was used throughout the study. The use of permeants, which are not controlled, may result in the leaching or replacement of ions within a soil [*7-10*], and this may ultimately lead to changes in the soil's characteristics.

Because one of the principal chemical constituents in the clay used in the study is magnesium, a permeant containing magnesium ions was used in all the tests. This permeant consisted of deaired, distilled water and 1 g/L of magnesium sulfate heptahydrate (epsom salt). This solution, when mixed with the clay, resulted in samples that were highly flocculated and represented the most permeable type of soil structure. Because the clay was flocculated, any change in ions in the permeant, in conjunction with the pressures applied to the sample, could easily have resulted in the collapse of the flocculated structure into a more dispersed form and thereby influenced the flow measurements.

It was reasoned that if the ions present in the permeant would tend to result in a flocculated structure then this permeant could be used universally. If the structure of the test sample was flocculated, it would not disturb this structure. If the test sample had a dispersed structure, then the structure could not go from a dispersed to a flocculated form without a remixing of the material to allow for the formation of a completely new flocculated structure.

Triaxial Permeability Testing Apparatus

A special triaxial cell was used to confine the samples during the tests. An air over water interface chamber was used to pressurize the cell. The standtubes, which were used for back-pressure saturation and for reading the inflow and outflow from the samples, were constructed of 1000 mm (39.37 in.) lengths of 9.53-mm (0.375-in.) outside diameter plexiglass tubes. This size constituted an inside cross-sectional area of 31.15 mm^2 (0.04828 in.^{2}). All pressures were applied to the system with compressed air that had been passed through two pressure tanks and two pressure regulators (to prevent pressure fluctuations) before being applied to the system. All pressures (that is, cell pressure as well as inflow and outflow pressures) were monitored with pore-pressure transducers. The volume of the standtubes was carefully calibrated at the operating pressures to insure accurate and repeatable measurement of flow volumes. Figure 1 shows the entire triaxial cell permeability apparatus that was used during the study.

Test Procedure, Data Measurements, and Calculations

A sample with the test dimensions was mounted in the permeameter and wrapped with a rubber membrane. The cell was filled with deaired tap water, the inflow and outflow standpipes were charged with permeant, and the cell connected to the cell pressure line. The system was then deaired using vacuum and flushing techniques. The specimen was then subjected to back-pressure saturation in the manner consistent with that done for normal triaxial shear strength tests. Following back-pressure saturation, the cell pressure was increased to its test pressure, and the sample allowed to consolidate. Following consolidation and back-pressure saturation, the inflow and outflow standtube readings were recorded and the volume change of the sample was calculated. These results were used to calculate the final pore volume of the specimen.

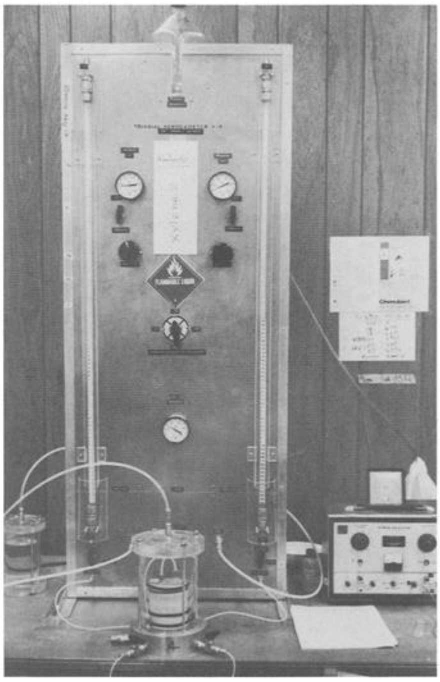

FIG. 1—*Permeability testing equipment.*

The test gradient was established across the specimen by increasing the air pressure in the inflow standtube while maintaining the outflow line pressure at the back-pressure value. Initial readings of in and out standtube permeant levels were taken. As flow occurred, readings were taken at intervals of every half pore volume of flow until the permeability stabilized.

