

CORRELATING INDEX PROPERTIES AND HYDRAULIC CONDUCTIVITY OF GCLs

The attached journal article presents the results of a recent study intended to evaluate the use of “surrogate” compatibility tests as indicators of long-term hydraulic conductivity of GCLs in contact with salt solutions. Bentonite index tests (Liquid Limit, Sedimentation Volume, and Swell Index) were selected as the surrogate compatibility tests. These index properties were selected because they are fast, inexpensive, and have been used by researchers in the past to understand how bentonite properties change when in contact with potentially incompatible liquids.

Surrogate compatibility tests and hydraulic conductivity tests were performed with deionized water and with several solutions of varying calcium chloride (CaCl_2) concentration. The results showed that as the CaCl_2 concentrations increased, all three surrogate index properties decreased, and hydraulic conductivity increased. However, universally applicable correlations could not be drawn from the test results. The correlation between the changes in index properties and changes in hydraulic conductivity depended on the particular index property, the bentonite quality, and the effective stress applied during the hydraulic conductivity test. For every index property, there was a critical threshold value, where relatively small decreases in an index property below this value resulted in significant increases in hydraulic conductivity. High-quality bentonite appeared to be more susceptible to chemical attack than low-quality bentonite. Effective stress appeared to play an even more significant role – less adverse affects on hydraulic conductivity were seen at higher effective stresses. For these reasons, the authors concluded that when surrogate tests are used to evaluate compatibility, testing criteria should incorporate bentonite quality and expected effective stress in the field.

Correlating Index Properties and Hydraulic Conductivity of Geosynthetic Clay Liners

Jae-Myung Lee¹; Charles D. Shackelford²; Craig H. Benson³; Ho-Young Jo⁴; and Tuncer B. Edil⁵

Abstract: Three index properties (liquid limit, sedimentation volume, and swell index) of two sodium bentonites from geosynthetic clay liners (GCLs) are correlated with the hydraulic conductivity (k) of the same GCLs to evaluate the suitability of index properties for evaluating chemical compatibility. Deionized water (DIW) and calcium chloride (CaCl_2) solutions were used for hydration (index tests) and permeation (hydraulic conductivity tests). In general, increasing the CaCl_2 concentration caused each index property to decrease and the hydraulic conductivity to increase relative to values obtained with DIW, with the strongest correlations obtained with the liquid limit. The correspondence between index properties and hydraulic conductivity differed by index property, the quality of the bentonite, and the effective stress applied during the hydraulic conductivity test. Thus, correlations used for compatibility assessments are specific to the bentonite in the GCL and the stress conditions being applied. Results of the study also show that appreciable changes in hydraulic conductivity can occur with little or no change in index properties and that the greatest changes in index properties may correspond to conditions causing low or modest changes in hydraulic conductivity. However, in this study, a critical threshold existed for each index property, beyond which further decreases in an index property correlated with substantial increases ($\geq 10\times$) in hydraulic conductivity.

DOI: 10.1061/(ASCE)1090-0241(2005)131:11(1319)

CE Database subject headings: Atterberg limits; Bentonite; Clay liners; Geosynthetics; Hydraulic conductivity; Inorganic chemicals; Sedimentation; Swelling.

Introduction

The performance of earthen hydraulic barriers depends to a great extent on the hydraulic conductivity of the soil to the liquid being contained. Consequently, hydraulic conductivity tests are often conducted on the soil barrier material using the actual liquid to be contained or a liquid with representative properties. Such tests often are referred to as compatibility tests, because the primary objective of the test is to determine whether or not the barrier soil and permeant liquid are compatible, i.e., permeation with the liquid causes no significant change in hydraulic conductivity (Bowders et al. 1986; Bowders and Daniel 1987; Shackelford 1994; Shackelford et al. 2000). In some cases, interactions between the permeating liquid and the soil can result in significant increases

($>10\times$) in the hydraulic conductivity of the soil relative to that based on water (Mitchell and Madsen 1987; Shackelford 1994; Shackelford et al. 2000).

The results of several studies have shown the need to perform compatibility tests until the effluent and influent have the same chemical composition to ensure that all possible interactions between the permeating liquid and the soil have occurred (e.g., Bowders and Daniel 1987; Daniel 1994; Shackelford 1994; Shackelford et al. 2000; Jo et al. 2005). However, due to the low hydraulic conductivity typically required for barrier soils (i.e., $\leq 10^{-7}$ cm/s), test durations required to achieve chemical equilibrium may be extensive, lasting months or even years, depending on the applied hydraulic gradient, the properties of the interacting liquid, and the mechanisms controlling the rate of reactions between the interacting liquid and the soil solids (e.g., Dobras and Elzea 1993; Daniel 1994; Imamura et al. 1996; James et al. 1997; Shackelford et al. 2000; Egloffstein 2001; Melchior 2002; Jo et al. 2005; Lee and Shackelford 2005). Therefore, compatibility testing can be considered prohibitive from the standpoint of timeliness in engineering practice. An alternative approach that is more rapid and less expensive, yet qualitative, is to evaluate how index properties of the barrier soil (e.g., Atterberg limits, particle size, etc.) change when the liquid to be contained is used as the hydrating liquid during index testing. The underlying premise of these tests, which are referred to herein as surrogate compatibility tests, is that physicochemical changes that alter index properties also cause a change in hydraulic conductivity (Dunn and Mitchell 1984; Bowders 1985; Bowders et al. 1986; Bowders and Daniel 1987; Daniel et al. 1988; Acar and Olivieri 1989; Shackelford 1994; Narejo and Memon 1995; Shackelford et al. 2000; Jo et al. 2001). An assumption that is often made, but generally has not been established, is that lack of a change in the properties from a surrogate compatibility test is indicative of

¹Post-Doctoral Research Assistant, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO 80523.

²Professor, Dept. of Civil Engineering, Colorado State Univ., Fort Collins, CO 80523 (corresponding author). E-mail: shackel@engr.colostate.edu

³Professor, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, WI 53706. E-mail: benson@engr.wisc.edu

⁴Assistant Professor, Dept. of Earth and Environmental Sciences, Korea Univ., Anam-dong, Sungbuk-ku, Seoul, 136-701, Korea. E-mail: hyjo@korea.ac.kr

⁵Professor, Dept. of Civil and Environmental Engineering, Univ. of Wisconsin-Madison, Madison, WI 53706. E-mail: edil@engr.wisc.edu

Note. Discussion open until April 1, 2006. Separate discussions must be submitted for individual papers. To extend the closing date by one month, a written request must be filed with the ASCE Managing Editor. The manuscript for this paper was submitted for review and possible publication on September 23, 2004; approved on April 18, 2005. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 131, No. 11, November 1, 2005. ©ASCE, ISSN 1090-0241/2005/11-1319-1329/\$25.00.

compatibility between the permeant liquid and soil (e.g., the liquid has no effect on hydraulic conductivity), or vice versa.

The objective of this paper is to evaluate the use of surrogate compatibility tests in the form of index properties as indicators of the long-term hydraulic compatibility of geosynthetic clay liners (GCLs) permeated with inorganic solutions with nearly neutral pH. The research was conducted as part of a collaborative study between Colorado State University (CSU) and the University of Wisconsin-Madison (UW) investigating the long-term permeation of GCLs with nonstandard inorganic aqueous liquids. Liquid limit, sedimentation volume, and swell index were measured for sodium bentonites from two GCLs using deionized water and solutions containing a range of calcium chloride (CaCl_2) concentrations. Hydraulic conductivity tests were conducted on the GCLs using the same solutions, because CaCl_2 solutions are known to cause alterations in the hydraulic conductivity of GCLs containing sodium bentonite, and the magnitude of the alterations depends on the CaCl_2 concentration (Alther et al. 1985; Daniel et al. 1993; Shackelford 1994; Gleason et al. 1997; James et al. 1997; Melchior 1997; Quaranta et al. 1997; Ruhl and Daniel 1997; Lin and Benson 2000; Shackelford et al. 2000; Egloffstein 2001; Jo et al. 2001, 2005; Vasko et al. 2001; Shan and Lai 2002; Kolstad et al. 2004; Jo et al. 2005; Lee and Shackelford 2005).

Background

Liquid limit (LL) tests have been used by several investigators as surrogate compatibility tests (Bowders et al. 1986; Sridharan et al. 1986; Bowders and Daniel 1987; Daniel et al. 1988; Acar and Olivieri 1989; Edil et al. 1991; Shackelford 1994; Gleason et al. 1997; Petrov and Rowe 1997; Lin and Benson 2000; Sridharan and Prakash 2000). Results of these studies generally have shown that an increase in cation valence and/or electrolyte concentration (inorganic chemical solutions) or a decrease in dielectric constant (aqueous solutions of organic compounds or non-aqueous phase liquids) causes the LL to decrease and the hydraulic conductivity to increase, with greater effects occurring for soils containing higher activity clays, such as bentonite. For example, Petrov and Rowe (1997) show that the LL of a bentonite from a GCL decreased from 530 to 96 as the sodium chloride (NaCl) concentration of the testing solution increased from 0 (i.e., water) to 2.0 M, and the hydraulic conductivity of the GCL increased from $\sim 10^{-9}$ to $\sim 10^{-6}$ cm/s for the same increase in NaCl concentration.

