

Jae-Myung Lee¹ and Charles D. Shackelford²

Solution Retention Capacity as an Alternative to the Swell Index Test for Sodium Bentonite

ABSTRACT: A new test, referred to as the solution retention capacity (SRC), is proposed as a potentially less tedious and quicker alternative to the swell index (SI) test (ASTM D 5890) for bentonite. The SRC represents the amount of a 50-mL solution retained in one gram of oven-dried bentonite after centrifugation at 2750 g, and the SRC values are reported in units of mL/g. The SRC for two sodium bentonites from geosynthetic clay liners measured using deionized water and solutions containing calcium chloride (CaCl₂) at concentrations ranging from 5 mM to 500 mM is compared with the SI for both bentonites and the same test liquids. In general, both SI and SRC decrease with increasing CaCl₂ concentration due to a decrease in the thickness of adsorbed layer of the bentonite particles. However, the SI is greater than the SRC, with SI falling in the range of 7.5 mL/2 g ≤ SI ≤ 30 mL/2 g and SRC falling in the range of 1.7 mL/g ≤ SRC ≤ 7.2 mL/g. The difference in the magnitudes of SI relative to SRC is attributed, in part, to the differences in the units (i.e., mL/2 g for SI versus mL/g for SRC) and the accelerations (i.e., 1 g in SI versus 2750 g in SRC) for the two procedures. Also, the SI includes the volume of the solid bentonite, whereas the SRC does not.

KEYWORDS: bentonite, geosynthetic clay liner, index properties, swell index

Introduction

In the presence of water, sodium montmorillonite can swell to as much as 20 times its own volume (Norrish 1954). This high swelling potential of montmorillonite is attributed to adsorption of hydrated cations and water molecules, resulting in strong repulsive forces and interlayer expansion in the presence of electrolyte solutions (Norrish 1954; Mitchell 1993; Shackelford et al. 2000). The primary factors contributing to the high swelling potential of montmorillonite relative to other clay minerals, such as illite and kaolinite, include a relatively high specific surface (i.e., 100–800 m²/g) and a relatively high net negative charge as reflected by relatively high cation exchange capacities that typically range from 80 meq/100 g to 150 meq/100 g (Grim 1953; Norrish and Quirk 1954; Mitchell 1993). Since montmorillonite also is the primary mineral in most bentonites (typically 60–90%), bentonites generally exhibit the same swelling characteristic as montmorillonite. In fact, the low hydraulic conductivity values to water typically measured for sodium bentonites (i.e., 10⁻⁸–10⁻⁹ cm/s) are attributed to the relatively high swelling potential of the bentonite in the presence of water (Mitchell 1993; Shackelford et al. 2000).

Two methods historically have been used to determine the swelling behavior of bentonite from geosynthetic clay liners (GCLs), i.e., Geosynthetic Research Institute (GRI) GCL-1, Free Swell of the Clay Component of Geosynthetic Clay Liners (e.g., Narejo and Memon 1995; Lin and Benson 2000), and ASTM D 5890, Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners, (e.g., Didier and Comeaga 1997; Ruhl and Daniel 1997; Shackelford et al. 2000; Egloffstein 2001; Jo et al. 2001; Ashmawy et al. 2002; Shan and Lai 2002).

Received January 16, 2004; accepted for publication June 22, 2004; published January 2005.

¹ Post-Doctoral Research Assistant and former Graduate Research Assistant, Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523.

² Professor, Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523, shackel@engr.colostate.edu.

The primary differences between these two tests are the method of hydration (i.e., 0.7-kPa confinement for GRI GCL-1 versus self-weight sedimentation for ASTM D 5890) and the longer equilibrium time required for GRI GCL-1 (i.e., >400 h versus <24 h) relative to that required for ASTM D 5890 (Lin and Benson 2000; Shackelford et al. 2000; Jo et al. 2001). However, only the test specified in ASTM D 5890 (i.e., swell index test) is currently accepted as a standard by the industry (Shackelford et al. 2000).

In general, the quality of bentonites is indicated macroscopically by the magnitude of the swelling capacity in the presence of water (i.e., the greater the montmorillonite content, the greater the swelling capacity). As a result, swell index tests have been used by the industry as a prescreening method for qualitatively assessing the quality of bentonites. In addition, several studies have shown that the swelling behavior of bentonite is directly correlated with the hydraulic conductivity of bentonite-based GCLs (Egloffstein 1995; Didier and Comeaga 1997; Ruhl and Daniel 1997; Shackelford et al. 2000; Egloffstein 2001; Jo et al. 2001; Kashir and Yanful 2001; Ashmawy et al. 2002; Shan and Lai 2002).

For example, Shackelford et al. (2000) and Jo et al. (2001) correlate the results of swell index tests on sodium bentonite taken from a GCL using solutions with various concentrations of several inorganic compounds (e.g., NaCl, CaCl₂, and LaCl₃) with the hydraulic conductivity of the GCL permeated with the same test solutions. Their results show that a decrease in swell index of the bentonite with increasing electrolyte concentration and/or cation valence is correlated with an increase in hydraulic conductivity of the GCL with increasing electrolyte concentration and/or cation valence. The observed effects are consistent with changes in the thickness of adsorbed layer such that an increase in cationic valence and/or electrolyte concentration reduces the swell index of sodium bentonite. Thus, the results of swell index tests may provide a qualitative indication of the expected hydraulic behavior of bentonite-based materials (e.g., GCLs), thereby providing a relatively simple, rapid, and inexpensive method for assessing the compatibility between the bentonite and the permeant liquid (Didier and Comeaga 1997; Ruhl and Daniel 1997; Shackelford et al. 2000;

Egloffstein 2001; Jo et al. 2001; Ashmawy et al. 2002; Shan and Lai 2002).

However, the measurement of swell index can be affected by several factors, including inconsistency in the hydration procedure, failure to spread the clay evenly, and friction between the bentonite and the graduated cylinder (Shackelford et al. 2000). In addition to these factors, the procedure for the swell index test is tedious and time consuming. As a result, a new test, referred to as the “solution retention capacity (SRC),” is proposed herein as a potentially less tedious and quicker alternative to the swell index test for bentonites. The development of the SRC test is described, and the results of SRC tests, using water and solutions containing a range of CaCl_2 concentrations with two sodium bentonites taken from GCLs, are compared with the results of swell index tests for the same bentonites using the same solutions. Finally, the advantages of the SRC test relative to the swell index test are discussed.