The coefficient of permeability (or simply, permeability as used in this report) k is computed by first calculating the coefficient of hydraulic conductivity K, by the falling head equation, and then converting it into permeability by using the relative viscosity and relative density of the permeant, compared to that of the standard permeant. The hydraulic gradient is computed in terms of head of water in all cases. The equations are given below

$$K = \frac{aL}{A(t_i - t_f)} \ln(h_i/h_f) \qquad (1)$$

where

K = hydraulic conductivity, cm/s,
a = cross-sectional area of stand pipe, cm^2,
L = length of the sample, cm,
A = cross-sectional area of sample, cm^2,
$t_i - t_f$ = elapsed time, s,
h_i = initial head difference between inflow and outflow stand tube (permeant + air pressure), cm of water, and
h_f = final head difference between inflow and outflow stand tube (permeant + air pressure), cm of water.

and

$$k = \frac{K \nu_r}{\rho_r} \tag{2}$$

where

k = permeability, cm/s,
ν_r = relative viscosity (dimensionless), and
ρ_r = relative density (dimensionless).

The relative viscosity and relative density were computed by dividing the absolute viscosity and density of the permeant by those of the standard permeant, which, because of its very low concentration (0.004 N), was considered to have the same viscosity and density as distilled water at 25°C.

Variables Affecting the Triaxial Permeability Results

There are several variables that may be investigated separately to determine the influence of each on the measured coefficient of permeability. Each of these are discussed separately below.

Boundary Influences

For determining boundary influences, a sample within a flexible membrane is confined in the triaxial cell. This membrane is held against the sides of the sample by cell pressure in excess of the maximum applied internal pore pressure. The contact zone between the membrane and the sample may thus be affected so that the cross-sectional area of the sample is decreased and the flow of the permeant thereby impeded. Because according to Darcy's law, it is assumed that the flow front of permeant, as it moves through the sample, lies in a plane that is perpendicular to the direction of flow, it is important to determine the influence the material has on the boundary of the flow front.

To determine this influence, samples of three different diameters were studied. The diameters were 102, 71.1, and 35.6 mm (4.0, 2.8, and 1.4 in.). A gradient of 200 was used to force the standardized permeant through all three samples. Fluorescein dye was added to the permeant so that the flow front could be visually examined. After each of the three samples had been partially permeated, it was removed from the triaxial cell and cut in half along the axis of the cylinder. It was then allowed to air dry for approximately 24 h. A sharp knife was used to trim the cut surface of each to remove any disturbed portions. The degree of penetration and shape of the flow front of dyed permeant were visible but difficult to define with any precision. Because the dye used in the permeant is fluorescent, the samples were examined in a dark room with an ultraviolet light.

Smear Zones on Sample Ends

The ends of permeability samples must be trimmed before they are tested. This trimming process creates disturbed zones that may impede flow [*11*]. The extent to which flow is impeded is a function of the trimming tool used, the properties of the soil, that is, how susceptible the soil is to smearing, and the care and skill of the operator.

To evaluate the influence of sample disturbance resulting from trimming, an intact sample was tested first in the triaxial permeability apparatus. It was then removed and cut perpendicular to its vertical axis. The same procedure was used as for trimming the ends. Four such cuts were made in each of two samples, one with a diameter of 102 mm (4.0 in.) and the other with a diameter of 71.1 mm (2.8 in.). Only three cuts were made in a sample with a diameter of 35.6 mm (1.4 in.) because of its small size. Each of these cuts was the equivalent of a trimmed surface at each end of a test sample. After the samples were cut, they were again tested. The difference in the measured permeabilities could then be attributed to the influence of the trimmed surfaces. The influence of different trimming techniques and tools was not investigated however.

Gradient Magnitude

Nine samples (three of each of the three selected diameters) were tested at four different gradients ranging from 50 to 300. Each sample was tested at each gradient until steady state flow was established. Steady state flow is defined as equal readings of permeant inflow and outflow.

