

July 6, 2010

Mr. Geoffrey H. Little  
Environmental Engineer – Solid Waste Section  
North Carolina Department of Environment and Natural Resources  
Division of Waste Management  
1646 Mail Service Center  
Raleigh, NC 27699-1646

**Re: Permit to Construct Application for Cell 2  
International Paper Industrial Landfill  
Columbus County, North Carolina  
Permit No. 24-02  
Doc ID No 10949**

Dear Mr. Little:

Below are responses to your June 25, 2010 letter, which contained nine comments regarding the above referenced application. For completeness we have reiterated your comments (*italicized*), and provided our response immediately below to facilitate your review. Further, one electronic updated copy of the specifications, drawings, and construction quality assurance plan are attached so that you can confirm receipt of a complete Permit to Construct Application (PTC) submittal.

1. *Table 2-1 and related drawings of the application need to be amended to account for the bottom elevation changes that occurred during placement of backfill and the underdrain system as noted in a meeting at our offices with you May 12, 2010. Text in the application and related drawings need to be reviewed for corrections.*

Table 2-1 and related drawings were modified to account for the bottom elevation changes that occurred during the installation of the underdrain system. Overlying landfill liner and leachate collection system components have similarly been modified to conform with the bottom elevation changes.

2. *Please note that volume increases of more than 10% is defined by statute [130A-294(b1)(1)] to be a substantial amendment in operation that would require a new application process. The basis for the facility will be the original approved volume of 2,619,000 cubic yards. Over the life of the presently permitted footprint, the maximum amount of expanded capacity will be 2,880,900 cubic yards encompassing the volume above the protective cover including the final cover.*

Table 2-1 has been amended to reflect the current landfill capacity, including the cell 2 bottom elevation changes. Table 2-1 shows the combined cell 1 and cell 2 gross volume (residual volume plus cover) has actually decreased from the originally permitted 2,619,000 cyds to the current 2,237,098 cyds.

3. *As discussed previously, the primary liner (the flexible membrane in closest proximity to the waste) consisting of HDPE must be constructed of nominal 60 mil (0.06 inches) thickness material. The EPA Technical Guidance Manual for Solid Waste Disposal Facility Criteria (1993) recommends 60 mil minimum thickness due to allow proper seaming. All drawings and specifications must be modified to reflect this change.*

The attached plan sheets and technical specifications were modified to show the primary liner as 60 mil HDPE geomembrane.

4. *Technical Specifications Section 02621 Tri-Planar Geonet – A thickness standard test (ASTM D 5199) is referenced but a value and test frequency does not appear in the tables at the end of the section.*

Table 1 of Section 02621 was modified to include a thickness value and test frequency.

5. *Only 1 Carbon Black standard test (ASTM D 1603) is referenced under the Description heading, but 2 tests (D 1603 and D 4218) and a footnote are included in Table 1 and 1 test (D 1603) is included in Table 3. Since the 2 tests are appropriate for differing blackening agents, please modify the references and tables, and include an explanation for the 2 tests in the Table 1 footnote.*

Table 1 of Section 02775 has been modified to show both ASTM specifications (D 1603 and D 4218) and an explanation has been included in the footnotes.

6. *ASTM D 5035, which is appropriate for woven textile fabrics, appears in the Geonet Core section of Table 1. Should the test be referenced in the Geocomposite or Geotextile sections of the table?*

ASTM D7179 is a newer test method, which is gradually replacing ASTM D 5035 as the standard for Geonet Core tensile property testing. The only difference between the two test methods is that ASTM D7179 prescribes a 4-inch wide test specimen, whereas ASTM D5035 uses a 2-inch wide specimen. ASTM D 5035, although written as a test procedure for woven fabrics, was heretofore commonly adapted for testing Geonets. The two test methods produce similar results on Geonets and Table 1 has been modified to allow either test method with the appropriate minimum value provided. Non-woven Geotextile tensile properties are commonly specified by Grab Strength (ASTM D 4632), and Table 1 correctly reflects the intended minimum tensile strength values using ASTM D 4632.

7. *The Table 1 specification (D 4716) for minimum average value (19.2 gal/min/ft) for the HyperNet product. Other products offer higher values (43.5 gal/min/ft). With respect given to the historical data listed in Section 2.3 Liner System modifications (actual measured historical secondary containment flow rate of 0.79 gal/acre/day, should the system be constructed to handle a higher rate of flow in case of a failure or accident?)*

The 2003 Cell 1 Construction Documentation Report shows the following TRI-PLANAR Geonet Drainage Media Properties were approved.

- Transmissivity of 2.0 gpm/ft (4.1E-04 m<sup>3</sup>/m/sec)

- Normal load of 25,000 psf, gradient = 0.2 after 24 hr load seating
- Boundary conditions were between soil and textured HDPE membrane

For Cell 2 URS is specifying a Tri-planar Geocomposite drainage media as follows:

- Transmissivity of 9.6 gpm/ft (2.0E-03 m<sup>2</sup>/sec)
- ASTM D 4716 @ 15,000 psf normal stress and a hydraulic gradient of 0.1
- between Ottawa sand and 60-mil textured HDPE liner

The transmissivity requirements for these two geocomposites are comparable, and differences primarily reflect test procedure refinements and current manufacturer literature values. Both Geocomposite tables were modified to reflect the properties of the Geocomposite currently installed in Cell 1. These products are currently functioning properly and IP plans to use comparable products for Cell 2 construction.

The Cell 1 secondary collection system long-term liquid removal rate was reported as 0.79 gal/acre/day. This is sometimes referred to as a leakage rate through the primary liner, for which an action rate of 500 gal/acre/day was approved in the Cell 1 permit.

$$0.79 \text{ gal/acre-day} * 13\text{-acres} = 10.27 \text{ gal/day}$$

A single 6 foot wide panel of Tri-Planar Geocomposite, as specified above is capable of transmitting:

$$9.6 \text{ gpm/ft} * 6 \text{ ft} * 60 \text{ min/hr} * 24 \text{ hr/day} = 82,944 \text{ gal/day}$$

Therefore, ignoring creep and clogging reduction allowances for the sake of discussion, a single Tri-Planar geonet entering one side of the collection sump can transmit 82,944 gal/day. This capacity provides a safety factor of  $82,944/10.27 = 8,076$ . The Tri-Planar geocomposite provides a capacity safety factor for the approved action leakage rate as follows:

$$FS = 82,944/(500*13\text{-ac}) = 12.8$$

Clearly, even with creep reduction and clogging allowances the specified Tri-Planar geonet is capable of transmitting far more liquid than is currently being observed, or specified by the action rate of 500 gallons/acre/day. Therefore, URS contends the currently specified Tri-Planar geocomposite is capable of transmitting far greater than the liquid volume expected in the secondary collection system.