Materials and Methods

Geosynthetic Clay Liners

Two geosynthetic clay liners (GCLs) containing bentonite 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, and the average gravimetric water contents of bentonites are ~4%. The physical and chemical properties and the mineralogical compositions for the bentonite portions of the two GCLs are given in Table 1. Both bentonites have aggregate-size

distributions similar to sands (i.e., classified as SP per Unified Soil Classification System [USCS], ASTM D 2487) based on the mechanical sieve analyses performed on the air-dried samples (ASTM D 421, D 422). However, the bentonites from both GCLs are classified as high-plasticity clays (CH) based on the wet analysis. The GCL with the higher quality bentonite (HQB) is characterized by a greater content of sodium montmorillonite (86% versus 77%), a higher plasticity index (548% versus 393%), and a greater cation exchange capacity (93 meq/100 g versus 64 meq/100 g) relative to the GCL with the lower quality bentonite (LQB).

Testing Liquids

The liquids used in this study consist of tap water that is processed to remove ions by passage through three Barnstead® ion exchange columns in series (electrical conductivity, EC, at 25°C ~0.2 mS/m, pH ~5.6) and inorganic chemical solutions containing a range in calcium chloride (CaCl_2) concentrations. The processed tap water classifies as Type IV de-ionized water (DIW) according to ASTM D 1193. Solutions of CaCl_2 were chosen because previous studies pertaining to the measurement of the hydraulic conductivity and/or index properties of bentonite-based hydraulic barrier materials (e.g., GCLs and sand-bentonite mixtures) with CaCl_2 solutions have shown significant effects of the solutions on the hydraulic conductivity and swelling of the materials (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; Kolstad 2000; Lin and Benson 2000; Shackelford et al. 2000; Egloffstein 2001; Jo et al. 2001; Vasko et al. 2001; Shan and Lai 2002).

The CaCl_2 solutions were prepared by dissolving CaCl_2 (powdered, >96% pure, Sigma-Aldrich Co., St. Louis, MO) in the DIW at concentrations of 5, 10, 20, 50, 100, and 500 mM. The solute concentrations of the testing liquids were measured using an ion chromatograph (Dionex® 4000i IC Module, Dionex Co., Sunnyvale, CA) for chloride (Cl^-) concentrations and an inductively coupled plasma—atomic emission spectrometer (IRIS® Advantage/1000 ICAP Spectrometer, Thermo Jarrell Ash Co., Franklin, MA) for calcium (Ca^{2+}) concentrations, respectively. The measured solute concentrations for the DIW and CaCl_2 solutions are given in Table 2. For the DIW, the measured solute concentrations were below the method detection limits (MDLs) of 0.02 mg/L for Ca^{2+} (EPA Method 200.7) and 0.04 mg/L for Cl^- (EPA Method 300.0).

Swell Index Testing

Materials and Equipment—The primary materials and equipment used to conduct the swell index tests according to ASTM D 5890 are shown in Fig. 1a. These materials and equipment include:

- a No. 200 (0.075-mm) U.S. Standard Sieve;
- a mortar and pestle;
- a clean 100-mL graduated cylinder;
- a stainless-steel laboratory scoop; and
- a disposable syringe.

Procedure—Swell index tests were conducted following the procedures described in ASTM D 5890 using both the DIW and CaCl_2 solutions. Samples of each bentonite taken from the two GCLs were prepared by passing the bentonite through the No. 200 U.S. Standard Sieve using the mortar and pestle. First, approximately 90 mL of each testing liquid (i.e., either DIW or one of CaCl_2

TABLE 1—Properties of the two bentonites used in this study.

Property	Standard	Average Value or Type [No. of Trials] ^d	
		LQB	HQB
Specific Gravity	ASTM D 854 ^b	2.74 [3]	2.78 [2]
Soil Classification:	ASTM D 2487		
Sieve Analysis (Air-Dried)		SP [3]	SP [1]
Hydrometer		CH [7]	CH [1]
Atterberg Limits (%):	ASTM D 4318	[1]	[1]
Liquid Limit, LL		430	589
Plasticity Index, PI		393	548
Bentonite Mass (kg/m^2)	ASTM D 5993	5.1 [5]	4.6 [5]
Principal Minerals (%):	^c	[3]	[2]
Montmorillonite		77.2	86.0
Cristobalite		10.3	4.5
Plagioclase Feldspar		5.1	2.5
Quartz		3.4	3.5
Others		4.0	3.5
Cation Exchange Capacity, CEC (meq/100 g)	^d	63.9 [3]	93.4 [2]
Exchangeable Cations (meq/100 g):	^d	[3]	[2]
Ca^{2+}		11.5	15.3
Mg^{2+}		3.7	7.0
Na^+		45.8	69.0
K^+		0.7	0.8
Sum		61.7	92.1

^a LQB = lower quality bentonite; HQB = higher quality bentonite.

^b Using a magnetic stirring device for de-airing.

^c Based on X-ray diffraction (XRD) analyses performed by Mineralogy Inc., Tulsa, OK and GeoServices Inc., Argyle, TX.

^d Based on procedures described in Shackelford and Redmond (1995).

TABLE 2—Properties of liquids used in this study.

Liquid	Target Concentration (mM)	Number of Analyses	Measured Salt Concentration, C_s		Measured Solute Concentrations (mg/L)		Density ^a , ρ_{sol} (g/mL)
			(mM)	(g/L)	Calcium (Ca^{2+})	Chloride (Cl^-)	
DIW ^b	0	10	<0.0005 ^c	0.000	<0.02 ^c	<0.04 ^c	0.997
CaCl ₂ (Sigma Co., 96%)	5	14	5.1 ± 0.2	0.566	216 ± 10	377 ± 38	0.997
	10	13	10.1 ± 0.2	1.12	436 ± 30	756 ± 65	0.998
	20	13	20.1 ± 0.6	2.23	872 ± 77	1457 ± 110	0.998
	50	9	50.7 ± 1.4	5.63	2055 ± 63	3548 ± 69	1.000
	100	6	100 ± 2.6	11.1	4072 ± 126	7030 ± 95	1.003
	500	5	505 ± 10	56.0	20289 ± 474	35755 ± 710	1.027

^a Calculated value at the standard state, i.e., 25°C and 101.325 kPa (Lide 1991).

^b De-ionized water.

^c Method detection limits (MDLs).

solutions) are added to the 100-mL graduated cylinder. Then, 2.0 g of oven-dried bentonite from the pulverized and sieved bentonite samples are dusted over the entire surface of the testing liquid in the graduated cylinder in increments of less than 0.1 g. Each increment of bentonite is added by tapping the bentonite out of the scoop over a period of approximately 30 s, which is allowed to stand for a minimum period of 10 min as required by ASTM D 5890. These requirements result in a minimum duration of 210 min (3.5 h). However, this minimum duration does not take into account the possibility of longer standing periods of >10 min (e.g., due to convenience) and/or the use of bentonite increments that typically are much less than 0.1 g. As a result, the average time required to add 2.0 g of bentonite in this study was approximately 6 h. After the entire bentonite specimen is added, the syringe filled with the same testing liquid is used to rinse any particles adhering to the sides of the cylinder and to fill the cylinder to the 100-mL mark. After 2 h, entrapped air bubbles and/or water separation in the sediment, if any, are removed by tipping and rolling the cylinder as per ASTM D 5890. Finally, the swell volume of the bentonite defined by the interface between the sediment and the supernatant is measured after an elapsed time of 16 h, which is the minimum hydration period required by ASTM D 5890, and recorded in units of mL/2 g.

