

THESIS

STANDARDIZED HYDRAULIC CONDUCTIVITY TESTING OF COMPACTED
SAND-BENTONITE MIXTURES

Submitted by

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ABSTRACT

STANDARDIZED HYDRAULIC CONDUCTIVITY TESTING OF COMPACTED SAND-BENTONITE MIXTURES

Compacted clay liners (CCLs) are commonly required as engineered barriers in waste containment applications (e.g., disposal of municipal solid waste) to protect groundwater from waste derived leachate. Typically, the primary consideration in the design and evaluation of a CCL is the achievement of suitably low hydraulic conductivity, k (e.g., $k < 10^{-9}$ m/s), so as to minimize the flow of leachate through the barrier into the surrounding environment. In cases where suitable natural clay is not available for use as a CCL, a compacted mixture of sand with a low percentage of sodium bentonite (≤ 15 % by dry weight) has been considered as an alternative CCL, primarily on the basis of ability of compacted sand-bentonite (SB) mixtures to achieve suitably low k values.

Standard test procedures for laboratory measurement of the k of saturated soils, such as ASTM D5084 *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*, are used extensively to evaluate the suitability of clays proposed for use in CCLs. However, no systematic evaluation of the standard has been conducted with respect to the measurement of k of compacted SB mixtures. Thus, this study was undertaken to evaluate the appropriateness of ASTM D5084 for measuring the k of compacted SB mixtures. In particular, five factors were evaluated with respect to the application of ASTM D5084 for measuring the k of compacted SB mixtures, viz, (1) the length of the test specimen, L (i.e., 29.1, 58.3, and 116.0 mm), (2) the magnitude of the applied hydraulic gradient,

i , to induce flow (i.e., 30 ± 1.5 vs. 60 ± 3.0), (3) the manner in which i was imposed (i.e., increasing only the headwater pressure vs. increasing the headwater pressure and decreasing the tailwater pressure), (4) the bentonite content, BC , of the SB mixture (i.e., 5, 10, and 15 % by dry weight), and (5) the type of permeant water (i.e., tap water vs. "standard water" or 10 mM CaCl_2). All of these factors were evaluated by performing k tests in accordance with ASTM D5084-10 on replicated specimens. In addition, most of the k tests were continued beyond the time required by the termination criteria defined in ASTM D5084-10 to evaluate the effect of test duration on the measured k values.

The effect of specimen length on the measured k was minor for the two thinner specimens ($L = 29.1$ mm and $L = 58.3$ mm), with the measured k values ranging from 1.2×10^{-11} m/s to 1.6×10^{-11} m/s. However, the measured k values for the thickest specimens ($L = 116.0$ mm) were more variable ranging from 1.1×10^{-11} m/s to 1.8×10^{-10} m/s. This greater variability in k was attributed to the increasing amount of bentonite with increasing size of specimen (i.e., at the same BC of 10 %), and the greater decrease in effective stress within the specimen required to maintain the same i of 30 with increasing L of specimen.

With respect to the magnitude of i , the measured k increased by approximately half an order of magnitude as i increased from 30 to 57, all other factors being the same. This increase in k with increasing i was consistent with an overall decrease in effective stress, σ' , in the specimens resulting from the application of the higher i .

With respect to bentonite content, the measured k values decreased by a factor ranging from approximately 1 to 1.5 as BC increased from 5 % to 15 %, respectively. However, some of the specimens containing 5 % bentonite exhibited particle migration due to the rapid application of the hydraulic gradient of 30. This issue of particle migration was overcome to some extent by

applying the hydraulic gradient of 30 incrementally, so as to allow the bentonite sufficient time to hydrate and swell.

In addition, despite a reasonable k value of 3.7×10^{-12} m/s for one of the specimens containing 15 % bentonite, the specimen exhibited negative outflow, which was attributed to the greater uptake of water by the bentonite relative to the amount of water flowing through the specimen due to the applied i . This result occurred because ASTM D5084-10 requires that the average of the inflow and outflow be used in the calculation of k , and the magnitude of the positive inflow was greater than the magnitude of the negative outflow. As a result, the use of the average of the inflow and outflow to calculate k in accordance with ASTM D5084-10 may result in reasonable estimates of k despite nonsensical flow behavior for compacted SB specimens with relatively high BC s.

With respect to the type of permeant water, the measured k for compacted SB specimen containing 10 % bentonite increased by less than an order of magnitude as the electrical conductivity of the permeant water increased from 13 mS/m (tap water) to 240 mS/m (standard water). This increase in k is consistent with a greater extent of interaction between the standard water with higher ionic strength and the bentonite, and suggests that the use of standard water as the permeant water in accordance with ASTM D5084-10 is likely to result in higher measured values of k relative to the use of tap water, which is also allowed by ASTM D5084-10.

The overall results of the research generally support the use of ASTM D5084-10 to measure k of compacted SB mixtures with BC ranging from 5 % to 15 %, for the range of test conditions and permeant solutions evaluated in this study. However, for testing specimens with BC below 5 %, special precautions may be required to avoid particle migration during permeation. In addition, when testing specimens with high BC (e.g., 15 %), negative outflow

may occur due to swelling of the bentonite such that the use of the equation for calculating k based on the average of the inflow and outflow in accordance with ASTM D5084-10 Method A may no longer be appropriate.

Finally, for the specimens that were permeated beyond the time required by the termination criteria in ASTM D5084-10, the final values of k were less than or equal to the values of k based on the standard termination criteria in the majority (79 %) of the tests. Thus, the values of k determined on the basis of the standard termination criteria in ASTM D5084-10 for the compacted SB specimens evaluated in this study generally were conservative (high) relative to those based on longer term permeation.

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CHAPTER 1. INTRODUCTION

1.1 Background

1.1.1 *Compacted Clay Liners*

Compacted clay liners (CCLs) are commonly used as engineered barriers for waste containment applications (e.g., municipal solid waste landfills, hazardous waste disposal) to limit the migration of contaminants into the surrounding environment and groundwater. Typically, CCLs are comprised of fine-grained silts and clays or admixtures of coarse-grained soils with high swelling clays (e.g., bentonite). The CCL material is compacted in lifts to form a 0.3-m to 0.9-m-thick barrier with low hydraulic conductivity (k), typically on the order of $\leq 10^{-9}$ m/s, to minimize advective (hydraulically driven) transport of contaminants (National Academies Press 2007).

1.1.2 *Compacted Sand-Bentonite Mixtures*

Sodium bentonite is commonly used in engineered barriers for waste containment applications due to the ability of the clay to exhibit high swell and low k (Gates et al. 2009). Compacted mixtures comprised of sand with a relatively small portion of bentonite (i.e., < 15 % by dry weight) have been shown to provide acceptably low values of k for use in CCLs (e.g., Lundgren 1981; Alther 1982, 1987; Garlanger et al. 1987; Cowland and Leung 1991; Chapuis et al. 1992; Shackelford 1994; O'Sadnick et al. 1995; Sällfors and Öberg-Högsta 2002; Teachavorasinskun 2006; Wang et al. 2013; Akgün 2015). Thus, compacted sand-bentonite (SB) mixtures are a common alternative for CCLs when a suitable source of natural clay is unavailable.

1.1.3 *Hydraulic Conductivity Testing*

Laboratory hydraulic conductivity tests, performed with rigid-wall (e.g., oedometer cells or compaction molds) or flexible-wall (triaxial) permeameters, typically are required to estimate the k of barrier materials (Olson and Daniel 1981; Zimmie et al. 1981; Daniel et al. 1985). Flexible-wall tests typically are preferred, as this test method allows for control of the effective stress conditions and degree of saturation by back-pressure, and prevention of side-wall leakage during permeation via use of a latex membrane maintained in close contact with the specimen (Black and Lee 1973). The current ASTM standard for flexible-wall k testing of saturated soils is ASTM D5084-10 *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*. This ASTM standard provides guidelines and recommendations regarding testing apparatus, specimen preparation, saturation of the specimen using back-pressure, method of hydraulic gradient application, maximum hydraulic gradient applied during permeation, type of permeant water, method of measurement and calculation of k , and criteria for termination of the test.

1.1.4 *Factors Affecting Hydraulic Conductivity of Soils*

The hydraulic conductivity, k , represents the ease with which a fluid (permeant liquid) can flow through a porous medium (e.g., soil) via advection, and is proportional to the volumetric flow rate (Q), in accordance with Darcy's law, as follows:

$$Q = kiA \tag{0.1}$$

where i is the hydraulic gradient and A is the cross-sectional area of the porous material perpendicular to the direction of flow. The value of i is equal to the difference in hydraulic total head across the specimen (Δh) divided by the length of the specimen in the direction of flow (L) (i.e., $i = -\Delta h / L$).

The value of k for a soil is a function of the properties of the soil matrix as well as the properties of the permeant liquid, as follows (e.g., Shackelford 1994):

$$k = K \left(\frac{\gamma}{\mu} \right) = K \left(\frac{\rho g}{\mu} \right) \quad (0.2)$$

where K is the intrinsic permeability of the soil, γ is the unit weight of the permeant liquid, μ is the dynamic viscosity of the permeant liquid, ρ is the mass density of the permeant liquid, and g is the acceleration due to gravity. The intrinsic permeability is affected by the soil type, particle size, void ratio, pore size distribution, and homogeneity of the soil. In addition to μ and γ , other properties of the permeant liquid that may affect k include the ionic strength and pH of the liquid (Shackelford 1994).

Previous research focused on the measurement of k of compacted SB mixtures has included evaluation of the effects of hydraulic gradient (e.g., Dunn 1985; Daniel 1994), effective stress (e.g., Shackelford 2000), soil fabric (e.g., Lambe and Whitman 1969; Kenney et al. 1992; Mollins et al. 1996; Stewart et al. 2003), bentonite content (e.g., Lundgren 1981; Daniel 1987; Garlanger et al. 1987; Chapuis et al. 1990; Cowland and Leung 1991; Kenney et al. 1992; Marcotte et al. 1994; O'Sadnick et al. 1995; Mollins et al. 1996; Komine and Ogata 1996; Alston et al. 1997; Gleason 1997; Howell and Shackelford 1997; Stern and Shackelford 1998;

Abichou et al. 2000; Abichou et al. 2002; Sällfors and Öberg-Högsta 2002; Thomson and Foose 2005; Mishra et al. 2009), and permeant liquid (Gipson 1985; Alther 1987; Shackelford 1994; Gleason et al. 1997; Stern and Shackelford 1998; Lo et al. 2004). Results of these studies relevant to this research are summarized subsequently.

1.1.4.1 Hydraulic Gradient

Permeation with relatively high values of i may cause particle migration within the specimen, changing the measured value of k due to clogging or loss of fine particles. In addition, application of high hydraulic gradients also may result in measurement of lower values of k due to high seepage forces (Dunn 1985; Daniel 1994). Shackelford et al. (2000) reported that the observed effects of using a high value of i on the measured values of k are due primarily to the related changes in the effective stress conditions and changes in the soil fabric.

1.1.4.2 Bentonite Content

The effect of bentonite content, BC , on the k of compacted sand-bentonite mixtures has been studied extensively, resulting in the well-established trend of decreasing k with increasing BC (e.g., Lundgren 1981; Daniel 1987; Garlanger et al. 1987; Chapuis et al. 1990; Cowland and Leung (1991); Kenney et al. 1992; Marcotte et al. 1994; O'Sadnick et al. 1995; Mollins et al. 1996; Komine and Ogata 1996; Alston et al. 1997; Gleason 1997; Howell and Shackelford 1997; Stern and Shackelford 1998; Abichou et al. 2000; Abichou et al. 2002; Sällfors and Öberg-Högsta 2002; Thomson and Foose 2005; Mishra et al. 2009). Based on the results of k tests, Garlanger et al. (1987) indicated that a minimum BC of 6 % was required to achieve an adequate distribution of bentonite in the compacted SB mixture with a low k of 1×10^{-10} m/s.

Cowland and Leung (1991) reported bentonite-soil mixtures with 5 % *BC* resulted in an uneven distribution of bentonite in the soil matrix, and recommended a minimum *BC* of 7 % for soil-bentonite liners to prevent preferential flow paths. Kenney (1992) also found that the bentonite cannot be adequately distributed within compacted SB mixtures with *BC* values less than 7 %.

Marcotte et al. (1994) investigated the occurrence of particle migration in compacted SB mixtures with relatively low *BC* (< 5 %). Marcotte et al. (1994) found that the bentonite content and the fines content of compacted SB mixtures have influence on soil structure stability, and can affect the possibility of particle migration. Marcotte et al. (1994) also identified a "bentonite washing domain" zone with low bentonite content (< 5 %) and fines content (< 8 %) corresponding to measurement of relatively high *k* values (i.e., 2×10^{-5} m/s). Finally, Sällfors and Öberg-Högsta (2002) indicated a the typical range of *BC* used for compacted SB mixtures for barrier applications ranging from 4 to 13 % based on the results in the literature and the high cost of bentonite addition and construction. As a result of consideration of all of the aforementioned factors affecting the *BC*, a *BC* range of 5 to 15 % was used for the compacted SB mixtures in this study.

1.1.4.3 Soil Fabric

A trend of increasing *k* in accordance with increasing void ratio, *e*, or porosity, $n (= e/(1 + e))$ of compacted SB mixtures has been widely reported (e.g., Lambe and Whitman 1969; Kenney et al. 1992; Mollins et al. 1996; Stewart et al. 2003). Several theoretical models have been developed to investigate the relationship between the soil matrix properties (*e* or *n*) and *k*. For example, a theoretical model of an "ideal mixture" was developed by Kenney et al. (1992) to

predict the minimum k of compacted SB mixtures. In this model, the compacted SB mixture was assumed to be a homogeneous mixture that consisted of dry impervious sand particles forming the soil matrix and saturated bentonite filling the pore spaces, with all water in the soil mixture being associated with the bentonite. Based on this model, Kenney et al. (1992) reported that the k of the ideal mixture would be controlled by the k of the bentonite, which is only controlled by the fabric and the void ratio of the bentonite.

In addition to development of theoretical models, the microstructure of simulated SB mixtures containing low BC ($< 10\%$) has been investigated using optical micrography (OM), and scanning electron microscopy (SEM) in order to investigate the bentonite distribution in the soil matrix (Abichou et al. 2002). Based on the results from OM and SEM, Abichou et al. (2002) reported that the mechanism of void filling for powdered bentonite versus granular bentonite are different, viz., the powdered bentonite fills the pore space by coating the sand particles, whereas the granular bentonite fills the pore space by occupying the pore space between the sand particles and then swelling. Also, the model of an "ideal mixture" generated by Kenney et al. (1992) was considered not applicable for compacted SB mixtures containing low BC ($< 4\%$ for powdered bentonite and $< 8\%$ for granular bentonite).

1.1.4.4 Permeant Liquid

Based on the literature, the measured k of compacted soil-bentonite mixtures when permeated with chemical solutions can be significantly higher than that of the identical mixtures permeated with water (e.g., Gipson 1985; Alther 1987; Shackelford 1994; Gleason et al. 1997; Stern and Shackelford 1998; Lo et al. 2004; Shariatmadari et al. 2011). For example, Alther (1987) reported that the k of a compacted SB specimen containing 8% bentonite increased by a

factor of 700 when permeated with a 2 % CaCl_2 solution relative to those permeated by water. Shackelford (1994) found that the k of the a SB mixture containing 16 % BC increased by approximately 2.8 orders of magnitude when permeated with a calcium saturated tailings solution relative to that of a similar specimen permeated by water. Finally, Gleason et al. (1997) indicated that the measured k of the mixtures increased by approximately 1.2 orders of magnitude when permeated with 1.5 M CaCl_2 relative to those permeated with water.

1.2 Objective of Research

Although ASTM D5084-10 has been used extensively to measure k of a variety of soil types, there has not been a systematic evaluation of the laboratory measurement of k of compacted SB mixtures to identify potential limitations of the standard or special testing requirements. Thus, this study was undertaken to evaluate the appropriateness of the procedures described in ASTM D5084-10 when applied to the measurement of k of compacted SB mixtures. In addition, variations in the k testing procedure, all of which fell within the guidelines of ASTM D5084-10, were evaluated to identify potential effects on the measured k of the SB mixtures. The objectives to achieve these two goals of the research were as follows:

- a) evaluate the relationship between measured values of k versus several factors: (1) the length, L , of the test specimen; (2) the magnitude of the applied hydraulic gradient, i ; (3) the method of hydraulic gradient application; (4) the bentonite content, BC ; and (5) the type of permeant water;

- b) compare the measured values of k according to the ASTM D5084-10 termination criteria versus the values of k measured when the permeation tests were extended to longer durations (i.e., after the termination criteria were achieved); and
- c) evaluate and identify potential limitations of application of ASTM D5084-10 to k testing of compacted SB mixtures.

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CHAPTER 2. STANDARDIZED HYDRAULIC CONDUCTIVITY TESTING OF COMPACTED SAND-BENTONITE MIXTURES

2.1 Introduction

Compacted clay liners (CCLs) commonly are required as engineered barriers in waste containment applications to protect groundwater from waste derived leachate (Lambe 1954; Mitchell et al. 1965; Garcia-Bengochea et al. 1979; Boynton and Daniel 1985; Acar and Oliveri 1989; Benson and Daniel 1990; Benson et al 1994; Chapuis 2013). In this regard, achieving a suitably low hydraulic conductivity, k , of the CCL, typically on the order of less than or equal to 10^{-9} m/s, generally is the primary consideration in order to minimize the amount of leachate migrating through the CCL (Gordon et al. 1984; Daniel 1990; Rowe and Fraser 1995; Bou-Zeid and El-Fadel 2004). In cases where a suitable natural clay is not available for use as a CCL, a compacted mixture of sand with a low percentage of sodium bentonite, typically less than or equal to about 15 % by dry weight, often is considered as an alternative to a natural clay CCL (Lundgren 1981; Alther 1982, 1987; Gipson 1985; Garlanger et al. 1987; Cowland and Leung 1991; Haug and Wong 1992; Kenney et al. 1992; Chapuis et al. 1992; Daniel 1993; Shackelford 1994; O'Sadnick et al. 1995; Mollins et al. 1996; Gleason et al. 1997; Howell and Shackelford 1997; Stern and Shackelford 1998; Abichou et al. 2000, 2002; Sällfors and Öberg-Högsta 2002; Lo et al. 2004; Teachavorasinskun 2006; Wang et al. 2013; Liu et al. 2014; Akgün 2015). Although these studies generally document the ability of compacted sand-bentonite (SB) mixtures to achieve suitably low k values, no systematic evaluation of the measurement of the k of compacted SB mixtures with respect to a recognized testing standard has been undertaken.

Accordingly, a study was undertaken to evaluate the measurement of k of compacted SB mixtures in accordance with ASTM D5084-10 *Standard Test Methods for Measurement of*

Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter. The potential effects of five factors on the measurement of k of compacted SB mixtures in accordance with ASTM D5084-10 were evaluated. These factors included: (1) length of specimen (i.e., 29.1, 58.3, and 116.0 mm); (2) magnitude of applied hydraulic gradient, i (i.e., 30 vs. 60); (3) manner of imposing i (i.e., increasing only the headwater pressure vs. increasing the headwater pressure and decreasing the tailwater pressure); (4) bentonite content, BC (i.e., 5, 10, and 15 % by dry weight); and (5) type of permeant water (i.e., tap water vs. "standard water" or 10 mM CaCl₂). Conclusions are drawn with respect to the influence of each of these factors on the standardized measurement of the k of compacted SB mixtures, and recommendations are provided relative to the application of ASTM D5084-10 for measurement of k of compacted SB mixtures with bentonite contents ranging from 5 % to 15 %.

2.2 Materials and Methods

2.2.1 Liquids

Three liquids were used in this study, viz., de-ionized water (DIW), tap water (TW), and "standard water" (SW). The chemical properties of all three liquids are summarized in Table 2.1. The electrical conductivity (EC) and pH were measured using an Orion Conductivity Cell (product Orion 013005MD, Thermo Fisher Scientific, Waltham, MA) and Orion Ross Ultra pH/ATC Triode (product Orion 8157BNUMD, Thermo Fisher Scientific Waltham, MA), respectively. The concentrations of anion and cation in TW and SW were measured by ion chromatography, IC (Dionex® 4000i 131 IC Module, Dionex Co., Sunnyvale, CA), and inductively coupled plasma-atomic emission spectrometry, ICP-AES (IRIS® Advantage/1000 ICAP Spectrometer, Thermo Jarrel Ash Co., Franklin, MA), respectively. Both IC and ICP-AES

analysis were performed by the Soil, Water and Plant Testing Laboratory, in Colorado State University, Fort Collins, CO.