The rate or extent of sedimentation also has been used for surrogate compatibility testing (Dunn and Mitchell 1984; Bowders 1985; Bowders et al. 1986; Bowders and Daniel 1987; Ryan 1987; Benson 1989; Edil et al. 1991; Shackelford 1994). These tests typically are similar to the particle-size distribution tests for fine-grained soils (i.e., *ASTM D 422*), except the permeant liquid in question is used instead of water, usually without a dispersing agent. The settling behavior typically is characterized by monitoring particle sedimentation using a hydrometer bulb (e.g., Dunn and Mitchell 1984) or by measuring the sedimentation volume as a function of time (e.g., Bowders 1985; Bowders et al. 1986; Bowders and Daniel 1987; Shackelford 1994). Measurement of sedimentation volume is more common in the case of highly swelling soils, such as bentonite, because these soils tend to inhibit displacement of the hydrometer bulb (Shackelford 1994). For example, Dunn and Mitchell (1984) performed hydrometer tests and hydraulic conductivity tests on two silty clay soils using water and synthetic tailings leachate and found that the leachate

caused larger apparent particle sizes, presumably due to flocculation. Hydraulic conductivity tests on the same soils showed significant increases ($>10\times$) in hydraulic conductivity. Similarly, Bowders et al. (1986) found that increasing the methanol content in methanol-water mixtures beyond 80% (by volume) caused significant ($10\times$) increases in hydraulic conductivity as well as more rapid settling of a kaolin clay in sedimentation tests. Similar results were reported by Ryan (1987) for two bentonites being considered for use in a soil-bentonite vertical cutoff wall.

Several studies also have shown that the swell index of bentonite is directly correlated with the hydraulic conductivity of bentonite-based GCLs (Didier and Comeaga 1997; Ruhl and Daniel 1997; Lin and Benson 2000; Shackelford et al. 2000; Egloffstein 2001; Jo et al. 2001; Shan and Lai 2002; Kolstad et al. 2004). For example, the results of swell index tests on sodium bentonite from a GCL reported by Shackelford et al. (2000) and Jo et al. (2001) show that swell index of the bentonite is sensitive to the cation valence and/or electrolyte concentration in a manner that is consistent with changes in the thickness of the adsorbed layer of cations. The hydraulic conductivity of the GCL also increased when permeated with stronger electrolyte solutions (i.e., higher cation valence and/or electrolyte concentration). That is, a decrease in swell index corresponded with an increase in hydraulic conductivity, with greater decreases in swell index correlated with greater increases in hydraulic conductivity.

Materials and Methods

Geosynthetic Clay Liners

Two GCLs containing chemically untreated bentonites with different montmorillonite contents were used in this study. Both GCLs consist of a thin layer of granular sodium bentonite sandwiched between two polypropylene geotextiles held together by needle-punched fibers. Both GCLs are 6 mm thick in the air-dried condition. The bentonites from both GCLs classify as high plasticity clays (CH) based on the Unified Soil Classification System (*ASTM D 2487*). However, one GCL contained higher quality bentonite (HQB) in terms of greater sodium montmorillonite content (86% versus 77%), higher plasticity index (548 versus 393), and greater cation exchange capacity (93 meq/100 g versus 64 meq/100 g) relative to the GCL containing the lower quality bentonite (LQB). The percentage of sodium on the exchange complexes of both bentonites is approximately the same (i.e., 75% for the HQB and 74% for the LQB). The bentonite masses (*ASTM D 5993*) were 5.1 kg/m² for the GCL with LQB and 4.6 kg/m² for the GCL with HQB. Tests at UW were performed using the GCL with LQB, whereas tests at CSU were performed using both GCLs. Further details regarding the properties and mineralogical compositions of both bentonites are provided by Lee and Shackelford (2005).

Testing Liquids

The liquids used in the experiments consisted of deionized water (DIW) and CaCl_2 solutions. The CaCl_2 solutions were prepared by dissolving CaCl_2 (powdered, $>96\%$ pure, Sigma-Aldrich Co., St. Louis) in DIW to yield solutions with CaCl_2 concentrations of 5, 10, 20, 50, 100, and 500 mM. This range of concentrations was selected so that a broad range of hydraulic conductivities would be obtained (Jo et al. 2005). The CaCl_2 solutions prepared at CSU and UW were essentially identical, with pH ranging from 5.7 ± 0.5

for the 5 mM CaCl_2 solution to 6.5 ± 0.2 for the 500 mM CaCl_2 solution, and measured electrical conductivity (EC) at 25°C ranging from 123 ± 2.1 mS/m for the 5 mM CaCl_2 solution to $7,690 \pm 30$ mS/m for the 500 mM CaCl_2 solution. However, the DIWs used at CSU and UW differed slightly, with the DIW used at UW ($\text{EC} \approx 0.04$ mS/m) classifying as Type II per *ASTM D 1193* ($\text{EC} \leq 0.1$ mS/m), and the DIW used at CSU ($\text{EC} \approx 0.21$ mS/m) classifying as Type IV ($\text{EC} \leq 0.5$ mS/m). Nonetheless, the calcium (Ca^{2+}) concentrations in both DIWs were determined to be below the method detection limit of 0.02 mg/L (EPA Method 200.7, U.S. EPA 1994).

Hydraulic Conductivity Testing

Specimens of each GCL were permeated with the DIW and CaCl_2 solutions in flexible-wall permeameters using the falling-head procedure in accordance with *ASTM D 5084*-Method B (i.e., falling head, constant tailwater elevation). Specimens were trimmed to a nominal diameter of 102 mm and assembled in the permeameters using the procedure described by Daniel et al. (1997) to prevent short circuiting through the geotextiles at the edge of the GCL. Backpressure was not used so that effluent liquid could be collected conveniently for EC and solute concentration measurements.

For all tests using DIW as the permeant liquid, the tests were conducted at least until the termination criteria specified in *ASTM D 5084* were achieved. For all tests using CaCl_2 solutions, the tests were continued at least until chemical equilibrium was established (e.g., Bowders et al. 1986; Daniel 1994; Shackelford et al. 1999, 2000). Chemical equilibrium was considered to have been established when EC of the effluent was within $\pm 10\%$ of the influent EC as recommended by Shackelford et al. (1999) and in accordance with *ASTM D 6766*, and the concentrations of both chloride (Cl^-) and calcium (Ca^{2+}) in the effluent were within $\pm 10\%$ of those in the source solutions. These chemical equilibrium requirements resulted in testing durations lasting from less than 1 day to more than 900 days with longer testing durations required for tests using lower CaCl_2 solutions [see Jo et al. (2005) and Lee and Shackelford (2005)].

The same methods for hydraulic conductivity testing were used at CSU and UW except for slight differences in the average effective stress (23.5 kPa at CSU versus 16.2 kPa at UW) and the average hydraulic gradient (200 at CSU versus 130 at UW). Although these hydraulic gradients are higher than the maximum gradient (i.e., 30) stipulated in *ASTM D 5084*, the use of elevated hydraulic gradients was considered desirable from a practical viewpoint to minimize the test durations required to achieve chemical equilibrium between the effluent and influent. Indeed, as will be shown subsequently, the tests using the 5, 10, and 20 mM CaCl_2 solutions as permeant liquids still required from 139 to 934 days of permeation to achieve chemical equilibrium. In addition, hydraulic gradients ranging from 50 to 600 typically are used for measuring the hydraulic conductivity of GCLs (e.g., Shan and Daniel 1991; Daniel et al. 1993; Didier and Comeaga 1997; Petrov and Rowe 1997; Petrov et al. 1997a,b; Quaranta et al. 1997; Ruhl and Daniel 1997; Lin and Benson 2000; Shackelford et al. 2000). As shown by Shackelford et al. (2000), the use of such elevated hydraulic gradients for permeating GCLs with nonstandard liquids (i.e., liquids other than water) does not appear to have a significant effect on the hydraulic conductivity of GCLs, because the hydraulic conductivity of GCLs appears to be affected to a greater extent by average effective stress than by the magnitude of hydraulic gradient due to the relative thinness

of GCLs. Further details of the methods used for hydraulic conductivity testing are provided by Jo et al. (2005) and Lee and Shackelford (2005).

Index Property Testing

Liquid Limit

Liquid limit (LL) tests for the bentonites taken from the two GCLs were conducted following the procedure in *ASTM D 4318* (Method A, multipoint test) using DIW and solutions with CaCl_2 concentrations ranging from 5 to 500 mM. Specimens were prepared by mixing air-dried bentonite with each testing liquid thoroughly for more than 30 min. The moistened bentonite was placed in sealed plastic bags and stored in a humidity-controlled chamber (i.e., relative humidity = $90 \pm 5\%$ and temperature = $20 \pm 1^\circ\text{C}$) for at least 16 h of tempering prior to testing. After the tempering, the bentonite was remixed thoroughly for at least 15 min before performing the first trial. A minimum of six trials was performed for each testing liquid to produce successive numbers of blow counts between 15 and 35 by repeatedly adding DIW or a CaCl_2 solution, remixing, tempering, and remixing. All of the LL tests were conducted at CSU.