Solution Retention Capacity Testing

Materials and Equipment—The primary materials and equipment required for the solution retention capacity (SRC) test are shown in Fig. 1b. These materials and equipment include:

- a clean 50-mL centrifuge tube (polypropylene, capacity of 6000 g, Fisher-Scientific Company, Pittsburgh, PA);
- a vortex mixer (Touch Mixer Model 231, Fisher Scientific Company, Pittsburgh, PA);
- a centrifuge (IEC Centra[®]-CL2, Fisher Scientific Company, Pittsburgh, PA); and
- a laboratory mass balance.

Procedure—The SRC represents the volume of a testing liquid retained per 1.0 g of oven-dried bentonite after centrifugation, which is related to the thickness of adsorbed layer of the bentonite. The SRC tests were conducted using the same liquids and bentonite samples used in the swell index tests. In addition, a soil-to-liquid ratio of 1 g-to-50 mL was used in the SRC tests to be consistent with the soil-to-liquid ratio in the swell index test, which is approximately the same (i.e., 2 g/(100 mL - V_s) \cong 1 g/50 mL, where V_s = the volume occupied by 2.0 g of bentonite, or \cong 0.75 mL).

The first step in the SRC test is to measure the mass of the 50-mL centrifuge tube (M_{tube}). After this measurement, 1.0 g of oven-dried bentonite (M_b) taken from the pulverized and sieved bentonite samples is placed into the tube followed by 50 mL (V_{sol}) of a testing liquid (i.e., either DIW or one of CaCl₂ solutions). The centrifuge tube then is shaken vigorously on the vortex mixer for 30 s to break apart any bentonite clods and improve the potential for hydrating individual bentonite particles, and then the shaken tube is allowed to stand for at least 16 h without operator intervention. This minimum 16-h standing period is the same as that required for the SI test (ASTM D 5890), i.e., after all of the 2 g of oven-dried bentonite have been placed in the 100-mL graduated cylinder. After the standing period, the tube is reshaken using the vortex mixer for 30 s to eliminate any nonhomogeneous pore-liquid distribution. The sample tube then is centrifuged for 30 min at 5000 rpm (i.e., acceleration = 2750 g). The acceleration of 2750 g was the maximum acceleration that could be imparted with the centrifuge used in this study, and the 30-min interval for centrifuging at 2750 g was found to provide greater compression of the bentonite plug than shorter, 10- and 20-min intervals, but essentially the same compression as a longer, 60-min interval. After centrifuging, the supernatant is decanted by tilting the tube, and the total mass of the tube with the remaining plug of hydrated bentonite (M_f) is measured.

For the tests performed with the DIW, the supernatant decanted after centrifugation (i.e., 30 min @ 2750 g) was found to contain a visible amount of a gel-like substance. In addition, either suspended particles and/or a fraction of sediment can be lost during the decanting process for the tests performed with CaCl₂ solutions. As a result, the SRC is defined as follows:

$$\text{SRC} = \left(\frac{M_b}{M_b - M_{b,\text{lost}}} \right) \left[\frac{M_f - M_{\text{tube}} - (M_b - M_{b,\text{lost}})}{\rho_{\text{sol}}} \right] \quad (1)$$

where SRC = the solution retention capacity per 1.0 g of bentonite in [mL/g], ρ_{sol} = the density of the solution (or water) in [g/mL] (see Table 2), and $M_{b,\text{lost}}$ = the mass of bentonite lost during decanting process. The mass of the bentonite lost ($M_{b,\text{lost}}$) can be estimated by measuring the oven-dried mass of the decanted supernatant (M_{dried}) as follows:

$$M_{b,\text{lost}} = \left(\frac{\rho_{\text{sol}}}{\rho_{\text{sol}} - C_s} \right) \times \left\{ M_{\text{dried}} - C_s \left[V_{\text{sol}} - \left(\frac{M_f - M_{\text{tube}} - M_b}{\rho_{\text{sol}}} \right) \right] \right\} \quad (2)$$

where C_s = the salt concentration of the test liquid in [g/mL] (see Table 2).



(a)



(b)

FIG. 1—Pictorial view of equipment: (a) swell index tests, and (b) solution retention capacity tests.

As shown in Table 2, the densities of the test liquids range from 0.997 g/mL (DIW) to 1.027 g/mL (500 mM CaCl₂ solution) at the standard state (i.e., 25°C and 101.325 kPa). Due to this narrow range of densities, the density of solution can be approximated as the density of water (ρ_w) at 4°C and 101.325 kPa (i.e., $\rho_w = 1.000$ g/mL)

with an error of <3% (Lide 1991). Thus, the SRC can be written more conveniently as follows:

$$\text{SRC} \cong \left(\frac{M_b}{M_b - M_{b,\text{lost}}} \right) \left[\frac{M_f - M_{\text{tube}} - (M_b - M_{b,\text{lost}})}{\rho_w} \right] \quad (3)$$

The procedure described above does not take into account the change in chemical composition of the bulk solution due to dissolution of the soluble salts originally in the bentonite (see Table 1) and/or chemical interaction between the bentonite and the test solution. Consequently, the mass of the bentonite lost ($M_{b,lost}$) for the tests performed using DIW as the test liquid is assumed to be equal to the oven-dried mass of the decanted supernatant (M_{dried}), i.e., since the salt concentration for DIW is essentially zero (i.e., $C_s = 0$). Also, the oven-dried mass of the decanted supernatant (M_{dried}) for the tests performed with CaCl_2 solutions is assumed to be equal to the bentonite lost during decanting process and the dissolved salts (CaCl_2) corresponding to the concentration of the test solution.

Although the SRC test as described above requires the use of a relatively expensive centrifuge, the SRC test has several advantages over the swell index test, including a shorter testing time of <1 h versus >3.5 h for the swell index test (i.e., excluding the standing time), minimal potential for loss of bentonite and entrapment of air bubbles, and greater measurement accuracy (i.e., ± 0.01 g for a typical mass balance versus ± 1.0 mL for a typical 100-mL graduated cylinder). In addition, the SRC test is potentially less affected by operator error than the swell index test, because the SRC tests are performed using only mechanical devices.