Length-to-Diameter Ratio

The influence of the length-to-diameter ratio was examined by performing permeability tests on samples of five different length-to-diameter ratios for each of the three selected diameters. Each of the tests was performed at a gradient of 200, and each test was conducted long enough to establish steady state flow.

Duration of Testing

The effect of test duration was evaluated by testing one sample of each of the three selected diameters for an extended period of time. Gradients of 25 and 200 were used to cover the range of gradients studied. The samples were tested first with the lower of the two gradients after which the gradient was increased to 200. The purpose was to evaluate the influence of microorganic growth or other long-term effects within the samples under prolonged periods of testing [*12*].

High Effective Stresses at Outflow End

When a permeability test is performed in a triaxial cell, there is no way to avoid elevated effective stresses at the outflow end of the sample (Fig. 2). Tests were conducted to examine this problem and its influence on the measured coefficient of permeability.

Degree of Saturation

When a sample is confined in a triaxial cell, the saturation of the sample is usually determined by evaluating the B coefficient. The B coefficient is defined as the ratio of the pore-pressure increase within the test specimen to the corresponding increase in the cell pressure ($B = \Delta u / \Delta \sigma_c$). In general, a B coefficient of 1.0 indicates complete specimen saturation. For permeability testing, the highest coefficient of permeability is measured when the sample is 100% saturated. To ensure that the test samples used in the study were saturated at the time of testing, each was back-pressure saturated, and the B coefficient was checked before the start of each test. Because the samples were consolidated from a slurry with a moisture content that exceeded the liquid limit, they were nearly saturated at the outset. Each sample was subjected to a back pressure of 276 kPa (40 lb/in.^{2}). For all samples, this resulted in a B coefficient of 0.94 or greater. With the B coefficients in excess of 0.94, all of the samples were believed to be in a saturated state at the time of testing.

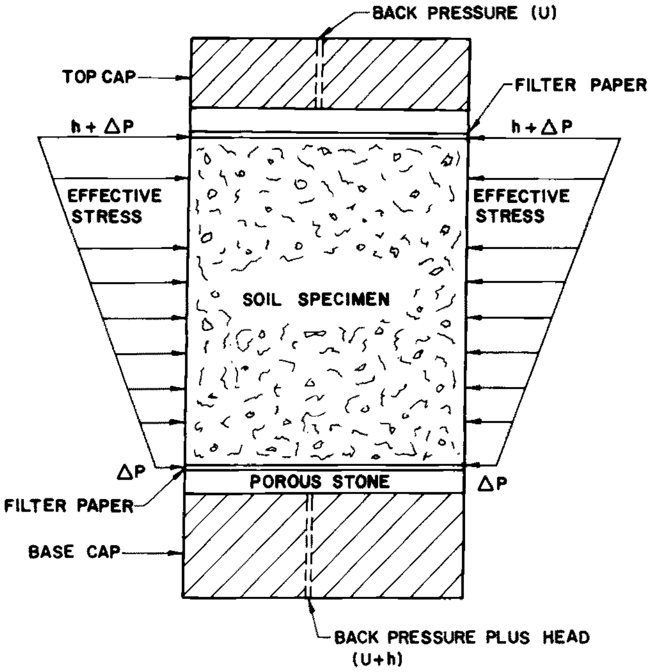

FIG. 2—*Effective stress distribution on test specimen.*

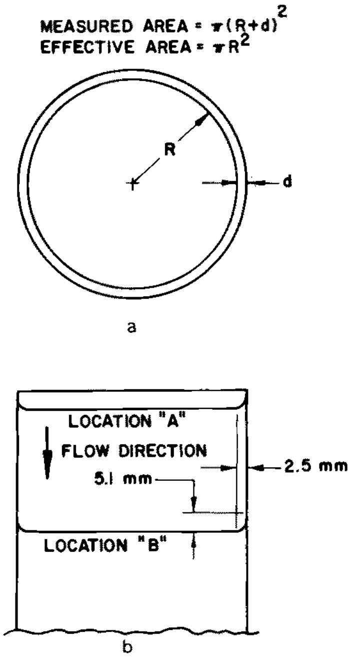

FIG. 3—*Flow front configuration.*

Initially, there was some concern that the degree of saturation of the samples might decrease during the testing process because of the pressure decrease on the permeant as it flowed through samples. Consequently, some of the samples were checked after they were tested to determine the B coefficient, and, hence, the degree of saturation had been changed.