Sedimentation Volume

Sedimentation tests were conducted using both DIW and CaCl_2 solutions with concentrations ranging from 5 to 500 mM and 30 g of air-dried bentonite from both GCLs. Dispersing agent was not added. Suspensions were prepared by mixing air-dry bentonite in a mechanical mixer (Model 936, Hamilton Beach/Proctor-Silex, Inc., Washington, N.C.) for 1 min with DIW or a CaCl_2 solution. A sedimentation (hydrometer) cylinder then was filled with the suspension to the 1,000 mL mark, and allowed to stand for at least 16 h before the start of a sedimentation test to ensure more extensive exposure of the bentonite to the liquid. After the standing period, the suspension was shaken vigorously for 1 min as per *ASTM D 422*. All of the sedimentation tests were conducted at CSU.

Due to the high swelling potential of sodium bentonite, sedimentation volume was measured in lieu of hydrometer bulb readings. The volume of sedimentation per 30 g of air-dried bentonite in 1 mL/30 g was determined by measuring with a ruler the depositional height (i.e., distance from the bottom to the interface between the suspension and the supernatant) at 24 h. The upper bound on the sedimentation volume is limited to the volume of the sedimentation cylinder (i.e., 1,000 mL), and corresponds to no discernable settlement in 24 h. A sedimentation duration of 24 h was considered to be consistent with the test durations for the other index tests as well as feasible from a practical viewpoint in terms of the use of surrogate compatibility tests in engineering practice.

Swell Index

Swell index tests were performed at both CSU and UW following the methods in *ASTM D 5890* using both DIW and the CaCl_2 solutions. Swell index tests were performed on both bentonites at CSU, whereas tests were performed only on the LQB at UW. Air-dried bentonite for the tests was crushed with a mortar and pestle, passed through a No. 200 U.S. Standard Sieve, and then

Table 1. Summary of Results for Hydraulic Conductivity (k) Tests

Permeant liquid	Laboratory	GCL type ^a	Effective stress (kPa)	Test duration ^b		k (cm/s) ^b	
				Time	Pore volumes of flow	Measured	Average
Deionized water	UW	LQB	16.2	120 days	3.0	1.7×10^{-9}	1.7×10^{-9}
	CSU	LQB	23.5	16 days	1.3	2.4×10^{-9}	2.3×10^{-9}
	CSU	LQB	23.5	26 days	1.2	2.3×10^{-9}	
	CSU	HQB	23.5	209 days	3.0	7.0×10^{-10}	7.0×10^{-10}
5 mM CaCl ₂	UW	LQB	16.2	281 days	82	1.4×10^{-8}	1.5×10^{-8}
	UW	LQB	16.2	551 days	92	1.5×10^{-8}	
	UW	LQB	16.2	416 days	84	1.5×10^{-8}	
	CSU	LQB	23.5	502 days	57	8.6×10^{-9}	8.6×10^{-9}
	CSU	LQB	23.5	779 days	79	8.7×10^{-9}	
	CSU	HQB	23.5	934 days	58	1.7×10^{-8}	1.7×10^{-8}
10 mM CaCl ₂	UW	LQB	16.2	161 days	68	1.3×10^{-8}	1.7×10^{-8}
	UW	LQB	16.2	299 days	61	2.0×10^{-8}	
	CSU	LQB	23.5	397 days	30	6.7×10^{-9}	8.2×10^{-9}
	CSU	LQB	23.5	297 days	36	9.7×10^{-9}	
	CSU	HQB	23.5	515 days	60	1.7×10^{-8}	1.7×10^{-8}
20 mM CaCl ₂	UW	LQB	16.2	139 days	120	1.9×10^{-8}	1.6×10^{-8}
	UW	LQB	16.2	263 days	59	1.2×10^{-8}	
	CSU	LQB	23.5	164 days	21	8.1×10^{-9}	8.8×10^{-9}
	CSU	LQB	23.5	178 days	31	9.4×10^{-9}	
	CSU	HQB	23.5	154 days	22	1.8×10^{-8}	1.8×10^{-8}
50 mM CaCl ₂	UW	LQB	16.2	6.5 h	8.0	1.6×10^{-6}	1.6×10^{-6}
	CSU	LQB	23.5	16 days	9.3	1.6×10^{-8}	1.8×10^{-8}
	CSU	LQB	23.5	15 days	8.9	1.9×10^{-8}	
	CSU	HQB	23.5	2.6 h	18	4.6×10^{-6}	4.1×10^{-6}
	CSU	HQB	23.5	4.2 h	17	3.6×10^{-6}	
100 mM CaCl ₂	UW	LQB	16.2	9.4 h	12	1.1×10^{-6}	1.1×10^{-6}
	CSU	LQB	23.5	19 h	6.8	3.0×10^{-7}	3.4×10^{-7}
	CSU	LQB	23.5	14 h	6.0	3.7×10^{-7}	
	CSU	HQB	23.5	5.9 min	4.6	3.1×10^{-5}	3.5×10^{-5}
	CSU	HQB	23.5	9.3 min	11	3.9×10^{-5}	
500 mM CaCl ₂	UW	LQB	16.2	58 min	3.0	1.9×10^{-6}	1.9×10^{-6}
	CSU	LQB	23.5	40 min	1.7	1.2×10^{-6}	1.5×10^{-6}
	CSU	LQB	23.5	27 min	1.6	1.8×10^{-6}	
	CSU	HQB	23.5	51 s	1.5	5.7×10^{-5}	6.0×10^{-5}
	CSU	HQB	23.5	54 s	1.6	6.2×10^{-5}	

Note: CSU=Colorado State University and UW=University of Wisconsin-Madison.

^aGCL with lower quality bentonite (LQB) or higher quality bentonite (HQB).

^bValues at chemical equilibrium except for the tests with water, in which case the values are based on the termination criteria in *ASTM D 5084*.

oven-dried at 105 °C for 24 h. Approximately 90 mL of each testing liquid was added to a 100-mL graduated cylinder. Then, 2.0 g of the oven-dried bentonite were dusted over the surface of the testing liquid in the graduated cylinder in less than 0.1-g increments. Each increment of bentonite was added over a period of 30 s with a minimum standing period of 10 min between each increment. Afterwards, additional testing liquid was used to rinse any particles adhering to the sides of the cylinder and to fill the cylinder to the 100-mL mark. The swell volume of bentonite per 2.0 g of bentonite in 1 mL/2 g was measured after an elapsed time of 16 h, i.e., the minimum hydration period required by *ASTM D 5890*.

Results

Hydraulic Conductivity

All of the hydraulic conductivities are summarized in Table 1. The hydraulic conductivity values for the tests using CaCl₂ solutions correspond to those at chemical equilibrium with the permeant liquid as previously defined. As shown in Table 1, the hydraulic conductivity (k) of the GCL with the LQB based on permeation with DIW measured at UW of 1.7×10^{-9} cm/s is slightly lower than the average value of 2.3×10^{-9} cm/s measured at CSU, even though the average effective stress for the test at UW (i.e., 16.2 kPa) was lower than that at CSU (i.e., 23.5 kPa).

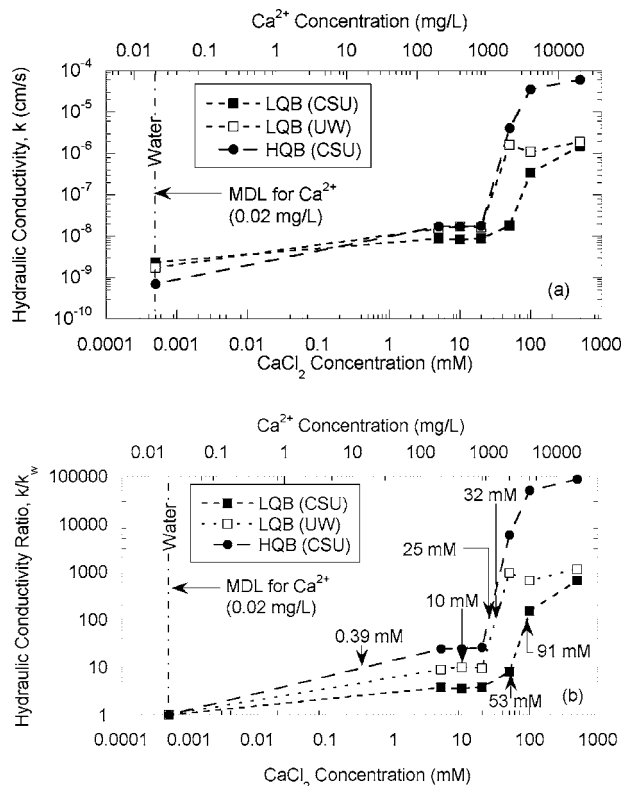


Fig. 1. Results of hydraulic conductivity (k) tests performed on the GCLs with water and CaCl_2 solutions: (a) k and (b) k based on any testing liquid to k based on water (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

This relatively minor difference in k may be attributed to the natural variation resulting from measuring the hydraulic conductivity of the same GCL to water in different laboratories (e.g., see Daniel et al. 1997), and/or to the slightly greater ionic strength for the DIW used at CSU relative to that used at UW as reflected by the aforementioned difference in the measured EC values for the two DIWs. Further discussion of the data obtained from the hydraulic conductivity tests is given by Jo et al. (2005) and Lee and Shackelford (2005).