8. *Technical Specifications Section 02777 GCL – Should the GCL be tested for chemical compatibility with the waste leachate? The roster of ASTM Standards does not include such a test.*

Most research has found, "the hydraulic performance of a GCL in a landfill bottom liner will not be significantly affected by a typical modern MSW leachate" [CETCO Lining Technologies TR-254]. In the writers experience, very high concentration cationic salt solutions (NaCl for example) potentially counteract the swelling potential of montmorillonite and bentonite clays, which can increase GCL hydraulic conductivity. However, review of IP-Riegelwood's landfill leachate chemistry shows Chloride concentrations are not high enough to negatively impact GCL liner material performance. Attached are Cell 1 landfill liquid analytical results for two events in 2009.

9. *Leachate Collection System – The Solid Waste Sections is uniformly requiring remote video inspection of leachate collection systems following construction and during the life of the facility. Please submit an addendum to the Phase 2 Landfill CQA/Specifications that include video and a plan for flushing/cleaning/video procedures for the maintenance of the collection system during the life of the facility*

Section 5.3 of the CQA Manual was modified to state the requirements for remote video inspection of leachate collection system.

URS Corporation is submitting herein 1 bound paper copies of Drawings and one electronic version of Drawings, Calculations, Construction Specifications, and a Quality Assurance Manual for the above referenced work. URS is resubmitting these plans on behalf of IP for your review and approval so a permit to construct the Cell 2 liner system can be granted. URS will be contacting the state to confirm your receipt of the plans and to estimate a review time so a construction schedule can be established.

Please do not hesitate to contact us with any questions concerning this submittal at 919-461-1100.

Sincerely yours,

**URS Corporation**



Richard K. Lowe  
Principal Geotechnical Engineer



Conan Fitzgerald, P.E.  
Sr. Project Manager

Enclosures:

CETCO Lining Technologies TR-254

International Paper Riegelwood Mill Cell 1 Landfill Analysis Results for 2009

International Paper Riegelwood Mill Cell 2 Landfill Liner System Permit Drawings, Sheets 1 through 21

cc: Edward Kreul



## HYDRAULIC CONDUCTIVITY AND SWELL OF NONPREHYDRATED GEOSYNTHETIC CLAY LINERS PERMEATED WITH MULTISPECIES INORGANIC SOLUTIONS

Kolstad, D.C., Benson, C.H. and Edil, T.B., *Journal of Geotechnical and Geo-environmental Engineering*, ASCE, Vol. 130, No. 12, December 2004, pp.1236-1249.

**Introduction.** This article examines the influence of multispecies inorganic solutions on swelling and hydraulic conductivity of non-prehydrated GCLs containing sodium bentonite. This is a continuation of the research done by Benson, Edil and their students in the area of clays, including GCLs (see CETCO TR-326). Multispecies inorganic solutions were mixed using deionized water, monovalent cation salts (NaCl and/or LiCl) and divalent cation salts (CaCl<sub>2</sub> and MgCl<sub>2</sub>). GCL hydraulic conductivity tests were performed using flexible wall permeameters at an average effective stress of 20 kPa (3 psi) and average head pressure of 2 feet. The GCL hydraulic conductivity tests were run per ASTM D6766 until the influent and effluent electrical conductivity deviated less than 10%. Free swell tests were also conducted per ASTM D6141 using the multispecies inorganic solutions as the test liquid.

Ionic strength and the ratio of monovalent cation concentration to the square root of divalent cation concentration (RMD) in the permeant solution were found to influence swell of the bentonite and hydraulic conductivity of GCLs. A regression model was developed relating hydraulic conductivity of the GCL to ionic strength and the RMD of the permeant solution. The results of this model are expressed in equation 3 and graphically in Figures 7 and 10(a) of the article.

A literature search of leachate chemistry data from different waste containment facilities was also conducted and listed in Table 4. Figure 10(b) plots the ionic strength and RMD of these various leachates onto a corresponding isoperm chart. The chart implies that many municipal solid waste (MSW) landfill leachates and mine waste site leachates, as well as some hazardous waste and fly ash leachates, would result in high (>10<sup>-7</sup> cm/s) GCL hydraulic conductivities.

**Errata.** An erratum was published by the authors in the July 2006 issue of ASCE *Journal of Geotechnical and Geo-environmental Engineering*. The following corrections were noted:

- The RMD units in the text, tables and figures should be M<sup>1/2</sup>, not mM<sup>1/2</sup>.
- Equation 3. The correct equation is:

$$\log K_v / \log K_{D1} = 0.965 - 0.976 * I + 0.0797 * RMD + 0.251 * I^2 * RMD$$

- The fly ash leachate point coordinates from Table 4 are plotted incorrectly in Figure 10(b). According to the data, all but one fly ash point should be between the 10<sup>-8</sup> and 10<sup>-9</sup> cm/s isoperm lines.

**Data Review.** Most of the MSW leachate chemistry data listed in Kolstad Table 4 is from prior to 1990. MSW leachate chemistry data for cells built prior to 1990 is not representative of modern MSW landfills because: 1) it was common practice to dispose of industrial waste, hazardous waste and various liquid wastes prior to promulgation of current national solid waste regulations, and 2) samples may not have been taken from controlled collection points because many landfills did not have leachate collection and recovery systems (Bonaparte et al., 2002). The difference between these two time periods in MSW leachate chemistry is quite apparent by segregating pre-1990 and post-1990 data. For those references published *prior to* 1990, the average ionic strength was 0.24 M with an average RMD of 0.22 M<sup>1/2</sup> and the maximum ionic strength was 0.62 M with a RMD of 0.31 M<sup>1/2</sup>. For those references published *after* 1990, the average ionic strength is 0.12 M with an RMD of 0.16 M<sup>1/2</sup> and a maximum ionic strength of 0.24 M with a RMD of 0.18 M<sup>1/2</sup> (Table A).