Results and Discussion

Swell Index

The results of the swell index (SI) tests for a 16-h hydration period are shown in Fig. 2. Since the measured calcium (Ca^{2+}) concentration for the DIW is below the method detection limit (MDL) of 0.02 mg/L for Ca^{2+} based on 10 independent measurements (see Table 2), the MDL is used to represent the Ca^{2+} concentration for the DIW, i.e., since the concentrations are plotted on a logarithmic scale.

As shown in Fig. 2a, the SI for the lower quality bentonite (LQB) decreases from approximately 27.5 mL/2 g when the DIW is used as the testing liquid to ~ 7.5 mL/2 g when the 500 mM CaCl_2 solution is used as the testing liquid. Similarly, the SI for the higher quality bentonite (HQB) decreases from approximately 30.0 mL/2 g when the DIW is used as the testing liquid to ~ 7.5 mL/2 g when the 500 mM CaCl_2 solution is used as the testing liquid. This decrease in SI with increasing CaCl_2 concentration is consistent with the individual granules of the bentonite becoming smaller due to the compression of the interlayer region induced by the elevated Ca^{2+} concentration in the bulk solution (Sposito 1981; McBride 1994; Shackelford et al. 2000; Jo et al. 2001).

The values for the ratio of SI based on either water (DIW) or one of CaCl_2 solutions to that based on water, or SI/SI_w , are shown in Fig. 2b. For both bentonites, the SI based on hydration with the 5 mM CaCl_2 solution is comparable, albeit slightly lower ($<2\%$), to that based on the DIW, whereas a further increase in the CaCl_2 concentration of the testing liquids results in a relatively significant decrease (i.e., 30–75%) in SI/SI_w . However, the change in SI/SI_w is greater for the HQB relative to the LQB, indicating that swelling of the HQB is affected to a greater extent than that of the LQB as the concentration of CaCl_2 increases.

As shown in Fig. 2c, the SI based on the DIW is greater by about 10% (~ 2.5 mL/2 g) for the HQB relative to the LQB. This difference can be attributed to the higher montmorillonite content of the HQB (see Table 1). Also, the SI for the HQB is greater than that for the LQB by 3–11% for the tests performed with solutions containing CaCl_2 concentrations ≤ 50 mM, with the magnitude in this

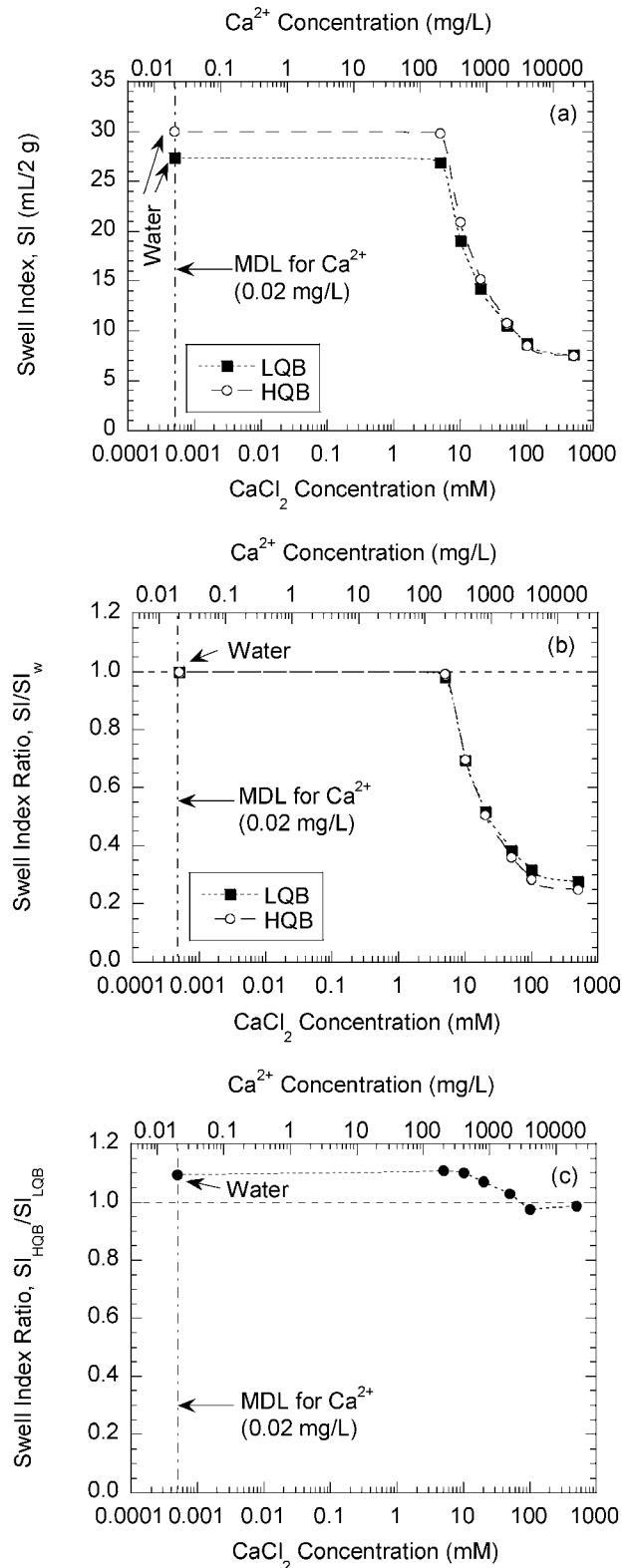


FIG. 2—Results of swell index (SI) tests performed with water and CaCl_2 solutions: (a) SI values, (b) SI normalized with respect to SI based on water, and (c) ratio of SI for higher quality bentonite (HQB) to SI for lower quality bentonite (LQB) (MDL: method detection limit).

difference decreasing with increasing CaCl_2 concentration. However, the ratio of SI for the HQB relative to that for the LQB, or SI_{HQB}/SI_{LQB} , is slightly less than unity (i.e., ~ 0.98) for 100

and 500 mM CaCl_2 solutions, indicating that these relatively strong CaCl_2 solutions have a more significant effect on the swelling behavior of the higher quality bentonite (HQB) relative to the lower quality bentonite (LQB).

Solution Retention Capacity

The results of the solution retention capacity (SRC) tests performed on both bentonites with the DIW and CaCl_2 solutions are shown in Fig. 3. For the tests performed with CaCl_2 solutions, no loss of bentonite was observed during the decanting process (i.e., $M_{b,\text{lost}} = 0$), such that the SRC was calculated using the following reduced form of Eq 3:

$$\text{SRC} \cong \frac{M_f - M_{\text{tube}} - M_b}{\rho_w} \quad (4)$$

As shown in Fig. 3a, the SRC for the lower quality bentonite (LQB) decreased from ~ 5.7 mL/g to ~ 1.8 mL/g with increasing CaCl_2 concentration in the testing liquid from 0 (DIW) to 500 mM. Similarly, the SRC for the higher quality bentonite (HQB) decreased from ~ 7.2 mL/g to ~ 1.7 mL/g with increasing CaCl_2 concentration in the testing liquid from 0 (DIW) to 500 mM. In fact, the SRC for the HQB is greater than that for the LQB by approximately 1.4 mL/g for the tests performed with the DIW and 5 mM CaCl_2 solution. Similarly, but to a lesser extent, the SRC for the HQB is about 11% higher than the SRC for the LQB based on the tests performed with the 10 mM CaCl_2 solution.