Averages of the hydraulic conductivities given in Table 1 are shown as a function of the CaCl_2 concentration for the permeant liquid in Fig. 1. In general, the trends in hydraulic conductivity (k) with CaCl_2 concentration [Fig. 1(a)] are similar for both GCLs and both testing laboratories, with a relatively gradual increase in k with increasing CaCl_2 concentration up to 20 mM CaCl_2 , followed by a more significant increase in k with further increase in CaCl_2 concentration. The increase in k with increasing CaCl_2 concentration is consistent with the results of previous studies and is attributed to a decrease in thickness of the adsorbed layer of cations and compression of the interlayer region of the bentonite, resulting in larger intergranular pores and higher k (Gleason et al. 1997; Petrov and Rowe 1997; Lin and Benson 2000; Shackelford et al. 2000; Jo et al. 2001, 2005).

At all CaCl_2 concentrations, the k measured at CSU for the GCL with LQB is similar to, but slightly lower ($\leq 3.3\times$) than, the k measured at UW, except for the specimens permeated with the 50 mM CaCl_2 solution, where the average k measured at CSU is $\sim 90\times$ lower than the single value of k measured at UW. The consistently lower k measured at CSU for a given CaCl_2 concen-

tration may be attributed, in part, to the higher average effective stress applied at CSU (23.5 kPa) relative to that at UW (16.2 kPa), although this difference in effective stress (7.3 kPa) is small. Fernandez and Quigley (1991) and Shackelford et al. (2000) show that the effects of chemical interactions on k are reduced when the effective stress is higher.

The hydraulic conductivities for each GCL normalized with respect to that based on permeation with DIW (k_w) are shown in Fig. 1(b) as a function of the CaCl_2 concentration in the permeant liquid. The CaCl_2 concentrations corresponding to $10\times$ and $100\times$ increases in hydraulic conductivity (i.e., $k/k_w=10$ and $k/k_w=100$) for each GCL based on log-log linear interpolation also are shown as numerals in Fig. 1(b). Due to the aforementioned difference in k_w measured at the two different laboratories (i.e., CSU and UW), any factors contributing to the difference in k_w are also assumed to be inherent in the measured k based on permeation with the CaCl_2 solution such that normalizing k relative to k_w measured at the same respective laboratory results in consistent trends.

In general, the CaCl_2 concentration corresponding to increases in k of $10\times$ and $100\times$ decreases with the type of bentonite in the GCL in the order $\text{HQB} < \text{LQB (UW)} < \text{LQB (CSU)}$. Thus, in the sense that a lower concentration of CaCl_2 in the permeant liquid required to result in a given change in k correlates with a greater susceptibility of the bentonite in the GCL to chemical attack, the GCL with HQB is more susceptible than is the GCL with LQB tested at UW, which is subsequently more susceptible than the GCL with LQB tested at CSU. Despite the lower mass per unit area for the HQB relative to the LQB, the greater susceptibility of GCL with HQB relative to the GCL with LQB can be attributed to the higher quality of the bentonite in the GCL with HQB (Lee and Shackelford 2005), whereas the greater susceptibility of the GCL with LQB tested at UW relative to the GCL with LQB tested at CSU may be attributed, in part, to the aforementioned slight difference in effective stresses used in the two laboratories.

Index Properties

Liquid Limit

Results of the LL tests performed using bentonites from both GCLs are shown in Fig. 2. As the CaCl_2 concentration increases from 0 (DIW) to 500 mM, the LL for the LQB decreases from 430 to 106 and the LL for the HQB decreases from 589 to 102 [Fig. 2(a)]. The decrease in LL with increasing CaCl_2 concentration can be attributed to the increasing predominance of calcium (Ca^{2+}) on the exchange complex of the bentonite particles resulting from cation exchange with sodium (Na^+) that causes stronger net interparticle forces (Lambe and Whitman 1969).

As shown in Fig. 2(b), the ratio of the LL obtained with the CaCl_2 solutions to that based on DIW (LL/LL_w) decreases as the CaCl_2 concentration increases for both bentonites. Moreover, LL/LL_w for the HQB is higher by ~ 0.08 than LL/LL_w for the LQB for the 5, 10, and 20 mM CaCl_2 solutions, whereas for the 50, 100, and 500 mM CaCl_2 solutions, LL/LL_w for the HQB is lower by ~ 0.08 than LL/LL_w for the LQB. Thus, although there is a noticeable difference between the absolute magnitudes in the LL values of the two bentonites for CaCl_2 concentrations ≤ 50 mM, there is little or virtually no difference in the ratio LL/LL_w .

Sedimentation Volume

Results of the sedimentation tests are shown in Fig. 3. As shown in Fig. 3(a), the sedimentation volume (SV) for both bentonites

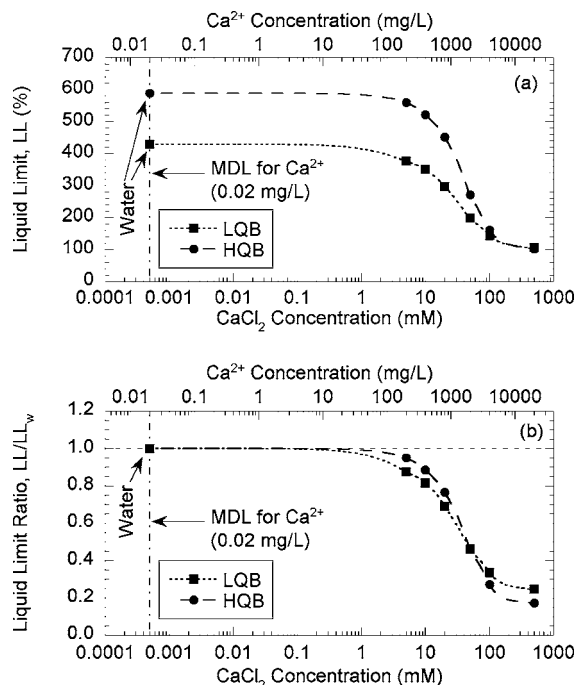


Fig. 2. Results of liquid limit (LL) tests performed on bentonites taken from two GCLs with water and CaCl_2 solutions: (a) LL and (b) LL based on any testing liquid to LL based on water (LQB=lower quality bentonite; HQB=higher quality bentonite; and MDL=method detection limit)

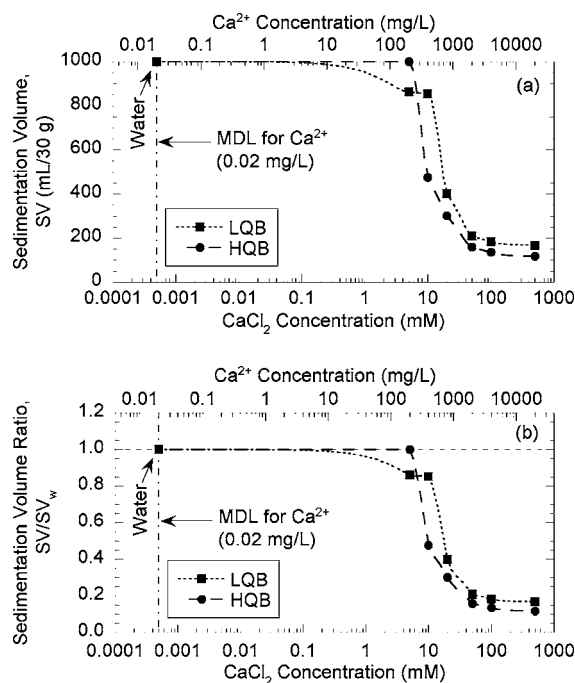


Fig. 3. Results of sedimentation volume (SV) tests performed on the bentonites taken from two GCLs with water and CaCl_2 solutions: (a) SV and (b) SV based on any testing liquid to SV based on water (LQB=lower quality bentonite; HQB=higher quality bentonite; and MDL=method detection limit)