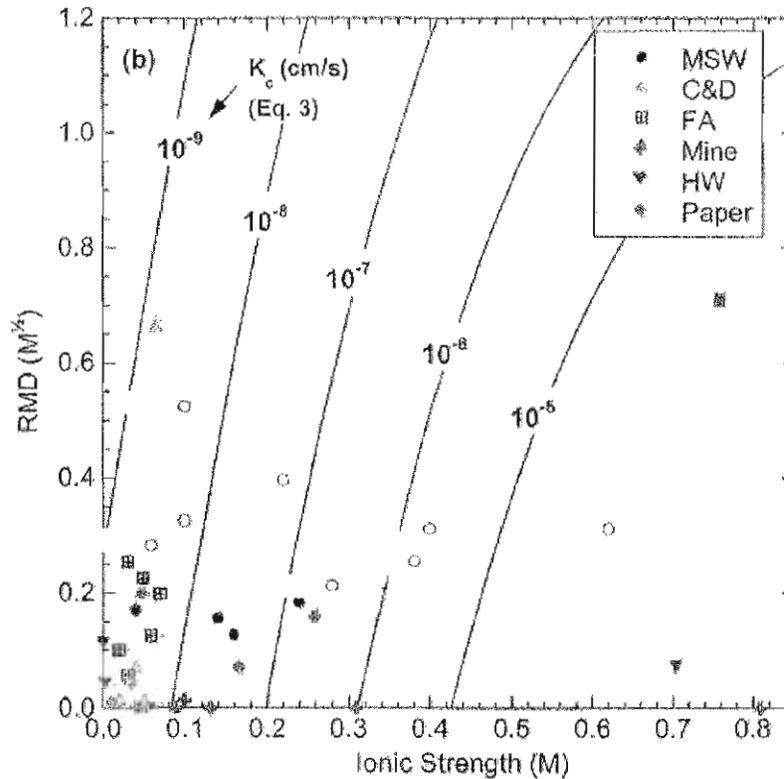
Table A. MSW Landfill Leachate Chemistry Data.

	Average		Maximum	
	Ionic Strength (M)	RMD (M <sup>1/2</sup> )	Ionic Strength (M)	RMD (M <sup>1/2</sup> )
Kolstad – 17 pre-1990 cases	0.24	0.22	0.62	0.31
Kolstad – 5 post-1990 cases	0.12	0.16	0.24	0.18
EPA Study – 26 post-1990 cases	0.06	0.11	0.22	0.22
Combined 31 post-1990 cases	0.07	0.11	0.24	0.18

The segregated Kolstad data shows that modern MSW leachates (post-1990) have a lower ionic strength than older MSW leachates (pre-1990).

Leachate chemistry data collected from 26 post-1990 MSW landfills as part of a major study by USEPA (Bonaparte et al. 2002) is also presented in Table A. Ionic strengths were estimated from specific conductance per Snoeyink and Jenkins (1980). RMDs were estimated from available calcium, magnesium and sodium concentrations. The MSW leachates in the USEPA study had an average estimated ionic strength of 0.06 M and a RMD of 0.11 M<sup>1/2</sup>. Combining post-1990 cases from both Kolstad and USEPA yields an average ionic strength of 0.07 M and RMD of 0.11 M<sup>1/2</sup>.

Modifying Figure 10(b) to correct the fly ash coordinates and to delete the Kolstad MSW data prior to 1990 yields Figure 1.



**Figure 1.** Modified Figure 10(b) from Kolstad et al. 2004 for nonprehydrated GCL permeated at 3 psi average effective stress. When fly ash coordinates are corrected and pre-1990 MSW leachate chemistry data is removed, few leachates cause a significant increase in GCL hydraulic conductivity.

**Data Interpretation.** The GCL tested in Kolstad’s research had a hydraulic conductivity of  $9 \times 10^{-10}$  cm/s when permeated with distilled water. Kolstad Equation 3 predicts the hydraulic conductivity of the nonprehydrated GCL permeated with inorganic chemicals. Using the post-1990 MSW leachate chemistry from Table A, the Kolstad model yields an estimated average nonprehydrated GCL long-term hydraulic conductivity of  $6.4 \times 10^{-9}$  cm/s and a maximum of  $1.7 \times 10^{-7}$  cm/s at 3 psi average effective stress.

However, as noted by the authors, the model expressed in Equation 3 does not take into account 1) higher effective stresses which tend to decrease permeability, 2) prehydration from subgrade or 3) increasing pH over time. The model should be adjusted to account for at least the first two important factors. Petrov (1997) developed the following equation for the effect of confining stress on GCL hydraulic conductivity permeated with distilled water:

$$\log K_{DI} = -8.0068 - 0.5429 \log \sigma$$

Where  $K_{DI}$  is in cm/s and  $\sigma$  is in kPa.

Bonaparte et al. found that 74 MSW cells in the USEPA study had maximum heights ranging from 26 to 226 feet, with an average of 90 feet. Assuming a MSW density of 60 pcf (Daniel 1993), the typical effective stress of a MSW liner is 37 psi. Although the expression developed by Petrov is stated to be valid only for effective stress between 3 and 120 kPa (0.4 to 17 psi), the correlation appears to trend linearly. Therefore, it is reasonable to use this expression for 37 psi stress, which is just slightly higher on the logarithmic scale. For an increase in maximum effective stress from 5 psi to 37 psi, the Petrov equation yields a 65% decrease in GCL hydraulic conductivity. Predictions from the Kolstad model, adjusted for post-1990 MSW leachate chemistry data and an effective stress of 37 psi, yield an estimated average nonprehydrated GCL long-term hydraulic conductivity of  $2.3 \times 10^{-9}$  cm/s and a maximum of  $6 \times 10^{-8}$  cm/s for MSW landfills.

Even lower hydraulic conductivity would be expected if the GCL prehydrates from subgrade moisture. Lee and Shackelford (2005) showed that GCL prehydrated with deionized water and then permeated with a 0.1M  $\text{CaCl}_2$  solution ( $I = 0.3 \text{ M}$ ) had a hydraulic conductivity 3 times lower compared to a nonprehydrated GCL. But testing at  $\text{CaCl}_2 = 0.05\text{M}$  ( $I = 0.15\text{M}$ ) indicated that the prehydration effect was insignificant. It is possible that prehydration of the GCL will improve long-term hydraulic conductivity at  $I = 0.24\text{M}$ , the upper end of the MSW ionic strength reported. However, more study in this area is needed.

The highest MSW leachate ionic strength was for young MSW leachate (<5 years). After waste placement ceases and the landfill is capped, methanogenic organisms begin to proliferate in a MSW landfill and the pH begins to approach neutrality as the acids are converted into methane and a bicarbonate buffering system is established during the methane fermentation stage (Bonaparte et al 2002). Concentrations of free divalent cations will decrease with increased pH, due to the solubility of divalent cations (Snoeyink and Jenkins 1980). Consequently, after closure, the ionic strength of the MSW leachate will decrease. Therefore, it can be argued that with GCL prehydration and/or leachate aging that the previously estimated average GCL hydraulic conductivity of  $2.3 \times 10^{-9}$  for MSW landfills is quite conservative.

