Charles D. Shackelford[1] *and Farhat Javed*[1]

Large-Scale Laboratory Permeability Testing of a Compacted Clay Soil

REFERENCE: Shackelford, C. D. and Javed, F., "**Large-Scale Laboratory Permeability Testing of a Compacted Clay Soil,**" *Geotechnical Testing Journal*, GTJODJ, Vol. 14, No. 2, June 1991, pp. 171–179.

ABSTRACT: Constant-head permeability (hydraulic conductivity) tests were performed on samples of a compacted clay soil using a 0.914 by 0.914 by 0.457-m (3 by 3 by 1.5-ft) large-scale, double-ring, rigid-wall permeameter. A naturally occurring silty clay soil was used for the permeability tests. The soil was separated into five different fractions representing five different ranges in precompaction clod sizes. Soil from each of the soil fractions was used for soil specimens. The soil for the large-scale permeameter was compacted in two 7.62-cm (3-in) lifts. Small-scale, constant-head permeability tests also were performed on soil specimens compacted into standard Proctor molds (9.44×10^{-4} m^3). Comparison of the results from the two different scales of permeameters indicated that, in all cases, the permeability for a given soil fraction was higher in the large-scale permeameter than it was in the small-scale permeameter. In addition, the permeability for all soil fractions measured in the large-scale permeameter ranged from 0.6 to 2.4 orders of magnitude higher than the value measured in the small-scale permeameter. As a result of the permeability tests performed in this study, there appears to be a scale effect associated with laboratory permeability testing, especially when a significant proportion of the soil being tested consists of precompaction clod sizes which are large relative to the size of the permeameter. The scale effect in this study is thought to be due to the relationship between the compactive effort and the different degrees of confinement associated with the different scales of permeameters. The implication of the study is that a more realistic evaluation of the field-measured permeability of a compacted clay soil may be possible in the laboratory if the permeameter is sufficiently large to test a representative sample of soil.

KEY WORDS: compaction, permeability, waste disposal

The permeability (hydraulic conductivity) of soil is an important property in geotechnical engineering since many of the problems associated with the design and construction of structures require that the permeability of the soil be determined (e.g., seepage through earth dams, dewatering of excavated sites, etc.). In addition, the evaluation of the permeability of fine-grained soils used as lining material for the containment of wastes has generated tremendous interest during the past decade.

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 the 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 Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures, Using 5.5-lb (2.49-kg) Rammer and 12-in. (304.8-mm) Drop (D 698)]. Some studies (Daniel 1981, 1984; Day and Daniel 1985; Elsbury and Sraders 1989; Olson and Daniel 1981) have indicated that the *in-situ* permeability of compacted clay soils can be as much as two to three orders of magnitude higher than the permeability values predicted by laboratory tests. At least 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 sizes of all soil particles or aggregates of soil particles (clods) are less than 4.75 mm. However, in the field, the size of the clods associated with compacted soils may be as much as 0.305 m (1 ft) in diameter (Daniel 1984). Second, the specimen in the standard Proctor mold is only 0.102 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. This study represents an attempt to evaluate these factors on the laboratory measurement of the permeability of a compacted clay soil.

Materials and Methods

Soil

A natural silty clay soil was selected for this study. The soil was recovered from the immediate vicinity of the Engineering Research Center of Colorado State University in Fort Collins, Colorado. The physical properties of the soil are listed in Table 1. Specimens of the soil were taken from the following five fractions of the natural soil:

1. Soil passing the 75-mm (3-in.) sieve size.
2. Soil passing the 75-mm (3-in.) sieve size and retained on the 25-mm (1-in.) sieve size.
3. Soil passing the 25-mm (1-in.) sieve size and retained on the No. 4 (4.75-mm) sieve.
4. Soil passing the No. 4 (4.75-mm) sieve.
5. Soil passing the No. 10 (2.00-mm) sieve.

The gradational characteristics of the air-dried natural soil as well as those based on the standard particle size analysis [ASTM Method for Particle-Size Analysis of Soils (D 422)] are shown in Fig. 1. The values of "percent finer" for the natural soil gradation curve shown in Fig. 1 represent average values of analyses

[1]Assistant professor and former graduate student, respectively, Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523.

© 1991 by the American Society for Testing and Materials

www.astm.org

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

performed on three separate samples of the air-dried natural soil. The variability in the average "percent finer" values also is indicated in Fig. 1. Whereas the soil for the standard particle size analysis (ASTM D 422) was broken up using a mortar and rubber-tipped pestle in accordance with ASTM Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants (D 421), no special effort was made to break up the air-dried natural soil. As a result, the differences between the two gradational curves shown in Fig. 1 can be attributed to the difference between individual particles and aggregates of particles, or clods. Therefore, the five different categories of soil used for specimens can be thought of as representing soils with different ranges in clod sizes. Also, based on Fig. 1, about 92% of the natural soil passes the 75-mm sieve size. For purposes of this study, the soil representing clod sizes less than 75 mm (3 in.) in size (i.e., category one) henceforth is referred to as "natural soil."

TABLE 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 moisture content, g/g	ASTM D 698—Method A	18%
Maximum dry unit weight	ASTM D 698—Method A	16.90 kN/m^3 (107.7 lb/ft^3)
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

NOTE: CL = clay of low plasticity.

The compaction characteristics of the five categories of soil used for specimens are presented in Fig. 2. As indicated in Fig. 2, the compaction curve for the fourth category of soil, i.e., for the soil passing the No. 4 (4.75-mm) sieve, represents the compaction curve based on the standard Proctor procedure (ASTM D 698, Method A). This standard Proctor curve was used as the reference compaction curve for control of the dry unit weight and molding water content of all specimens used for the permeability tests.