Results

Boundary Influences

It was observed that the plane of the permeant's flow front was approximately perpendicular to the vertical axes of the sample cylinders with a small amount of distortion near the boundaries. This distortion was estimated to be about 2.5 mm (0.10 in.) regardless of the diameters of the samples. It was also evident that the intensity of the dye in the permeant attenuates the farther the permeant penetrates a sample.

By using 2.5-mm estimate of the boundary effect, the total effect, which might be attributed to boundary effects, was evaluated. The values arrived at are maxinum values, if it is assumed that the flow is completely restricted along the boundaries.

From Darcy's law and Fig. 3, a decrease in the effective area of flow results in an underestimation of the coefficient of permeability by a percentage equal to $[1 - R^2/(R+d)^2]\,100$. When this percentage is calculated for the three specimen diameters used in the study, the results are 26.5% for the 35.6 mm (1.4 in.) diameter, 13.8% for the 71.1 mm (2.8 in.) diameter, and 9.8% for the 101.6 mm (4.0 in.) diameter.

After the flow front is initially formed as shown in Fig. 3*b* (Location A), it progresses through the sample (Location B) without changing its configuration. It was concluded that the only time any underestimation of the coefficient of permeability might occur is during the initial formation of the flow front. As shown in Fig. 3*b*, the flow front's distortion occasioned by boundary effects extends back about 5.1 mm (0.20 in.) into the sample. This indicates that at a gradient of 200, the restricted flow area may have an influence on the calculated coefficient of permeability for a period of about 14 h. Tests of shorter duration would produce significant errors because of the boundary effects.

Smear Zones on Sample Ends

The results of the influence that smear zones on sample ends have on permeability are shown in Table 1. All of these tests were conducted at a gradient of approximately 200, and the flow before and after the samples were cut was allowed to continue until a steady state condition developed. From the results, it is evident that for the particular clay tested, the sample ends, when prepared with a fine, tensioned wire, reduced the coefficient of permeability by about 5%. The two larger samples, which had four cut surfaces, both showed a reduction of about 18 to 20%. The 35.6-mm (1.4-in.) diameter samples exhibited a reduction in the coefficient of permeability of about 43% for three cuts, or the equivalent of about a 14% reduction for the trimmed surfaces at the ends of the specimen. As

TABLE 1—*Summary of end effect data.*[a]

Number of Cuts	Specimen Dimensions, mm	k Before Cuts, cm/s	k After Cuts, cm/s
3	35.6 diameter 53.3 length	16.7×10^{-8}	9.6×10^{-8}
4	71.1 diameter 108.0 length	5.1×10^{-8}	4.2×10^{-8}
4	101.6 diameter 152.4 length	5.0×10^{-8}	4.0×10^{-8}

[a] 1 in. = 2.54 cm.

previously stated, this latter sample, because of its small size, was much more difficult to work with during the cutting process, though the cuts were carefully made. Consequently, the portions disturbed during the cutting process may have been responsible for the larger indicated reduction in the coefficient of permeability.

Gradient Magnitude

The coefficient of permeability when determined in the triaxial permeability apparatus was found to decrease as the gradient was increased. Figure 4 represents the measured values of the coefficient of permeability as a function of the gradient used during testing. The decrease in permeability may be attributed to the high effective stress applied to the outflow end of the sample. This is discussed more fully below.

If the relationship between the measured coefficient of permeability at a gradient of 200 and the length of the sample is examined (Fig. 5), it can be seen that the coefficient of permeability decreases with an increase in the length of the sample. Although the data are scattered, it appears that most of the decrease can be attributed to the increase in applied effective stress at the outflow end of the sample. This increase in effective stress is necessary to achieve the same gradient as the length of the sample is increased.