Giroud (1997) has formulated equations for leakage rates through defects in geomembranes. Under typical MSW landfill conditions; these formulas indicate that the leakage rate through geomembrane defects is controlled by the hydraulic conductivity of the underlying clay. Thus, based upon the estimated GCL long-term hydraulic conductivities stated above, a GM/GCL composite MSW liner would be expected to have a lower leakage rate than a GM/CCL composite MSW liner, where the CCL has a hydraulic conductivity of  $10^{-7}$  cm/s. This is supported by the MSW landfill leakage rate data of GM/GCL and GM/CCL composite liners collected in the USEPA study by Bonaparte et al. (see CETCO TR-316).

**Conclusion.** In their conclusions Kolstad et al. state that, "high hydraulic conductivities (i.e.,  $>10^{-7}$  cm/s) are unlikely for nonprehydrated GCLs in base liners in many solid waste containment facilities". Based on the data review compiled above, it is reasonable to refine this conclusion to a) the hydraulic performance of a GCL in a landfill bottom liner will not be significantly affected by a typical modern MSW leachate and that b) high GCL hydraulic conductivities will only occur in certain cases at non-MSW wastes (e.g., hazardous waste, mine waste, fly ash) when the waste leachate contains higher ionic strengths.

## References

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- Snoeyink & Jenkins, *Water Chemistry*, John Wiley & Sons Publishers, New York, 1980.

# Hydraulic Conductivity and Swell of Nonprehydrated Geosynthetic Clay Liners Permeated with Multispecies Inorganic Solutions

Dale C. Kolstad, M.ASCE<sup>1</sup>; Craig H. Benson, M.ASCE<sup>2</sup>; and Tuncer B. Edil, M.ASCE<sup>3</sup>

**Abstract:** The influence of multispecies inorganic solutions on swelling and hydraulic conductivity of non-prehydrated geosynthetic clay liners (GCLs) containing sodium bentonite was examined. Ionic strength and the relative abundance of monovalent and divalent cations (RMD) in the permeant solution were found to influence swell of the bentonite, and the hydraulic conductivity of GCLs. Swell is directly related to RMD and inversely related to ionic strength, whereas hydraulic conductivity is directly related to ionic strength and inversely related to RMD. RMD has a greater influence for solutions with low ionic strength (e.g., 0.05 M), whereas concentration effects dominate at high ionic strength (e.g., 0.5 M). No discernable effect of cation species of similar valence was observed in the swell or hydraulic conductivity data for test solutions with similar ionic strength and RMD. A strong relationship between hydraulic conductivity and free swell was found, but the relationship must be defined empirically for a particular bentonite. A regression model relating hydraulic conductivity of the GCL to ionic strength and RMD of the permeant solution was developed. Predictions made with the model indicate that high hydraulic conductivities (i.e.,  $>10^{-7}$  cm/s) are not likely for GCLs in base liners in many solid waste containment facilities. However, for wastes with stronger leachates or leachates dominated by polyvalent cations, high hydraulic conductivities may occur.

DOI: 10.1061/(ASCE)1090-0241(2004)130:12(1236)

CE Database subject headings: Hydraulic conductivity; Swelling; Inorganic chemicals; Clay liners; Bentonite.

## Introduction

Geosynthetic clay liners (GCLs) are factory-manufactured clay liners consisting of a layer of bentonite clay encased by geotextiles or glued to a geomembrane. GCLs have become a popular alternative to compacted clay liners in waste containment applications because of their relatively low cost, ease of installation, perceived resistance to environmental distress (e.g. freeze-thaw and wet-dry cycling), smaller air-space requirements, and low hydraulic conductivity to water ( $<10^{-8}$  cm/s). For GCLs that do not contain a geomembrane, bentonite is responsible for the low hydraulic conductivity. Sodium (Na) montmorillonite mineral is the primary component of bentonite, and largely controls the hydraulic conductivity of GCLs (Shackelford et al. 2000).

A variety of studies have shown that the hydraulic conductivity and swelling of bentonite can be affected by inorganic permeant solutions (Alther et al. 1985; Shan and Daniel 1991; Egloffstein 1997, 2001; Quaranta et al. 1997; Ruhl and Daniel 1997;

Petrov and Rowe 1997; Shackelford et al. 2000; Jo et al. 2001; Vasko et al. 2001; Ashmawy et al. 2002; Katsumi et al. 2002, 2003; Shan and Lai 2002). The general conclusion of these studies is that the hydraulic conductivity and swelling of GCLs is sensitive to the concentration of the permeant solution and the cation valence. In general, higher hydraulic conductivity and lower swell are obtained in more concentrated solutions or solutions with a preponderance of divalent cations. However, no systematic study has been made regarding how the concentration and relative proportions of monovalent and polyvalent cations in a multispecies (i.e., more than one cation species) solution affect swelling and hydraulic conductivity of bentonite and GCLs.

Several studies have been conducted in soil science regarding the effect of multispecies solutions on the hydraulic conductivity of montmorillonitic soils (Reeve and Bower 1960; McNeal and Coleman 1966; McNeal et al. 1966; Mustafa and Hamid 1975; Malik et al. 1992). However, these studies have focused on increasing the hydraulic conductivity of montmorillonitic soils for land drainage and agricultural applications rather than maintaining low hydraulic conductivity for containment applications. Moreover, none of these studies has focused on clay soils very rich in montmorillonite, such as the Na-bentonites used for GCLs.

This paper discusses how the ionic strength and relative amounts of monovalent and divalent cations in multispecies solutions affect swelling and hydraulic conductivity of nonprehydrated GCLs containing Na-bentonite. The focus is on applications where inorganic solutes are the primary factor affecting hydraulic conductivity (e.g., conventional solid waste containment facilities for municipal, hazardous, or mining wastes) and where complete prehydration (i.e., prehydration by permeation with distilled, deionized, or potable water) is unlikely. The effects of complete prehydration and organic compounds are discussed

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Note. Discussion open until May 1, 2005. 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 July 23, 2003; approved on April 6, 2004. This paper is part of the *Journal of Geotechnical and Geoenvironmental Engineering*, Vol. 130, No. 12, December 1, 2004. ©ASCE, ISSN 1090-0241/2004/12-1236-1249/\$18.00.

by others (e.g., Shan and Daniel 1991; Petrov and Rowe 1997; Ruhl and Daniel 1997; Shackelford et al. 2000).