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 (2.00-mm) sieves. Second, the soil from the sieving procedure was separated into the five categories outlined above and enough tap water was added through a spray bottle to each soil fraction to raise the water content to the desired value. The sieving procedure was repeated until a

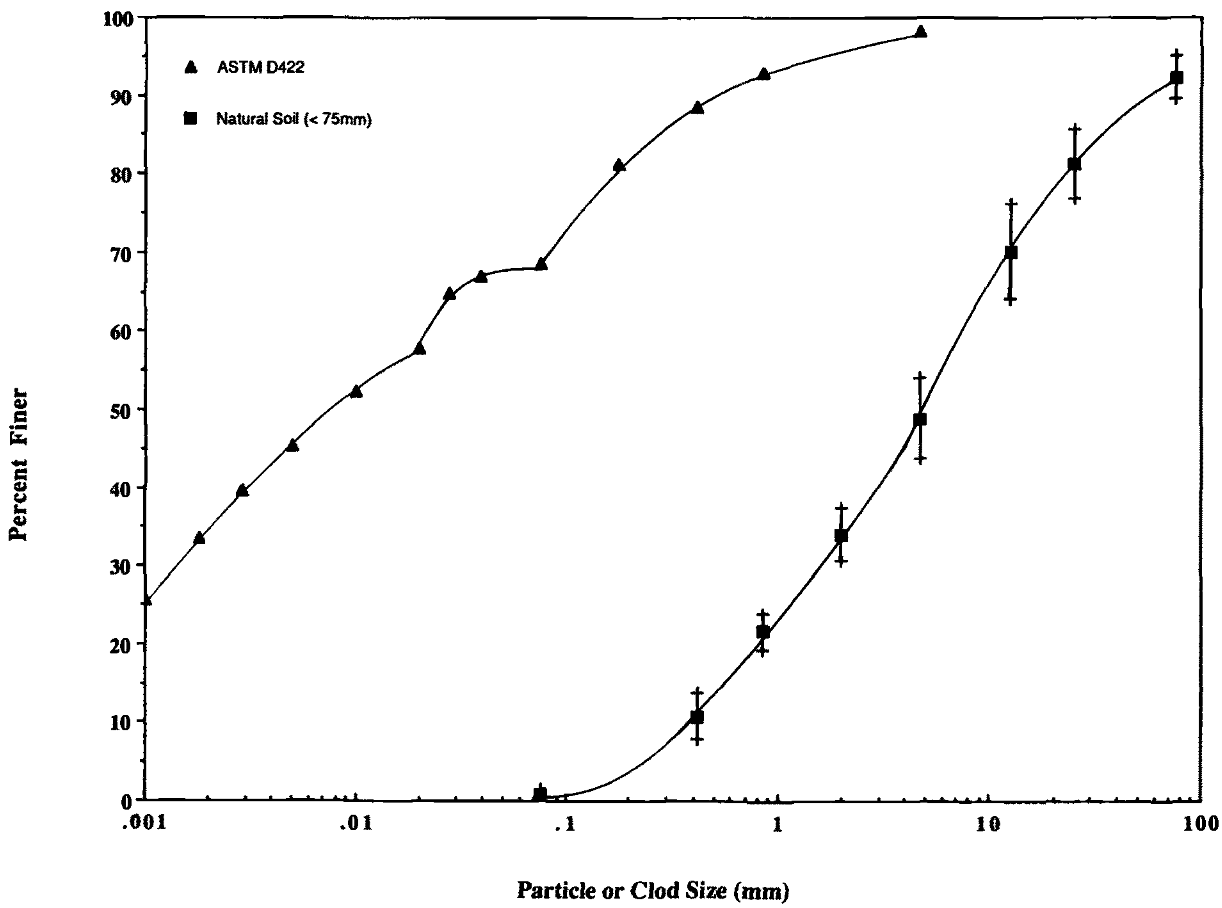

FIG. 1—*Gradational characteristics of soil.*

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

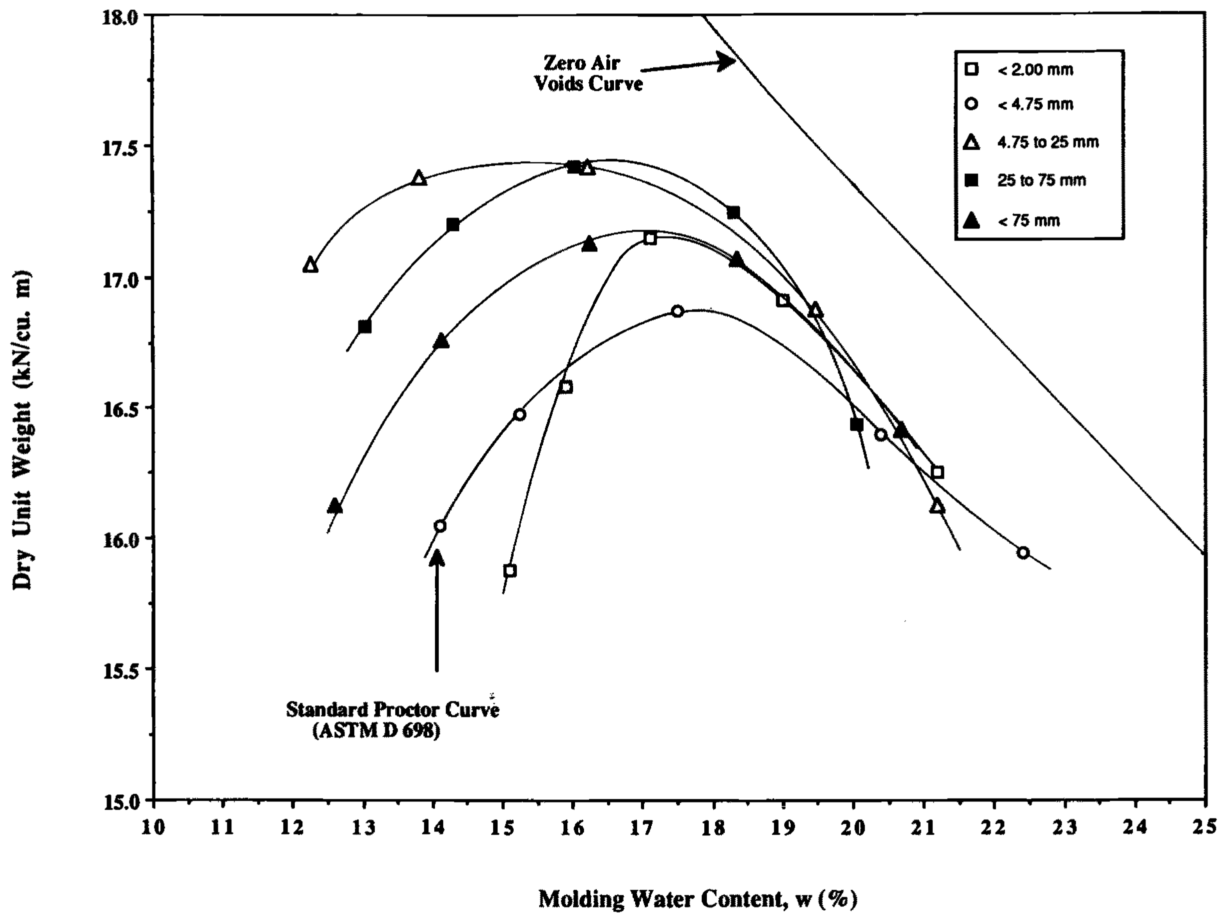

FIG. 2—*Compaction curves for designated soil fractions.*

sufficient amount of soil (2.24 kN, or 500 lb) for each of the five categories was obtained. The sieved soil for each of the specimens was separated into 111-N (25-lb) units for ease of handling before adding the water. The wet soil was placed in double plastic bags and allowed to hydrate for at least 48 h.

Permeameters

Two rigid-wall permeameters were used in this study: a small-scale permeameter, with a standard Proctor mold (9.44×10^{-4} m^3) being used as the permeability cell, and a large-scale permeameter. A schematic diagram for the large-scale permeameter is presented in Fig. 3; a pictorial view is shown in Fig. 4. In principle, the large-scale permeameter is similar to the double-ring permeameter described by Daniel et al. (1985), except it is square. The overall dimensions of the large-scale permeameter are 0.914 by 0.914 by 0.457 m (3 by 3 by 1.5 ft) with an inner ring area of 0.372 m^2 (4 ft^2). The inner ring extends only 5.08 cm (2 in.) into the permeameter. The top cap was sealed to the permeameter through a rubber gasket and a series of bolts. The entire permeameter, including the top cap, was constructed of 1.27-cm (0.5-in.)