The DIW ($EC = 1$ mS/m, $pH = 7.0$) was used for measurement of the Atterberg limits (ASTM D4318-10) of the bentonite. The TW ($EC = 13$ mS/m, $pH = 7.0$) also was used for measurement of the Atterberg limits of the bentonite and SB mixtures, as the mixing liquid for preparing wetted mixtures of the sand and bentonite for compaction, and as a permeant water for hydraulic conductivity testing as allowed by ASTM D5084-10 (see section 6.1.2). Finally, the SW in the form of a solution of 10 mM $CaCl_2$ ($EC = 240$ mS/m, $pH = 5.5$) was used as a permeant water as allowed in ASTM D5084-10 (see section 6.1.2.1) to determine the effect, if any, of permeating with "standard water" relative to permeating with tap water. As a result of the significantly greater EC for the SW relative to that of the TW, the ionic strength, I , of the SW ($I = 30$ mM) was expected to be significantly greater than that of the TW (e.g., Griffin and Jurinak 1973). The k of bentonite based barriers, such as geosynthetic clay liners, has been shown to increase with increasing I of the permeant water, all other factors being equal (Kolstad et al. 2004).

Although not required by ASTM D5084-10, a biocide (product QK-20 Antimicrobial, The Dow Chemical Company, Midland, MI) at a concentration of 0.5 g/L was added to the permeant water, because preliminary hydraulic conductivity testing conducted on compacted SB mixtures permeated with TW indicated the potential for biological clogging (see Appendix A). The addition of the small amount of biocide to the TW and SW resulted in slightly higher EC values (i.e., $\Delta EC < 2$ mS/m), and little effect in terms of the pH of the different permeant water ($\Delta pH < 0.50$).

2.2.2 *Constituent Soils*

The constituent soils used for the soil mixtures included sand and bentonite. The grain-size distributions (ASTM D422-63) of these two constituent soils are shown in Fig. 2.1, and a summary of the properties of each constituent soil is provided in Table 2.2.

The sand was Ottawa silica fine sand (product F-60, U.S.Silica, Frederick, MD) with no fines (see Fig. 2.1). The measured specific gravity of the sand (ASTM D854-10) was 2.66, and the sand classified as poorly graded sand (SP) based on the Unified Soil Classification System (ASTM D2487-11).

The bentonite was a Wyoming sodium bentonite referred to as "natural gel" (Wyo-Ben, Inc., Billings, MT). Based on the particle-size distributions shown in Fig. 2.1, the bentonite contained 87.4 % clay-sized particles based on the ASTM D422-63 definition of < 0.005 mm, and 82.8 % clay-sized particles based on the common practical definition of < 0.002 mm. Based on the results of the mineralogical analysis (Mineralogy, Inc., Tulsa, OK), the bentonite consisted of 70 percent montmorillonite, 15 percent albite feldspar, 9 percent quartz, 3 percent K-feldspar-microcline, 2 percent illite/mica and 1 percent calcite. Both bound cations and soluble metals of the bentonite were analyzed using ICP-AES (IRIS® Advantage/1000 ICAP Spectrometer, Thermo Jarrel Ash Co., Franklin, MA) by the Soil, Water and Plant Testing Laboratory, in Colorado State University, Fort Collins, CO. The measured total bound cations (or exchangeable metals) in the bentonite was 86.1 cmol/kg (ASTM D7503-10), which was reasonably close to typical values of cation exchange capacity (CEC) for Wyoming sodium bentonite. The measured soluble metals (ASTM D7503-10) in the bentonite consisted 4183.1 mg/kg of Na⁺, 183.4 mg/kg of K⁺, 91.5 mg/kg of Ca²⁺ and 14,9 mg/kg of Mg²⁺, which confirmed that the sodium ion is the domain cation in the bentonite. The measured soil pH (ASTM

D4972-01) for the bentonite was 9.7 determined with DIW. The measured specific gravity of the bentonite (ASTM D854-10) was 2.81. The measured liquid limit (*LL*), plastic limit (*PL*) and plastic index (*PI*) of the bentonite using DIW (based on ASTM D4318-10) were 426 %, 33 % and 393 %, respectively. Based on these Atterberg limits and the grain-size distribution for the bentonite, the bentonite classified as high plasticity clay (CH) according to ASTM D2487-11.

2.2.3 Sand-Bentonite Mixtures

Sand-bentonite (SB) mixtures with three bentonite contents, *BC*, of 5 %, 10 %, or 15 % by dry weight, were evaluated in this study. The Atterberg limits also were measured for each SB mixture using both DIW and TW. The use of DIW is in accordance with ASTM D4318-10, whereas measurement of the Atterberg limits using TW was conducted to correlate the use of TW as a permeant water for measurement of *k*. The values for the Atterberg limits of the SB mixtures are summarized in Table 2.3. As shown in Table 2.3, the Atterberg limits measured with TW were essentially the same as those measured with DIW for the SB mixtures with bentonite contents of 5 to 15 %.

The values for the *PI* of the SB mixtures in this study are shown as a function of clay particle content (i.e., % < 0.002 mm) in Fig. 2.2. Since the clay content of the sand and the bentonite used in this study were 0.0 % and 82.8 %, respectively (Fig. 2.1), the clay particle contents in the SB mixtures were 4.1 %, 8.3 % and 12.4 %, corresponding to *BC*s of 5 %, 10 % and 15 %, respectively. The activity, *A*, of each soil mixture is given by the slope of a linear relationship between *PI* and the clay content as follows (Seed et al. 1964a):

$$A = \frac{\Delta PI}{\Delta(\% < 0.002mm)} \quad (2.1)$$

Seed et al. (1964a) reported the value of pure kaolinite and pure montmorillonite were 0.4 and 5, respectively. The value for A of 3.5 for the SB mixtures evaluated in this study is similar to, but lower than, the value for A of 4.2 for the SB mixtures evaluated by Howell et al. (1997). Thus, despite the use of different constituent soils for the sand-bentonite mixtures in the two studies, the values of A from both studies are consistent. Moreover, based on the classification system developed by Skempton (1953) where a clay with a value for A greater than 1.25 was defined as an "active clay," the SB mixtures from both this study and that by Howell et al. (1997) would be considered to be active clays.

2.2.4 *Compaction of Sand-Bentonite Mixtures*

The SB mixtures evaluated in this study were compacted in accordance with the following procedure. First, the appropriate masses of sand and bentonite were mixed with TW. The measured air-dried (hygroscopic), gravimetric water content of the bentonite, which varied from 9.3 to 11.0 %, was included in the initial water content of each SB mixture. The sand and bentonite then were added into a 0.3-m-diameter bucket in layers that were approximately five to nine mm in thickness, and a sufficient amount of TW was sprayed and mixed into each layer to achieve a desired, initial gravimetric water content, w , for compaction. The final, wetted mixtures typically consisted of five or six layers representing approximately $2.12 \times 10^{-3} \text{ m}^3$ of wetted soil mixture. The wetted soil mixture was sealed in the bucket and preserved in a humidity chamber that maintained a constant humidity of 75 % at a constant temperature of 23

°C for a minimum curing period of 48 hours. After the first 24 hours of curing, the wetted soil mixture was cut by a spatula into small pieces, mixed, sealed, and then allowed to cure for another 24 hours in an attempt to impart an even distribution of water and bentonite in the soil mixture.

After the 48-hour curing period, the SB mixture was removed from the mixing bucket, and pushed by hand through a No. 4 (4.75 mm) sieve in accordance with the procedures described in the ASTM D698-12 for standard (Proctor) compaction (see Appendix B). The weight of soil particles retained on the sieve typically was less than two percent of the weight of the total soil mixture, and the material passing the No. 4 sieve (4.75 mm) was used to prepare the compacted SB specimens in accordance with ASTM D698-12.

In order to evaluate the potential effect of size of specimen on the measured k , three different sizes of test specimens were prepared for a SB mixture with a BC of 10 % (see Table 2.4). The full-size specimens correspond to those extruded from a standard compaction mold (ASTM D698-12) after compaction, whereas the half-size and quarter-size specimens represent specimens with essentially the same cross-sectional areas as that of the full-size specimen (i.e., 0.0081 m^2), but with approximately one half and one quarter of the length of the full-size specimen, respectively (see Appendix C).

As a result of the three different lengths of compacted specimens, three compaction curves were measured for each SB mixture using the full-sized, half-sized and quarter-sized compaction molds following the procedure described by Cotton et al. (1998). In this procedure, the compaction of half-sized specimens was achieved by using two lifts of soil with 19 blows for each lift, whereas the compaction of quarter-sized specimens was achieved by using one lift of soil with 19 blows. The compaction energies of quarter-sized and half-sized specimens were ~99

% and ~101 %, respectively, of the approximate standard compaction energy of 600 kN-m/m³ (12,400 ft-lb/ft³) specified in ASTM D698, or ~99 % and ~101 % of the exact standard compaction energy of 593 kN-m/m³ (12,426 ft-lb/ft³).

The resulting compaction curves are shown in Fig. 2.3. Based on the considerations described by Howell et al. (1997), each compaction curve was regressed with a third-order polynomial to determine the values for the maximum dry unit weight, $\gamma_{d,max}$, and the optimum water content, w_{opt} . The resulting values of $\gamma_{d,max}$ and w_{opt} for each mixture are summarized in Table 2.5.

2.2.5 Acceptable Zones

Despite evidence that the k of compacted SB mixtures is relatively insensitive to the compaction (molding) water content (e.g., Haug and Wong 1992; Kraus et al. 1997), an acceptable zone (AZ) as described by Daniel and Benson (1990) was developed for each compacted SB mixture. An AZ represents the zone of acceptable values of the molding (compaction) water content, w , and dry unit weight, γ_d , required to impart a specified engineering property, which in this case is a suitably low value of k . In this study, the boundaries for the AZ were considered to consist of the zero air voids (ZAV) curve as the upper bound on both w and γ_d , and a curve of constant saturation corresponding to the optimum water content, designated as S_o as the lower bound, as suggested by Benson et al. (1999) and Yesiller and Shackelford (2011). The ZAV curve represents the relationship between w and γ_d , corresponding to 100 % saturation, which is a function of the specific gravity, G_s , of the soil mixture, where the G_s of the soil mixture is given by the harmonic mean of the values of G_s for the individual soil constituents as follows:

$$G_s = \frac{\sum_{i=1}^n W_i}{\sum_{i=1}^n \frac{W_i}{G_{s,i}}} \quad (2.2)$$

where W_i is the dry weight of each soil constituent in the SB mixture, and $G_{s,i}$ is the specific gravity of each soil constituent. The resulting AZs for each SB mixture are shown in Figs. 2.4 and 2.5.

2.2.6 Hydraulic Conductivity Testing

The specimens for hydraulic conductivity testing were mixed at a target water content that was one percentage point wetter than w_{opt} for the specific SB mixture in an attempt to ensure that all specimens would lie within the corresponding AZs. The initial water content for each compacted specimen was based on the trimmings of the wetted soil mixture during compaction. Following compaction, trimming, and extrusion, the k of each compacted specimen was measured in flexible-wall permeameters in accordance with ASTM D5084-10.

Schematic diagrams of the flexible-wall cell and the entire testing apparatus are shown in Fig. 2.6. Each specimen was back-pressured using the permeant water (i.e., TW or SW with added biocide) at an effective stress of 34.5 kPa (5 psi) to achieve a B value of at least 0.95 prior to permeation in accordance with ASTM D5084. Pore-water pressures were measured with pressure transducers (S5456 Portable Pore Pressure Systems, Geotest Instrument Corporation, Burr Ridge, IL) with an accuracy of ± 0.69 kPa (± 0.1 psi).

Permeation commenced upon completion of the back-pressure stage of the test in accordance with constant-head (constant-gradient) conditions (Method A in ASTM D5084-10).

For the base case of this study, the headwater (bottom) pressure was increased by 17.25 kPa (2.5 psi) resulting in an applied i of 30, such that the permeant water would flow upward through the specimen. Note that this method of gradient application is specified for Method A in ASTM D5084-10 (see section 9.5.2) so as to not reduce the back pressure and allow air bubbles to reappear in the system. Also, the upper limit of 30 for i was chosen on the assumption that the measured k values for all specimens would be lower than 10^{-9} m/s in accordance with ASTM D5084-10 (see section 9.5.1). The values for k were calculated based on the following equation from Method A in ASTM D5084-10 (see Eq. 1 in section 10.1.1):

$$k = \frac{\Delta V \cdot L}{A \cdot \Delta h \cdot \Delta t} = \frac{(\Delta V_{in} + \Delta V_{out}) \cdot L}{(\Delta h_1 + \Delta h_2) \cdot A \cdot \Delta t} \quad (2.3)$$

where ΔV is the volume of flow for given time interval Δt taken as the average of incremental volumes of inflow (ΔV_{in}) and outflow (ΔV_{out}) (i.e., $\Delta V = ((\Delta V_{in} + \Delta V_{out})/2)$, L is the length of specimen, A is the cross-sectional area of specimen, Δh is the average head loss across the specimen (i.e., $\Delta h = (\Delta h_1 + \Delta h_2)/2$), where Δh_1 is the head loss across the specimen at the start of permeation per time interval, and Δh_2 is the head loss across the specimen at the end of permeation per time interval. Note that ΔV in Eq. 2.3 is designated as ΔQ in ASTM D5084-10 for incremental quantity of flow.

For some of the specimens containing the lowest BC of 5 %, rapid application of a hydraulic gradient of 30 resulted in particle migration (piping) and washout of bentonite from the specimen (e.g., Mitchell and Younger 1967). This particle migration was evident visually by murkiness in the tailwater (see Appendix D), and resulted in high measured values of k (i.e., $k >$

1.0×10^{-8} m/s). As a result, the hydraulic gradient for specimens containing 5 % bentonite was increased gradually in small increments ($\Delta i \leq 5$) from 0 to 30 in order to minimize the likelihood of particle migration.

For all specimens, permeation continued until the termination criteria specified in ASTM D5084-10 were achieved. These termination criteria are as follows:

- (1) at least four values of the ratio of outflow to inflow between 0.75 and 1.25, and
- (2) four or more consecutive k values within ± 25 % of the "mean" value (k_{mean}) for $k \geq 1 \times 10^{-10}$ m/s or within ± 50 % of k_{mean} when $k < 1 \times 10^{-10}$ m/s.

With respect to the second of these termination criteria, ASTM D5084-10 does not specify the increment in time associated with the "last four or more k values", nor does ASTM D5084-10 distinguish whether the mean value for k should be an arithmetic mean or a geometric mean. As a result, both arithmetic mean and geometric mean values for k were determined to ascertain whether or not such a distinction is necessary. The arithmetic and geometric mean values of the k corresponding to these termination criteria were defined for four consecutive measured k values as follows:

$$k_{am} = \frac{\sum_{i=1}^N k_i}{N} \quad (2.4)$$

and

$$k_{gm} = \prod_{i=1}^N (k_i)^{1/N} \quad (2.5)$$

where k_{am} designates the arithmetic mean value of k , k_{gm} designates the geometric mean value of k , and N represents the number of consecutive values of k upon which the calculation of k_{am} or k_{gm} is based (e.g., $N = 4$ in the case of ASTM D5084-10). In essence, k_{am} represents the average of the actual measured k values, whereas k_{gm} represents the average of the exponents of the measured k values. Shackelford et al. (2010) note that, since k can vary over orders of magnitude, k_{am} favors the higher of the measured k values when plotted on a logarithmic scale, whereas k_{gm} represents geometrically the "middle" of the measured k values when plotted on a logarithmic scale. For this reason, k_{am} is greater than or equal to k_{gm} (Shackelford et al. 2010).

2.2.7 Testing Program

A summary of the testing program is given in Table 2.6. The base case for comparison of results corresponded to Test Series 1 with a 58.3-mm-length specimen containing 10 % bentonite content (by dry weight) and permeated with tap water via constant-head conditions by increasing only the headwater pressure resulting in an applied, constant hydraulic gradient of 30. Test Series 2 through 8 were conducted to evaluate the effects of (1) the length of test specimen (Test Series 1, 2, and 3), (2) the magnitude of the applied hydraulic gradient to induce flow (Test Series 1 and 4), (3) the method of hydraulic gradient application (Test Series 1 and 5), (4) the bentonite content (Test Series 1, 6 and 7), and (5) the type of permeant water (Test Series 1 and 8). The hydraulic conductivity tests conducted for all Test Series were replicated. A five percent variability on the desired hydraulic gradient is noted in Table 2.6 (i.e., $i \pm 0.05i$) to take into account the possibility of slight variations in specimen dimensions and practical limitations on the application of the boundary pressures required to apply the hydraulic gradient in some cases, as will be discussed when necessary.

2.3 Results

The results of all the tests are summarized in Tables 2.7, 2.8 and 2.9. The initial and final values for γ_d , w , and degree of water saturation (S) for all test specimens are provided in Table 2.7. As expected, swelling of the compacted specimens during permeation resulted in a decrease in γ_d and an increase in both w and S . The increases in w ranged from 4.3 percentage points for Test No. 5a to 10.0 percentage points for Test No. 4a, whereas the increase in S ranged from 15.7 percentage points for Test No. 5a to 32.6 percentage points for Test No. 4b. In some cases (e.g., Test Nos. 4a, 4b, 7a, and 7b), the final measured values of S were slightly greater than 100 %, which is not physically possible. These erroneously high values of S resulted from difficulty in accurately measuring the total volume of the specimens upon disassembling the testing cells. Nonetheless, these specimens with final values of $S > 100$ % can be considered to have been essentially saturated at the time of termination of the respective tests.

The chemical characteristics of the permeant water used in the tests in terms of EC and pH are summarized in Table 2.8. As indicated, the variations among the values of EC and pH for the tests using TW as the permeant water (i.e., Test Series 1-7) were relatively minor, with EC ranging from 13.5 mS/m for Test No. 7a to 15.5 mS/m for Test Nos. 3a and 3b, and pH ranging from 6.4 for Test Nos. 3a, 3b, 6b and 7c to 6.9 for Test No.4b. These narrow variations in EC and pH for the tests with TW suggest that differences in the chemical properties of the permeant waters were minimal and should not have affected the test results for the tests using TW as the permeant water. However, as previously noted, the values of EC and pH for the tests using the standard water (i.e., 10 mM $CaCl_2$) as the permeant water (i.e., Test Series 8) were significantly different from those for the TW, with EC for the standard water used as the permeant water for the two tests of Test Series 8 ranging from approximately 14.9 to 17.2 times greater than that for

the TW, and the pH for the standard water being about one pH unit lower (more acidic) than that for the TW.

The results of the hydraulic conductivity tests for all Test Series are summarized in Table 2.9. The durations of permeation corresponding to the standard termination criteria defined for flexible-wall, constant-head k testing in ASTM D5084-10 Method A are reported both in terms of elapsed time, t , and pore volumes of flow, PVF . The PVF represents the cumulative volume of outflow normalized with respect to the void or pore volume of the specimen, which was based on the porosity, n , or void ratio, $e [= n/(1 - n)]$, of the specimen corresponding to the condition of the specimen after compaction. The value of t corresponding to the standard termination criteria is designated as t_s , whereas the corresponding value for PVF is designated as PVF_s . The value of k corresponding to t_s and PVF_s was designated as the standardized k , or k_s , and the value for k_s based on the arithmetic mean (Eq. 2.4) or the geometric mean (Eq. 2.5) was designated as $k_{s,am}$ or $k_{s,gm}$, respectively.

In some tests, permeation was continued after t_s in order to evaluate any changes in k subsequent to the standardized testing duration and the applicability of the termination criteria defined by ASTM D5084-10 for indicating the true steady-state value of k . In these tests, a final k value, k_f , also was determined corresponding to the duration of permeation designated as t_f ($\geq t_s$), and the value for k_f based on the arithmetic mean (Eq. 2.4) or the geometric mean (Eq. 2.5) of the final four consecutive value of k (i.e., $N = 4$) was designated as $k_{f,am}$ or $k_{f,gm}$, respectively.

As indicated in Table 2.9, the values of $k_{s,am}$ were identical to the values of $k_{s,gm}$ for all tests except Test No. 4a, where the difference between $k_{s,am}$ of 5.6×10^{-11} m/s and $k_{s,gm}$ of 5.5×10^{-11} m/s was negligible. Similarly, the values of $k_{f,am}$ were identical to values of $k_{f,gm}$ for all tests. Thus, the manner in which the mean values for k_s and k_f were calculated, i.e., Eq. 2.4 or Eq. 2.5,

had essentially no effect on the resulting values. As a result, all subsequent reference to standardized values of k will be designated as k_s , whereas all subsequent reference to final values of k will be designated simply as k_f .

2.3.1 Test Series 1

Test Series 1 served as the base case for the study. Duplicate specimens of a SB mixture containing 10 % bentonite and compacted in half-size (58.3-mm-long) molds (i.e., Test Nos. 1a and 1b) were permeated with TW under a constant hydraulic gradient of 30 that was applied by increasing the headwater pressure by 17.25 kPa (2.5 psi) according to Method A of ASTM D5084-10. Upon completion of back-pressure, the cell pressure and back-pressure were 379.2 kPa (55 psi) and 344.7 kPa (50 psi), respectively, such that the initial effective stress, σ' , prior to permeation was 34.5 kPa (5 psi). The results in terms of hydraulic conductivity (k) and volumetric flow ratio (Q_{out}/Q_{in}) versus time (t) and pore volumes of flow (PVF), as well as the incremental volumes of inflow and outflow (ΔV_{in} and ΔV_{out}) and volumetric strain (ϵ_{vol}) versus elapsed time for the tests conducted in Test Series 1 are shown in Fig. 2.7 and summarized in Table 2.9.