## Background

### *Exchangeable Cations, Mobility of Water, and Hydration of Bentonite*

A weak interlayer bond allows the montmorillonite crystal layers to separate during hydration as water molecules enter the interlayer space (Grim 1968; van Olphen 1977). Consequently, cations on the interlayer surfaces become exchangeable, which renders the physical properties of Na-montmorillonite susceptible to interactions with the permeant liquid. The degree of exchange depends on the valence, relative abundance, and size of the cations. Generally, cations of greater valence and smaller size replace cations of lower valence and larger size. The preference for replacement is the lyotropic series, which is  $\text{Li}^+ < \text{Na}^+ < \text{K}^+ < \text{Rb}^+ < \text{Cs}^+ < \text{Mg}^{2+} < \text{Ca}^{2+} < \text{Ba}^{2+} < \text{Cu}^{2+} < \text{Al}^{3+} < \text{Fe}^{3+}$  (Sposito 1981; 1989; McBride 1994). Because  $\text{Na}^+$  is at the lower end of the lyotropic series, Na-bentonites are prone to cation exchange when permeated with solutions containing divalent or trivalent ions (Sposito 1981).

Water in the pores of bentonite can be considered mobile or immobile. Mobile water is bulk pore water that is free to move under a hydraulic gradient. Immobile water is bound to the external and internal (i.e., interlayer) mineral surfaces by strong electrical forces, and is believed to act as an extension of the solid surface. When the amount of immobile water in the system increases, the hydraulic conductivity of bentonite decreases because the interparticle flow paths for mobile water become more constricted and tortuous. This is especially true in bentonites where swell is constrained (e.g., needle-punched GCLs or GCLs under confining pressure) (Reeve and Ramadoni 1965; McNeal and Coleman 1966; McNeal et al. 1966; Lagerwerff et al. 1969; Mesri and Olson 1971; Petrov and Rowe 1997; Shackelford et al. 2000; Jo et al. 2001). Changes in the volume of immobile water also cause volume changes in the bentonite (swell occurs as the volume of immobile water increases). Thus swell and hydraulic conductivity are generally inversely related for bentonites (Shackelford et al. 2000; Jo et al. 2001; Ashmawy et al. 2002; Katsumi et al. 2002).

The fraction of the pore water that is immobile is proportional to the number of layers of water molecules hydrating the interlayer surfaces of the montmorillonite particles (McBride 1994). Hydration of montmorillonite in electrolyte solutions occurs in two phases: the crystalline phase and the osmotic phase (Norris and Quirk 1954; McBride 1994, Zhang et al. 1995; Prost et al. 1998). The crystalline phase occurs first as several molecular layers of water hydrate the interlayer and outer surfaces from the completely dry state. Osmotic hydration occurs when additional water molecules hydrate the interlayer surfaces, resulting in large interlayer distances (McBride 1994). Crystalline hydration generally results in a small expansion of the interlayer space and a limited amount of immobile water, which is manifested at the macroscale as a small amount of swelling (referred to as "crystalline swell") and higher hydraulic conductivity. Osmotic hydration can result in appreciable expansion of the interlayer space, a large fraction of the pore water being bound, and is responsible for the large amount of swelling (referred to as "osmotic swell") and low hydraulic conductivity often associated with Na-bentonites.

When the interlayer cations are monovalent, both crystalline and osmotic hydration occur, allowing the interlayer spacings to become large. However, only crystalline swelling occurs when the interlayer cations are divalent or trivalent, limiting expansion of the interlayer region to approximately 1.96 nm (four layers of water molecules). Strong electrostatic attraction between the montmorillonite sheets and the interlayer cations prevent osmotic swelling when the cations are polyvalent, despite the larger hydration energy associated with polyvalent cations (McBride 1994; 1997; Quirk and Marčelja 1997). Thus, appreciable swelling and lower hydraulic conductivity occur when the interlayer cations are monovalent, whereas very little swelling and higher hydraulic conductivity occur when the cations are divalent or trivalent (Norris and Quirk 1954; McBride 1994; Wu et al. 1994; Egloffstein 1997, 2001; Onikata et al. 1999; Jo et al. 2001; Ashmawy et al. 2002). In monovalent solutions, the volume of swelling and spacing of the interlayer region is inversely proportional to the square root of the concentration of the solution (Norris and Quirk 1954; McBride 1994; Zhang et al. 1995; Onikata et al. 1999).

### *Hydraulic Conductivity to Single-Species Inorganic Solutions*

Mesri and Olson (1971) studied the mechanisms controlling the hydraulic conductivity of bentonite when the interlayer cation was sodium or calcium. At similar void ratios, the hydraulic conductivity of Na-bentonite was approximately five times lower than that of the Ca-bentonite. Mesri and Olson (1971) attributed the lower hydraulic conductivity of the Na-bentonite to the presence of immobile water, which resulted in smaller and more tortuous flow paths for mobile water.

Petrov and Rowe (1997) investigated how NaCl solutions of varying concentration affected the hydraulic conductivity of a GCL containing Na-bentonite. Tests were conducted with distilled (DI) water and NaCl solutions having concentrations between 0.1–2.0 M. Hydraulic conductivity of the GCL generally increased as the NaCl concentration increased. At 2.0 M, the hydraulic conductivity was as much as 800 times higher than that with distilled water. For concentrations less than 0.1 M, the hydraulic conductivity was comparable to that obtained with distilled water. Prehydration with at least one pore volume of distilled water tempered the sensitivity of hydraulic conductivity to salt concentration. For 2.0 M NaCl, prehydration with distilled water resulted in a hydraulic conductivity 25 times lower than that obtained by direct permeation with 2.0 M NaCl. Tests conducted over a range of confining stresses (3 to 118 kPa) showed that, at a given concentration, the hydraulic conductivity can vary by a factor of 10 to 50 depending on the effective stress.

Jo et al. (2001) investigated how cation valence and concentration of single-species salt solutions affect free swell and hydraulic conductivity of nonprehydrated GCLs containing Na-bentonite. Salt solutions with cation valences of 1, 2, and 3 and concentrations between 0.005 and 1.0 M were used. All tests were conducted until the physical and chemical termination criteria in ASTM D 6766 were achieved. Permeation with salt solutions having concentrations less than 0.1 M (monovalent) or 0.01 M (divalent or trivalent) yielded hydraulic conductivities similar to those with DI water ( $\approx 10^{-9}$  cm/s), regardless of cation valence. For higher concentrations, swell decreased and hydraulic conductivity increased as the concentration or valence increased. Swelling in the presence of monovalent cations followed the order of the hydrated radius ( $r_h$ ) and the lyotropic series, with Li ( $r_h \approx 0.6$  nm) solutions yielding the greatest swell and K ( $r_h$

≈ 0.3 nm) solutions yielding the lowest swell at a given concentration. In contrast, hydraulic conductivity to the monovalent solutions was insensitive to cation species. No dependence on species was observed for swell or hydraulic conductivity when the solutions contained divalent or trivalent cations. In addition, solutions with trivalent cations resulted in swell and hydraulic conductivity essentially identical to those obtained with solutions having divalent cations at the same concentration.