As shown in Fig. 3b, values for the ratio of the SRC based on either water (DIW) or one of CaCl_2 solutions to that based on water, or SRC/SRC_w , decreased significantly from unity to between 0.51 and 0.58 for both bentonites with increasing CaCl_2 concentration in the testing liquid from 0 (DIW) to 5 mM (see Fig. 5). Thereafter, the value of SRC/SRC_w continues to decrease with a further increase in CaCl_2 concentration, but to a lesser extent. However, the value of SRC/SRC_w for the HQB is always slightly lower than that for the LQB by 0.05–0.09 based on the tests performed with CaCl_2 solutions, except for the tests performed with the 5 mM CaCl_2 solution. In fact, SRC/SRC_w for the HQB is slightly higher (i.e., by ~ 0.09) than that for the LQB for the tests performed with the 5 mM CaCl_2 solution. In general, the greater change observed in the SRC/SRC_w with increasing CaCl_2 concentration for the HQB relative to the LQB is similar to the trends for the swell index tests, such that the thickness of adsorbed layer of the HQB is affected to a greater extent than that for the LQB as the concentration of CaCl_2 in the testing liquid increases.

As shown in Fig. 3c, the SRC ratio based on two bentonites (i.e., $\text{SRC}_{\text{HQB}}/\text{SRC}_{\text{LQB}}$) was slightly less than unity (i.e., 0.96–0.98) for the solutions with CaCl_2 concentrations ranging from 20 to 500 mM. These results are similar to the results of swell index tests such that the relatively strong (i.e., 100 and 500 mM) CaCl_2 solutions result in more significant decreases in the thickness of adsorbed layer of the HQB relative to the LQB.

Swell Index versus Solution Retention Capacity

The swell index (SI) and solution retention capacity (SRC) are plotted as a function of CaCl_2 concentration of the testing liquids in Fig. 4. For both bentonites, the SI for the tests performed with the DIW is comparable to the SI for the tests performed with the 5 mM CaCl_2 solution, whereas the SRC for the tests performed with the 5 mM CaCl_2 solution is approximately half of that performed with the DIW. Thus, the SRC apparently is more sensitive to the relatively weak, 5 mM CaCl_2 solution than is the SI. However, when

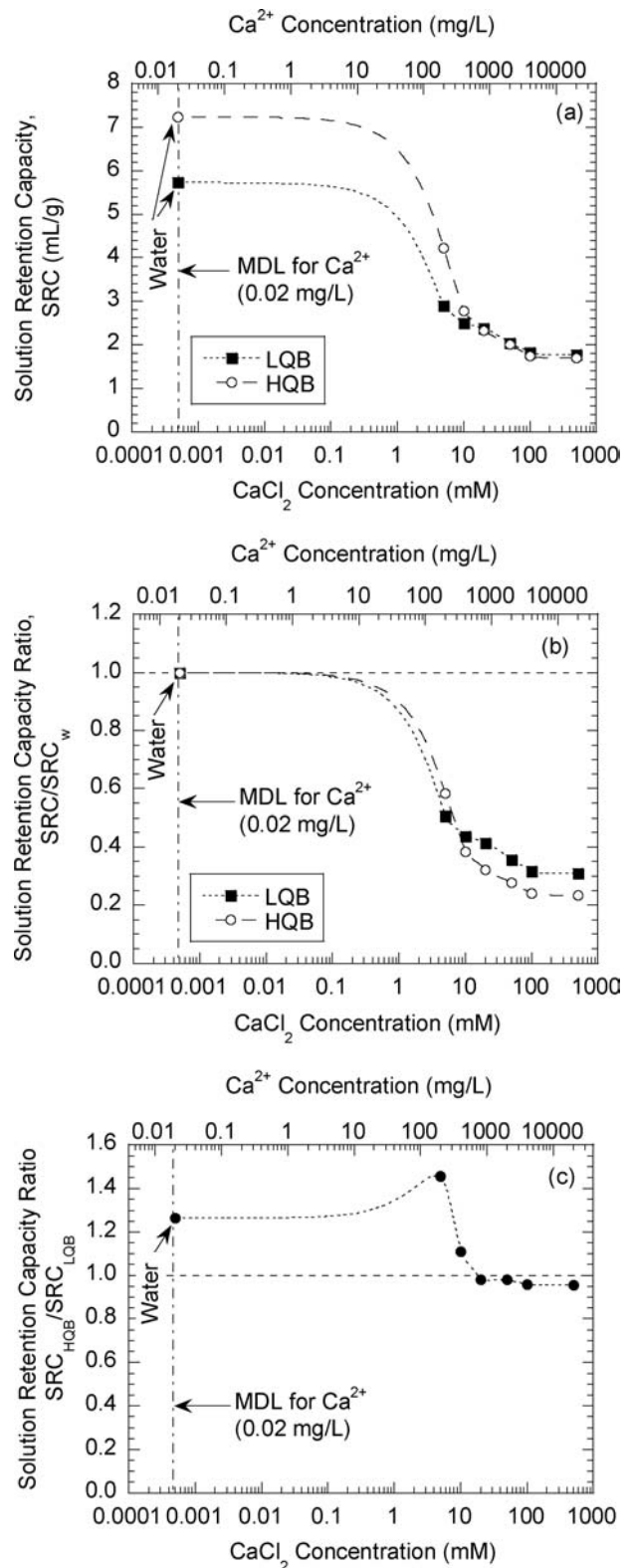


FIG. 3—Results of solution retention capacity (SRC) tests performed with water and CaCl_2 solutions: (a) SRC values, (b) SRC normalized with respect to SRC based on water, and (c) ratio of SRC for higher quality bentonite (HQB) to SRC for lower quality bentonite (LQB) (MDL: method detection limit).

the tests are performed with stronger solutions containing from 10 to 500 mM CaCl_2 , the trends in both the SRC and SI with CaCl_2 concentration are in close agreement for both bentonites, although