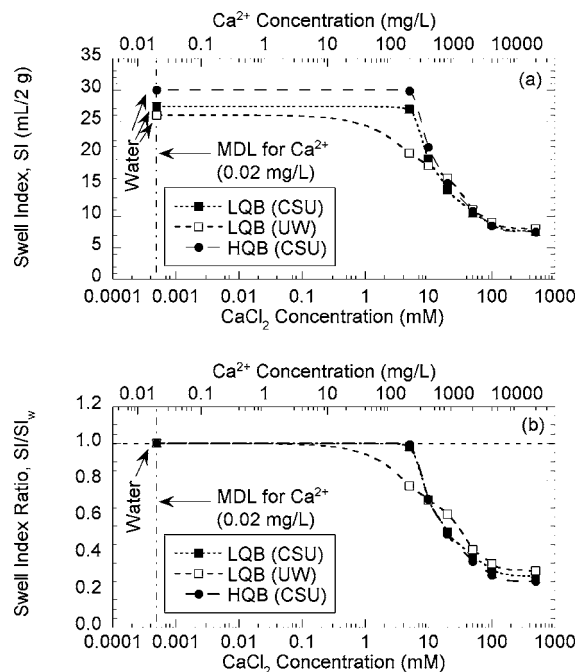


Fig. 4. Results of swell index (SI) tests performed on the bentonites taken from two GCLs with water and CaCl_2 solutions: (a) SI and (b) SI based on any testing liquid to SI based on water (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; UW=University of Wisconsin–Madison; and MDL=method detection limit)

equals the volume of the sedimentation cylinder (i.e., 1,000 mL/30 g) for the tests with DIW and for the test performed using the HQB with the 5 mM CaCl_2 solution (i.e., no discernable settlement occurred for these three tests). In contrast, the 5 mM CaCl_2 solution resulted in a SV of 862 mL/30 g for the LQB. As the concentration increases, the SV decreases from 1,000 g to 168 mL/30 g (LQB) and 117 mL/30 g (HQB) at the highest concentration. This decrease in SV with increasing CaCl_2 concentration is consistent with the results of previous studies and is attributed to compression of the adsorbed layer of cations resulting in the formation of flocs of particles, more rapid settling, and lower SV (Dunn and Mitchell 1984; Bowders and Daniel 1987; Shackelford 1994).

The ratio of the SV obtained with the CaCl_2 solutions to that based on DIW (SV/SV_w) is shown in Fig. 3(b). The SV/SV_w decreases as the CaCl_2 concentration increases for both bentonites. In addition, SV/SV_w typically is higher for the LQB (0.05–0.38) than SV/SV_w for the HQB (i.e., except for the 5 mM CaCl_2 solution, for which the $\text{SV}/\text{SV}_w=1.0$ and 0.86 for LQB and HQB, respectively). These differences reflect the aforementioned differences in the qualities of the two bentonites.

Swell Index

Results of the swell index (SI) tests are shown in Fig. 4. The SI for the HQB decreases from 30.0 to 7.5 mL/2 g as the CaCl_2 concentration increases from 0 (DIW) to 500 mM [Fig. 4(a)]. The trends in SI with CaCl_2 concentration are similar for the LQB, with the average value for SI between the two laboratories decreasing from 26.8 to 7.8 mL/2 g as the CaCl_2 concentrations increase from 0 (DIW) to 500 mM. In fact, for the LQB, the SI measured at both laboratories are close (<13% difference), except for the tests performed with the 5 mM CaCl_2 solution

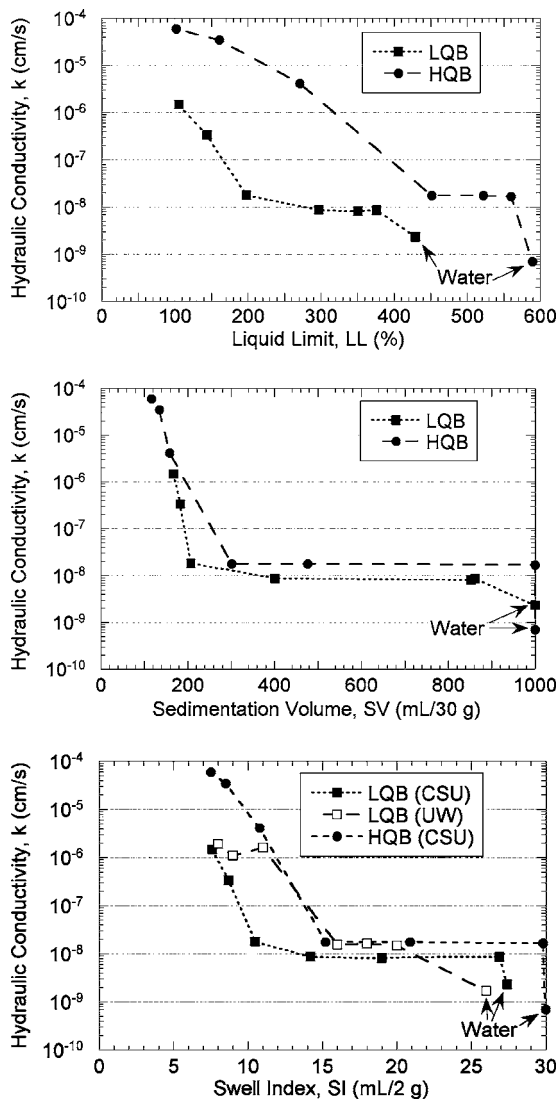


Fig. 5. Correlations between hydraulic conductivity and three index properties for tests performed using two GCLs (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

(~34% higher at CSU). This decrease in SI with increasing CaCl_2 concentration is consistent with the individual granules of bentonite becoming smaller due to compression of the interlayer region induced by the elevated calcium concentration in the bulk solution (Sposito 1981; McBride 1994; Shackelford et al. 2000; Jo et al. 2001).

The ratio of SI obtained with the CaCl_2 solutions to that based on DIW (SI/SI_w) decreases as the CaCl_2 concentration increases for both bentonites [Fig. 4(b)]. Except at 5 mM, the relationship between SI/SI_w and CaCl_2 concentration is nearly unique. Thus, similar to LL/LL_w but unlike SV/SV_w , the difference in the quality of the two bentonites does not affect significantly the trend between SI/SI_w and CaCl_2 concentration.

Discussion

Comparisons between the hydraulic conductivities of the GCLs and the LLs, SVs, and SIs are shown in Figs. 5 and 6 in terms of individual values and as ratios of values normalized with respect

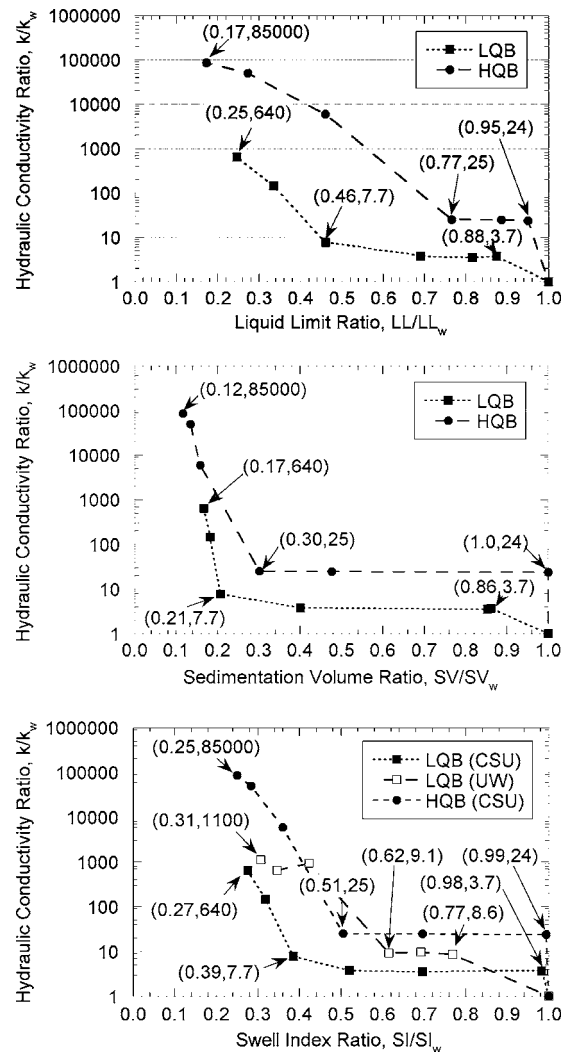


Fig. 6. Correlations between hydraulic conductivity ratios and index property ratio for three index properties based on the tests performed using two GCLs (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

to the value based on DIW, respectively. The correlations between hydraulic conductivity (k) and the index properties shown in Figs. 5 and 6 are similar regardless of the type of index property or GCL, and can be separated into three distinct regions. First, an initial increase in k correlates with relatively little or no change in an index property. Second, greater decreases in the index property correlate with little change in k until some limiting value of an index property is reached. Third, further decreases in an index property below the limiting value correlate with substantial increases ($\geq 10\times$) in k . However, each trend shown in Figs. 5 and 6 is unique to the type of index property, the quality of the bentonite in the GCL, and the effective stress used in the hydraulic conductivity tests for a given GCL.