-thick steel plate. However, the plate for the top cap was sealed with steel I-beams. The steel reinforcement for the top cap was required when preliminary tests indicated that the steel plate would bend under pressures exceeding about 172 kPa (25 psi), causing the seal between the top plate and the sides of the permeameter to leak excessively. No leakage was detected after the reinforcement was added. The excessive weight of the top cap required that a portable hand crane be used to manuever it, as shown in Fig. 4*a*. In addition, the entire permeameter was supported by four wheels for ease of movement.

Permeability Tests

Both small-scale and large-scale permeability tests were performed at ambient laboratory temperatures which ranged from 21°C (70°F) to 27°C (80°F). The permeant fluid used for all of the permeability tests was tap water. The characteristics of the tap water based on analysis of three samples are provided in Table 2. The procedures for performing the permeability tests are described below.

Small-scale permeability tests—A soil sample from each category of soil was compacted using the same energy specified in the standard Proctor test (ASTM D 698). These samples were compacted at water contents which ranged from 20.7 to 21.4%, or about 2 to 3% water content greater than optimum water content, and at dry unit weights which were at least 95% of the maximum dry unit weight of the soil based on the standard Proctor curve (see Fig. 2). Each of the resulting five specimens (B1, B2, B3, B4, and B5) was subjected to a hydraulic gradient of about 90. The effect of water content on the permeability of the soil passing the No. 4 (4.75-mm) sieve was determined using four specimens prepared at water contents of 15.4, 17.0, 20.0, and 21.5%, by weight (tests B6, B7, B8, and B9, respectively).