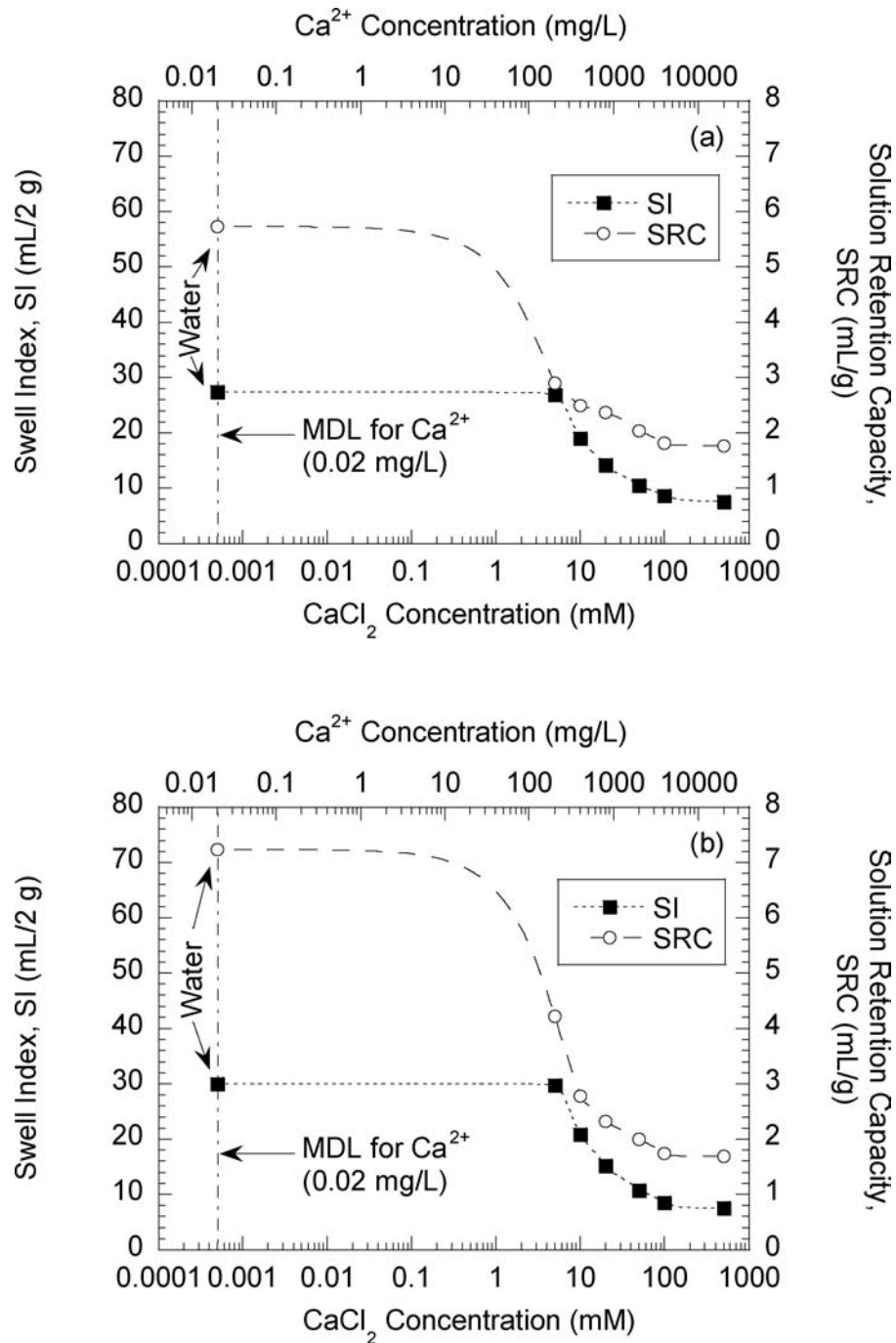


FIG. 4—Comparison between swell index (SI) and solution retention capacity (SRC) based on the tests performed with water and CaCl_2 solutions: (a) lower quality bentonite (LQB) and (b) higher quality bentonite (HQB) (MDL: method detection limit).

the values of SRC in mL/g are significantly lower than the values of SI in mL/2 g. The difference in magnitudes of SI versus SRC can be attributed, in part, to the differences in the units (i.e., mL/2 g for SI versus mL/g for SRC) and the accelerations imposed in the two test procedures, i.e., self-weight sedimentation at the acceleration of gravity (i.e., 1 g) in the SI procedure versus centrifugation at an acceleration of 2750 g in the SRC procedure. That is, lower values of SI would be expected if the SI procedure involved only 1 g of oven-dried bentonite, such as in the case for the SRC procedure, as opposed to the 2 g required by ASTM D 5890. Also, the greater

the force imparted to the bentonite, the lower the expected porosity and, therefore, the lower the magnitude of the volume of solution that can be retained in the bentonite.

The results of the SRC tests based on the CaCl_2 solutions are correlated with the results of the SI tests based on the CaCl_2 solutions for each bentonite in Fig. 5. The linear regression of the data in Fig. 5 results in the coefficient of determination (r^2) close to unity (i.e., 0.958 for LQB and 0.970 for HQB), supporting a strong correlation between SRC and SI for the case where the testing liquid is a CaCl_2 solution. This strong correlation between the SRC and SI

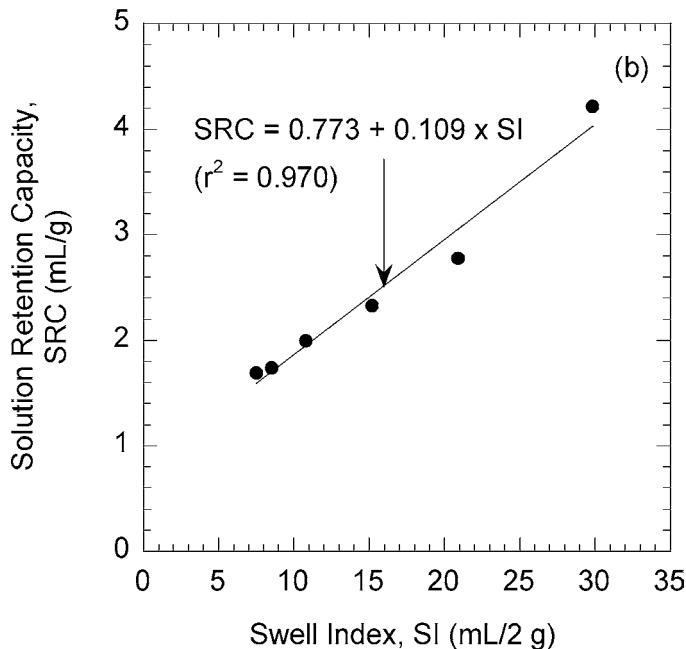
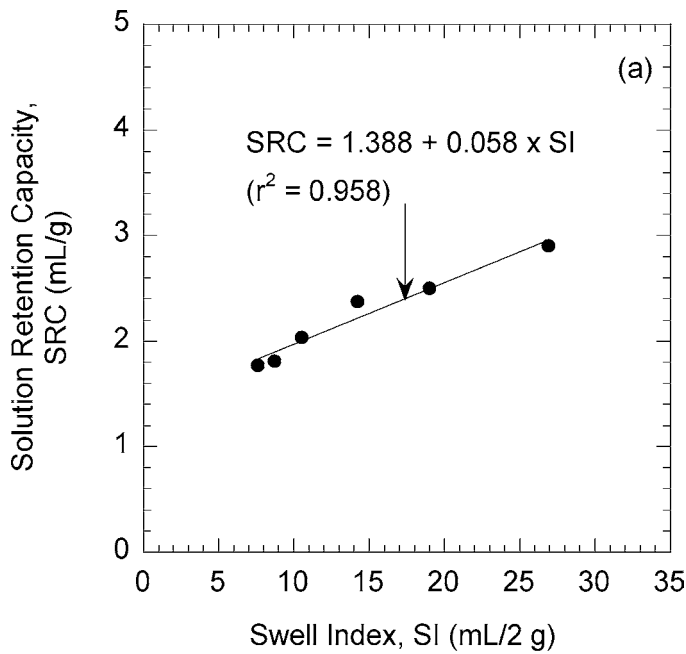