The trends in k versus t and k versus PVF for both tests were similar (Figs. 2.7a,b), with t_s of 21.0 d for Test No. 1a and 32.0 d for Test No. 1b, corresponding to values of PVF_s of 0.13 and 0.22, respectively. Thus, less than a quarter of each specimen was exposed to the permeant water at the time corresponding to the standard termination criteria. The resulting values of k corresponding to the standard termination criteria, k_s , were 1.5×10^{-11} m/s for Test No. 1a and 1.6×10^{-11} m/s for Test No. 1b. Thus, the k_s values for the duplicate specimens were essentially the same.

Both test specimens also were permeated beyond the durations corresponding to the standard termination criteria, with final durations, t_f , of 54.8 d for Test No. 1a and 52.0 d for Test No. 1b, corresponding to values of PVF_s of 0.31 and 0.37, respectively. The final values of k_f were 1.3×10^{-11} m/s for Test No. 1a and 1.9×10^{-11} m/s for Test No. 1b. Thus, the value of k_f for

Test No. 1a was about 13 % lower than the value of k_s , whereas the value of k_f for Test No. 1b was about 19 % higher than the value of k_s . These differences between the values of k_s and k_f may be considered as relatively minor, although higher k values would correspond to higher seepage rates in cases where the compacted sand-bentonite mixture is used as a hydraulic barrier, all other factors being equal.

Both specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.7e), indicating that the net incremental volume of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.7f, both specimens experienced slight compression ($\leq \sim 1$ %) during permeation, although some specimen expansion (swelling) was evident periodically in Test No. 1a. Such specimen compression would occur when $\Delta V_{out} > \Delta V_{in}$.

2.3.2 Test Series 2

The purpose of Test Series 2 was to evaluate the potential effect of the length of the compacted SB specimens (i.e., 29.1 mm) relative to that for the specimens evaluated in Test Series 1 (i.e., 58.3 mm), with all other conditions being the same as those for Test Series 1. The results for the duplicate tests of Test Series 2 (Test Nos. 2a and 2b) are shown in Fig. 2.8 and summarized in Table 2.9.

The trends in k versus t and k versus PVF for both tests were similar (Figs. 2.8a,b), with t_s of 16.0 d for Test No. 2a and 24.1 d for Test No. 2b, corresponding to values of $PVFs$ of 0.19 and 0.22, respectively. Thus, less than a quarter of each specimen was exposed to the permeant water at the time corresponding to the standard termination criteria. The resulting values of k_s

were 1.6×10^{-11} m/s for Test No. 2a and 1.2×10^{-11} m/s for Test No. 2b. Thus, the k_s values for the duplicate specimens were close.

Test No. 2a also was permeated beyond the duration corresponding to the standard termination criteria, with t_f of 17.9 d corresponding to value of PVF_f of 0.21. However, Test No. 2b was terminated at the same time as the standard termination criteria, i.e., $t_f = t_s = 24.1$ d, corresponding to $PVF_f = PVF_s = 0.22$. The resulting values of k_f were 1.6×10^{-11} m/s for Test No. 2a and 1.2×10^{-11} m/s for Test No. 2b (i.e., $k_f = k_s = 1.2 \times 10^{-11}$ m/s). Thus, the values of k_f for both specimens were identical to the values of k_s .

Both specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.8e), indicating that the net incremental volume of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.8f, Test No. 2a experienced slight compression ($\leq \sim 1$ %) during permeation, whereas the cumulative volumetric strain of Test No. 2b was close to nil throughout the permeation.

2.3.3 Test Series 3

The purpose of Test Series 3 was to evaluate the potential effect of the length of the compacted SB specimens (i.e., 116.0 mm) relative to that for the specimens evaluated in Test Series 1 (i.e., 58.3 mm), all other conditions being the same as those for Test Series 1. The results for the triplicate tests of Test Series 3 (i.e., Test Nos. 3a, 3b, 3c) are shown in Fig. 2.9 and summarized in Table 2.9.

The trends in k versus t and k versus PVF for all tests were similar (Figs. 2.9a,b) in that the k of each specimen tended to decrease with time, eventually reaching an essentially stable

value. This decreasing trend in k with time can be attributed to swelling of the specimens during permeation (see Fig. 2.9f), which results in an increasingly tighter specimen and increasingly lower k values. The values of t_s were 57.8 d for Test No. 3a, 46.1 d for Test No. 3b and 27.0 for Test No. 3c, corresponding to values for PVF of 0.60, 0.12 and 1.01, respectively. These values of t_s generally were longer than those previously noted for the shorter (58.3 mm) specimens of Test Series 1, indicating that longer test durations can be expected for larger test specimens.

Although the trends in k versus t for all three specimens were similar, the resulting values of k_s for the three specimens were noticeably different, with k_s values of 5.8×10^{-11} m/s for Test No. 3a, 1.1×10^{-11} m/s for Test No. 3b, and 1.8×10^{-10} m/s for Test No. 3c. Thus, the values of k_s varied by slightly more than an order of magnitude, which is significantly greater than the variation in k_s noted for the test specimens of Test Series 1. In fact, the significant difference between the k_s of 5.8×10^{-11} m/s for Test No. 3a and the k_s of 1.1×10^{-11} m/s for Test No. 3b was the reason for the decision to perform a third test (Test No. 3c) for Test Series 3. Again, this greater variability in k_s can be attributed, in part, to the larger specimen size, as the larger the size of specimen, the more likely the possibility of differences among replicated specimens. Test Nos. 3a and 3b were terminated immediately upon achievement of the termination criteria, whereas Test No. 3c was permeated beyond the duration corresponding to the standard termination criteria, with final durations, t_f , of 52.8 d for Test No. 3c corresponding to value of PVF_f of 1.59. Thus, the values of k_f were identical with values of k_s for Test Nos. 3a and 3b, whereas the value of k_f for Test No. 3c was 1.3×10^{-10} m/s, which was about 30 % lower than the value for k_s of 1.8×10^{-10} m/s.

All three specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.9e), indicating that the net incremental volume

of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.9f, all three specimens experienced swelling ($\leq \sim 5\%$) during permeation. This swelling can be attributed to at least two factors.

First, the amount of bentonite in the specimens of Test Series 3 was approximately twice that for the specimens in Test Series 1, due to the size of the specimens for the Test Series 3 being essentially twice that of the specimens for Test Series 1. Second, in order to apply the same hydraulic gradient of 30 to the longer specimens of Test Series 3, the headwater pressure had to be increased by twice that for the shorter specimens of Test Series 1, or 34.5 kPa (5 psi) versus 17.25 kPa (2.5 psi). Such a greater increase in headwater pressure results in a greater reduction in σ' , which results in the tendency towards a greater degree of swelling.

From a practical standpoint, increasing the headwater pressure by 34.5 kPa (5 psi) would theoretically reduce the effective stress at the bottom (inflow side) of the specimens to zero, which runs the risk of separation or blowout of the flexible membrane from the specimen. As a result, the headwater was increased by only 33.1 kPa (4.8 psi) resulting in a value for σ' of 1.4 kPa (0.2 psi) at the bottom of the specimen, and an applied, constant hydraulic gradient of 29.

2.3.4 *Test Series 4*

The purpose of Test Series 4 was to evaluate the potential effect of the hydraulic gradient (i.e., $i = 60 \pm 3.0$) on the measured k relative to that for the specimens in Test Series 1 (i.e., $i = 30 \pm 1.5$), all other conditions being the same as those for Test Series 1. For these tests, the headwater pressure was increased by 33.1 kPa (4.8 psi) resulting in a value for σ' of 1.4 kPa (0.2

psi) at the bottom of the specimen, and an applied, constant hydraulic gradient of 58. The results for the duplicate tests for Test Series 4 are shown in Fig. 2.10.

The trends in k versus t and k versus PVF for both tests were similar (Figs. 2.10a,b) in that the k of each specimen tended to decrease with time, eventually reaching an essentially stable value. This decreasing trend in k with time can be attributed to swelling of the specimens during permeation (see Fig. 2.10f), which results in increasingly tighter specimens and increasingly lower k values. The values of t_s were 17.3 d for Test No. 4a and 14.3 d for Test No. 4b, corresponding to values of PVF_s of 1.83 and 0.49, respectively. The significantly greater PVF_s for Test No. 4a is attributable to the initially significantly higher k values, which resulted in greater amounts of flow for the same applied hydraulic gradient.

The values of k_s were 5.5×10^{-11} m/s for Test No. 4a and 2.5×10^{-11} m/s for Test No. 4b. These values of k_s are somewhat greater than those for the test specimens permeated for Test Series 1. Higher k_s values were expected on the basis that the application of a higher hydraulic gradient via a greater increase in the headwater pressure results in an overall lower σ' and, therefore, an expected overall larger void ratio (e) (e.g., Haug and Wong 1992, Shackelford and Glade 1994).

Both test specimens were permeated beyond the durations corresponding to the standard termination criteria, with final durations, t_f , of 23.4 d for Test No. 4a and 20.0 d for Test No. 4b, corresponding to values of PVF_f of 1.98 and 0.58, respectively. The values of k_f were 4.0×10^{-11} m/s for Test No. 4a and 2.3×10^{-11} m/s for Test No. 4b. Thus, both values of k_f were lower than the respective k_s values.

Both specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.10e), indicating that the net incremental

volume of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.10f, both specimens experienced swelling ($\leq \sim 6\%$) during permeation. Since the test specimens in Test Series 4 contained the same amounts of bentonite as the test specimens in Test Series 1, the difference in volume change behavior during permeation can be attributed to the greater decrease in σ' experienced by the specimens in Test Series 4 due to the application of the greater hydraulic gradient.

2.3.5 Test Series 5

The purpose of Test Series 5 was to evaluate the potential effect of the hydraulic gradient application (i.e., increasing headwater pressure and decreasing tailwater pressure) on the measured k relative to that for the specimens evaluated in Test Series 1 (i.e., only increasing the headwater pressure), all other conditions being the same as those for Test Series 1. For the specimens in Test Series 5, the tailwater was decreased by the same magnitude as the increase in the headwater pressure, i.e., 8.6 kPa (1.25 psi), so as to apply a constant hydraulic gradient of 30 while maintaining an average σ' in the test specimen during permeation of 34.5 kPa (5 psi), i.e., the same as that established at the end of back-pressure. The results for the duplicate tests of Test Series 5 (Test Nos. 5a and 5b) are shown in Fig. 2.11 and summarized in Table 2.9.

The trends in k versus t and k versus PVF for both tests were similar (Figs. 2.11a,b), with minimal variation in the measured k values throughout permeation. The values of t_s were 22.7 d for Test No. 5a and 31.0 d for Test No. 5b, corresponding to values of PVF_s of 0.14 and 0.13, respectively. Thus, less than 15 % of each specimen was exposed to the permeant water at the time corresponding to the standard termination criteria. These values of t_s and PVF_s were similar

to those for the specimens tested for Test Series 1. The resulting values of k_s were 1.7×10^{-11} m/s for Test No. 5a and 1.2×10^{-11} m/s for Test No. 5b. Thus, the k_s values for the duplicate specimens were similar, and close to the k_s values of 1.5×10^{-11} m/s for Test No. 1a and 1.6×10^{-11} m/s for Test No. 1b.

Both test specimens were permeated beyond the durations corresponding to the standard termination criteria, with values for t_f of 30.7 d for Test No. 5a and 36.9 d for Test No. 5b, corresponding to values for PVF_f of 0.19 and 0.16, respectively. The values of k_f were 1.6×10^{-11} m/s for Test No. 5a and 1.2×10^{-11} m/s for Test No. 5b. Thus, the value of k_f for Test No. 5a was about 6 % lower than the value of k_s , whereas the value of k_f for Test No. 5b was identical with the value of k_s . These differences between the values of k_s and k_f for Test No. 5a may be considered as insignificant.

Both specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.11e), indicating that the net incremental volume of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.11f, both specimens experienced very slight compression ($\leq \sim 0.25$ %) during permeation which was consistent with almost identical incremental volumes of inflow versus outflow in Fig. 2.11e.

2.3.6 Test Series 6

The purpose of Test Series 6 was to evaluate the potential effect of a lower BC of 5 % relative to the BC of 10 % for the specimens evaluated in Test Series 1, all other conditions being

the same as those for Test Series 1. The results for the three replicate tests of Test Series 6 (Test Nos. 6a and 6b) are shown in Fig. 2.12 and summarized in Table 2.9.

Because of the relatively low bentonite content of the specimens for Test Series 6, particle migration was a significant issue, resulting in the failure of several test specimens (see Appendix C). This issue resulted primarily because of the combination of the low *BC* of 5 % and the rapid application of the hydraulic gradient of 30. As a result, upon completion of the back-pressure stage of each test, the hydraulic gradient was increased incrementally in stages (i.e., $\Delta i \leq 2$) until the final hydraulic gradient of 30 was achieved. This procedure was followed to expose the bentonite to increasingly greater amounts of water in the hope that gradually hydrating the bentonite would promote swelling thereby preventing the bentonite from being forced through the specimen. Although the procedure generally was successful, some specimens still failed via particle migration despite this procedure.

The trends in *k* versus *t* and *k* versus *PVF* for all three tests were similar (Figs. 2.12a,b), with *t_s* of 40.3 d for Test No. 6a, 11.9 d for Test No. 6b and 20.5 d for Test No. 6c, corresponding to values of *PVF_s* of 1.88, 1.08 and 1.49, respectively. Also, all the test specimens were permeated beyond the durations corresponding to the standard termination criteria, with values for *t_f* of 58.2 d for Test No. 6a, 19.1 d for Test No. 6b, and 25.4 d for Test No. 6c, corresponding to values for *PVF_f* of 2.30, 1.31 and 1.67, respectively. Several observations are apparent with respect to these trends in *k* versus *t* and *k* versus *PVF*.

First, the measured *k* values for all specimens decreased significantly during permeation. For example, the values of *k* for Test No. 6a decreased two orders of magnitude from an initial value of 5.2×10^{-9} m/s to a final value, *k_f*, of 4.9×10^{-11} m/s, the values of *k* for Test No. 6b decreased by approximately 2.1 orders of magnitude from an initial value of 1.3×10^{-8} m/s to a

final value, k_f , of 9.7×10^{-11} m/s, whereas the values of k for Test No. 6c decreased by approximately 1.1 orders of magnitude from an initial value of 1.2×10^{-9} m/s to a value for k_f of 1.0×10^{-10} m/s. The initially high values of k suggest that the bentonite did not initially swell sufficiently to fill all of the pore space between the sand grains. However, the subsequent exposure of the test specimen to increasing amounts of water resulted in continued swelling of the bentonite and progressively greater occupation of the pores between the sand grains with a corresponding decrease in k .

Second, the k_s for Test No. 6a of 5.4×10^{-11} m/s was approximately two times lower than the k_s for Test Nos. 6b and 6c of 1.1×10^{-10} m/s and 1.2×10^{-10} m/s, which suggests that application of the standard termination criteria in the case of Test Nos. 6b and 6c resulted in prematurely high k values for these specimens. Third, the relatively high values of PVF_s and PVF_f for both specimens can be attributed to the initially high rates of flow due to the initially high k values in each specimen.

All three specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and outflow ($\Delta V_{out} > 0$) throughout permeation (Fig. 2.12e), indicating that the net incremental volume of flow was into the specimen on the inflow side (bottom) of the specimen and out from the specimen on the outflow side (top) of the specimen throughout permeation. Also, as shown in Fig. 2.12f, all specimens experienced compression ($\leq \sim 5\%$) during permeation, which is consistent with values of ΔV_{out} being greater than those of ΔV_{in} (see Fig. 2.12f). The fact that compression of the specimens occurred despite the aforementioned decrease in k due to swelling of the bentonite supports the likelihood that the relatively low BC of 5% was initially not sufficient to fill the pore spaces between the sand grains in these sand-bentonite mixtures.

2.3.7 Test Series 7

The purpose of Test Series 7 was to evaluate the potential effect of a higher BC of 15 % for the compacted sand-bentonite mixtures relative to the BC of 10 % for the specimens tested in Test Series 1, all other conditions being the same as those for Test Series 1. The results for the three replicate tests of Test Series 7 (Test Nos. 7a, 7b, 7c) are shown in Fig. 2.13 and summarized in Table 2.9.

As shown in Figs. 2.13a and b, Test No. 7a resulted in consistent trends in k versus t and k versus PVF , with t_s of 122.0 d and PVF_s of 0.4. However, Test No. 7a experienced an impossibly large compression ($\leq \sim 25$ %), as shown in Fig. 2.13f, which was possibly attributed to a leakage in the piping of cell water connecting the panel board and the permeameter.

As for Test No. 7b, the resulted trend of k versus PVF was unusual, with all values for PVF being less than zero (Fig. 2.13b) and the resulting calculated k values being negative (Fig. 2.13a). As apparent from Fig. 2.13e, the negative values of PVF resulted because the incremental volumes of outflow, ΔV_{out} , were greater in magnitude but opposite in sign (i.e., negative) relative to the incremental volumes of inflow, ΔV_{in} , such that the overall net flow was into the specimen from both sides. This phenomenon is possible from the viewpoint that, upon the start of permeation following back-pressure, the absorption of water by the bentonite in the specimen was greater than the amount of water emanating from the outflow side of the specimen due to the applied hydraulic gradient. In this case, the average of ΔV_{in} (> 0) and ΔV_{out} (< 0) will be less than zero, such that the use of Eq. 2.3 resulted in calculated k values that were negative ($k < 0$), which clearly are meaningless. Moreover, despite these values of $PVF < 0$, the termination criteria specified in ASTM D5084-10 were achieved in this test, as indicated in Figs. 2.13a,c. These results for Test No. 7b highlight potential issues related to the standardized termination criteria

specified in ASTM D5084-10 and the use of the average rates of inflow and outflow as allowed by Eq. 2.3.

Because of the issues related to Test No. 7a and 7b, a third specimen, designated as Test No. 7c, was permeated. As shown in Fig. 2.13, all of the trends in the data for Test No. 7c were similar to those for Test No. 7a, with values for t_s , PVF_s , and k_s of 140.0 d, 0.12 and 5.1×10^{-12} m/s, respectively, for Test No. 7c versus 122.0 d, 0.40, and 5.9×10^{-12} m/s, respectively, for Test No. 7a. Also, although the initial values for ΔV_{out} for Test No. 7c were negative (i.e., $\Delta V_{out} < 0$), the magnitudes of these values of ΔV_{out} were much lower than those for ΔV_{in} , which were all positive (i.e., $\Delta V_{in} > 0$), such that the specimen exhibited a net inflow throughout permeation.

All specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and negative outflow ($\Delta V_{out} < 0$) at the beginning stage of permeation and then stabilized as positive ($\Delta V_{out} > 0$) throughout the remainder of permeation (Fig. 2.13e). For all specimens in Test Series 7, the incremental volume of flow was into the specimen on the inflow side (bottom) of the specimen throughout permeation, whereas the flow was into the specimen on the outflow side (top) of the specimen at the beginning of permeation due to swelling of bentonite and then flow out of the specimen throughout the remainder of permeation. Also, as shown in Fig. 2.13f, Test Nos. 7b and 7c experienced slight swelling ($\leq \sim 3\%$) during permeation, whereas the compression for Test No. 7a was relatively large ($\leq \sim 25\%$) which likely was a result of piping leakage.

2.3.8 Test Series 8

The purpose of Test Series 8 was to evaluate the potential effect of the use of SW in the form of 10 mM CaCl_2 as the permeant water as allowed in ASTM D5084-10 (see section 6.1.2.1)

relative to the use of TW as the permeant water in Test Series 1, all other conditions being the same as those for Test Series 1. For Test Series 8, the SB specimens were mixed with TW, and then back-pressured and permeated with SW. The test specimens were back-pressured using SW instead of TW to simulate the field-compacted condition whereby the CCL is exposed to the waste liquid without back-pressure stage (Stern and Shackelford 1998). The results for the duplicate tests of Test Series 8 (Test Nos. 8a and 8b) are shown in Fig. 2.14 and summarized in Table 2.9.

The trends in k versus t and k versus PVF for both tests were similar (Figs. 2.14a,b), with t_s of 13.1 d for Test No. 8a and 15.1 d for Test No. 8b, corresponding to values of PVF_s of 0.96 and 0.39, respectively. The difference in PVF_s despite similar elapsed times of permeation can be attributed to the initially higher k values for Test No. 8a relative to Test No. 8b. The resulting values of k_s were 1.7×10^{-10} m/s for Test No. 8a and 6.0×10^{-11} m/s for Test No. 8b. Thus, the k_s values for the duplicate specimens varied by about a half an order of magnitude. Both test specimens also were permeated beyond the durations corresponding to the standard termination criteria until at least two PVF was achieved, as recommended by Daniel (1994) in the case of permeation with chemical solutions, in an attempt to ensure that the remnant pore water prior to permeation has been flushed out of the specimen such that all soil-liquid interactions that may alter the k have concluded. The resulting values for t_f were 77.0 d for Test No. 8a and 93.0 d for Test No. 8b, corresponding to values for PVF_f of 3.29 and 2.13, respectively. The resulting values of k_f were 5.1×10^{-11} m/s for Test No. 8a and 7.3×10^{-11} m/s for Test No. 8b. Thus, the similar values of k_f were measured for both specimens.