Jo et al. (2001) conclude that swell and hydraulic conductivity depend more on valence at intermediate concentrations (0.025 M to 0.1 M), whereas concentration dominates at low (0.005 M) and high (1 M) concentrations. They also conclude that hydraulic conductivity and swelling have a strong inverse relationship, and suggest that swell tests can be used as an indicator of adverse chemical interactions that affect the hydraulic conductivity of GCLs.

### Hydraulic Conductivity to Multispecies Inorganic Solutions

Reeve and Bower (1960) investigated how sodium adsorption ratio (SAR) of the permeant solution and electrolyte concentration affected the hydraulic conductivity of a sodic (sodium rich) soil with a montmorillonitic clay fraction. SAR is a ratio describing the relative amounts of sodium, calcium, and magnesium in the pore water equilibrated with the soil, and can be written as (McBride 1994):

$$\text{SAR} = \left[ \frac{\text{Na}^+}{[(\text{Ca}^{2+} + \text{Mg}^{2+})/2]^{1/2}} \right]_e \quad (1)$$

where the cation ( $\text{Na}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ) concentrations are expressed in meq/L (note: 1 meq/L = 1 mN). The soil had a cation exchange capacity (CEC) = 8.9 meq/100 g. The permeant solutions were Salton sea water (SAR = 57) and diluted Salton sea water with SAR = 40, 27.2, 18.2, and 2.2. Reeve and Bower (1960) found that the rate of monovalent for divalent exchange is a function of the divalent cation concentration and SAR of the permeant solution. At a given SAR, solutions with higher ionic strength resulted in more rapid exchange and higher hydraulic conductivity.

McNeal and Coleman (1966) and McNeal et al. (1966) used Na–Ca solutions to investigate how concentration and SAR affect swelling and hydraulic conductivity of Gila clay from New Mexico, USA, which has CEC = 41.2 meq/100 g and consists of 29% montmorillonite. Swelling was quantified as the mass of “bound” solution per mass of clay. Test solutions were prepared with NaCl and  $\text{CaCl}_2$  salts at concentrations of 0.8, 0.2, 0.05, 0.012, and 0.003 mN with SAR = 0, 15, 25, 50, 100, and  $\infty$ . Specimens for hydraulic conductivity testing were initially equilibrated by permeation with 10 pore volumes of a 0.8 N solution having the same SAR as the test solution, and then were sequentially permeated with test solutions of decreasing concentration.

McNeal et al. (1966) found no appreciable swell in solutions with SAR = 0 (all divalent) regardless of concentration, which is consistent with the lack of an osmotic swelling phase when the interlayer contains polyvalent cations (Norris and Quirk 1954). Measurable swelling began at 0.012 N and SAR = 25, and increased as the SAR of the solution increased. Decreases in hydraulic conductivity occurred with decreasing concentration and increasing SAR of the permeant solution. For example, the hydraulic conductivity was  $1.5 \times 10^{-5}$  cm/s for a 0.8 N solution with SAR = 0,  $5.9 \times 10^{-6}$  cm/s for a 0.050 N solution with SAR = 100, and  $1.5 \times 10^{-7}$  cm/s for a 0.012 N solution with SAR =  $\infty$  (all sodium).

McNeal et al. (1966) concluded that salt concentration and SAR affect swelling and hydraulic conductivity of Gila clay in an inverse manner, which was also reported by Jo et al. (2001) for GCLs permeated with single-species solutions. Increasing the concentration or relative abundance of divalent cations (lower SAR) results in less swell and higher hydraulic conductivity. McNeal et al. (1966) postulate that swelling of montmorillonite is the dominant mechanism affecting its hydraulic conductivity because it affects the opening and closing of pores.

Mustafa and Hamid (1975) investigated how electrolyte concentration and SAR of the permeant solution affected the hydraulic conductivity of two montmorillonitic soils, one containing 32% montmorillonite and the other 14% montmorillonite. The hydraulic conductivity of both soils exhibited the same trends with concentration and SAR as reported by McNeal et al. (1966). However, Mustafa and Hamid (1975) indicate that the relationships between swell, hydraulic conductivity, and characteristics of the permeant solution are unique for each soil.

Malik et al. (1992) investigated how mixed Na–Ca solutions of various concentrations affect swelling, dispersion, and flow in two unsaturated clays reported to be montmorillonitic (the montmorillonite content was not reported). NaCl and  $\text{CaCl}_2$  solutions with SAR = 0, 5, 15, 25, and 50 and concentrations of 3.1, 12.5, 50, 200, and 500 mM were used. Their results were also similar to those reported by McNeal et al. (1966); swell of both soils increased and the hydraulic conductivity decreased as the concentration decreased or the SAR increased.

## Materials and Methods

### Geosynthetic Clay Liner

The GCL used in this study contains granular sodium bentonite encapsulated between a 170 g/m<sup>2</sup> slit-film monofilament woven geotextile and a 206 g/m<sup>2</sup> staple-fiber nonwoven geotextile. The geotextiles are bonded by needle-punching fibers that are thermally fused to the geotextiles. The specific gravity of the bentonite is 2.65, and the average mass of bentonite per area is 4.3 kg/m<sup>2</sup>. The initial thickness of the GCL ranges from 5.5 to 6.5 mm, and the average initial gravimetric water content of the bentonite was 9%.

X-ray diffraction showed that the bentonite contains 86% montmorillonite, 3% quartz, 5% tridymite, 3% plagioclase feldspar, 1% K-feldspar, 1% aragonite, 1% illite/mica, and trace amounts of calcite, siderite, clinoptilolite, rutile, and gypsum. The granule size distribution for the GCL (determined by mechanical sieve analysis on the air-dry bentonite) is shown in Fig. 1 along with the granule size distribution for the GCL used by Jo et al. (2001). Both GCLs contain sand-size bentonite granules, but the GCL used in this study has smaller granules.

The CEC and composition of the exchange complex (Ca, Mg, Na, and K) were measured on two samples of bentonite from the GCL using the procedures in *Methods of Soil Analysis* (Spark 1996). Soluble salts were extracted with DI water and exchangeable metals were extracted with ammonium acetate. These replicate measurements yielded CECs of 65.2 and 73.5 meq/100 g and the following exchange complex: Na—56.1 and 40.0 meq/100 g, K—0.6 and 0.8 meq/100 g, Ca—12.0 and 15.7 meq/100 g, Mg—4.0 and 4.8 meq/100 g. Thus, the bentonite used in this study is predominantly Na-montmorillonite.