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

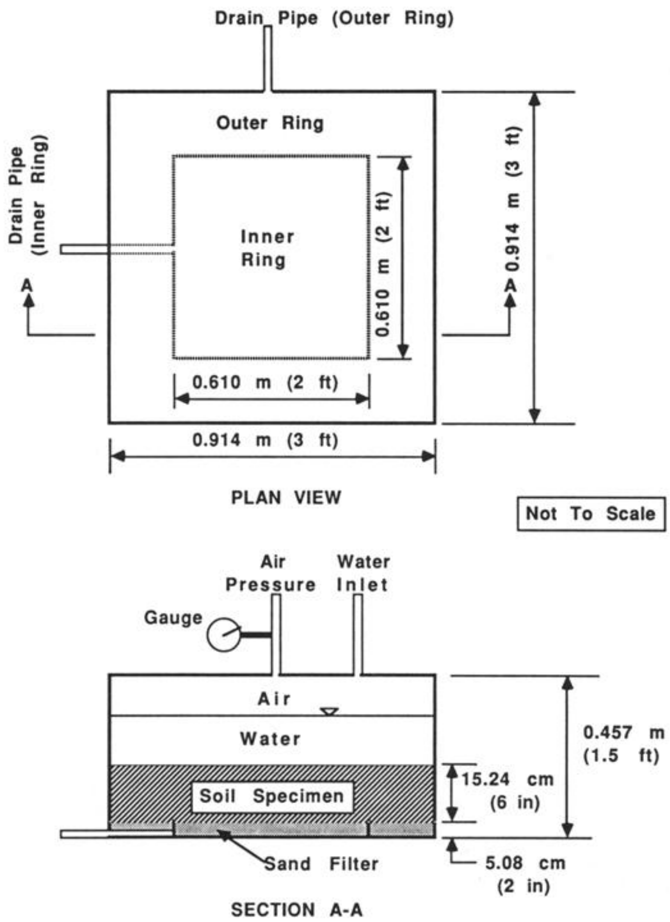

FIG. 3—*Schematic of large-scale permeameter.*

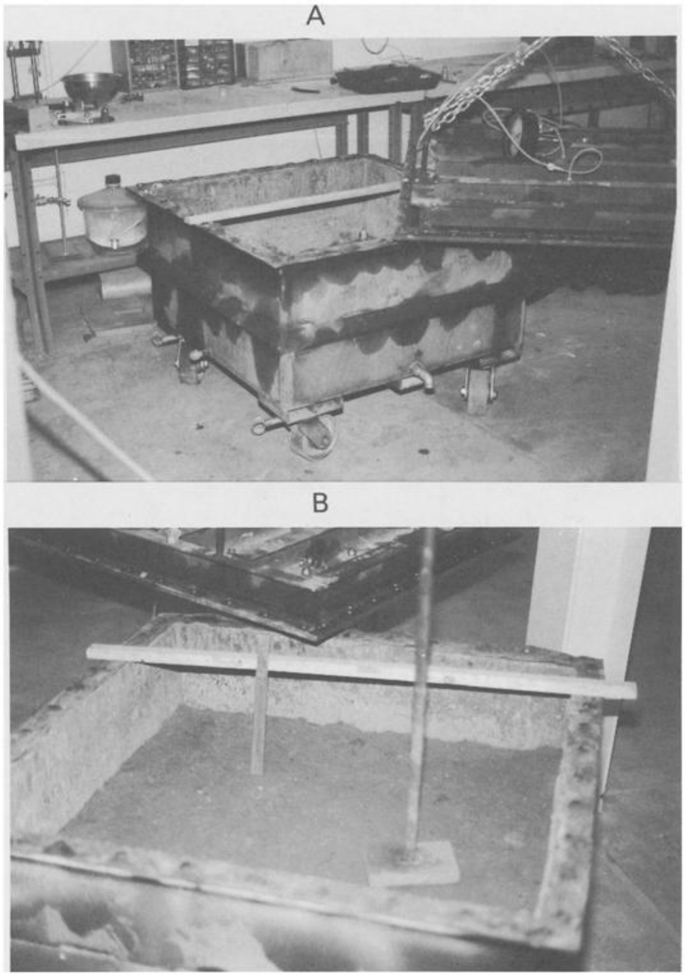

FIG. 4—*Pictorial view of large-scale permeameter:* (a) *exterior;* (b) *interior.*

Large-scale permeability tests—Specimens representing four different ranges of precompaction clod sizes (tests T1, T2, T3, and T4) were prepared. First, the outflow pipes of the permeameter were covered with Whatman 60 filter paper and the bottom of the permeameter was filled with a fine sand to a depth of 5.08 cm (2 in.). Then the soil to be tested was placed in the cell and compacted in two, 7.62-cm (3-in.) lifts with a 44.48-N (10-lb), 15.24 by 10.16 by 2.54 cm (6 by 4 by 1 in.) hammer (see Fig. 4*b*) at water contents of either 20.7 or 20.9%, or within 2 to 3% water content above optimum water content based on the standard Proctor curve (see Fig. 2). A known weight of wet soil was compacted to achieve a 15.24-cm (6-in.) layer in such a manner that at least 95% of the maximum dry unit weight based on the standard Proctor compaction test (Fig. 2) was achieved. The lift thicknesses were measured using a ruler referenced to a network of strings tied across the top of the permeameter (see Fig. 4*b*). After compaction, the cell was filled immediately with tap water to prevent dessication, and the specimen was allowed to saturate for one week. The permeameter was then closed from the top, and an air pressure system was used to apply the desired hydraulic gradient, through an air-water interface, to perform the permeability test (see Fig. 3). The drainage pipes were vented to the atmosphere. The hydraulic gradients used for the large-scale tests ranged from 10 to 50 during the course of the test. Each large-scale permeability test lasted about four weeks.

As a check on the dry unit weights of the specimens, four core samples of soil were recovered from the large-scale permeameter after termination of the test. Steel rings used to recover the core samples were 10.2-cm (4-in.) in diameter and either 6.35-cm (2.5-in.) or 5.72-cm (2.25-in.) in length. Two of the rings were inserted after removing 2.54 cm (1 in.) of soil from the top of the compacted soil layer, and the other two were inserted after removing the top 7.62 cm (3 in.) of compacted soil. The final water contents and dry unit weights determined from the core samples are provided in Table 3. Due to swelling, the average dry unit weight determined from the core samples was expected to be less than the as-compacted dry unit weight estimated from the wet weight

TABLE 2—*Characteristics of tap water used in the study.*

	Values			
Parameter	Sample 1	Sample 2	Sample 3	Average
pH	6.45	6.27	6.25	6.32
Electrical conductivity at 25°C, μmhos/cm	22 400	32 700	28 700	27 900
Temperature	27°C (80°F)	27°C (80°F)	27°C (80°F)	27°C (80°F)
Total dissolved solids, mg/L	15.76	19.57	17.87	17.73

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

TABLE 3—*Water contents and dry unit weights from core samples recovered after termination of large-scale permeability tests.*

			Core Sample Data		Compaction Data	
Test Designation	Precompaction Soil Clod Sizes, mm	Sample	Water Content, %	Dry Unit Weight, kN/m³	Water Content, %	Dry unit Weight[a], kN/m³
T1	<4.75	A	22.2	16.51		
		B	22.1	16.54		
		C	21.9	16.58		
		D	21.9	16.61		
		Average	**22.0**	**16.56**	**20.7**	**16.71**
T2	4.75 to 25	A	23.0	16.42		
		B	23.1	16.39		
		C	22.9	16.47		
		D	22.8	16.48		
		Average	**23.0**	**16.44**	**20.9**	**16.68**
T3	25 to 75	A	22.3	16.57		
		B	22.2	16.58		
		C	21.6	16.63		
		D	21.8	16.66		
		Average	**22.0**	**16.61**	**20.7**	**16.71**
T4	<75	A	21.9	16.72		
		B	21.5	16.71		
		C	20.9	16.75		
		D	21.0	16.78		
		Average	**21.3**	**16.74**	**20.9**	**16.68**

[a]Estimated from molding water content and wet weight of soil added to permeameter.

of the soil added to the permeameter and the molding water content. In all cases, the final dry unit weights determined after termination of the permeability tests were found, on the average, to be within 1.5% of the as-compacted dry unit weights. However, the final dry unit weight for sample T4 was slightly greater than the as-compacted dry unit weight. This discrepancy probably represents an error in estimating the as-compacted dry unit weight.