All specimens experienced positive incremental volumes of inflow ($\Delta V_{in} > 0$) and positive outflow ($\Delta V_{out} > 0$) during permeation (Fig. 2.14e), such that the incremental volumes of

flow throughout permeation were into the specimen on the inflow side (bottom) of the specimen and out of the specimen on the outflow side (top) of the specimen. Also, as shown in Fig. 2.14f, Test Nos. 8a experienced slightly swelling ($\leq \sim 0.5\%$), whereas Test No. 8b experienced slight compression ($\leq \sim 0.3\%$) during permeation.

2.4 Discussion

2.4.1 *Standardized versus Final Values of Hydraulic Conductivity*

Of the 19 hydraulic conductivity tests conducted in this study, 14 of these tests included permeation beyond the durations corresponding to the standard termination criteria, resulting in values of t_f greater than values of t_s . The resulting values of k_s and k_f for these 14 tests are compared in Fig. 2.15.

As shown in Fig. 2.15a, 79 % (= 11/14) of the values of k_f were lower than or equal to the respective values of k_s . Thus, the standardized values of k measured in this study generally were conservative (high) relative to the final, or longer term, values of k . In addition, as shown in Fig. 2.15b, the three tests where k_s was lower than k_f (i.e., Test Nos. 1b, 7b and 8b) were from different Test Series, suggesting that any differences between respective k_s and k_f values were random rather than systematic.

2.4.2 *Effect of Size of Compacted Sand-Bentonite Specimen*

The effect of size of the compacted sand-bentonite specimens, i.e., quarter-, half- and full-sizes, is reflected directly in terms of the different length, L , of the respective specimens because the cross-sectional areas of all the specimens were essentially identical. Thus the effect of size of specimen can be evaluated by comparing the results for Test Series 1, 2, and 3 with

specimen lengths of 58.3, 29.1 and 116.0 mm, respectively. The resulting measured values of k_s and k_f are shown versus L in Fig. 2.16.

As shown in Fig. 2.16, there was little or no change in k with increasing L , until the largest specimens with L of 116.0 mm were tested, where the relatively large variability in the measured k among the triplicate specimens resulted in an increase in k relative to the two smaller sizes of specimens ranging from nil to almost one order of magnitude. From an intuitive viewpoint, the significant variability in the measured k values associated with the largest specimens with L of 116.0 mm can be attributed, in part, to a greater difficulty in ensuring a homogeneous mixture of sand and bentonite with increasing size in specimen.

Fundamentally, the increase in k with increasing size (L) of the specimen can be attributed to different amounts of swelling (see Figs. 2.7e, 2.8e and 2.9e) of sand-bentonite specimens during permeation, as an increase in swell correlates with an increase in void ratio (e) with a concomitant increase in k . This increased swelling with increasing size of specimen can be attributed to two factors, viz.: (1) an increasing amount (mass) of bentonite with increasing size of specimen, and (2) a greater decrease in effective stress, σ' , within the specimen with increasing length of specimen.

With respect to the amount of bentonite, because the BC for all the specimens was maintained constant at 10 % by dry weight, the masses of bentonite in the specimens increased with increasing size in proportion to the relative values of L for the specimens. Thus, the full-size specimens with L of 116.0 mm contained approximately twice as much bentonite as the half-size specimens with L of 58.3 mm, and approximately four times as much bentonite as the quarter-size specimens with L of 29.1 mm. From a mineralogical perspective, the amount of swell would be expected to increase with increasing bentonite content, such that the swell for the

largest specimens would be expected to be the greatest among the three sizes of specimens considered in this study.

With respect to the magnitude of σ' within the specimens, in order to maintain the same constant hydraulic gradient of 30 ± 1.5 for all the test specimens, the magnitudes of the increase in headwater pressure for each of the different length specimens increased with increasing L of the specimens. Thus, the increases in headwater pressures during permeation for the specimens with L of 29.1, 58.3, and 116 mm were 8.6 kPa (1.25 psi), 17.25 kPa (2.5 psi), and 33.1 kPa (4.8 psi), respectively. These increases in headwater pressures during permeation were equivalent to decreases in the initial σ' at the bottom of the specimen of 34.5 kPa (5 psi), such that the resulting σ' at the bottom of the specimens with L of 29.1, 58.3, and 116 mm during permeation were 25.9 kPa (3.75 psi), 17.25 kPa (2.5 psi) and 1.4 kPa (0.2 psi), respectively. Thus, for a given specimen, since a decrease in σ' correlates with an increase in e , the increase in k shown in Fig. 2.16 for the two of the three largest specimens can be attributed, in part, to a greater extent of swelling occurring in these two specimens resulting from the overall greater decrease in σ' for these specimens relative to that for the two smaller sizes of specimens.

2.4.3 *Effects of Magnitude of Hydraulic Gradient*

The effect of magnitude of i on k was evaluated by comparing the results for Test Series 1 with i of 30 versus those for Test Series 4 with i of 57. In general, an increase in i is expected to result in a decrease in k due an increase in seepage forces (e.g., see Daniel 1994). This is the reason for ASTM D5084-10 limiting the magnitudes of the hydraulic gradient that can be applied to test specimens.

As illustrated in Fig. 2.17, increasing i from 30 to 57 actually resulted in an increase in k of approximately a half an order of magnitude. Thus, the trend in the data in Fig. 2.17 actually appears to be opposite to the typical trend. The reason for the apparent discrepancy is related to the manner in which the hydraulic gradient was applied. That is, because the hydraulic gradient was applied by increasing only the headwater pressure as per ASTM D5084-10 (i.e., ΔHWP), application of the greater i of 57 to the test specimens in Test Series 4 was achieved by increasing the headwater pressure of specimens by 33.1 kPa (4.8 psi), which was approximately twice the increase in headwater pressure of 17.25 kPa (2.5 psi) applied to the specimens of Test Series 1 to achieve an i of 30. As a result of the greater increase in headwater pressure to the specimens in Test Series 4, the overall σ' of these test specimens was lower than that for the test specimens of Test Series 1, such that the resulting values of e and, therefore, k , for the test specimens for Test Series 4 likely were greater than those for the test specimens of Test Series 1. This observation is consistent with that of Shackelford et al. (2000) with respect to measuring the k of geosynthetic clay liners, i.e., that the control of σ' is more important than the control of i in terms of measuring k of compressible porous media.

2.4.4 *Effects of Method of Hydraulic Gradient Application*

The effect of method of hydraulic gradient application on k was evaluated by comparing the results for Test Series 1, where only the headwater was increased to apply the hydraulic gradient of 30 in accordance with ASTM D5084-10 (i.e., ΔHW), versus the results for Test Series 5, where the tailwater was decreased by the same magnitude as the increase in headwater (i.e., $\Delta\text{HWP} = -\Delta\text{TWP}$) to apply the same hydraulic gradient of 30. As previously noted, increasing the headwater pressure results in an overall decrease in the σ' relative to the value for σ' established

at the end of the back-pressure stage (i.e., 34.5 kPa (5 psi) in this study), and is specified in ASTM D5084-10 so as to minimize the possibility that air dissolved in the pore water during back-pressure is not released back into the system. Such a release of dissolved air could result in clogging of pores and the measurement of an unrepresentative low k value. In contrast, simultaneously decreasing the tailwater pressure and increasing the headwater pressure by the same magnitudes leads to the possibility of release of air back into the system, but maintains an average value of σ' during permeation that is the same as the value of σ' at the end of the back-pressure stage of the test.

As shown in Fig. 2.18, there was little difference in the values of k measured on the basis of the two methods of hydraulic gradient application. There are at least two possible explanations for this outcome. First, all the specimens that were tested were sufficiently saturated by the end of permeation (i.e., $S \geq 90.8$ %; see Table 2.7) such that the measured values of k were not significantly different than those that would have been measured at complete saturation. Second, the small decrease in tailwater pressure of 17.25 kPa (2.5 psi) for the tests of Test Series 5 was not sufficient to result in significant release of dissolved air back into the system. Regardless of the reason, the results of this study suggest that the measured k of the compacted sand-bentonite mixture evaluated in this study was essentially independent of the two methods of hydraulic gradient application.

2.4.5 *Effect of Bentonite Content*

The effect of bentonite content, BC , on the k of compacted sand-bentonite mixtures has been studied extensively, resulting in the well-established trend of decreasing k with increasing BC (e.g., Lundgren 1981; Daniel 1987; Garlanger et al. 1987; Chapuis et al. 1990; Cowland and

Leung (1991); Kenney et al. 1992; Marcotte et al. (1994); O'Sadnick et al. 1995; Mollins et al. 1996; Komine and Ogata 1996; Alston et al. 1997; Gleason 1997; Howell and Shackelford 1997; Stern and Shackelford 1998; Abichou et al. 2000; Abichou et al. 2002; Sällfors and Öberg-Högsta 2002; Thomson and Foose 2005; Mishra et al. 2009) The effect of BC on the k of the compacted sand-bentonite specimens evaluated in this study can be evaluated by comparing the results for Test Series 6, 1, and 7 pertaining to BC s of 5 %, 10 % and 15 %, respectively. The results of this comparison are shown in Fig. 2.19

As shown in Fig. 2.19, the measured values of k_s decreased by approximately 1 to 1.5 orders of magnitude as BC increased from 5 % to 15 % (Fig. 2.19a), whereas the measured values of k_f decreased by approximately 0.9 to 1.4 orders of magnitude as BC increased from 5 % to 15 % (Fig. 2.19b). The variability in the decrease in the k with increasing BC results primarily from the variability in the individual values of k_s and k_f measured for the compacted sand-bentonite specimens with 5 % BC (i.e., Test Series 6). The overall high k values for the specimens with BC of 5 % can be attributed to the BC being inadequate to completely fill all of the pores of the mixture, and the variability in the k values for these same specimens can be attributed to the difficulty in ensuring a uniform distribution in the bentonite due to the relatively small amount of bentonite. Regardless of these issues, the trend of decreasing k with increasing BC observed in this study is similar to that noted in several previous studies.

2.4.6 *Effect of Type of Permeant Water*

The effect of type of permeant water of the hydraulic conductivity tests is reflected indirectly by the EC of the water which, as previously noted, is correlated directly to the ionic strength, I , of the water (Griffin and Jurinak 1973). Thus, the effect of type of permeant water

can be evaluated by comparing the results for Test Series 1 where TW with a measured EC of 13 mS/m was used as the permeant water versus the results of Test Series 8 where SW with a measured EC of 240 mS/m was used as the permeant water. The resulting measured values of k are shown versus EC in Fig. 2.20.

As illustrated in Fig. 2.20, the values of k_s increase from about 0.5 to 0.9 orders of magnitude as the EC of the permeant water increased from 13 to 240 mS/m (Fig. 2.20a), whereas the values of k_f increased from about 0.4 to 0.7 orders of magnitude as the EC of the permeant water increased from 13 to 240 mS/m (Fig. 2.20b). Thus, the use of SW as the permeant water resulted in conservatively higher values of measured k relative to the use of TW as the permeant water for the compacted sand-bentonite mixture evaluated in this study. Whether the higher k measured using SW is significant or not will depend on the specific application of the test results, and the relation between the chemical characteristics of the permeant liquid in the field relative to those of the SW used in this study (e.g., Shackelford 1994).

2.5 Conclusions

This study involved a systematic evaluation of the measurement of the hydraulic conductivity, k , of compacted sand-bentonite mixtures in accordance with ASTM D5084-10, *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*, with respect to several factors. The factors evaluated included: (a) the size (length, L) of specimen; (b) the magnitude of hydraulic gradient (i); (c) the method of hydraulic gradient application (ΔHWP vs. $\Delta HWP = -\Delta TWP$); (d) the bentonite content (BC), and (e) the type of permeant water (TW vs. SW). The results of this evaluation lead to the following conclusions.

For the two smaller sizes of specimens ($L = 29.1$ mm and 58.3 mm), there was little variability in the results between duplicate specimens of each size and essentially no effect on the standardized values of k , or k_s , due to the size of specimen. However, for the largest size specimen ($L = 116.0$ mm), significant variability in the results among triplicate specimens resulted in an increase in k_s relative to the two smaller size specimens ranging from nil to approximately 1.2 orders of magnitude. This result was attributed to three possible factors, viz., (1) the relatively higher swelling corresponding to the greater total amount bentonite (at the same BC) in the largest size specimens, (2) the greater decrease in overall σ' within the specimen resulting from the application of the same i of 30, which led to an overall increase in void ratio (e), and (3) the greater difficulty in ensuring a homogeneous mixture of sand and bentonite with increasing size in specimen. Thus, the limiting maximum applied i of 30 as specified for ASTM D5084-10 for specimens with k_s less than 1×10^{-9} m/s may result in the measurement of conservative (high) values of k_s for relatively large specimens of compacted sand-bentonite mixture with relatively high BC (≥ 10 %).

With respect to the magnitude of i , the measured k_s of compacted sand-bentonite specimens with 10 % BC increased by approximately a half an order of magnitude as i increased from 30 to 57, all other factors being the same. This trend is opposite of that typically expected, and was attributed to the manner in which i was applied as required by ASTM D5084-10. That is, because ASTM D5084-10 requires that i be applied by only increasing the headwater pressure (ΔHWP), application of the greater i of 57 resulted in an overall lower σ' for these test specimens, which correlated with an overall greater e and corresponding higher k_s . Thus, limiting the maximum applied i to 30 as per ASTM D5084-10 resulted in lower measured values of k_s , all other factors being the same. Whether such lower values of k_s are conservative or not will depend

on the magnitude of i for the intended application, i.e., if the magnitude of i in the field is lower than 30, then the measured values of k_s should be conservatively high, and vice versa.

With respect to bentonite content, the measured k_s decreased by approximately 1 to 1.5 as BC increased from 5 % to 15 %, respectively, which is consistent with previous results for other compacted sand-bentonite mixtures. However, application of the i of 30 to the specimens in this study with the lowest BC of 5 %) was problematic due to issues with particle migration, such that the i had to be applied gradually in order to prevent a sudden pressure change to the specimen that could induce particle migration before the bentonite became sufficiently hydrated. Thus, the abrupt application of the limiting i based on ASTM D5084-10 to compacted sand-bentonite mixtures with relatively low bentonite contents may be problematic with respect to the potential for particle migration.

In addition, one of the three specimens with BC of 15 % experienced negative flow during the beginning stage of permeation, despite the calculation of a consistent value of k_s based on the equation for constant head testing in accordance with ASTM D5084-10 Method A (see Eq.2.3). This negative flow was attributed to the possible dominance of swelling of the bentonite for this specimen resulting from the greater total amount of bentonite relative to the specimens with the lower BC . Thus, caution should be exercised in applying the specified equation for calculation of k_s for compacted sand-bentonite specimens with high BC .

With respect to type of permeant water, the measured k_s increased by less than 1 order of magnitude as the EC of the permeant water increased from 13 mS/m (TW) to 240 mS/m (SW). Thus, the use of SW as the permeant water in accordance with ASTM D5084-10 (see 6.1.2.1) resulted in conservatively higher values of k_s relative to the TW that was used in this study as the permeant water.

In addition to the aforementioned conclusions drawn from the systematic evaluation of the application of ASTM D5084-10 to the compacted sand-bentonite mixtures evaluated in this study, two additional conclusions can be drawn. First, whether the termination criteria in ASTM D5084-10 pertaining to the mean of the measured k values were based on an arithmetic mean or a geometric mean had no effect on the measured values of k_s . Second, for specimens permeated beyond the termination criteria specified in ASTM D 5084-10 the majority of the final measured values of k , or k_f , were lower than or equal to the respective values of k_s , such that the measured values of k_s were, in general, conservatively high.

Table 2.1. Chemical properties of liquids used in this study.

Property	Liquid		
	DIW ^a	TW ^b	SW ^c
Electronic Conductivity, <i>EC</i> (mS/m), @ 25 °C	1	13	240
pH	7.0	7.0	5.5
Anion Concentration ^d (mg/L):	NA		
Br ⁻		0.0	0.0
Cl ⁻		3.7	690.0
F ⁻		0.7	0.0
NO ₂ ⁻		0.0	0.0
NO ₃ ⁻		0.0	0.0
SO ₄ ²⁻		11.7	0.0
Cation Concentration ^e (mg/L):	NA		
Ca ²⁺		15.3	369.8
Mg ²⁺		2.0	0.0
Na ⁺		3.5	1.3
K ⁺		0.5	0.0

^a De-ionized Water

^b Tap Water

^c Standard Water (10 mM CaCl₂)

^d Based on ion chromatography analysis performed by the Soil, Water and Plant Testing Laboratory, CSU, Fort Collins, CO.

^e Based on inductively coupled plasma-atomic emission spectrometry analysis performed by the Soil, Water and Plant Testing Laboratory, CSU, Fort Collins, CO.

Table 2.2. Physical and chemical properties and mineralogical compositions of constituent soils.

Property	Standard	Constituent Soil	
		Sand	Bentonite
Specific Gravity, G_s	ASTM D854-10	2.66	2.81
Liquid Limit, LL (%)	ASTM D4318-10	NA	426
Plastic Limit, PL (%)	ASTM D4318-10	NA	33
Plasticity Index, PI (%)	ASTM D4318-10	NA	393
Classification	ASTM D2487-11	SP	CH
Principal Minerals (%):	a	NA	
Montmorillonite			70
Albite Feldspar			15
Quartz			9
K-Feldspar-Microcline			3
Illite/Mica			2
Calcite			1
Bound Cations (cmol/kg):	ASTM D7503-10	NA	
Ca^{2+}			34.4
Mg^{2+}			12.0
Na^+			39.0
K^+			0.7
Sum			86.1
Soluble Metals (mg/kg):	ASTM D7503-10	NA	
Ca^{2+}			91.5
Mg^{2+}			14.9
Na^+			4183.1
K^+			183.4
Soil pH	ASTM D4972-01	NA	9.7 ^b

^a Based on X-ray diffraction analysis performed by Mineralogy Inc., Tulsa, OK.

^b Determined with DIW

Table 2.3. Measured Atterberg limits (ASTM D4318) of sand-bentonite mixtures.

Liquid for Mixing ^a	Bentonite Content, <i>BC</i> (%)	Atterberg Limits		
		Liquid Limit, <i>LL</i> (%)	Plastic Limit, <i>PL</i> (%)	Plastic Index, <i>PI</i> (%)
DIW	5	26	17	9
DIW	10	40	15	25
DIW	15	55	17	38
DIW	100	426	33	393
Tap Water	5	24	16	8
Tap Water	10	37	13	24
Tap Water	15	50	13	37
Tap Water	100	480	36	444

^a DIW = De-ionized Water

Table 2.4. Dimensions of three different compaction molds.

Size of Compaction Mold	Diameter, D (mm)	Length, L (mm)	Cross-sectional Area, A (m ²)	Volume, V (m ³)
Full	101.4	116.0	8.09×10^{-3}	9.41×10^{-4}
Half	101.5	58.3	8.07×10^{-3}	4.71×10^{-4}
Quarter	102.9	29.1	8.31×10^{-3}	2.42×10^{-4}

Table 2.5. Compaction properties based on third-order polynomial fits to measured compaction data for sand-bentonite mixtures.

Test Series	Bentonite Content, BC (%)	Size of Compaction Mold	Values for Constants in Fitted Third-Order Polynomial Expression (A, B, C, D) ^a , Coefficient of Determination (r^2), and Number of Compaction Tests (N)						Compaction Properties			
			A	B	C	D	r^2	N	Optimum Water Content, w_{opt}	Maximum Dry Unit Weight, γ_{dmax}		% of γ_{dmax}
									%	kN/m ³	lb/ft ³	%
1	5	Full	-0.0267	0.9300	-10.3810	145.54	1.000	6	14.0	17.2	109.3	-
2	5	Half	-0.0272	1.001	-11.9060	153.85	0.998	6	14.4	17.1	108.8	99.5
3	5	Quarter	-0.0101	0.3188	-3.0100	113.99	0.980	6	14.0	16.8	106.8	97.7
4	10	Full	-0.0039	0.1300	-1.3700	21.69	0.994	7	12.6	17.3	109.9	-
5	10	Half	-0.0030	0.0959	-0.9460	19.86	0.998	6	13.2	17.1	108.9	99.1
6	10	Quarter	-0.0006	-0.0043	0.3990	14.20	0.998	6	14.9	17.2	109.5	99.6
7	15	Full	-0.0042	0.1316	-1.2511	20.96	0.994	6	13.9	17.9	113.7	-
8	15	Half	-0.0036	0.1138	-1.0592	20.30	0.991	6	14.0	17.8	113.6	99.9
9	15	Quarter	-0.0007	0.0091	0.0844	16.29	0.956	6	12.2	17.4	111.0	97.6

^a $\gamma_d = Aw^3 + Bw^2 + Cw + D$, where γ_d = dry unit weight and w = gravimetric water content in %.

Table 2.6. Testing program for measuring hydraulic conductivity of compacted sand-bentonite (SB) mixtures.