**Table 1.** Summary of Permeant Solutions

Type of solution	Ionic strength (M)	Monovalent concentration $10^{-2}$ (M)	Divalent concentration $10^{-2}$ (M)	RMD ( $\text{mM}^{1/2}$ )	pH	EC (S/m)
Li-Ca	0.05	5.00	0.00	$\infty$	7.4	0.50
		4.35	0.22	0.93	7.6	0.48
		3.33	0.56	0.45	7.7	0.43
		2.00	1.00	0.20	7.2	0.42
		0.00	1.67	0.00	7.8	0.36
Na-Mg		3.33	0.56	0.45	7.4	0.43
Li-Na		3.33	0.56	0.45	7.2	0.43
Ca-Mg		Li(1):Na(3) <sup>a</sup>	Ca(1):Mg(3) <sup>b</sup>			
Li-Ca	0.1	10.0	0.00	$\infty$	6.8	0.88
		8.70	0.44	1.32	7.9	0.87
		8.33	0.56	1.12	8.5	0.88
		7.77	0.77	0.88	8.1	0.87
		6.67	1.11	0.64	7.7	0.86
		5.00	1.67	0.38	7.3	0.80
		2.50	2.50	0.16	7.5	0.77
		1.00	3.00	0.06	7.4	0.72
		0.00	3.33	0.00	7.9	0.70
		Na-Mg		8.70	4.35	1.32
		6.67	1.11	0.64	6.6	0.86
		1.00	3.00	0.06	7.2	0.73
Li-Na		8.33	0.56	1.12	7.1	0.88
Ca-Mg		Li(3):Na(1) <sup>a</sup>	Ca(3):Mg(1) <sup>b</sup>			
Li-Na		2.50	2.50	0.16	6.5	0.77
Ca-Mg		Li(1):Na(1) <sup>a</sup>	Ca(1):Mg(1) <sup>b</sup>			
Li-Ca	0.2	20.0	0.00	$\infty$	8.1	1.86
		16.7	1.11	1.58	7.2	1.72
		13.3	2.22	0.89	7.1	1.62
		8.00	4.00	0.40	7.2	1.50
		0.00	6.67	0.00	7.2	1.29
Na-Mg		13.3	2.22	0.89	6.7	1.61
Li-Na		8.00	4.00	0.40	7.2	1.50
Ca-Mg		Li(1):Na(3) <sup>a</sup>	Ca(3):Mg(1) <sup>b</sup>			
Li-Ca	0.5	50.0	0.00	$\infty$	8.1	3.45
		38.5	3.85	1.97	7.3	3.46
		31.3	6.25	1.24	8.2	3.29
		20.0	10.0	0.64	8.1	3.03
		0.0	16.7	0.00	7.6	2.74
Na-Mg		31.3	6.25	1.24	7.2	3.30
Li-Na		38.5	3.85	1.97	6.6	3.46
Ca-Mg		Li(3):Na(1) <sup>a</sup>	Ca(1):Mg(3) <sup>b</sup>			
Li-Na		20.0	10.0	0.64	6.9	3.02
Ca-Mg		Li(2):Na(1) <sup>a</sup>	Ca(1):Mg(2) <sup>b</sup>			

Note: RMD=Relative abundance of monovalent and divalent cations; EC=Exchange capacity.

<sup>a</sup>Molar ratio of monovalent cations when two species are present.

<sup>b</sup>Molar ratio of divalent cations when two species are present

The hydraulic conductivity tests were terminated when the termination criteria in ASTM D 5084 and D 6766 were satisfied. The hydraulic conductivity was required to be steady ( $\pm 25\%$  of the mean with no statistically significant trend for at least four values), the ratio of outflow to inflow was between 0.75 and 1.25 for four consecutive values, and the pH and EC of the influent and

effluent deviated less than 10%. A minimum of 2 pore volumes of flow (PVF) was also stipulated, although all tests required more than 2 PVF to satisfy all of the termination criteria (some tests required more than 150 PVF). A pH meter and a portable electrical conductivity probe were used to measure the pH and EC.

**Table 2.** Summary of Free Swell Data

Ionic strength (M)	RMD $\text{mM}^{1/2}$	Free swell (mL/2 g)		
		Li-Ca solutions	Na-Mg solutions	Li-Na-Ca-Mg solutions
0.05	0.93	30.5	—	—
	0.45	24.5	24.5	—
	0.20	22.0	—	—
	0.00	19.0	—	—
0.1	1.32	21.5	21.0	—
	1.12	21.0	—	21.0
	0.88	19.0	—	—
	0.64	17.5	17.5	—
	0.38	14.0	—	—
	0.16	13.5	—	13.0
	0.06	11.5	12.0	—
	0.00	11.0	—	—
0.2	1.67	19.0	—	—
	0.89	15.0	15.5	—
	0.40	12.0	—	12.5
	0.00	9.5	—	—
0.5	1.97	11.5	—	12.0
	1.24	10.5	10.0	—
	0.64	8.5	—	8.5
	0.00	6.5	—	—

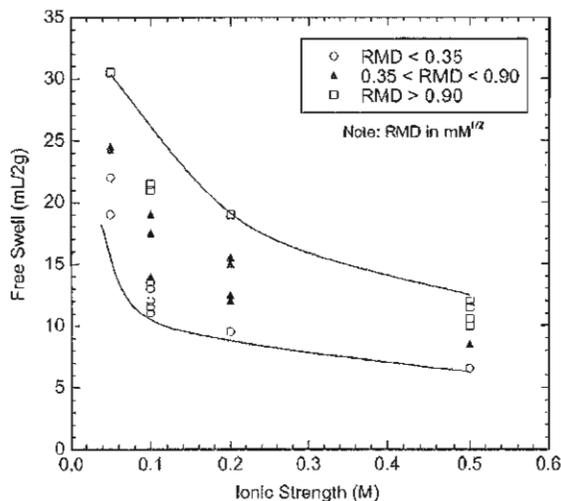
Note: Free Swell in distilled water=36.5 mL/2 g; RMD=Relative abundance of monovalent and divalent cations.

**Results of Free Swell Tests**

**Effect of Concentration and Relative Abundance of Monovalent and Divalent Cations**

Free swell tests were conducted using solutions with ionic strengths ranging from 0.05 M to 0.5 M and RMD ranging from 0 to 1.97  $\text{mM}^{1/2}$ . The multispecies solutions were prepared with Li and Ca, Na, and Mg, or Li, Na, Ca, and Mg. Results of the tests are summarized in Table 2.