These three regions are more evident when the logarithm of k/k_w is plotted versus the percentage decrease in an index property relative to that for DIW, as shown in Fig. 7. For both GCLs, increases in k occur with little or no percentage decrease in index properties in the first region. In the second region, little change in k occurs, even though significant percentage decreases in the index properties occur. The third region occurs after the percent-

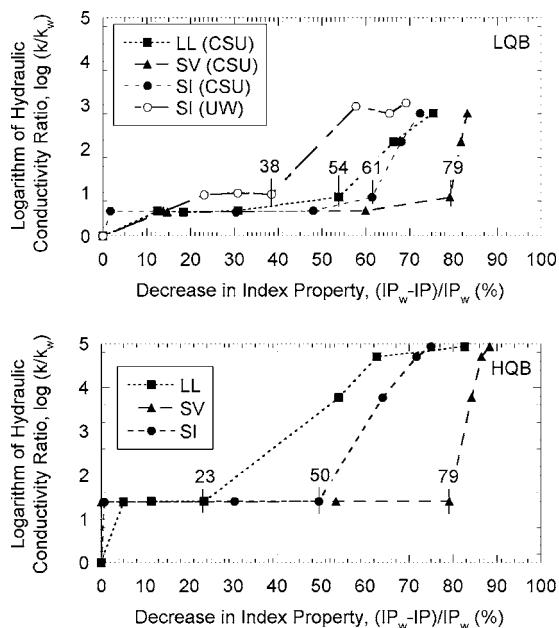


Fig. 7. Correlations between logarithm of the hydraulic conductivity ratio and the relative decrease in liquid limit (LL), sedimentation volume (SV), and swell index (SI) (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

age decrease in the index property reaches a limit, beyond which substantial increases ($\geq 10\times$) in k occur. This point is referred to herein as the “critical threshold.” For example, for the GCL with HQB, the k increases slightly more than an order of magnitude with no decrease in SV, which is followed by no change in k as the percentage decrease in SV increases from 0 to 79%, followed by a significantly greater increase in k as the percentage decrease in SV exceeds 79% (i.e., the critical threshold).

The behavior in the first region, where the hydraulic conductivity increases but no change in index properties occurs, probably reflects differences in equilibration time in the hydraulic conductivity tests and the index tests. This behavior was observed for the permeant liquid with low concentration (5 mM CaCl_2). Changes in hydraulic conductivity caused by permeation with solutions this dilute generally occur after years of permeation and tens of pore volumes of flow because of the slow rate at which cations diffuse in and out of the interlayer space in montmorillonite (Jo et al. 2005; Lee and Shackelford 2005). However, index tests are conducted relatively quickly such that the time available for sufficient diffusion into the interlayer region for dilute solutions is insufficient. In contrast, at higher concentrations such as those corresponding to the third region in Fig. 7, diffusion occurs more rapidly due to the elevated concentration gradient between the bulk pore water and the interlayer water. Consequently, changes occur in both the hydraulic conductivity and the index properties. For the second region corresponding to intermediate concentrations, an increase in concentration apparently is insufficient to affect significantly the hydraulic conductivity of the GCL, whereas a more substantial effect (decrease) in index property occurs. This difference in behavior likely is due, in part, to the difference in exposure of the bentonite particles to the liquid, since the gravimetric water contents (i.e., liquid-to-solid ratios by weight) for the index tests are greater than those for the GCLs in the hydraulic conductivity tests, resulting in greater exposure of

the bentonite particles to the liquid in the case of the index properties.

When only the CSU data are considered, the critical thresholds vary in the order $\text{LL} < \text{SI} < \text{SV}$. Thus, the LL apparently is the most sensitive among the three index properties in that greater decreases in SI and SV relative to LL would be required before substantial increases in k can be assumed. When the UW data are included in the comparison, SI could be inferred to be the most sensitive index property. For example, the critical threshold for SI is 38% for the UW data, whereas the critical threshold for LL (measured at CSU) is 54%. This difference likely reflects, in part, the lower effective stress applied in the hydraulic conductivity tests performed at UW relative to those conducted at CSU (Jo et al. 2005). For example, when the index properties measured at CSU for the LQB are used with the hydraulic conductivities measured at UW, the same order exists for the critical thresholds ($\text{LL} < \text{SI} < \text{SV}$).

The LL probably is more sensitive than SI or SV because the LL is strongly affected by net interparticle forces, which are controlled by interparticle distances. Concentration of the hydrating liquid affects interparticle distance because the thickness of the adsorbed layer of cations on the outer surfaces of montmorillonite is strongly influenced by electrolyte concentration (Mitchell 1993). In contrast, SI is controlled by expansion and contraction of the interlayer region, which may not be fully realized in a short term index test due to the diffusion limitations mentioned previously. The reason for the lower sensitivity of SV is not immediately apparent, but the lower sensitivity may reflect the shorter equilibration time of the SV test (30 h total) relative to the liquid limit test (80 h total for 5 data points).

The critical thresholds also are a function of bentonite quality. Comparison of the CSU data in Figs. 7(a and b) shows that critical thresholds for the GCL with HQB are less than or equal to those for the GCL with LQB. That is, significant changes in k occur with lower changes in index properties for the GCL with HQB, which reflects the greater susceptibility of the HQB to chemical attack (Lee and Shackelford 2005).

The effects of bentonite quality and effective stress are further illustrated in Fig. 8, where the order-of-magnitude increase in k is shown as a function of the percent decrease in index property for each index property. Two observations are readily apparent from the data shown in Fig. 8. First, the critical threshold is independent of bentonite quality for SV, but depends on bentonite quality for LL and SI. Second, at least for SI, the influence of effective stress appears to be more significant than the effect of bentonite quality. For the CSU data, the critical thresholds for SI differ by only 11% for the GCL with HQB and the GCL with LQB (61% versus 50%), whereas the critical threshold for SI for the GCL with LQB obtained from CSU (higher effective stress) and UW (lower effective stress) differ by 23% (61% versus 38%).

The results from this study are compared with the results of the study by Jo et al. (2001) in Fig. 9 in terms of the free swell ratio (FSR), defined as the free swell volume, S_c , in the salt solution divided by the volume of solids in 2 g of air-dried bentonite, V_{db} (i.e., $\text{FSR} = S_c/V_{db}$). The results reported by Jo et al. (2001) were based on tests performed using specimens of a single GCL containing granular bentonite using DIW and single-species salt solutions consisting of the chloride salts of several cations (Na^+ , K^+ , Li^+ , Ca^{2+} , Mg^{2+} , Zn^{2+} , Cu^{2+} , La^{3+}) with concentrations ranging from 5 to 1,000 mM. However, to be consistent with this study, only the results based on water and CaCl_2 solutions are shown in Fig. 9. In comparison with this study, Jo et al. (2001) used the same methods for k and swell index testing, except for

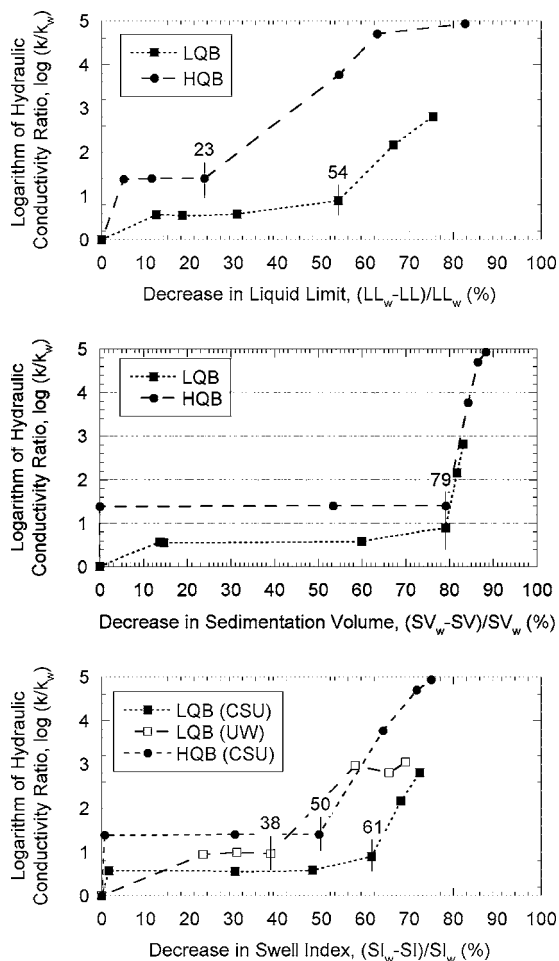


Fig. 8. Correlations between logarithm of the hydraulic conductivity ratio and the relative decrease in three index properties (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

slight differences in their average effective stress (i.e., 20.0 kPa), average hydraulic gradient (i.e., 100), and termination criteria (i.e., $0.90 < p_{H_{out}}/p_{H_{in}} < 1.10$ and $0.90 < EC_{out}/EC_{in} < 1.10$).