Length-to-Diameter Ratio

The results of the tests performed to evaluate the influence of the length to diameter ratio are presented in Fig. 6. These results indicate a slight decrease in the measured coefficient of permeability as the length to diameter ratio is increased except for the small, 35.6-mm (1.4-in.) diameter samples. Figure 6 also shows that the smaller the diameter of the sample, the greater the deviation in the measured value of the coefficient of permeability from the average.

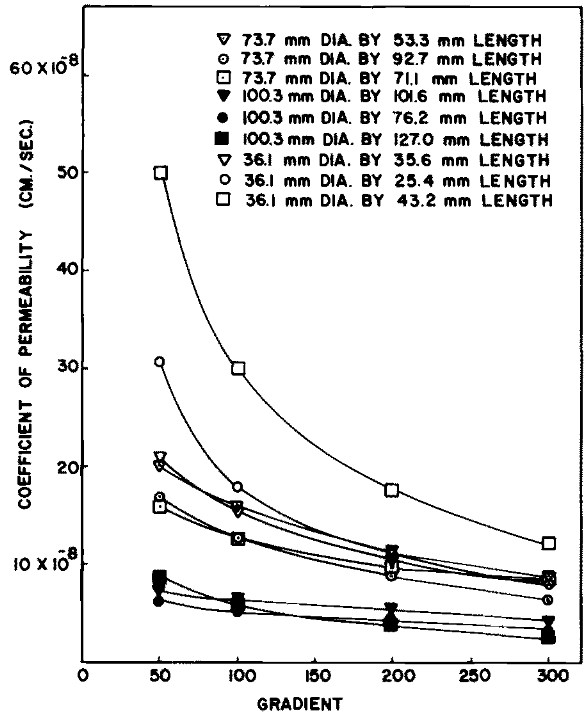

FIG. 4—*Gradient versus coefficient of permeability.*

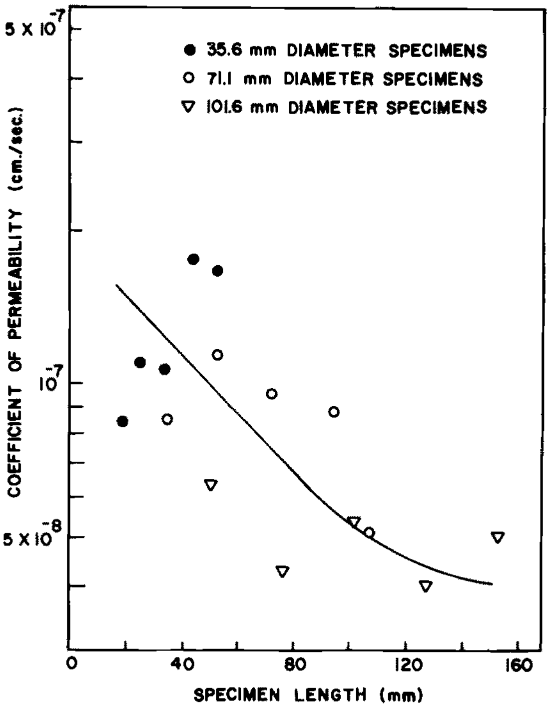

FIG. 5—*Specimen length versus coefficient of permeability (i = 200).*

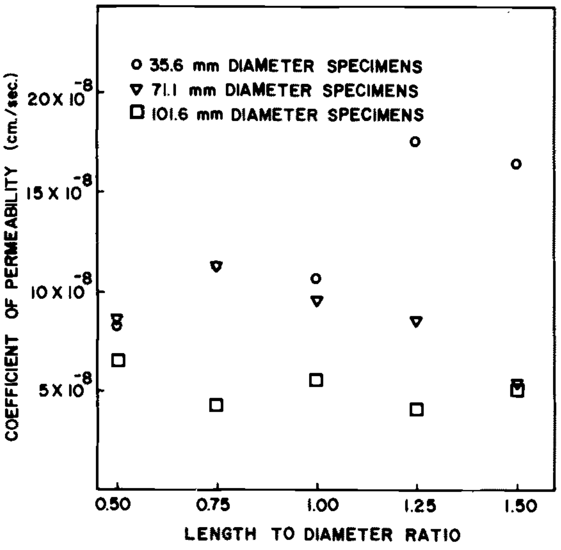

FIG. 6—L/D *versus coefficient of permeability (i = 200).*

The increased amount of data scatter in the measured value of the coefficient of permeability for the small diameter sample may be attributed to the fact that it was a less representative sample, and this increased the number of minor measurement errors, which influenced the results. The increased data scatter may also be attributed to the fact that with the small diameter sample the ratio of disturbance to size may be a much greater influence on the measured value than on the large diameter samples.

The tendency for the measured coefficient of permeability to decrease with an increase in the length to diameter ratio is probably caused by a necessary increase in the effective stress at the outflow end of a sample so that it retains the same gradient as a longer sample. This effect is discussed below.

Duration of Testing

The results of test duration indicate that there is a tendency for the measured coefficient of permeability to become stable after a period of about 1 to 2 h. After the period required for the attainment of steady state flow, there is a tendency for the measured coefficient of permeability to decrease slightly with time (Fig. 7). This