Test Series	Length, L (mm)	Hydraulic Gradient, i	Gradient Application ^a	Bentonite Content, BC (%)	Permeant Water	Comment
1	58.3	30 ± 1.5	ΔHWP	10	Tap	Base Case
2	29.1	30 ± 1.5	ΔHWP	10	Tap	Effect of Specimen Length
3	116.0	30 ± 1.5	ΔHWP	10	Tap	Effect of Specimen Length
4	58.3	60 ± 3.0	ΔHWP	10	Tap	Effect of Magnitude of Gradient
5	58.3	30 ± 1.5	$\Delta HWP = -\Delta TWP$	10	Tap	Effect of Method of Gradient Application
6	58.3	30 ± 1.5	ΔHWP	5	Tap	Effect of Bentonite Content
7	58.3	30 ± 1.5	ΔHWP	15	Tap	Effect of Bentonite Content
8	58.3	30 ± 1.5	ΔHWP	10	Standard ^b	Effect of Permeant Water

^a ΔHWP = change in headwater pressure; ΔTWP = change in tailwater pressure.

^b10 mM $CaCl_2$

Table 2.7. Initial and final properties of compacted sand-bentonite specimens.

Test No.	Specific Gravity, G_s	Dry Unit Weight, γ_d				Water Content, w (%)		Saturation, S (%)	
		Initial		Final		Initial	Final	Initial	Final
		(kN/m ³)	(lb/ft ³)	(kN/m ³)	(lb/ft ³)				
1a	2.68	17.38	110.6	17.09	108.8	13.3	19.0	69.9	94.8
1b	2.68	17.15	109.2	17.12	109.0	13.8	19.2	72.0	96.1
2a	2.68	17.22	109.7	17.16	109.2	13.7	19.6	70.2	98.7
2b	2.68	17.33	110.3	17.09	108.8	13.8	19.5	71.9	97.1
3a	2.68	17.14	109.1	16.63	105.9	15.3	21.2	78.2	97.9
3b	2.68	17.20	109.5	16.95	107.9	15.3	21.2	79.7	103.2
3c	2.68	17.38	110.6	16.37	104.2	15.0	22.3	78.7	98.4
4a	2.68	17.27	109.9	16.35	104.1	14.0	24.0	72.7	103.9
4b	2.68	17.34	110.4	16.81	107.0	14.1	22.4	73.8	106.4
5a	2.68	17.24	109.7	16.92	107.7	14.5	18.8	75.1	90.8
5b	2.68	17.31	110.2	17.27	109.9	13.8	18.7	71.8	96.1
6a	2.67	16.65	106.0	16.70	106.3	15.3	19.8	72.8	93.1
6b	2.67	16.88	107.4	16.65	106.0	15.2	20.1	72.1	93.7
6c	2.67	16.94	107.8	16.65	107.9	15.2	19.8	71.4	96.9
7a	2.68	17.72	112.8	17.32	110.2	15.0	20.3	82.7	105.0
7b	2.68	17.59	112.0	17.27	110.0	14.2	20.4	82.1	104.5
7c	2.68	17.51	111.4	17.16	109.2	14.2	20.3	76.8	102.3
8a	2.68	17.23	109.7	17.22	109.6	14.0	19.6	71.5	99.6
8b	2.68	17.24	109.8	17.24	109.7	13.8	19.5	70.6	99.4

Table 2.8. Chemical properties of permeant water for hydraulic conductivity tests.

Test Series	Test No.	Type of Permeant Water	Electrical Conductivity, <i>EC</i> (mS/m) @ 20 °C	pH	Temperature, <i>T</i> (°C)
1	1a	Tap	13.6	6.6	22.1
	1b	Tap	13.6	6.5	22.2
2	2a	Tap	13.6	6.6	22.0
	2b	Tap	13.9	6.6	22.1
3	3a	Tap	15.5	6.4	22.3
	3b	Tap	15.5	6.4	23.0
	3c	Tap	15.3	6.5	22.4
4	4a	Tap	13.8	6.5	21.8
	4b	Tap	15.0	6.9	22.3
5	5a	Tap	14.4	6.7	22.1
	5b	Tap	14.6	6.8	22.1
6	6a	Tap	15.1	6.5	23.1
	6b	Tap	14.9	6.4	21.7
	6c	Tap	14.9	6.4	21.7
7	7a	Tap	13.5	6.6	21.6
	7b	Tap	13.6	6.6	22.2
	7c	Tap	14.2	6.4	22.1
8	8a	Standard ^a	232.2	5.4	23.2
	8b	Standard ^a	230.6	5.5	23.2

^a 10 mM CaCl₂

Table 2.9. Results of hydraulic conductivity tests conducted on compacted specimens of sand-bentonite mixtures.

Test Series	Test No.	Duration of Permeation				Volumetric Flow Ratio, Q_{out}/Q_{in}		Hydraulic Conductivity, k (m/s)			
		ASTM D5084		Final		ASTM D5084	Final	ASTM D5084		Final	
		t_s (d)	PVF_s	t_f (d)	PVF_f			$k_{s,am}^a$	$k_{s,gm}^a$	$k_{f,am}^a$	$k_{f,gm}^a$
1	1a	21.0	0.13	54.8	0.31	0.83	1.06	1.5×10^{-11}	1.5×10^{-11}	1.3×10^{-11}	1.3×10^{-11}
	1b	32.0	0.22	52.0	0.37	1.00	1.06	1.6×10^{-11}	1.6×10^{-11}	1.9×10^{-11}	1.9×10^{-11}
2	2a	16.0	0.19	17.9	0.21	0.82	0.82	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}	1.6×10^{-11}
	2b	24.1	0.22	24.1	0.22	0.92	0.92	1.2×10^{-11}	1.2×10^{-11}	1.2×10^{-11}	1.2×10^{-11}
3	3a	57.8	0.60	57.8	0.60	0.76	0.76	5.8×10^{-11}	5.8×10^{-11}	5.8×10^{-11}	5.8×10^{-11}
	3b	46.1	0.12	46.1	0.12	0.84	0.84	1.1×10^{-11}	1.1×10^{-11}	1.1×10^{-11}	1.1×10^{-11}
	3c	27.0	1.01	52.8	1.59	0.78	0.83	1.8×10^{-10}	1.8×10^{-10}	1.3×10^{-10}	1.3×10^{-10}
4	4a	17.3	1.83	23.4	1.98	0.82	0.93	5.6×10^{-11}	5.5×10^{-11}	4.0×10^{-11}	4.0×10^{-11}
	4b	14.3	0.49	20.0	0.58	0.97	0.99	2.5×10^{-11}	2.5×10^{-11}	2.3×10^{-11}	2.3×10^{-11}
5	5a	22.7	0.14	30.7	0.19	0.84	0.82	1.7×10^{-11}	1.7×10^{-11}	1.6×10^{-11}	1.6×10^{-11}
	5b	31.0	0.13	36.9	0.16	0.79	0.77	1.2×10^{-11}	1.2×10^{-11}	1.2×10^{-11}	1.2×10^{-11}
6	6a	40.3	1.88	58.2	2.30	1.22	1.26	5.4×10^{-11}	5.4×10^{-11}	4.9×10^{-11}	4.9×10^{-11}
	6b	11.9	1.08	19.1	1.31	1.05	1.03	1.1×10^{-10}	1.1×10^{-10}	9.7×10^{-11}	9.7×10^{-11}
	6c	20.5	1.49	25.4	1.67	1.02	1.02	1.2×10^{-10}	1.2×10^{-10}	1.0×10^{-10}	1.0×10^{-10}
7	7a	122.0	0.40	122.0	0.40	0.99	0.99	5.9×10^{-12}	5.9×10^{-12}	5.9×10^{-12}	5.9×10^{-12}
	7b	87.1	-0.28	124.3	-0.23	0.78	0.45	3.7×10^{-12}	3.7×10^{-12}	4.1×10^{-12}	4.1×10^{-12}
	7c	140.0	0.12	140.0	0.12	0.83	0.83	5.1×10^{-12}	5.1×10^{-12}	5.1×10^{-12}	5.1×10^{-12}
8	8a	13.1	0.96	77.0	3.29	0.97	0.96	1.7×10^{-10}	1.7×10^{-10}	5.1×10^{-11}	5.1×10^{-11}
	8b	15.1	0.39	93.0	2.13	0.93	1.04	6.0×10^{-11}	6.0×10^{-11}	7.3×10^{-11}	7.3×10^{-11}

^a t = elapsed time; PVF = pore volumes of flow; $k_{s,am}$ & $k_{s,gm}$ = arithmetic and geometric mean k values, respectively, based on ASTM D5084-10; $k_{f,am}$ & $k_{f,gm}$ = final arithmetic and geometric mean k values, respectively.

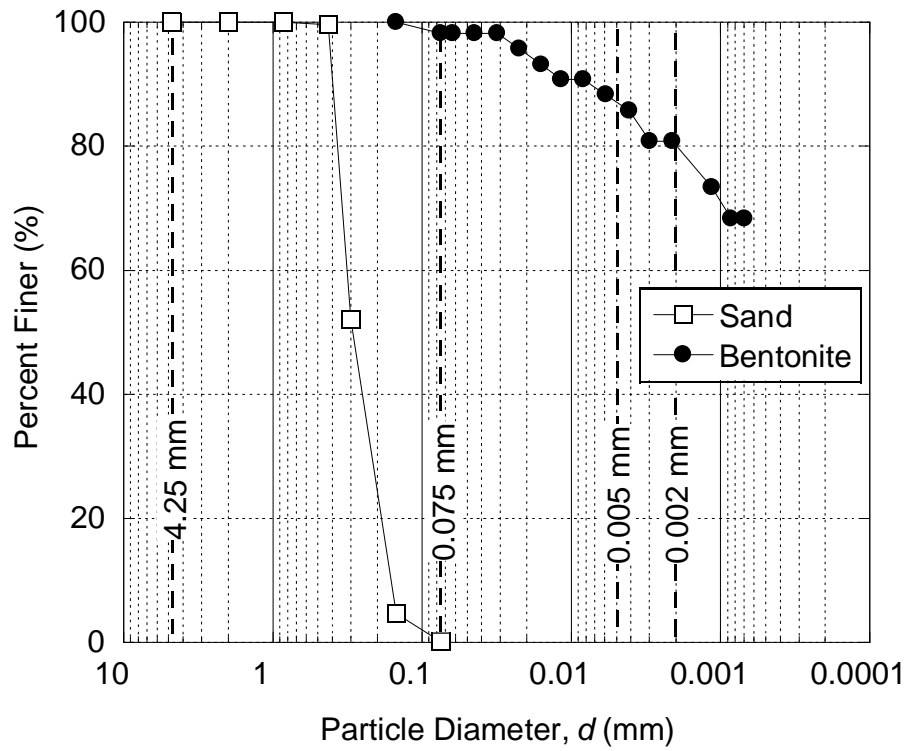


Fig. 2.1 Grain-size distributions (ASTM D422) of sand and bentonite used for compacted sand-bentonite mixtures.

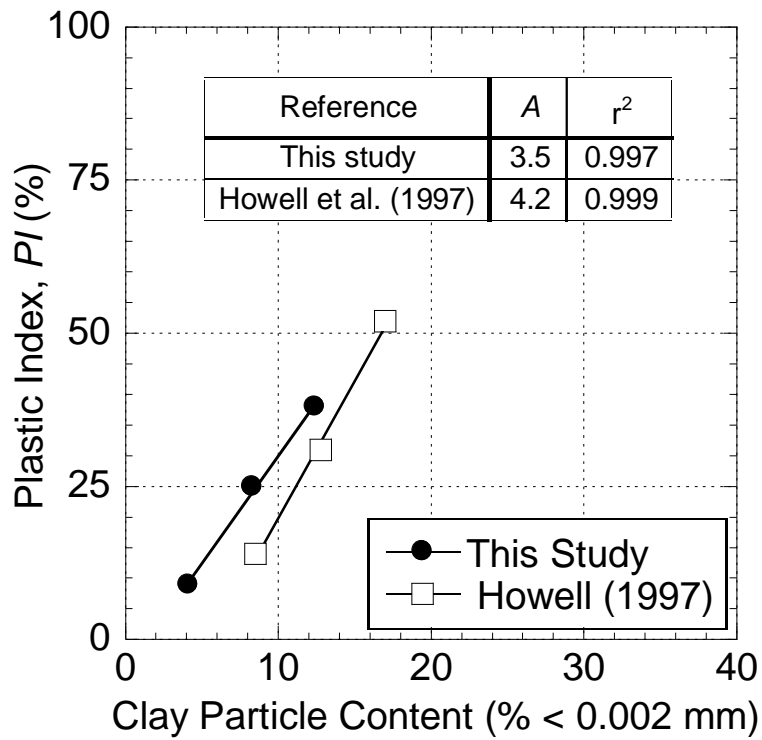


Fig. 2.2 Activities of sand-bentonite mixtures determined in this study versus those reported by Howell et al. (1997).

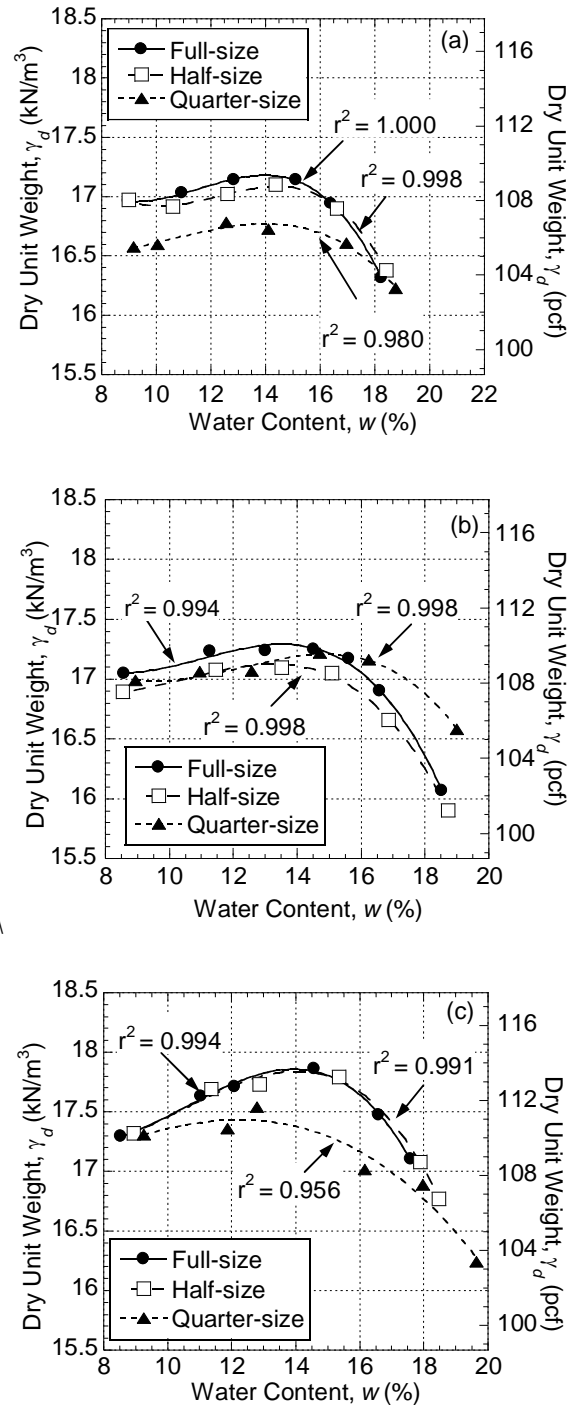


Fig. 2.3 Compaction curves based on 3rd-order polynomials for sand-bentonite mixtures compacted using full-sized, half-sized and quarter-sized compaction molds: (a) 5 % bentonite; (b) 10 % bentonite; (c) 15 % bentonite.

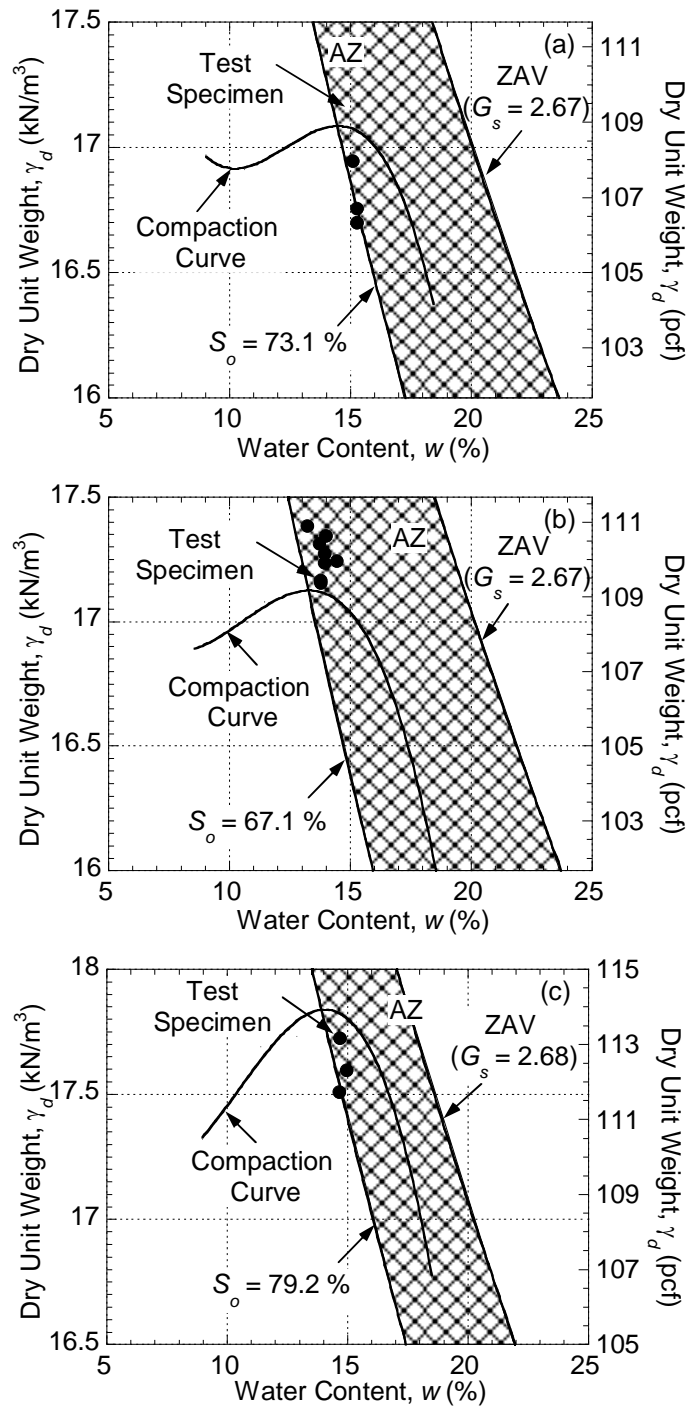


Fig. 2.4 Locations of compacted sand-bentonite specimens within the acceptable zones (AZ) for a half-sized compaction mold: (a) 5 % bentonite; (b) 10 % bentonite; (c) 15 % bentonite. Note: S_o = degree of saturation corresponding to the optimum water content.

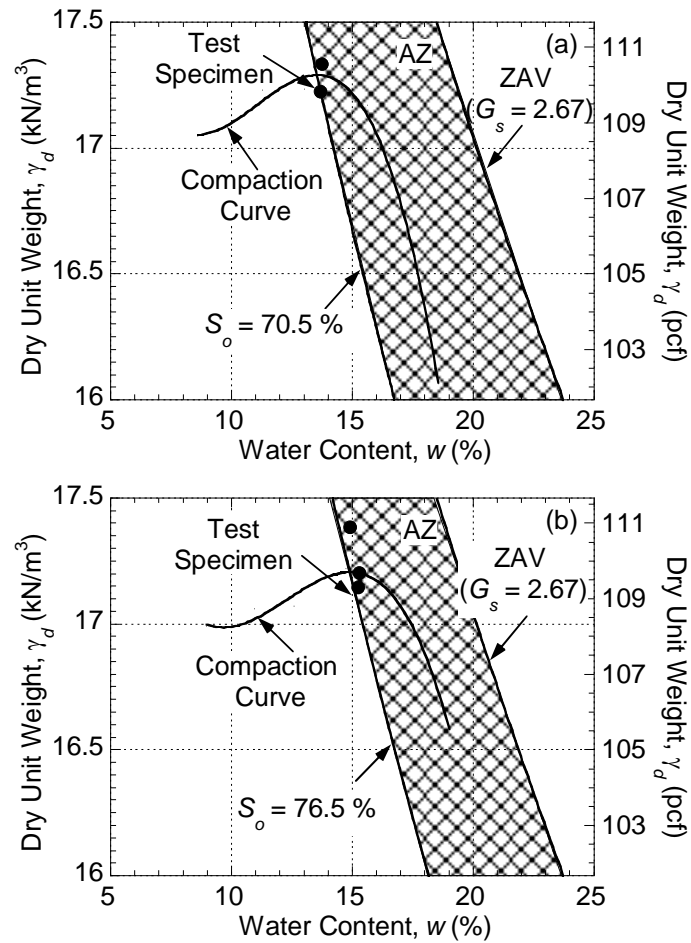


Fig. 2.5 Locations of compacted sand-bentonite specimens containing 10 % bentonite within the acceptable zones (AZ) for different size compaction molds: (a) quarter-sized mold; (b) full-sized compaction molds. Note: S_o = degree of saturation corresponding to the optimum water content.