As shown in Fig. 9, the trends in the data are essentially the same, except the results from Jo et al. (2001) show a more gradual increase in k with decrease in FSR than the results in this study. This more gradual increase in k may be attributed, in part, to differences in montmorillonite content. Bentonite in the GCL tested by Jo et al. (2001) contained 67% montmorillonite, whereas bentonite in the GCLs tested in this study contained 77% montmorillonite (LQB) or 86% montmorillonite (HQB). That is, lower montmorillonite content correlates with a lower susceptibility of the bentonite to chemical attack upon exposure to salt solutions (Lee and Shackelford 2005).

Based on their results, Jo et al. (2001) proposed a threshold FSR of 20 as a criterion for determining whether or not a GCL would be susceptible to increases in k , with $FSR \geq 20$ representing potentially no or moderate effect on k (i.e., $k/k_w < 10$), and $FSR < 20$ representing the potential for a significant effect on k (i.e., $k/k_w > 10$). As shown in Fig. 9(a), their criterion is consistent with the results for the GCL with the LQB tested in this study such that a $FSR \geq 20$ correlates with relatively moderate changes in k (i.e., $k/k_w < 10$). However, as shown in Fig. 9(a), the results of this study are not in total agreement with the criterion proposed

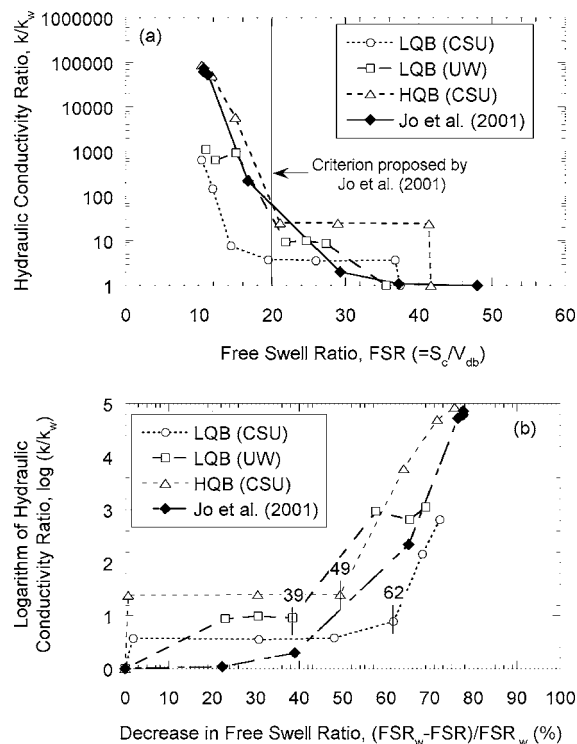


Fig. 9. Comparison of data from this study with results reported by Jo et al. (2001): (a) k/k_w versus FSR; (b) $\log(k/k_w)$ versus relative decrease in FSR (LQB=lower quality bentonite; HQB=higher quality bentonite; CSU=Colorado State University; and UW=University of Wisconsin)

by Jo et al. (2001). For example, for the GCL with HQB, a $FSR=20$ correlates with a relatively significant change in k (i.e., $k/k_w \approx 24$). Thus, for the specific test results of this study, the criterion proposed by Jo et al. (2001) was found to be valid provided (1) moderate changes in k (i.e., $k/k_w < 10$) for the GCL are considered acceptable for $FSR \geq 20$, (2) the quality of the bentonite in the GCL is such that the montmorillonite content is $\leq 77\%$, and (3) the average effective stress in the GCL during hydraulic conductivity testing is ≥ 16.2 kPa.

As shown in Fig. 9(b), the critical threshold for FSR from Jo et al. (2001) falls between those for the GCL with LQB tested at CSU and the GCL with LQB tested at UW and follows the same order as the effective stresses used in the hydraulic conductivity tests. That is, effective stress apparently plays a significant role in terms of the correlation between an index property and the k . However, as the montmorillonite content in the bentonite increases, the potential for $\log(k/k_w)$ being > 1 with little or no change in FSR increases.

Conclusions

This study evaluated the use index properties (liquid limit, sedimentation volume, and swell index) of bentonite hydrated with chemical solutions as surrogate measures of the effect of chemical solutions on the hydraulic conductivity of two GCLs. One GCL contained higher quality bentonite (HQB) and the other lower quality bentonite (LQB). Calcium chloride ($CaCl_2$) solutions were used for the testing program because these solutions are known to alter the hydraulic conductivity of GCLs.

In general, an increase in CaCl_2 concentration resulted in a decrease in liquid limit (LL), sedimentation volume (SV), or swell index (SI), and an increase in hydraulic conductivity (k) of the GCL. However, little or no change in an index property did not necessarily ensure that there was no change in k , and significant changes in an index property occurred without significant changes in k . Nevertheless, for all index properties, a critical threshold existed for each index property, beyond which increases in k were substantial ($\geq 10\times$). Increases in k ranging from approximately two to four orders of magnitude were observed for decreases in an index property beyond the critical threshold.

The aforementioned correlations between changes in index properties and increases in k are functions of the type of index property, the quality of the bentonite, and the effective stress used when measuring k . The LL was found to be the most sensitive among the three index properties, in that greater decreases in SI and SV relative to LL were required before substantial increases in k occurred. Significant increases in k occurred with lower decreases in an index property for the GCL with HQB, reflecting the greater susceptibility of the HQB to chemical attack relative to the LQB. Use of a higher effective stress tended to mask any adverse effects of the permeant liquid on k , although the range in effective stresses evaluated in this study was small (i.e., from 16.2 to 23.5 kPa). As a result, the critical threshold in a given index property is higher when the correlation between the index property and k is based on hydraulic conductivity tests performed at a higher effective stress. Results of this study also showed that the effective stress used in the hydraulic conductivity testing can play a significant role in terms of the correlation between an index property and k . Consequently, when index tests are used as surrogate compatibility tests, the criteria used to evaluate compatibility must be specific to the bentonite being evaluated and the effective stress anticipated in the field.

An analysis of the criterion proposed by Jo et al. (2001) using a free swell ratio as a surrogate indicator of compatibility showed that the threshold FSR for compatibility depends on the magnitude of the change in k considered acceptable, the quality of the bentonite, and the effective stress. For the specific test results in this study, the criterion proposed by Jo et al. (2001) was found to be valid provided (1) moderate changes in k (i.e., $k/k_w < 10$) for the GCL are considered acceptable, (2) the quality of the bentonite in the GCL is such that the montmorillonite content is $\leq 77\%$, and (3) the average effective stress in the GCL during hydraulic conductivity testing is ≥ 16 kPa.

Acknowledgments

Financial support for this study was provided by the U.S. National Science Foundation (NSF), Arlington, Va., under Grant No. CMS-9820863 to Colorado State University and CMS-9900336 to the University of Wisconsin-Madison. The opinions expressed in this paper are solely those of the writers and are not necessarily consistent with the policies or opinions of the NSF.