FIG. 5—Correlation between swell index (SI) and solution retention capacity (SRC) based on the tests performed with only CaCl_2 solutions: (a) lower quality bentonite (LQB) and (b) higher quality bentonite (HQB).

suggests that the SRC test may be used as an alternative to the SI test when assessing qualitatively the potential impact of inorganic salt solutions on the bentonites from GCLs.

The results of the SRC tests based on the CaCl_2 solutions are correlated with the results of the SI tests based on the CaCl_2 solutions for both bentonites in Fig. 6a, i.e., to evaluate the potential independence of the correlation on the quality of the bentonite. The relatively low value for r^2 of 0.887 based on linear regression of the data suggests that the correlation between SRC and SI is not particularly unique (i.e., not particularly independent of the quality of the bentonite). However, when the results based on the 5 mM CaCl_2 solution are excluded from the data set, the correlation between SRC and SI improves significantly such that $r^2 = 0.965$ based on

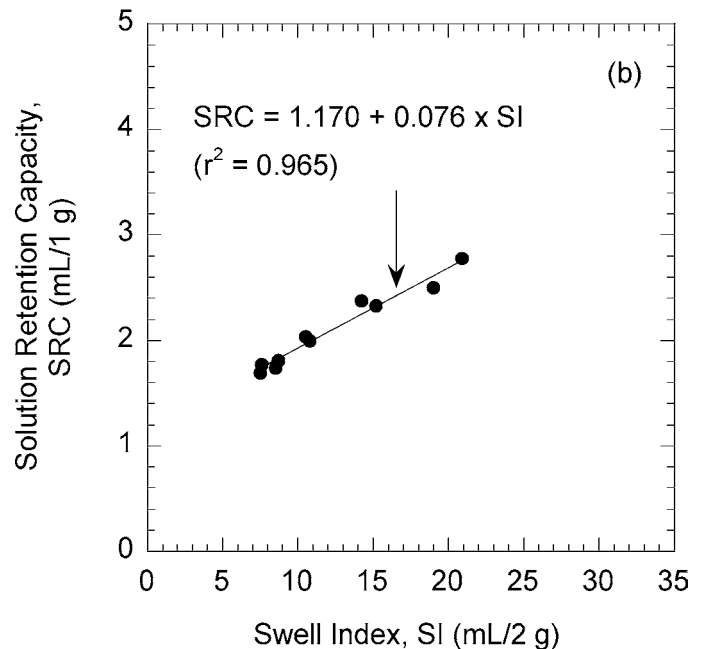
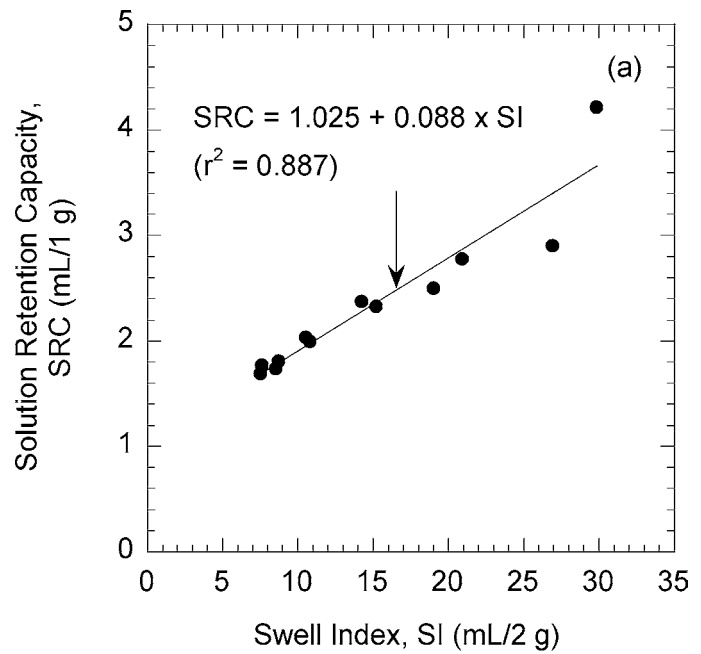


FIG. 6—Correlation between swell index (SI) and solution retention capacity (SRC) based on the tests performed with only CaCl_2 solutions: (a) all results and (b) all results except for values based on the 5 mM CaCl_2 solution.

linear regression, as shown in Fig. 6b. Thus, based on the limited data set for this study, the correlation between SRC and SI appears to be relatively unique, i.e., provided the correlation is based on solutions containing ≥ 10 mM CaCl_2 .

Summary and Conclusions

A solution retention capacity (SRC) test was developed and evaluated as an alternative to the swell index (SI) test (ASTM D 5890) for bentonite of geosynthetic clay liners (GCLs). The SRC represents the amount of a 50-mL solution retained in one gram of oven-dried bentonite after centrifugation at 2750 g, and the SRC

values are reported in units of mL/g. Both SI and SRC tests were performed on samples of different quality bentonites taken from two GCLs using de-ionized water (DIW) and chemical solutions containing from 5 to 500 mM CaCl₂. The results show a decrease in both SI and SRC with increasing CaCl₂ concentration of the testing liquids. This decrease in both SI and SRC is consistent with the individual granules of the bentonite becoming smaller with increasing CaCl₂ concentration due to the compression in the thickness of adsorbed layer of the bentonite. Also, the relatively strong, 100 and 500 mM CaCl₂ solutions caused a greater decrease in the thickness of adsorbed layer for the higher quality bentonite relative to the lower quality bentonite.

The SI for the tests performed with the DIW is equivalent to the SI for the tests performed with the 5 mM CaCl₂ solution, but the SRC for the tests performed with the 5 mM CaCl₂ solution is only about half of that performed with the DIW. Thus, the SRC appears to be more sensitive to slight changes in solution chemistry for the relatively weak salt solutions, such as the 5 mM CaCl₂ solution, used in this study.