TABLE 4—*Permeability test results for small-scale (Proctor mold) Permeameter.*

Precompaction Soil Clod Sizes, mm	Test Designation	Molding Water Content, %	Dry Unit Weight, kN/m³	Permeability, cm/s
<2.00	B1	20.7	16.59	2.0×10^{-8}
<4.75	B2	20.7	16.64	1.5×10^{-8}
4.75 to 25	B3	20.7	16.44	2.5×10^{-8}
25 to 75	B4	20.8	16.41	7.0×10^{-8}
<75	B5	21.4	16.38	2.5×10^{-7}

NOTE: 1 kN/m³ = 6.371 lb/ft³

TABLE 5—*Effect of compaction water content on the permeabiity of the soil passing the No. 4 (4.75 mm) sieve.*

Test Designation	Molding Water, Content, %	Dry Unit Weight, kN/m³	Permeability, cm/s
B6	15.4	16.82	6.0×10^{-8}
B7	17.0	16.87	2.0×10^{-8}
B8	20.0	16.78	1.5×10^{-8}
B9	21.5	16.71	1.0×10^{-8}

NOTE: 1 kN/m³ = 6.371 lb/ft³.

Results

Small-Scale Permeability Tests

The results of the small-scale (Proctor mold) permeability tests are presented in Tables 4 and 5 and illustrated in Figs. 5 and 6. All permeability values reported in Tables 4 and 5 represent final, stabilized values. The data in Table 4 and Fig. 5 indicate a slight increase in permeability with an increase in the range of precompaction clod sizes associated with the soil sample tested. Overall, there is about an order-of-magnitude increase in the permeability as the range of precompaction clod sizes for the soil increases from the less than 2.00-mm size to the less than 75-mm size (i.e., the natural soil). However, the permeability values did not begin to increase significantly until soil sample B4, consisting of only relatively large precompaction clod sizes (25 to 75 mm), was tested. This suggests that the relatively high permeability values for the compacted natural soil samples (B5) can be attributed, in part, to the incorporation of the larger precompaction clod sizes into the overall soil matrix.

From the gradation of the natural soil (Fig. 1), the proportions of the natural soil passing the 75-mm sieve size that are less than 4.75 mm, between 4.75 and 25 mm, and between 25 and 75 mm are about 53, 35, and 12%, respectively. Based on these proportions, a weighted-mean permeability of the compacted natural soil can be calculated using the average permeability values for the individual soil fractions reported in Table 4, or

$$K_{SS} = 0.53(1.5 \times 10^{-8}) + 0.35(2.5 \times 10^{-8}) + 0.12(7.0 \times 10^{-8}) = 2.5 \times 10^{-8} \text{ cm/s}$$

where K_{SS} represents the weighted-mean, small-scale permeability. This weighted-mean value is an order of magnitude lower than the reported value of 2.5×10^{-7} cm/s for the compacted

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

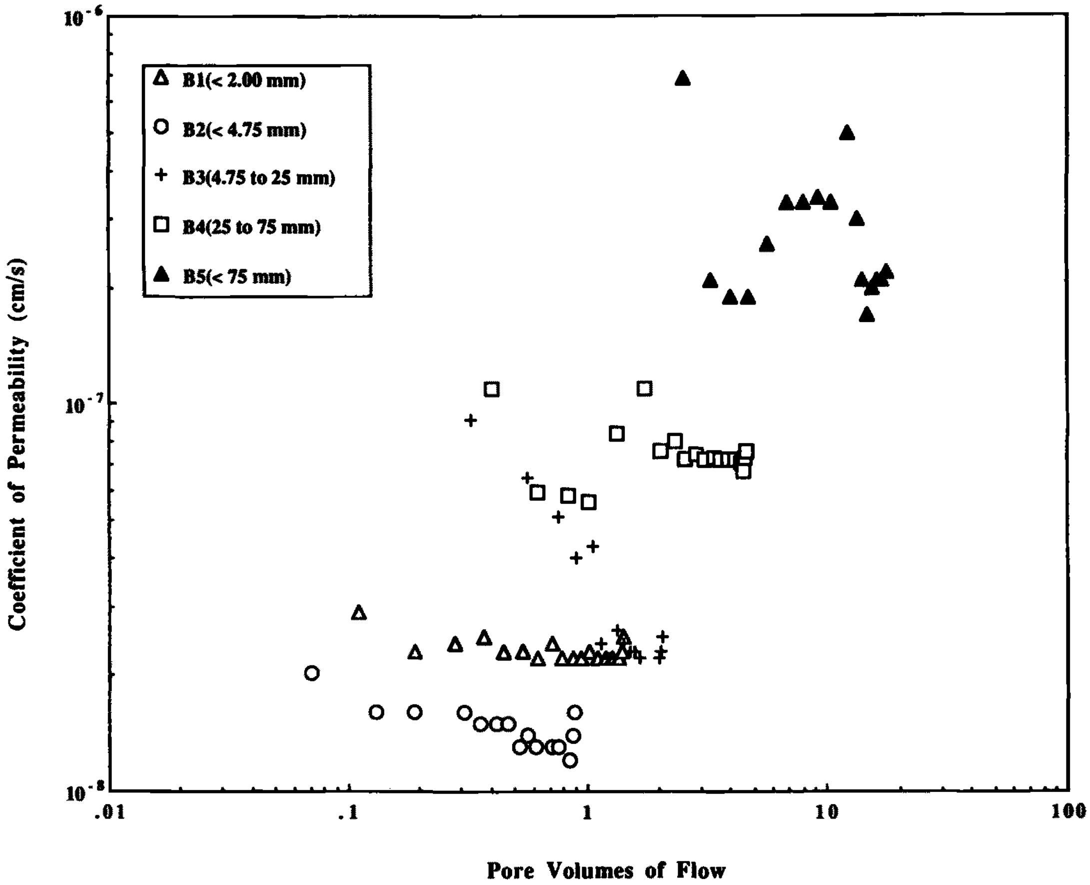

FIG. 5—*Permeability versus pore volumes for small-scale (Proctor mold) permeability tests.*

natural soil (see Table 4). Therefore, the effect of the larger precompaction clod sizes is to increase the permeability of the soil relative to the smaller clod sizes, but the effect of the increase in the permeability is not proportional to the percentage of the larger clod sizes present in the compacted natural soil.