decrease is in all probability due either to the presence of microorganisms or to the effects of secondary consolidation or both. No antibacterial agent was added to the permeant because it was feared that the agent might have a greater influence on the permeability than on the microorganisms. Apparently, the small amount of decrease in the measured coefficient of permeability occasioned by the extension of testing time had only a minor effect on the results in comparison with the many other testing problems and variables. However, no microbe population count was conducted so the presence or absence of microbes was not verified.

High Effective Stress at Outflow End

Figure 8 shows the experimental results of the relationship between volumetric strain and the applied effective stress at the outflow end of a sample. This indicates that when the applied stress at the outflow end exceeds the pre-consolidation pressure, the relationship becomes nonlinear. Although no measurement of volumetric strains were taken during this study, when the applied effective stress at the outflow boundary exceeds the pre-consolidation pressure, the soil is in transition from a preconsolidated state to a consolidated state and experiences increased strain. The figure also shows that the curves have similar slopes. This implies sample reproducibility.

The conclusion is that samples tested in a triaxial falling head permeability apparatus should be tested at a gradient that results in an applied effective stress at the outflow end of the sample that is less than the preconsolidation pressure. The proper gradient can be determined by performing permeability tests at several gradients and plotting the data of the volumetric strain-applied effective stress at the outflow end. Based on the results of this study, if the relationship is linear, one is assured that the applied effective stress at the outflow end does not exceed the preconsolidation pressure of the material.