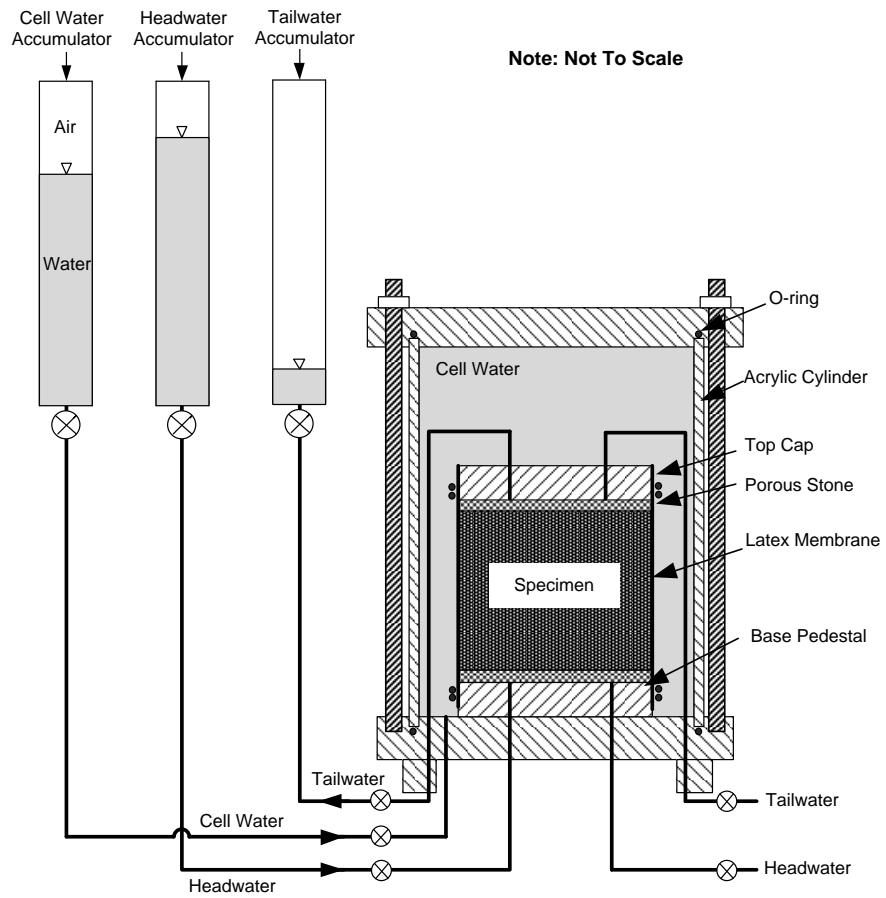


Fig. 2.6 Schematic diagrams of flexible-wall testing apparatus.

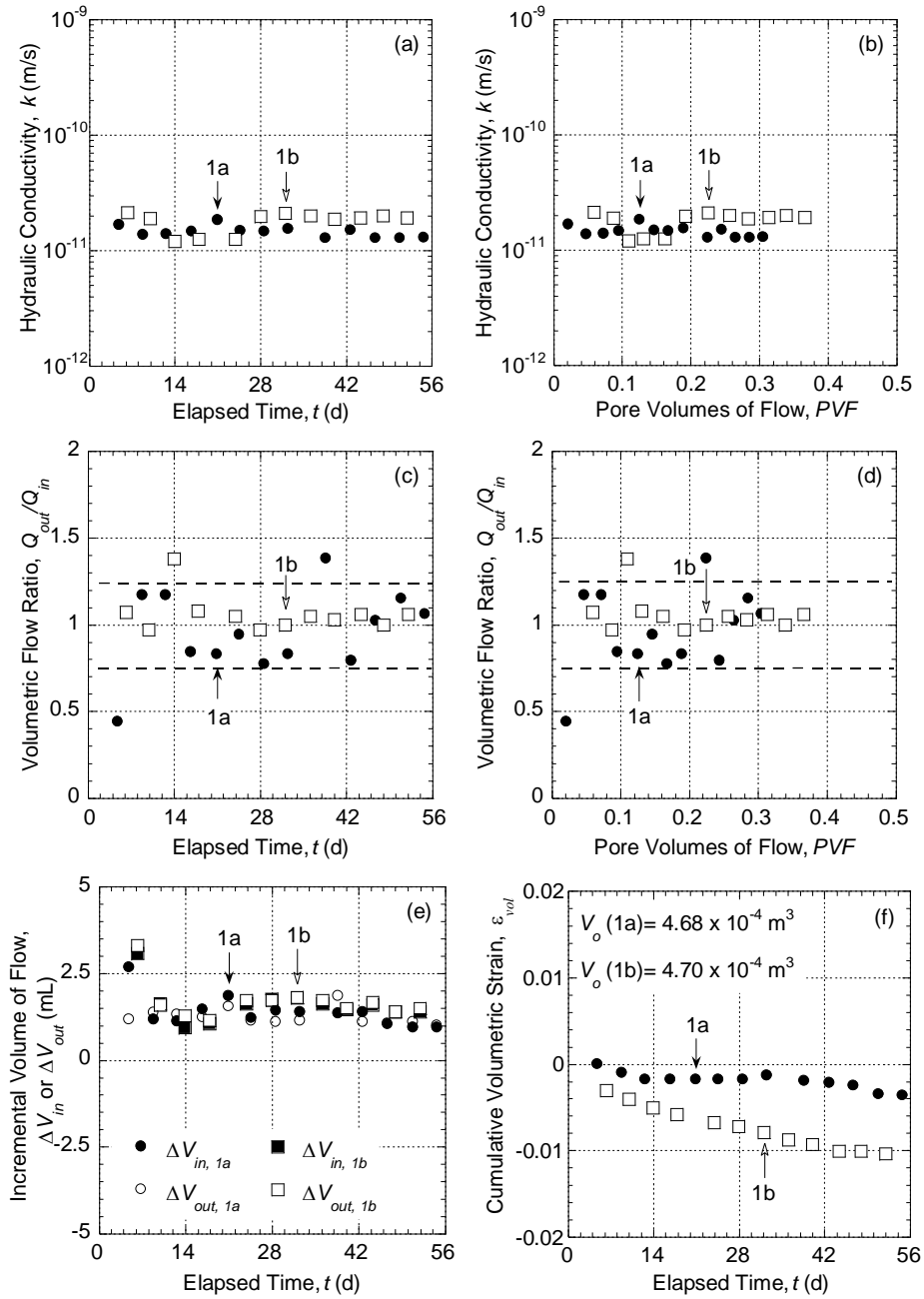


Fig. 2.7 Results for Test Series 1: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

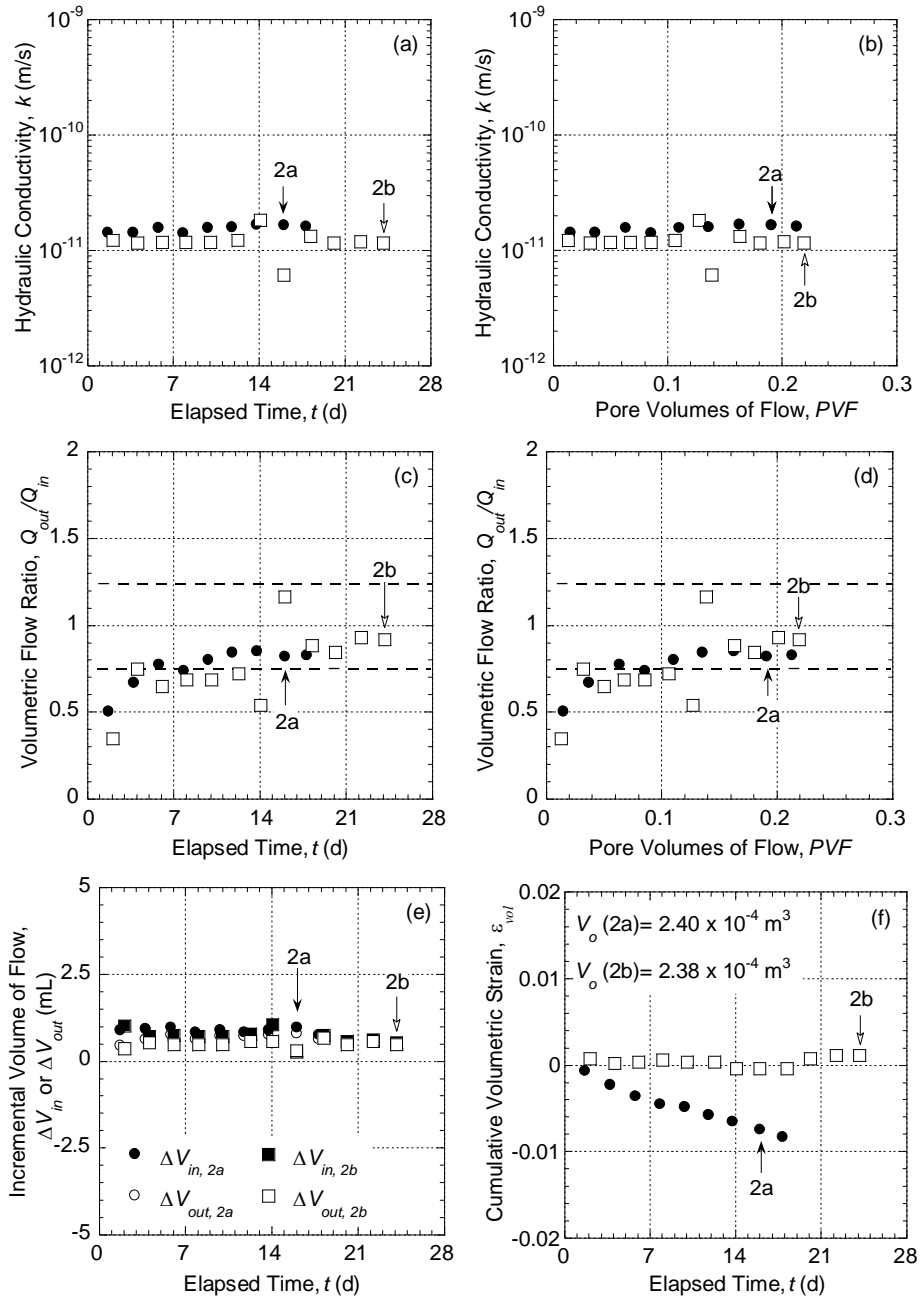


Fig. 2.8 Results for Test Series 2: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

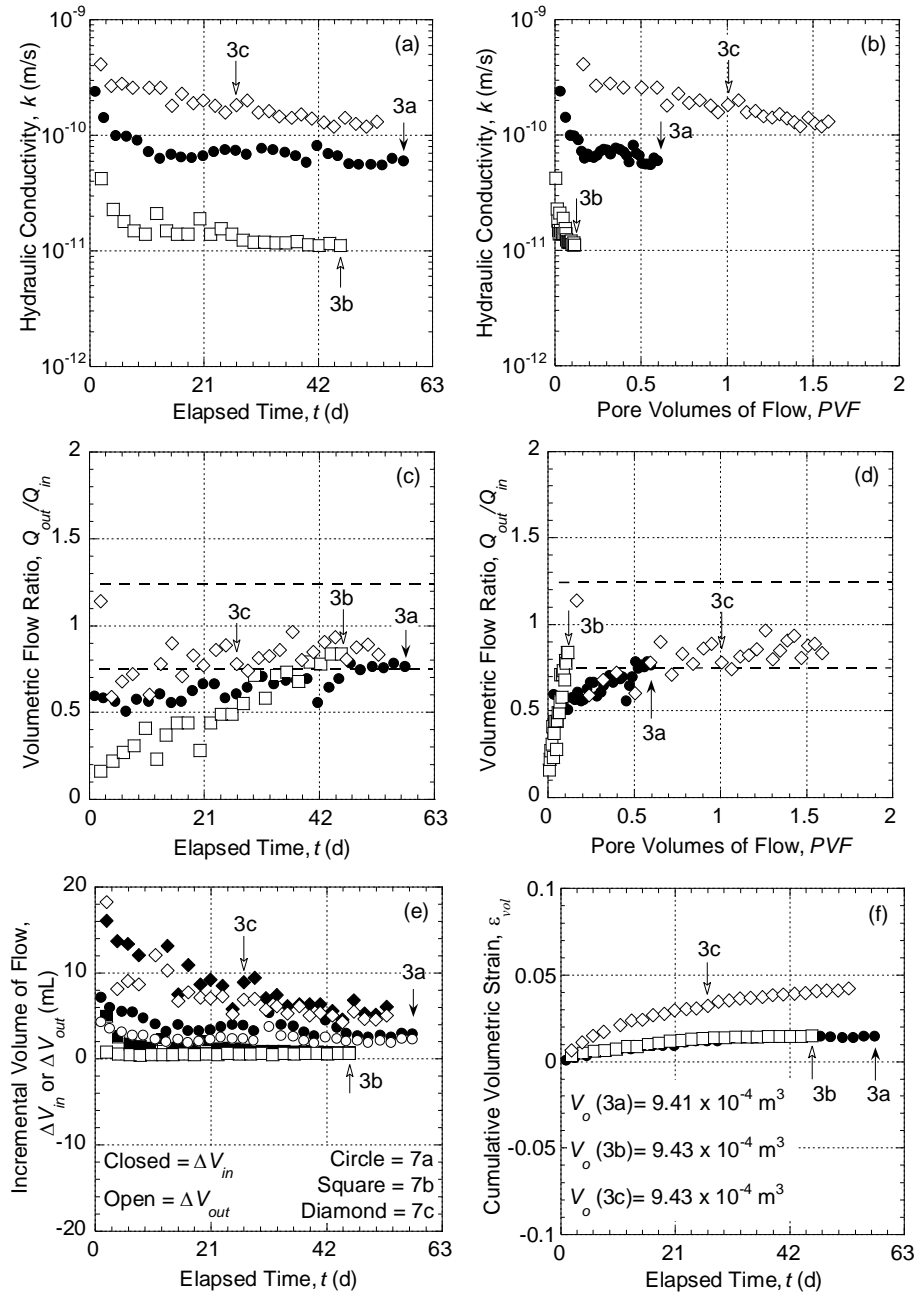


Fig. 2.9 Results for Test Series 3: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ε_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

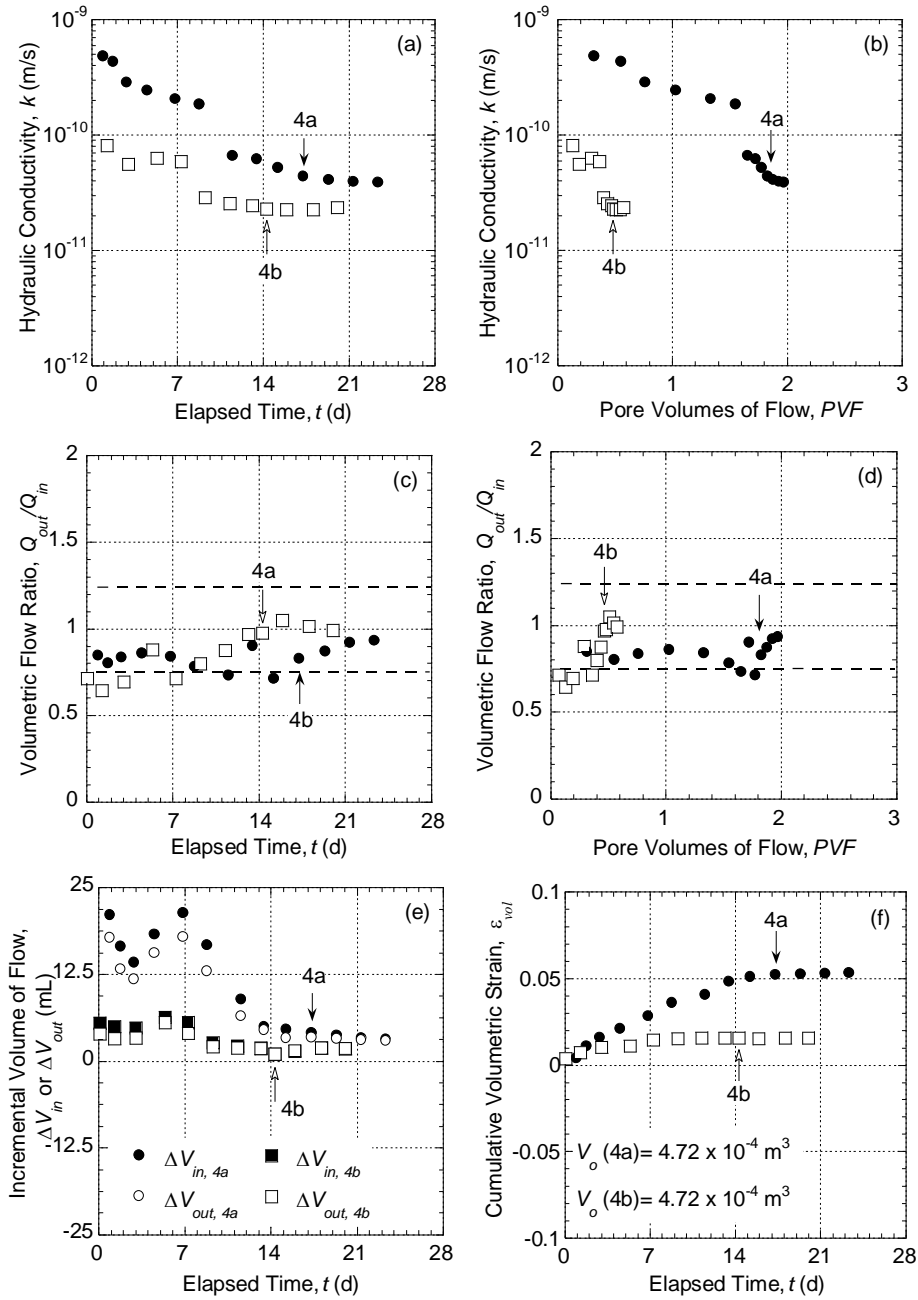


Fig. 2.10 Results for Test Series 4: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

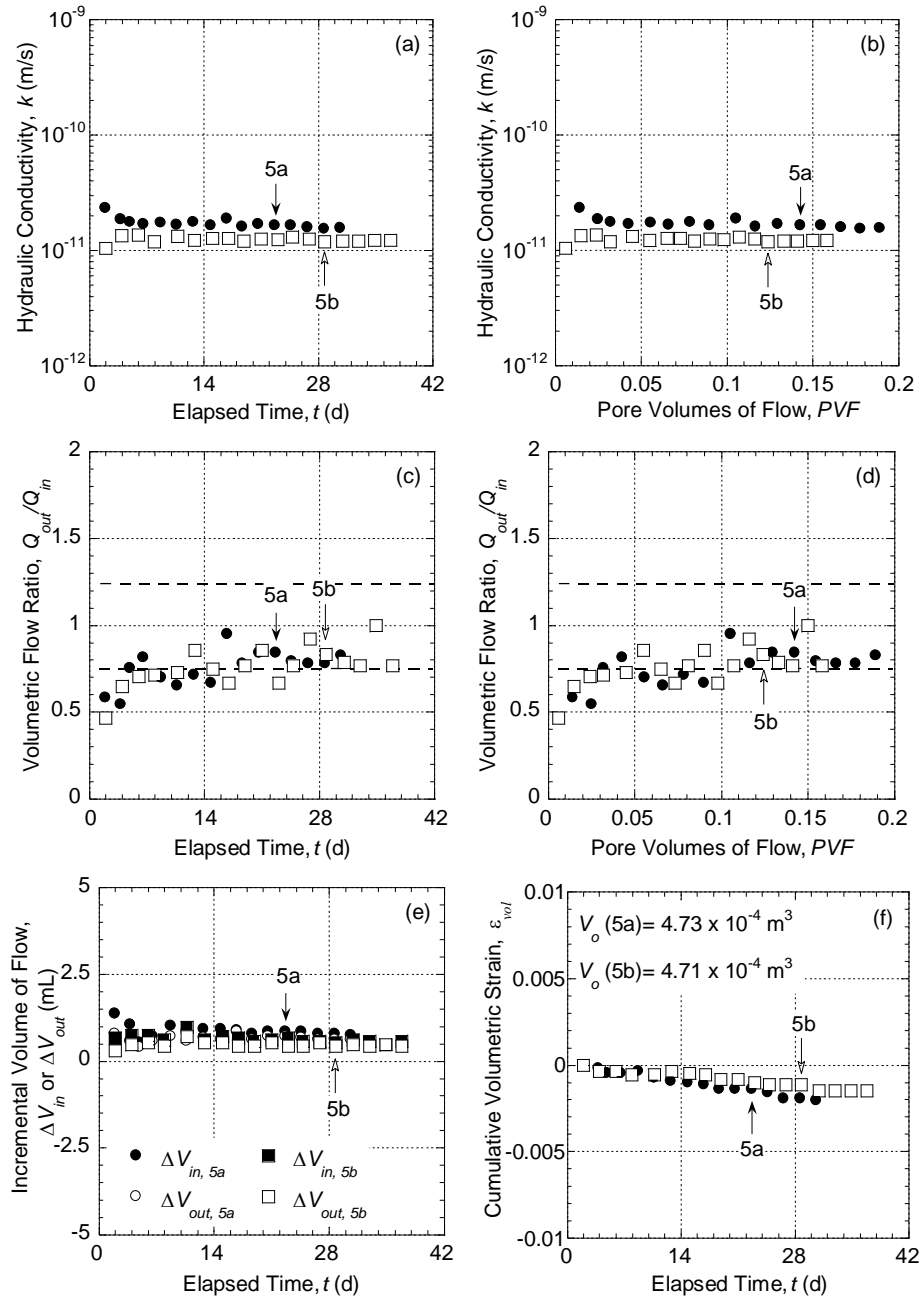


Fig. 2.11 Results for Test Series 5: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