The results for tests B6, B7, B8, and B9 are summarized in Table 5 and illustrated in Fig. 6. Although the permeability for sample B6 (compacted dry of optimum moisture content) is higher than the permeability of the other samples, the drastic decline (i.e., two to three orders of magnitude) in permeability wet of optimum moisture content reported by Mitchell et al. (1965) is not evident. However, it took about 18 pore volumes of flow through sample B6 before the permeability stabilized at the reported value of 6.0×10^{-8} cm/s. If the test had been terminated before 10 pore volumes of flow, as were the other tests, then the permeability for sample B6 would have been reported as about 6.0×10^{-7} cm/s, or an order of magnitude higher (see Fig. 6).

Large-Scale Permeability Tests

The results of the permeability tests using the large-scale permeameter are listed in Table 6 and shown in Fig. 7. The permeability values shown in Table 6 represent final, stabilized values. The results indicate a stronger dependence of the permeability value as a function of the precompaction clod sizes of the specimens than did the small-scale tests. On the average, there is about two orders of magnitude increase in permeability as the range of precompaction clod sizes for the specimens increases from the less than 4.75-mm size to sizes ranging between 25 and 75 mm. This increase in permeability is about ten times greater than that recorded for the small-scale tests.

The permeability of the compacted natural soil (sample T4) is about four times higher than the permeability of the specimen with the smallest range of precompaction clod sizes (sample T1). The large-scale, weighted-mean permeability value (K_{LS}) calculated for the compacted natural soil from the various proportions of the natural soil and the corresponding average permeability values listed in Table 6 is about 3.8×10^{-6} cm/s, which is higher than the measured value of 9.2×10^{-7} cm/s for sample T4. Therefore, the effect of the larger precompaction clod sizes on the large-scale permeability of the compacted natural soil also is not proportional to the percentage of the larger clod sizes present in the natural soil, and the effect is less in the large-scale permeameter than it is in the small-scale permeameter.

Comparison of Large-Scale and Small-Scale Permeability Tests

The permeability values for each range of precompaction clod sizes in Tables 4 and 6 are compared in Table 7. In all cases, a higher permeability for a soil sample with a given range of precompaction clod sizes was measured using the large-scale permeameter. Since the permeability values based on both the inner and outer rings of the large-scale permeameter for each test are essentially the same (Table 6), the relatively higher permeability values measured in the large-scale permeameter cannot be attributed to side-wall leakage.

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

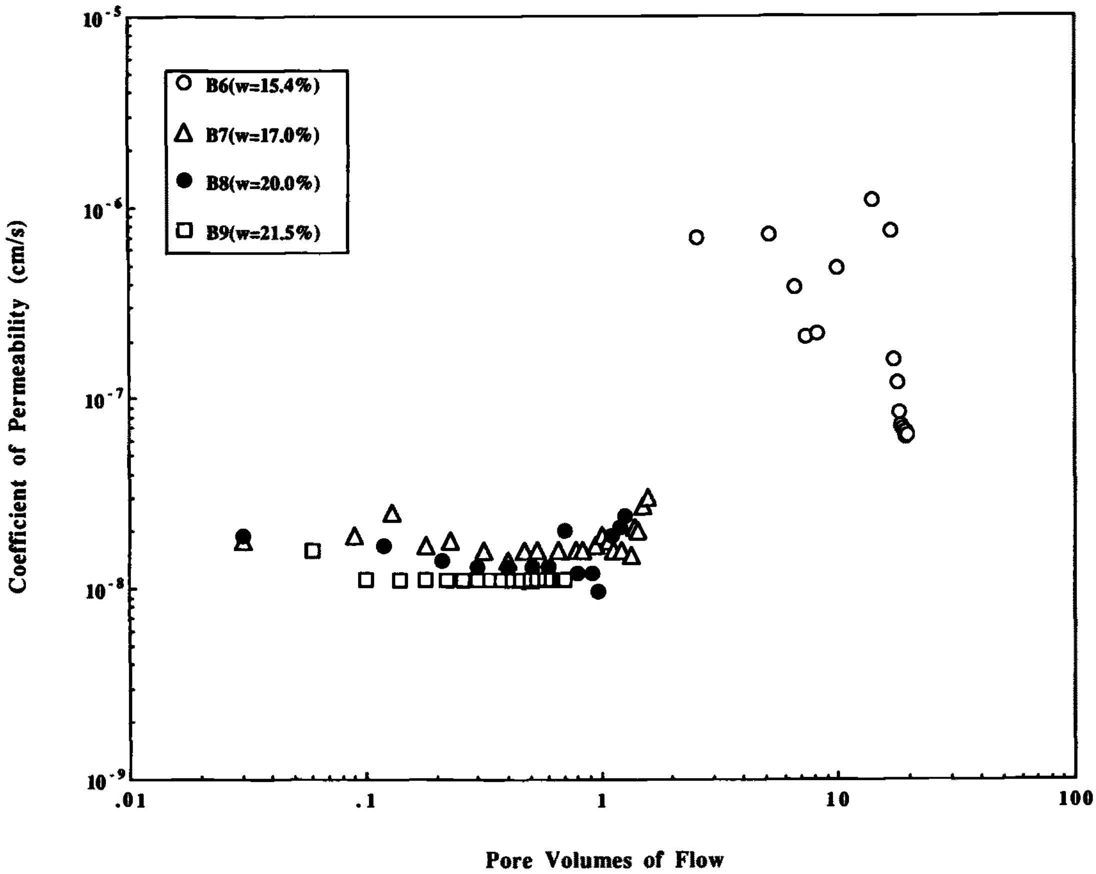

FIG. 6—*Permeability versus pore volumes for small-scale (Proctor mold) permeability tests for samples of soil passing the No. 4 sieve.*

For both small-scale and large-scale permeability tests, the permeability values of the natural soil samples (< 75 mm) are higher than the permeability values of the soil samples consisting only of the precompaction clod sizes passing the No. 4 sieve (< 4.75 mm). As a result, it appears that the effect of the incorporation of the larger precompaction clod sizes (i.e., 4.75 to 75 mm) into the overall soil matrix results in a higher permeability value for the natural soil samples (< 75 mm), regardless of the scale of permeameter.