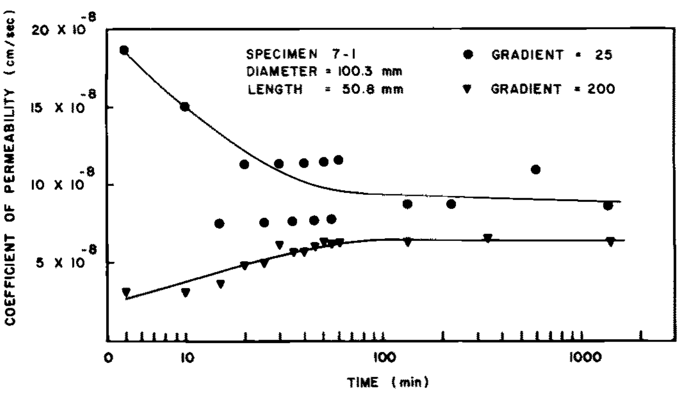

FIG. 7—*Coefficient of permeability versus testing time.*

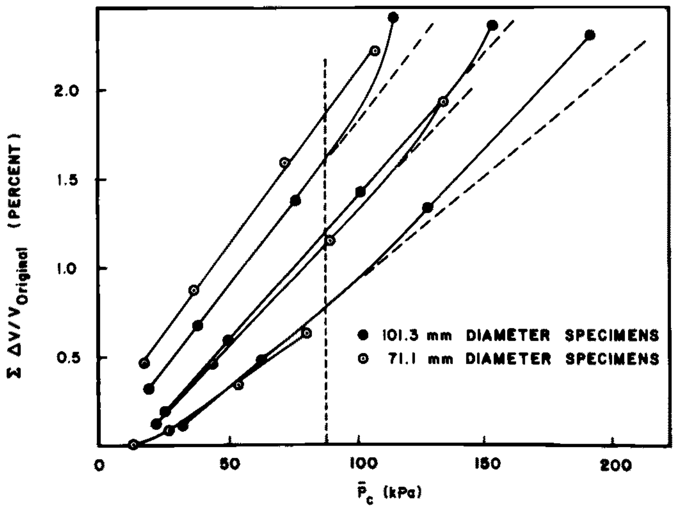

FIG. 8—ΔV/V *versus applied effective stress at outflow end.*

Figure 9 depicts the relationship between the coefficient of permeability and the applied effective stress at the outflow end of a sample. The curve indicates that the measured coefficient of permeability is much less sensitive to changes in the applied effective stress for 102-mm (4.0-in.) diameter samples as the applied effective stress is increased but is much less pronounced. For the clay used in the present study, the test data for the 71.1 mm (2.8 in.) diameter samples resulted in a measured coefficient of permeability that was about twice that of the 102-mm (4.0-in.) diameter samples when the gradient for the applied effective stress at the outflow end was equal to the preconsolidation pressure.

Degree of Saturation in Permeability

In general, the *B* coefficient tends to increase slightly during testing, although a few samples showed a very slight decrease. Because

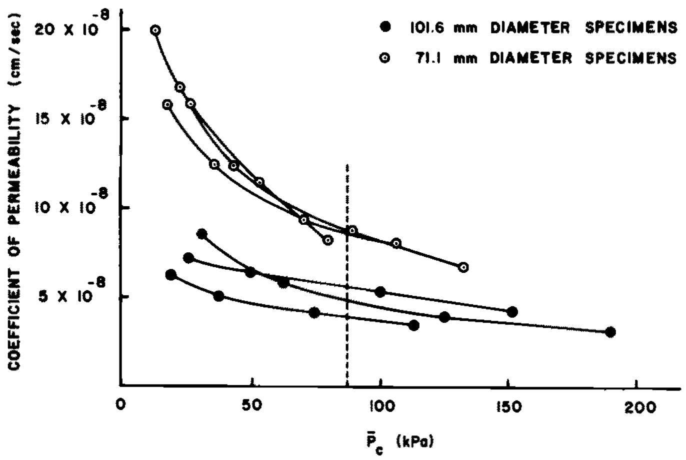

FIG. 9—*Coefficient of permeability versus applied effective stress at outflow end.*

at the termination of the testing process, none of the samples had a B coefficient of less than 0.94, it was assumed that the samples were fully saturated for the duration of the tests.

Conclusions and Recommendations

1. A standardized permeant should be used for all permeability testing where comparisons are to be made between different soils or soils with different physical properties such as density or structure. (The permeant used in the present study seems to be suitable, but in special cases, it may be desirable to use another type of permeant as well as a standard to determine the effect of changes at a particular site.) This is so because of the influence of permeant viscosity, density, and chemistry on the measured permeability and its reactions with the clay under study.
2. Back-pressure saturation is essential if a permeability test is to predict soil permeabilities at a particular site and for comparative study of different soils caused by the influence of degree of saturation on measured flow rates.
3. Based on this study, large specimens yield more consistent and repeatable results. Therefore, large diameter specimens are preferred for permeability testing.
4. Permeability specimens tested in a triaxial, falling head, permeability apparatus should have a length to diameter ratio of between 0.5 and 1.0.
5. The gradient used should not result in an applied effective stress at the outflow end of the sample that is in excess of the preconsolidation stress of the material.
6. Data should be collected during any triaxial, falling head, permeability test to ensure that steady state flow conditions exist before the coefficient of permeability is measured.

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