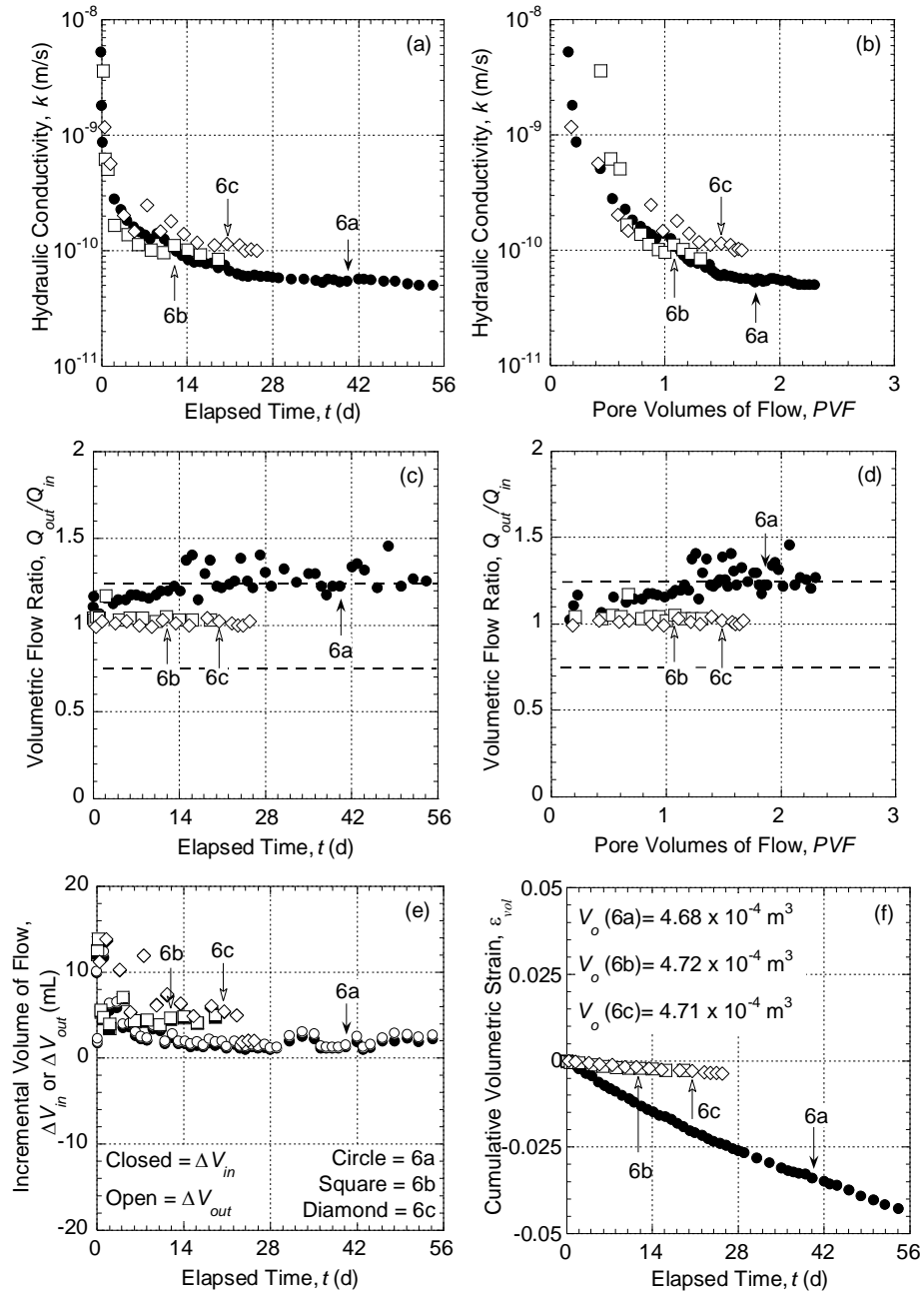


Fig. 2. 12 Results for Test Series 6: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

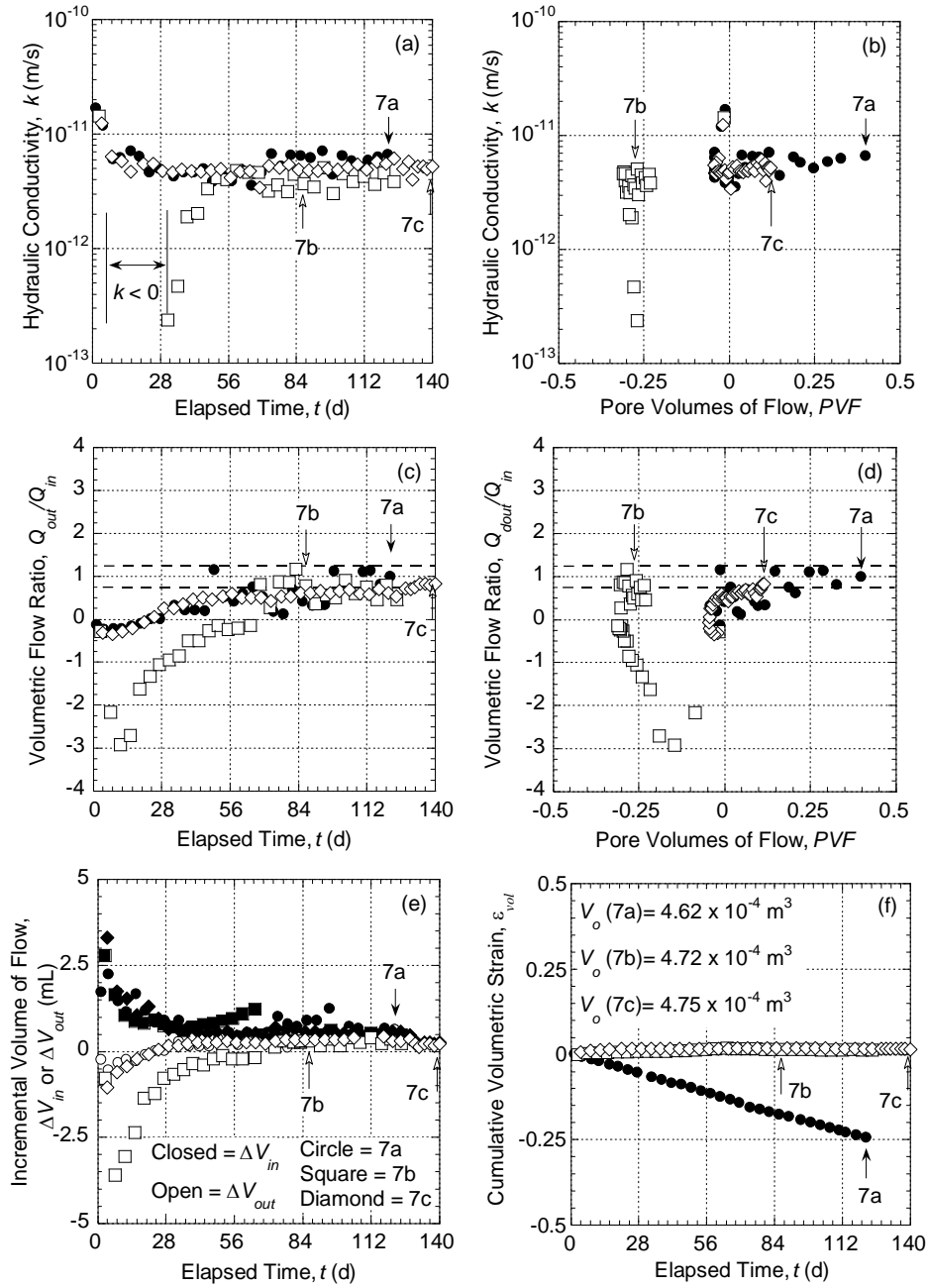


Fig. 2.13 Results for Test Series 7: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

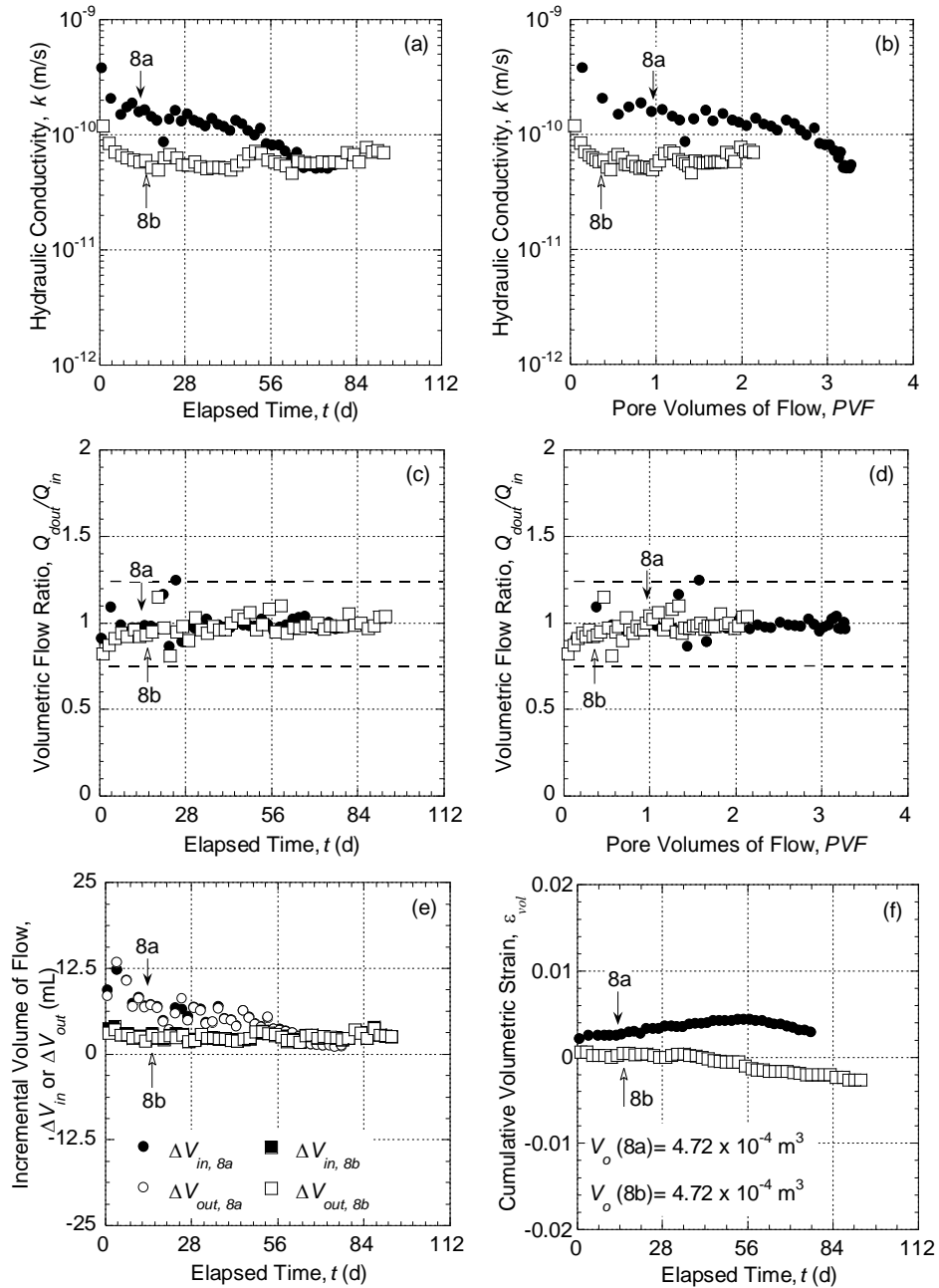


Fig. 2.14 Results for Test Series 8: (a) k versus t ; (b) k versus PVF ; (c) Q_{out}/Q_{in} versus t ; (d) Q_{out}/Q_{in} versus PVF ; (e) ΔV_{in} or ΔV_{out} versus t ; (f) ϵ_{vol} versus t . (Note: arrows designate values corresponding to the standard termination criteria; V_o designates initial volume of specimen).

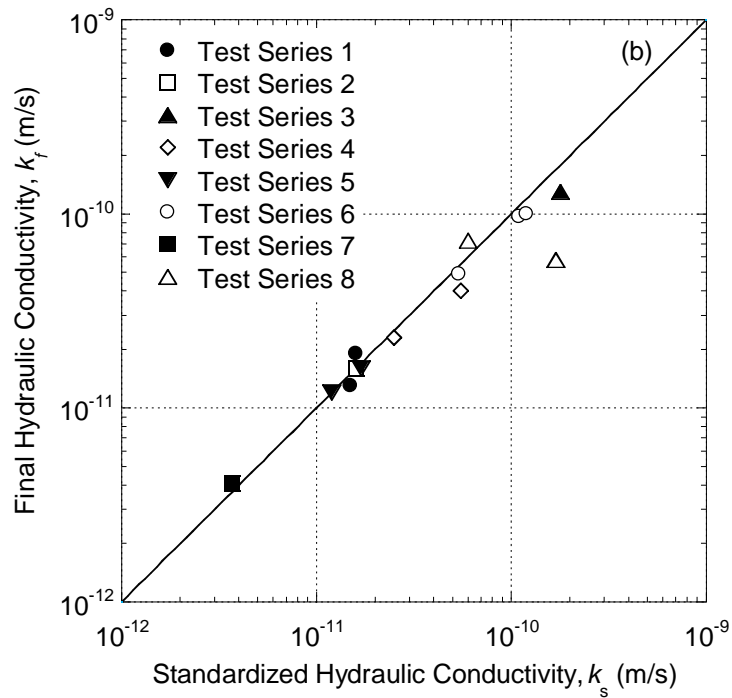
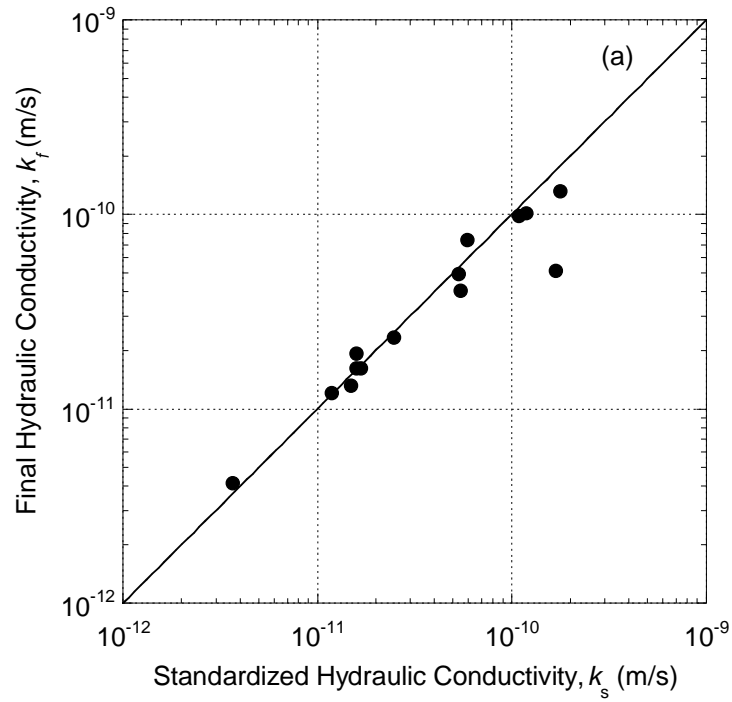


Fig. 2.15 Standardized hydraulic conductivity versus final hydraulic conductivity: (a) all results; (b) results distinguished with respect to Test Series.

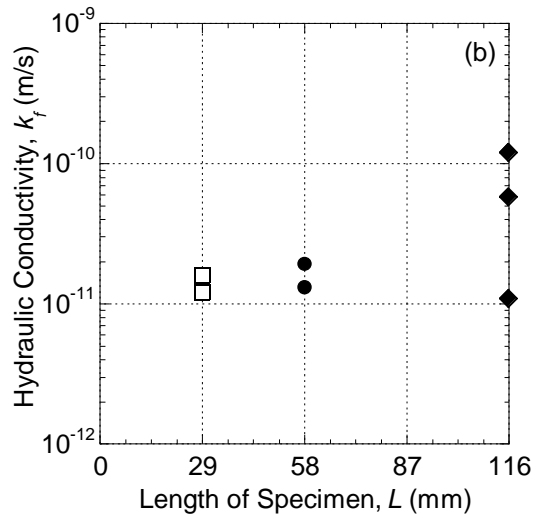
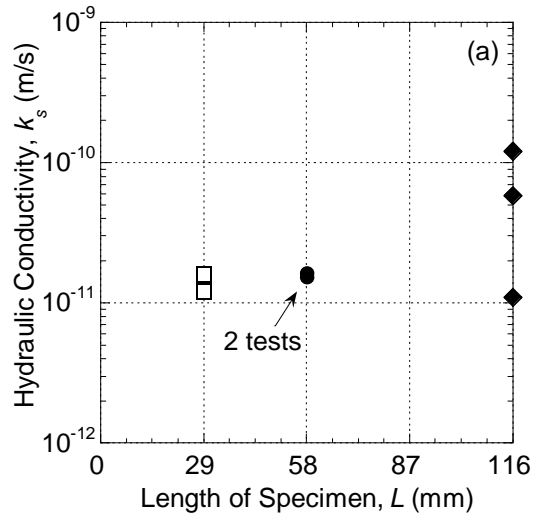


Fig. 2.16 Effect of length of specimen on measured hydraulic conductivity, k : (a) standardized values of k , k_s ; (b) final values of k , k_f .

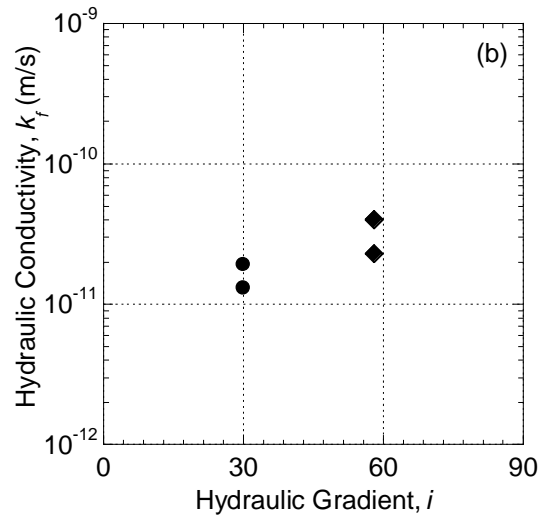
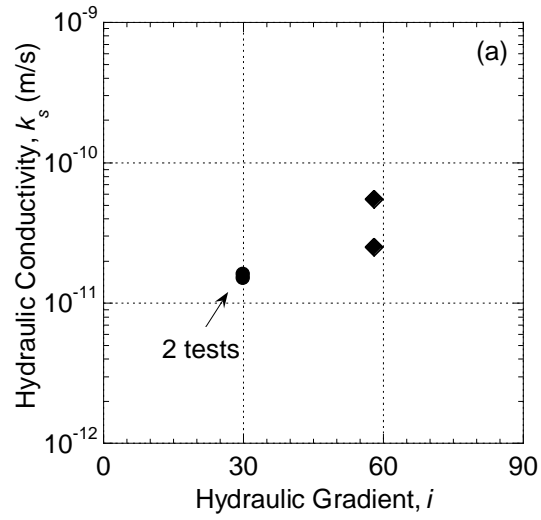


Fig. 2.17 Effect of magnitude of hydraulic gradient on measured hydraulic conductivity, k : (a) standardized values of k , k_s ; (b) final values of k , k_f .

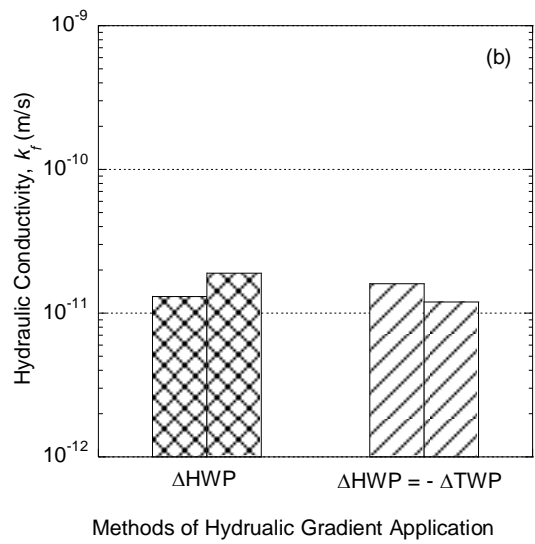
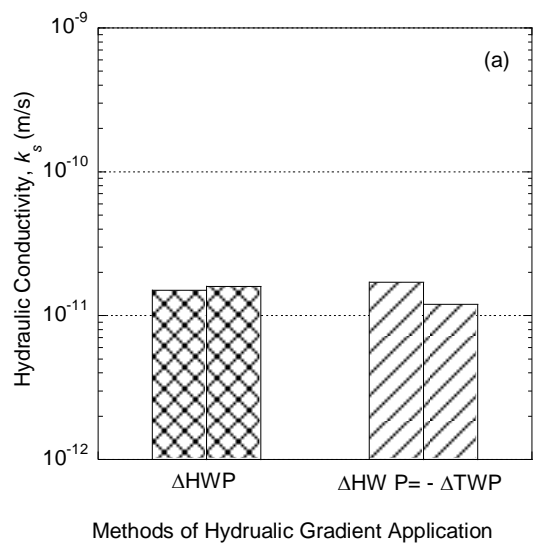


Fig. 2.18 Effect of method of hydraulic gradient application on measured hydraulic conductivity, k : (a) standardized values of k , k_s ; (b) final values of k , k_f .