For the specimens consisting of only the larger precompaction clod sizes (4.75 to 25 mm and 25 to 75 mm), the large-scale permeability values are 2.3 to 2.4 orders of magnitude higher than the corresponding values from the small-scale permeameter. However, for the specimens with a more gradual variation in precompaction clod sizes, i.e., < 4.75 and < 75 mm, the large-scale permeability values are only 1.2 and 0.6 orders of magnitude higher than the small-scale permeability values, respectively. For the soil samples with precompaction clod sizes less than 4.75 mm and less than 75 mm, the void spaces between the larger clods probably were filled with smaller clods, thus reducing the effect of the larger clod sizes on the permeability of the overall specimen.

The large-scale permeability value measured for the natural soil sample (T4) of 9.2×10^{-7} cm/s is higher than the calculated weighted-mean value of 3.8×10^{-6} cm/s based on the permeabilities of the proportions of the natural soil that are less than 4.75 mm, between 4.75 and 25 mm, and between 25 and 75 mm. This trend would not have been predicted from the small-scale test results, which indicated a lower measured permeability value for the natural soil sample relative to the calculated weighted-mean value. In the large-scale permeability test on the natural soil sample (T4), the smaller precompaction clod sizes (< 4.75 mm) apparently filled the void spaces between the larger precompaction clod sizes (4.75 to 75 mm), thereby reducing the effect of the larger precompaction clod sizes on the overall permeability of the natural soil sample. This was not the case in the small-scale permeability test on the natural soil because the permeability values for the samples consisting of only the larger precompaction clod sizes (i.e., 4.75 to 25 mm and 25 to 75 mm) are significantly lower than the corresponding values from the large-scale permeability tests. These lower permeability values measured in the small-scale permeability tests probably reflect a reduction during compaction in void sizes (i.e., due to smaller clod sizes) in the small-scale specimens relative to those in the large-scale specimens, possibly due to a greater degree of confinement experienced by the small-scale specimens. Therefore, in the small-scale permeability tests, the tendency to measure a lower permeability value for the natural soil sample apparently was offset by the incorporation of larger clod sizes into the overall soil matrix, whereas the tendency to measure a high permeability value for the natural soil sample in the large-scale permeameter was offset by the incorporation of smaller clod sizes in the void spaces between larger clod sizes.

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

Discussion

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 more strongly related to the precompaction clod sizes of the soil, with a higher permeability value being associated with larger precompaction clod sizes. Specimens in both types of permeameters were compacted at essentially the same water contents and dry unit weights, so the void ratio of the compacted soil in either case should have been about the same. However, the distribution of the voids is probably quite different. 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 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 is less effective in destroying all of the clods. Also, the large-scale compaction hammer probably is less effective in destroying clods than is the small-scale compaction hammer due to the larger cross-sectional area associated with the large-scale hammer. Therefore, in the large-scale permeameter, the soil is not well compacted, large clods become embedded in the soil matrix, and flow occurs between, rather than through, the clods with the resulting higher values of permeability. However, in the standard Proctor mold, the void ratio is relatively more uniform and, therefore, uniform vertical flow through the soil is more likely to occur in the small-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 others (Daniel 1981, 1984; Elsbury and Sraders 1989) for the discrepancy between the laboratory- and field-measured permeability of compacted clay soils.

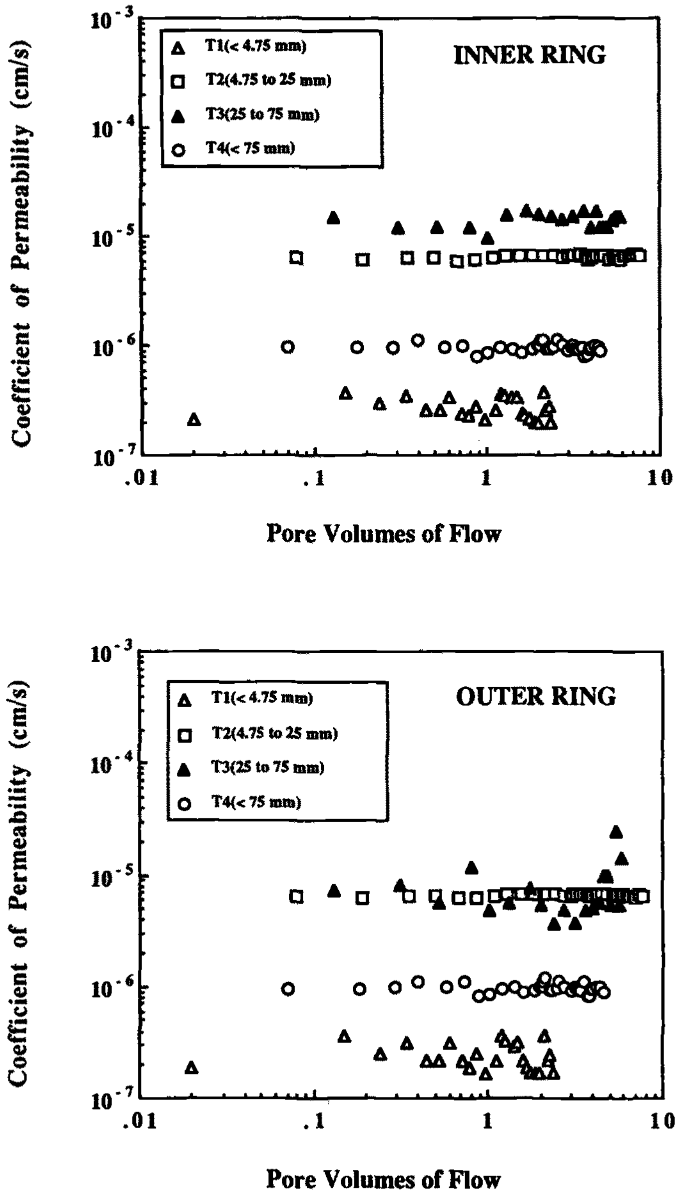

FIG. 7—*Permeability versus pore volumes for large-scale (double-ring) permeability tests.*