References

- Acar, Y. B., and Olivieri, I. (1989). "Pore fluid effects on the fabric and hydraulic conductivity of laboratory-compacted clay." *Transportation Research Record 1219*, Transportation Research Board, Washington, D.C., 144–159.
- Alther, G., Evans, J. C., Fang, H.-Y., and Witmer, K. (1985). "Influence of inorganic permeants upon the permeability of bentonite." *Hydraulic barriers in soil and rock*, A. I. Johnson, R. K. Frobel, N. J. Cavalli, and C. B. Pettersson, eds., ASTM STP 874, West Conshohocken, Pa., 64–73.
- Benson, C. (1989). "Index tests for evaluating the effect of leachate on compacted soil liners." *Proc., 2nd Int. Symp. on Environmental Geotechnology*, Technometric, Lancaster, Pa., 222–228.
- Bowders, J. J., Jr. (1985). "The influence of various concentrations of organic liquids on the hydraulic conductivity of compacted clay." PhD dissertation, Univ. of Texas, Austin, Tex.
- Bowders, J. J., Jr., and Daniel, D. E. (1987). "Hydraulic conductivity of compacted clay to dilute organic chemicals." *J. Geotech. Eng.*, 113(12), 1432–1448.
- Bowders, J. J., Jr., Daniel, D. E., Broderick, G. P., and Liljestrand, H. M. (1986). "Methods for testing the compatibility of clay liners with landfill leachate." *Hazardous and industrial solid waste testing*, J. K. Petros, Jr., W. J. Lacy, and R. A. Conway, eds., ASTM STP 886, West Conshohocken, Pa., 233–250.
- Daniel, D. E. (1994). "State-of-art: Laboratory hydraulic conductivity tests for saturated soils." *Hydraulic conductivity and waste contaminant transport in soil*, D. E. Daniel, and S. J. Trautwein, eds., ASTM STP 1142, West Conshohocken, Pa., 30–78.
- Daniel, D. E., Bowders, J. J., Jr., and Gilbert, R. B. (1997). "Laboratory hydraulic conductivity testing of GCLs in flexible-wall permeameters." *Testing and acceptance criteria for geosynthetic clay liners*, L. W. Well, ed., ASTM STP 1308, West Conshohocken, Pa., 208–226.
- Daniel, D. E., Liljestrand, H. M., Broderick, G. P., and Bowders, J. J., Jr. (1988). "Interaction of earthen liner materials with industrial waste leachate." *Hazard. Waste Hazard. Mater.*, 5(2), 93–107.
- Daniel, D. E., Shan, H.-Y., and Anderson, J. D. (1993). "Effects of partial wetting on the performance of the bentonite component of a geosynthetic clay liner." *Proc., Geosynthetics'93*, Industrial Fabrics Association International, St. Paul, Minn., 3, 1483–1496.
- Didier, G., and Comeaga, L. (1997). "Influence of initial hydration conditions on GCL leachate permeability." *Testing and acceptance criteria for geosynthetic clay liners*, L. W. Well, ed., ASTM STP 1308, West Conshohocken, Pa., 181–195.
- Dobras, T. N., and Elzea, J. M. (1993). "In-situ soda ash treatment for contaminated geosynthetic clay liners." *Proc., Geosynthetics'93*, Industrial Fabrics Association International, St. Paul, Minn., 3, 1145–1160.
- Dunn, R. J., and Mitchell, J. K. (1984). "Fluid conductivity testing of fine-grained soils." *J. Geotech. Eng.*, 110(11), 1648–1665.
- Edil, T. B., Berthouex, P. M., Park, J. K., Hargett, D. L., Sandstrom, L. K., and Zelmanowitz, S. (1991). "Effects of volatile organic compounds on clay landfill liner performance." *Waste Manage. Res.*, 9(3), 171–187.
- Egloffstein, T. (2001). "Natural bentonites—influence of the ion exchange and partial desiccation on permeability and self-healing capacity of bentonites used in GCLs." *Geotext. Geomembr.*, 19(7), 427–444.
- Fernandez, F., and Quigley, R. M. (1991). "Controlling the destructive effects of clay—organic liquid interactions by application of effective stresses." *Can. Geotech. J.*, 28(3), 388–398.
- Gleason, M. H., Daniel, D. E., and Eykholt, G. R. (1997). "Calcium and sodium bentonite for hydraulic containment applications." *J. Geotech. Geoenviron. Eng.*, 123(5), 438–445.
- Imamura, S., Sueoka, T., and Kamon, M. (1996). "Long term stability of bentonite/sand mixtures at L.L.R.W. storage." *Environmental geotechnics*, M. Kamon, ed., A. A. Balkema, Rotterdam, The Netherlands, 1, 545–550.
- James, A. N., Fullerton, D., and Drake, R. (1997). "Field performance of GCL under ion exchange conditions." *J. Geotech. Geoenviron. Eng.*, 123(10), 897–901.
- Jo, H. Y., Benson, C. H., Shackelford, C. D., Lee, J.-M., and Edil, T. B. (2005). "Long-term hydraulic conductivity of a geosynthetic clay liner (GCL) permeated with inorganic salt solutions." *J. Geotech.*

- Geoenviron. Eng.*, 131(4), 405–417.
- Jo, H. Y., Katsumi, T., Benson, C. H., and Edil, T. B. (2001). “Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions.” *J. Geotech. Geoenviron. Eng.*, 127(7), 557–567.
- Kolstad, D., Benson, C., and Edil, T. (2004). “Hydraulic conductivity and swell of nonprehydrated GCLs permeated with multi-species inorganic solutions.” *J. Geotech. Geoenviron. Eng.*, 130(12), 1236–1249.
- Lambe, T. W., and Whitman, R. V. (1969). *Soil mechanics*, Wiley, New York.
- Lee, J.-M., and Shackelford, C. D. (2005). “Impact of bentonite quality on hydraulic conductivity of geosynthetic clay liners.” *J. Geotech. Geoenviron. Eng.*, 131(1), 64–77.
- Lin, L.-C., and Benson, C. H. (2000). “Effect of wet-dry cycling of swelling and hydraulic conductivity of GCLs.” *J. Geotech. Geoenviron. Eng.*, 126(1), 40–49.
- McBride, M. B. (1994). *Environmental chemistry of soils*, Oxford University Press, New York.
- Melchior, S. (1997). “In-situ studies on the performance of landfill caps (compacted clay liners, geomembranes, geosynthetic clay liners, capillary barriers).” *Proc., Int. Containment Technology Conf.*, St. Petersburg, Fla., National Technical Information Service, Springfield, Va., 365–373.
- Melchior, S. (2002). “Field studies and excavations of geosynthetic clay barriers in landfill covers.” *Proc. of GCL Conf., Clay Geosynthetic Barriers*, H. Zanzinger, R. M. Koerner, and E. Gartung, eds., Nuremberg, Germany, International Geosynthetics Society (www.geosyntheticsociety.org), 321–330.
- Mitchell, J. K. (1993). *Fundamentals of soil behavior*, 2nd Ed., Wiley, New York.
- Mitchell, J. K., and Madsen, F. T. (1987). “Chemical effects on clay hydraulic conductivity.” *Proc., Geotechnical Practice for Waste Disposal '87*, R. D. Woods, ed., ASCE, Reston, Va., 87–116.
- Narejo, D. B., and Memon, G. Q. (1995). “Compatibility of geosynthetic clay liners with three Pennsylvania municipal solid waste leachates.” *Geosynthet. Int.*, 2(5), 889–892.
- Petrov, R. J., and Rowe, R. K. (1997). “Geosynthetic clay liner (GCL)—chemical compatibility by hydraulic conductivity testing and factors impacting its performance.” *Can. Geotech. J.*, 34(6), 863–885.
- Petrov, R. J., Rowe, R. K., and Quigley, R. M. (1997a). “Comparison of laboratory-measured GCL hydraulic conductivity based on three permeameter types.” *Geotech. Test. J.*, 20(1), 49–62.
- Petrov, R. J., Rowe, R. K., and Quigley, R. M. (1997b). “Selected factors influencing GCL hydraulic conductivity.” *J. Geotech. Geoenviron. Eng.*, 123(8), 683–695.
- Quaranta, J. D., Gabr, M. A., and Bowders, J. J., Jr. (1997). “First-exposure performance of the bentonite component of a GCL in a low-pH, calcium-enriched environment.” *Testing and acceptance criteria for geosynthetic clay liners*, L. W. Well, ed., ASTM STP 1308, West Conshohocken, Pa., 162–180.
- Ruhl, J. L., and Daniel, D. E. (1997). “Geosynthetic clay liners permeated with chemical solutions and leachates.” *J. Geotech. Geoenviron. Eng.*, 123(4), 369–381.
- Ryan, C. R. (1987). “Vertical barriers in soil for pollution containment.” *Proc., Geotechnical Practice for Waste Disposal '87*, R. D. Woods, ed., Geotechnical Special Publication No. 13, ASCE, Reston, Va., 182–204.
- Shackelford, C. D. (1994). “Waste-soil interactions that alter hydraulic conductivity.” *Hydraulic conductivity and waste contaminant transport in soil*, D. E. Daniel and S. J. Trautwein, eds., ASTM STP 1142, West Conshohocken, Pa., 111–168.
- Shackelford, C. D., Benson, C. H., Katsumi, T., Edil, T. B., and Lin, L. (2000). “Evaluation the hydraulic conductivity of GCLs permeated with non-standard liquids.” *Geotext. Geomembr.*, 18(2–4), 133–161.
- Shackelford, C. D., Malusis, M. A., Majeski, M. J., and Stern, R. T. (1999). “Electrical conductivity breakthrough curves.” *J. Geotech. Geoenviron. Eng.*, 125(4), 260–270.
- Shan, H.-Y., and Daniel, D. E. (1991). “Results of laboratory tests on a geotextile/bentonite liner material.” *Proc., Geosynthetics '91*, Industrial Fabrics Association International, St. Paul, Minn., 2, 517–535.
- Shan, H.-Y., and Lai, Y.-J. (2002). “Effect of hydrating liquid on the hydraulic properties of geosynthetic clay liners.” *Geotext. Geomembr.*, 20(1), 19–38.
- Sposito, G. (1981). *The thermodynamics of soil solutions*. Oxford University Press, London.
- Sridharan, A., and Prakash, K. (2000). “Percussion and cone methods of determining the liquid limit of soils: Controlling mechanisms.” *Geotech. Test. J.*, 23(2), 236–244.
- Sridharan, A., Rao, S. M., and Murphy, N. S. (1986). “Compressibility behaviour of homoionized bentonites.” *Geotechnique*, 36(4), 551–564.
- U.S. Environmental Protection Agency (U.S. EPA). (1994). “Methods for the determination of metals in environmental samples. Supplement 1.” *EPA/600/R-94/111*, Cincinnati.
- Vasko, S. M., Jo, H. Y., Benson, C. H., Edil, T. B., and Katsumi, T. (2001). “Hydraulic conductivity of partially prehydrated geosynthetic clay liners permeated with aqueous calcium chloride solutions.” *Proc., Geosynthetics '01*, Industrial Fabrics Association International, St. Paul, Minn., 685–699.