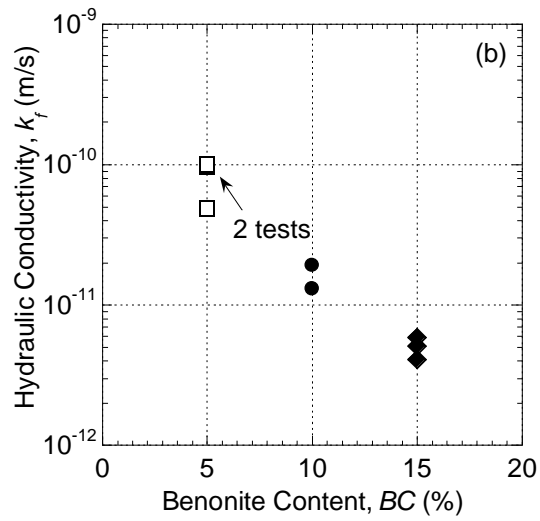
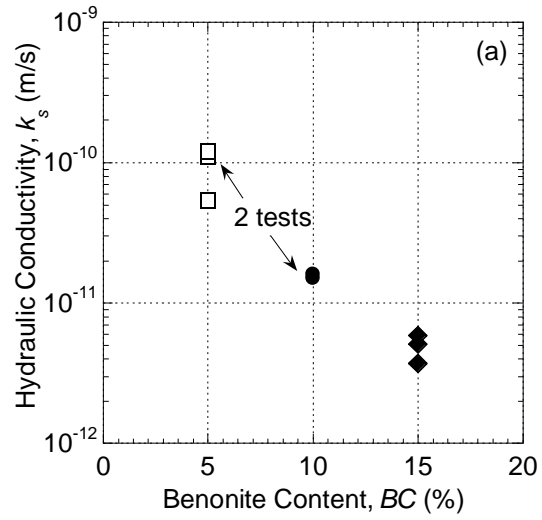


Fig. 2.19 Effect of bentonite content on measured hydraulic conductivity, k : (a) standardized values of k , k_s ; (b) final values of k , k_f .

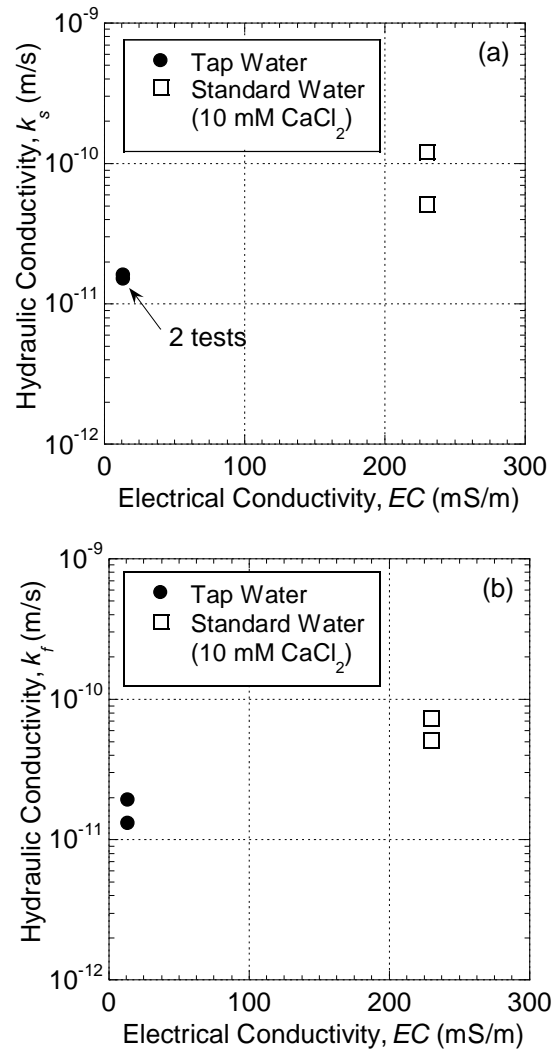


Fig. 2.20 Effect of type of permeant water on measured hydraulic conductivity, k : (a) standardized values of k , k_s ; (b) final values of k , k_f .

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APPENDIX A: PHOTOS SHOWING EFFECT OF BACTERIAL ACTIVITY DURING
PERMEATION OF COMPACTED SAND-BENTONITE SPECIMENS



Fig. A.1 Effect of biological activity on permeation: (a) entire specimen after permeation without biocide; (b) vertically sliced specimen after permeation without biocide; (c) horizontally sliced specimen after permeation and oven dried without biocide; (d) flexible membrane for specimens permeated with and without biocide in permeant liquid.

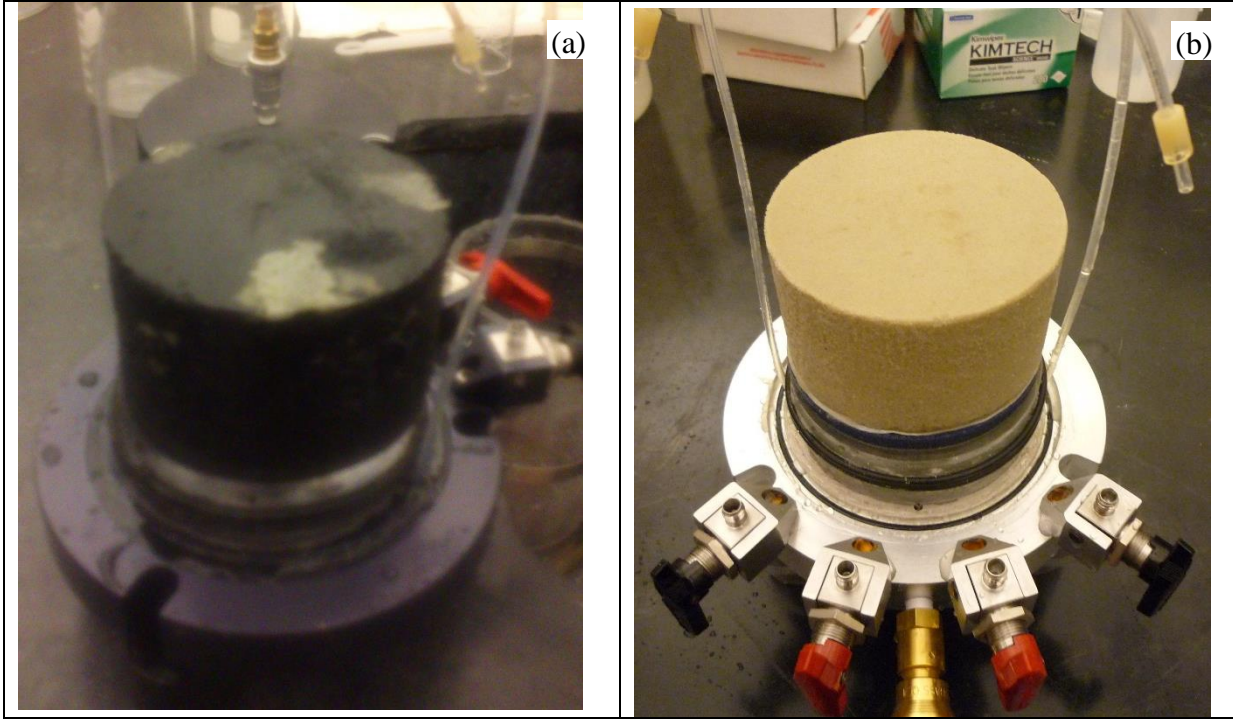


Fig. A.2 Compacted sand-bentonite specimens after completion of permeation: (a) without biocide added to permeant liquid; (b) with biocide added in permeant liquid.

APPENDIX B: PHOTOS SHOWING PROCEDURE FOR PREPARING COMPACTED
SAND-BENTONITE SPECIMENS

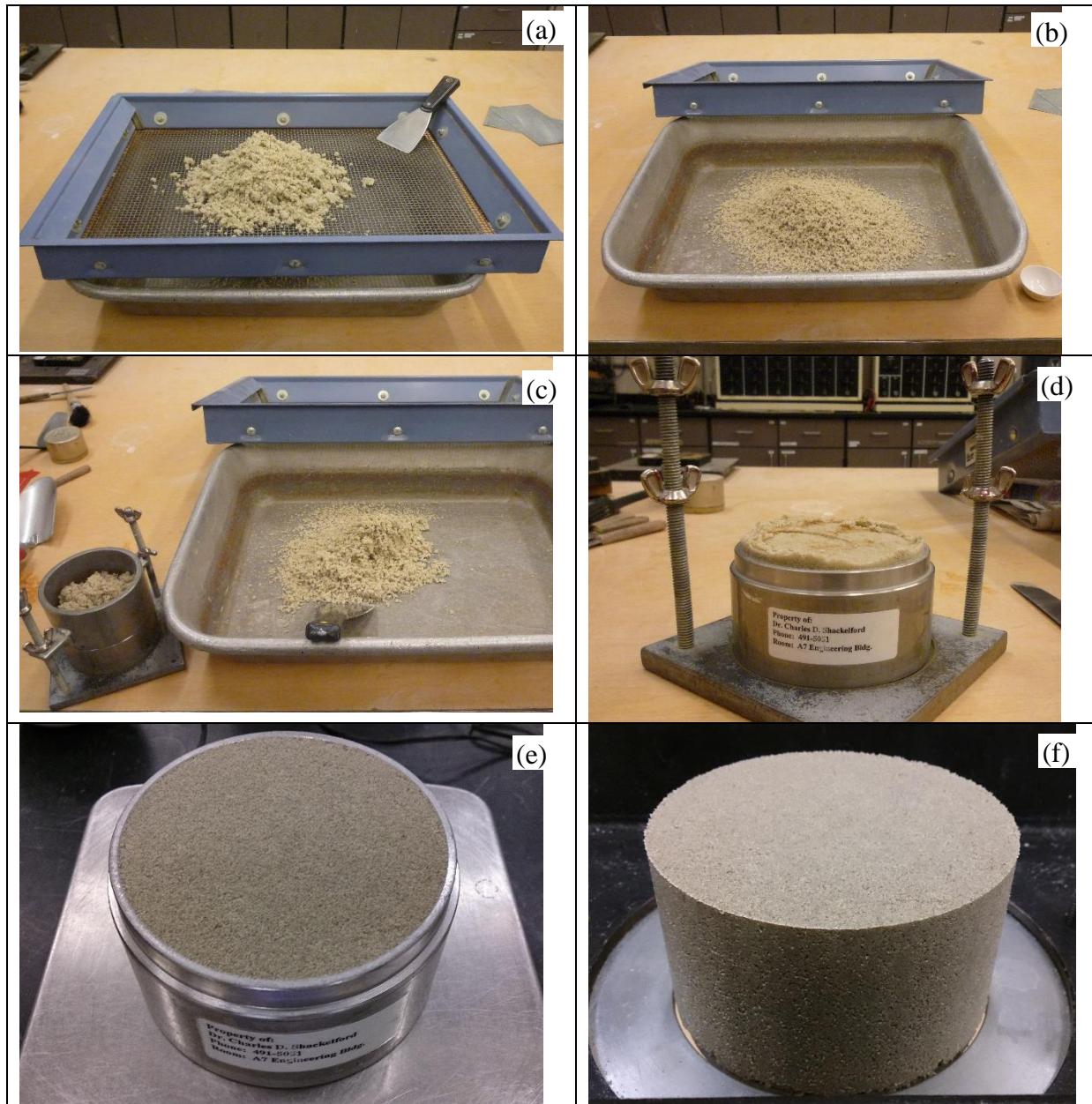


Fig. B.1 Procedure of compaction of a sand-bentonite mixture containing 10 % bentonite (by dry weight) in half-size compaction mold includes: (a) taking soil mixture out of storage container; (a) passing soil through the No.4 sieve by hand; (b) adding soil to compaction mold; (c) compacting soil by two layers and 19 lift per layer; (d) trimming the compacted sand-bentonite specimen; and (e) extruding the specimen out from the compaction mold.

APPENDIX C: PHOTOS OF COMPACTED SAND-BENTONITE SPECIMENS

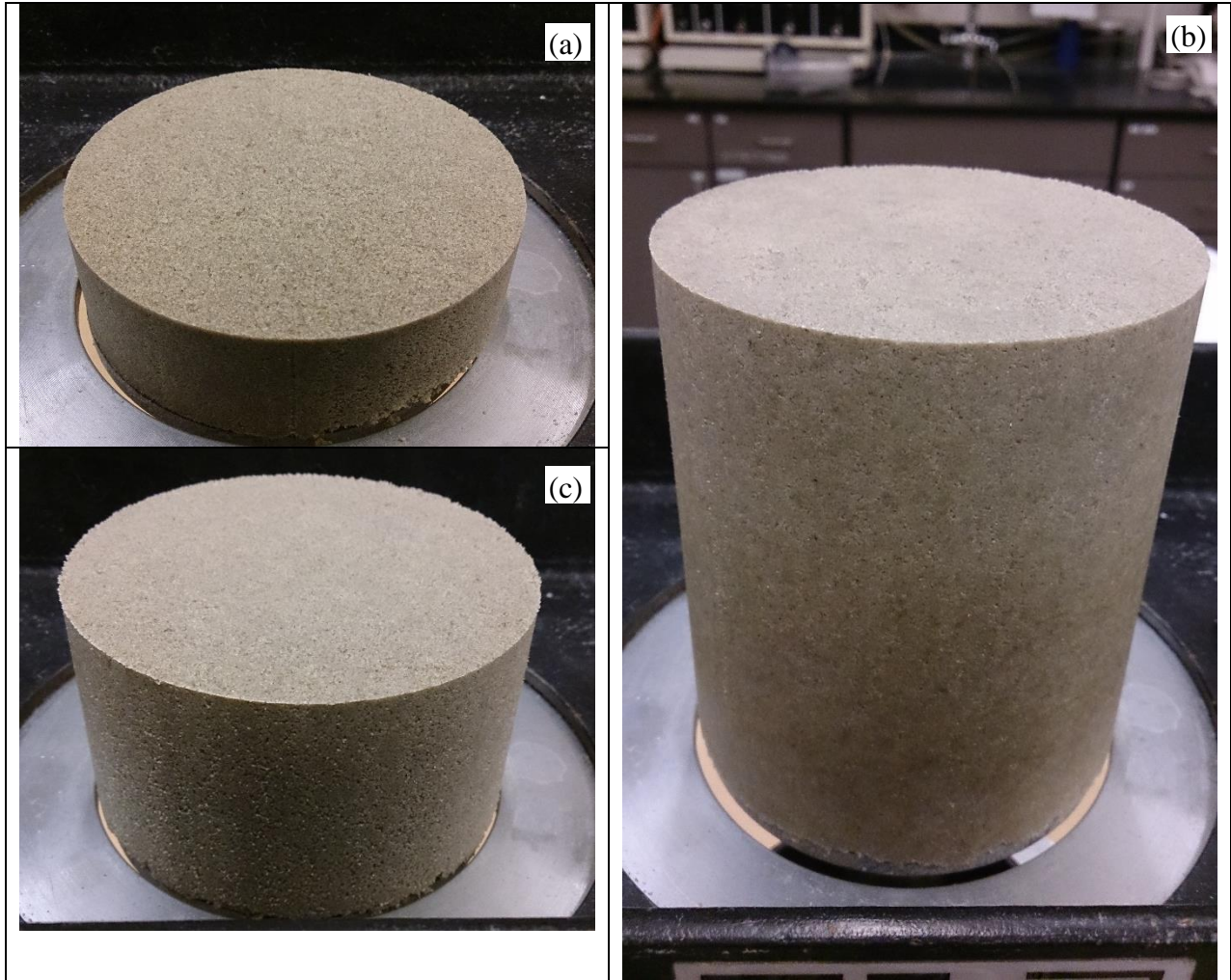


Fig. C.1 Different lengths of compacted sand-bentonite specimens containing 10 % bentonite by dry weight: (a) 29.1 mm; (b) 58.3 mm; (c) 116.5 mm.

APPENDIX D: PHOTOS OF EVIDENCE OF PARTICLE MIGRATION

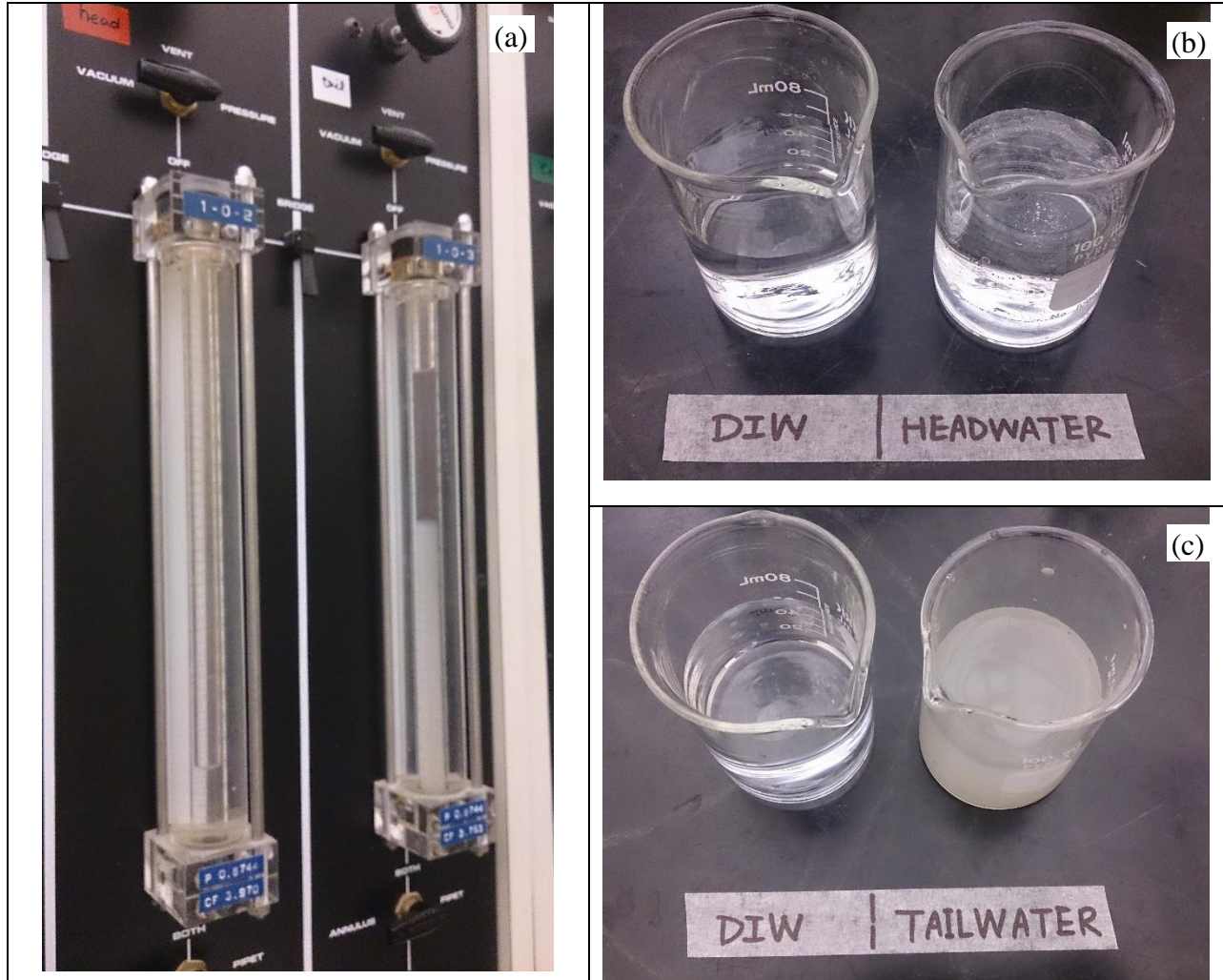


Fig. D.1 Visual evidence of particle migration for compacted specimens of the sand-bentonite mixture containing 5 % bentonite by dry weight: (a) murkiness in the tailwater accumulator (right) versus the headwater accumulator (left); (b) comparison between de-ionized water (DIW) and permeant water in the headwater accumulator; (c) comparison between DIW and permeant water in the tailwater accumulator.



Fig. D.2 Disassembled, compacted sand-bentonite specimen containing 5 % bentonite content after completion of permeation with preferential flow-path shown on the side of specimen