Summary and Conclusions

Based on the results of this study, there was a scale effect associated with laboratory permeability testing of a compacted silty clay soil, with higher permeability values being associated with large-scale permeability tests. The effect was more pronounced when a significant proportion of the soil sample tested consisted of relatively large precompaction clod sizes. Also, the ratio of the large-scale to small-scale permeability values was found to range from 0.6 to 2.4 orders of magnitude, which is consistent with the relationship reported for the ratio of field-measured to laboratory-measured (small-scale) permeability (Daniel 1981, 1984; Elsbury and Sraders 1989). As a result, it appears that a more realistic evaluation of the field-measured permeability of a compacted clay soil may be possible in the

TABLE 6—*Results of large-scale permeability tests.*

Test Designation	Precompaction Soil Clod Sizes, mm	Molding Water Content, %	As-Compacted Dry Unit Weight, kN/m^3	Permeability, cm/s		
				Outer Ring	Inner Ring	Average
T1	<4.75	20.7	16.71	2.0×10^{-7}	2.5×10^{-7}	2.2×10^{-7}
T2	4.75 to 25	20.9	16.68	6.5×10^{-6}	6.5×10^{-6}	6.5×10^{-6}
T3	25 to 75	20.7	16.71	9.0×10^{-6}	1.5×10^{-5}	1.2×10^{-5}
T4	<75	20.9	16.68	9.5×10^{-7}	9.0×10^{-7}	9.2×10^{-7}

NOTE: 1 kN/m^3 = 6.371 lb/ft^3.

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.

TABLE 7—*Comparison of large-scale and small-scale (Proctor mold) permeability results.*

Precompaction Soil Clod Sizes, mm	Measured Permeability, cm/s		K_{LS}/K_{SS}	
	Small-Scale, K_{SS}	Large-Scale[a], K_{LS}	Arithmetic Ratio	Orders of Magnitude
<4.75	1.5×10^{-8}	2.2×10^{-7}	15	1.2
4.75 to 25	2.5×10^{-8}	6.5×10^{-6}	260	2.4
25 to 75	7.0×10^{-8}	1.2×10^{-5}	180	2.3
<75	2.5×10^{-7}	9.2×10^{-7}	3.7	0.6

[a]Average of inner and outer ring values.

laboratory if the permeameter is sufficiently large to test a representative sample. However, due to the limited scope of this study, additional research is required to verify this implication. In particular, there is a need (1) to perform large-scale permeability tests on several different types of clay soil, (2) to correlate the compaction energy used in preparation of the soil samples for the different scales of laboratory permeability tests, (3) to correlate the compaction energy and type of compaction used in preparation of the soil samples for laboratory permeability tests versus that used in the field for construction, and (4) to perform field permeability tests for verification of the large-scale, laboratory-measured permeability values.

The natural soil in the air-dried state was found to consist primarily of aggregates of soil particles (clods) instead of individual particles. In addition, the permeability tests performed on the different fractions of the natural soil used in this study indicate that the larger (> 4.75 mm) precompaction clod sizes of the soil have a significant effect on the permeability of the compacted natural soil. Therefore, laboratory permeability tests performed on specimens which represent only the smaller clod sizes of the soil (e.g., the portion of the soil which passes the No. 4 sieve) probably will not be representative of the permeability of the overall soil. Based on the results of this study, laboratory permeability tests should be performed on specimens of the natural soil in which the full range of precompaction clod sizes is present. In addition, no effort should be made to break clods into smaller sizes or individual particles before preparation of specimens.

References

Day, S. R. and Daniel, D. E., August 1985, "Hydraulic Conductivity of Two Prototype Clay Liners," *Journal of Geotechnical Engineering*, ASCE, Vol. 111, No. 8, pp. 957–970.

Daniel, D. E., 1981, "Problems in Predicting the Permeability of Compacted Clay Liners," *Proceedings, Symposium on Uranium Mill Tailings Management*, Geotechnical Engineering Program, Department of Civil Engineering, Colorado State University, Fort Collins, CO, 26–27 Oct. 1981, pp. 665–673.

Daniel, D. E., February 1984, "Predicting Hydraulic Conductivity of Clay Liners," *Journal of Geotechnical Engineering*, ASCE, Vol. 110, No. 2, pp. 285–300.

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. Pettersson, Eds., American Society for Testing and Materials, Philadelphia, pp. 107–126.

Elsbury, B. R. and Sraders, G. A., April 1989, "Building a Better Landfill Liner," *Civil Engineering*, pp. 57–59.

Mitchell, J. K., Hooper, D. R., and Campanella, R. G., February 1965, "Permeability of Compacted Clay," *Journal of Geotechnical Engineering*, ASCE, Vol. 91, No. SM4, pp. 41–65.

Olsen, H. W., 1962, "Hydraulic Flow through Saturated Clays," *Clays and Clay Minerals*, Vol. 9, pp. 131–161.

Olson, R. E. and Daniel, D. E., 1981, "Measurement of Hydraulic Conductivity of Fine-Grained Soils," *Permeability and Groundwater Contaminant Transport, ASTM STP 746*, T. F. Zimmie and C. O. Riggs, Eds., American Society for Testing and Materials, Philadelphia, pp. 18–64.

Copyright by ASTM Int'l (all rights reserved); Fri Sep 18 14:30:12 EDT 2009
Downloaded/printed by
Colorado State Univ pursuant to License Agreement. No further reproductions authorized.