For tests performed with stronger solutions containing from 10 to 500 mM CaCl₂, the trend in SRC with increasing CaCl₂ concentration correlates well with that for the SI. The resulting correlation between SI and SRC also appears to be independent of the quality of the bentonite for the test results based on the stronger solutions containing from 10 to 500 mM CaCl₂. However, the magnitudes for the SI are significantly greater than those for the SRC. The difference in the magnitudes of SI relative to SRC is attributed, in part, to the differences in the units (i.e., mL/2 g for SI versus mL/g for SRC) and the accelerations (i.e., 1 g for SI versus 2750 g for SRC) for the two test procedures, as well as to the difference in the definitions of the two parameters (e.g., the SI includes the volume of the solid bentonite, whereas the SRC does not).

The proposed SRC test has several advantages over the SI test, including a shorter testing time (i.e., <1 h versus >3.5 h), minimal potential for bentonite loss and entrapped air bubbles, and greater measurement accuracy (i.e., ±0.01 g versus ±1.0 mL). In addition, the SRC test is less susceptible to operator error than the SI test, because the SRC tests are performed using only mechanical devices that require less operator judgment. Therefore, on the basis of these advantages and the strong correlation between SRC and SI, the SRC test may be a more useful alternative to the SI test in terms of evaluating the quality of a sodium bentonite or the potential impact of inorganic salt solutions on the bentonite of GCLs.

Acknowledgment

Financial support for this study was provided by the U. S. National Science Foundation (NSF), Arlington, VA, under Grant CMS-9820863 entitled, "Long-Term Performance of GCLs Permeated with Aqueous Inorganic Solutions." 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

- Ashmawy, A. K., El-Hajji, D., Sotelo, N., and Muhammad, N., 2002, "Hydraulic Performance of Untreated and Polymer-Treated Bentonite in Inorganic Landfill Leachates," *Clays and Clay Minerals*, Vol. 50, No. 5, pp. 546–552.
- 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*, ASTM STP 874, A. I. Johnson, R. K. Frobel, N. J. Cavalli, and C. B. Pettersson, Eds., ASTM International, West Conshohocken, PA, pp. 64–73.
- 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," *Geosynthetics '93*, Industrial Fabrics Association International, St. Paul, MN, Vol. 3, pp. 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*, ASTM STP 1308, L. W. Well, Ed., ASTM International, West Conshohocken, PA, pp. 181–195.
- Egloffstein, T. A., 1995, "Properties and Test Methods to Assess Bentonite Used in Geosynthetic Clay Liners," *Geosynthetic Clay Liners*, R. M. Koerner, E. Gartung, and H. Zanzinger, Eds., Balkema, Rotterdam, pp. 51–72.
- Egloffstein, T. A., 2001, "Natural Bentonites—Influence of the Ion Exchange and Partial Desiccation on Permeability and Self-Healing Capacity of Bentonites Used in GCLs," *Geotextiles and Geomembranes*, Vol. 19, No. 7, pp. 427–444.
- Gleason, M. H., Daniel, D. E., and Eykholt, G. R., 1997, "Calcium and Sodium Bentonite for Hydraulic Containment Applications," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 5, pp. 438–445.
- Grim, R. E., 1953, *Clay Mineralogy*, McGraw-Hill Publishing Company, London.
- James, A. N., Fullerton, D., and Drake, R., 1997, "Field Performance of GCL Under Ion Exchange Conditions," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 10, pp. 897–902.
- 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," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 127, No. 7, pp. 557–567.
- Kashir, M. and Yanful, E. K., 2001, "Hydraulic Conductivity of Bentonite Permeated with Acid Mine Tailings," *Canadian Geotechnical Journal*, Vol. 38, No. 5, pp. 1034–1048.
- Kolstad, D. C., 2000, *Compatibility of Geosynthetic Clay Liners (GCLs) with Multi-Species Inorganic Solutions*, M.S. Thesis, University of Wisconsin at Madison, WI.
- Lide, D. R., 1991, *CRC Handbook of Chemistry and Physics*, 72th ed., CRC Press, Boca Raton, FL.
- Lin, L.-C. and Benson, C. H., 2000, "Effect of Wet-Dry Cycling of Swelling and Hydraulic Conductivity of GCLs," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 126, No. 1, pp. 40–49.
- McBride, M. B., 1994, *Environmental Chemistry of Soils*, Oxford University Press, New York, N.Y.
- Melchior, S., 1997, "In-Situ Studies on the Performance of Landfill Caps (Compacted Clay Liners, Geomembranes, Geosynthetic Clay Liners, Capillary Barriers)," *Proceedings, International Containment Conference*, Florida State University, Tallahassee, pp. 365–373.
- Mitchell, J. K., 1993, *Fundamentals of Soil Behavior*, 2nd ed., John Wiley & Sons, New York, N.Y.
- Narejo, D. B. and Memon, G. Q., 1995, "Compatibility of Geosynthetic Clay Liners with Three Pennsylvania Municipal Solid Waste Leachates," *Geosynthetics International*, Vol. 2, No. 5, pp. 889–892.

- Norrish, K., 1954, "Manner of Swelling of Montmorillonite," *Nature*, Vol. 173, pp. 256–257.
- Norrish, K. and Quirk, J., 1954, "Crystalline Swelling of Montmorillonite, Use of Electrolytes to Control Swelling." *Nature*, Vol. 173, pp. 255–256.
- 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*, ASTM STP 1308, L. W. Well, Ed., ASTM International, West Conshohocken, PA, pp. 162–180.
- Ruhl, J. L. and Daniel, D. E., 1997, "Geosynthetic Clay Liners Permeated with Chemical Solutions and Leachates," *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 123, No. 4, pp. 369–381.
- 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 International, ASTM STP 1142, West Conshohocken, PA, pp. 111–168.
- Shackelford, C. D. and Redmond, P. L., 1995, "Solute Break-through Curves for Processed Kaolin at Low Flow Rates," *Journal of Geotechnical Engineering*, Vol. 121, No. 1, pp. 17–32.
- 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," *Geotextiles and Geomembranes*, Vol. 18, pp. 2–4, 133–161.
- Shan, H.-Y. and Lai, Y.-J., 2002, "Effect of Hydrating Liquid on the Hydraulic Properties of Geosynthetic Clay Liners," *Geotextiles and Geomembranes*, Vol. 20, No. 1, pp. 19–38.
- Sposito, G., 1981, *The Thermodynamics of Soil Solutions*, Oxford University Press, London.
- 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," *Proceedings, Geosynthetics '01*, Industrial Fabrics Association International, St. Paul, MN, pp. 685–699.