Free swell is shown as a function of ionic strength in Fig. 2 for



**Fig. 2.** Free swell of geosynthetic clay liner bentonite as a function of ionic strength for low, intermediate, and high relative abundance of monovalent and divalent cation

the Li-Ca solutions. The data are segregated by solutions that are predominantly divalent ( $\text{RMD} < 0.35 \text{ mM}^{1/2}$ ), solutions with comparable fractions of monovalent and divalent cations ( $0.35 \text{ mM}^{1/2} < \text{RMD} < 0.90 \text{ mM}^{1/2}$ ), and solutions that are predominantly monovalent ( $\text{RMD} > 0.90 \text{ mM}^{1/2}$ ). Free swell of the bentonite decreases with increasing concentration for each range of RMD. Lower free swell also occurs as the RMD decreases because the presence of more divalent cations suppresses the osmotic component of swelling. RMD also affects the sensitivity to concentration. For the predominantly monovalent solutions ( $\text{RMD} > 0.90 \text{ mM}^{1/2}$ ), the free swell decreases 19 mL/2 g, on average, as the ionic strength is varied between 0.05 to 0.5 M. For the predominantly divalent solutions ( $\text{RMD} < 0.35 \text{ mM}^{1/2}$ ), the free swell decreases 14 mL/2 g, on average, over the same range of ionic strengths.

The influence of RMD on swell at constant ionic strength is shown in Fig. 3. The relationships are approximately linear, with trend lines fitted to the data using least-squares linear regression. The slope of each trend line reflects the sensitivity of swell to RMD; the intercept is the free swell when the solution only contains divalent cations. When the ionic strength is lower, the trend lines have a larger slope (e.g., slope=12.1 for  $I=0.05 \text{ M}$  and 2.6 for  $I=0.5 \text{ M}$ ), which indicates that RMD has a stronger influence on swelling at low ionic strength and less effect at high ionic strength.

The trends in the free swell tests are consistent with those reported by McNeal et al. (1966) for swelling of Gila clay in mixed Na-Ca solutions. They found a unique relationship between swell and SAR when the concentration was fixed, and that the sensitivity to SAR diminished as the concentration increased. Jo et al. (2001) report similar findings for single species solutions. They found that concentration has a greater effect on free swell for monovalent solutions than divalent solutions.

The sensitivity of free swell to concentration and RMD is

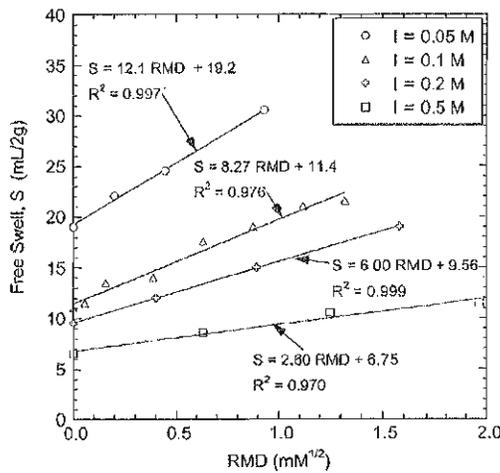


Fig. 3. Free swell of GCL bentonite as a function of RMD for ionic strengths of 0.05, 0.1, 0.2 and 0.5 M

caused by expansion and contraction of the interlayer space as a result of crystalline and osmotic swelling. This effect is illustrated in Fig. 4, which shows basal spacing (i.e., sum of interlayer separation distance and thickness of one montmorillonite layer, also referred to as  $d_{001}$ ) as a function of ionic strength. The basal spacing was computed using the method in Smalley (1994), which is based on particle geometry, free swell of the bentonite, the thickness of a montmorillonite layer ( $\approx 0.9$  nm), the basal spacing of Ca-montmorillonite in water ( $\approx 1.96$  nm), and the free swell of Ca-montmorillonite in water ( $\approx 8.0$  mL/2 g). The symbol size in Fig. 4 is proportional to RMD (larger symbols for larger RMD). At high ionic strength (0.5 M), the basal spacing ( $d_{001}$ ) ranges between 1.5 and 2.9 nm, indicating that the swelling is in the crystalline phase ( $d_{001} \leq 1.96$  nm) or the low end of the osmotic phase ( $d_{001} > 1.96$  nm). In contrast, the basal spacing ranges between 4.5 and 8.6 nm at lower concentration ( $I \leq 0.05$  M), which corresponds to crystalline and osmotic swelling ( $d_{001} > 1.96$  nm). Moreover, the smallest symbols (lowest RMD)

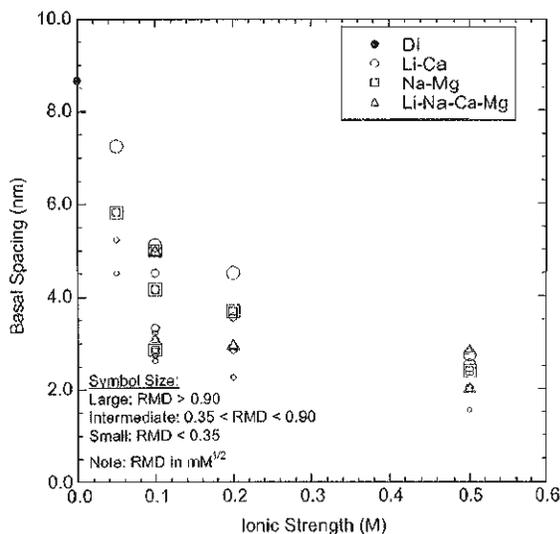


Fig. 4. Free swell of GCL bentonite as a function of computed basal spacing of montmorillonite

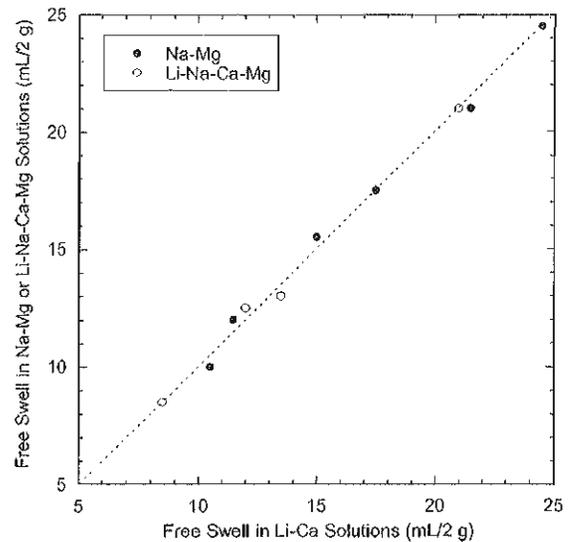


Fig. 5. Comparison of free swell of bentonite in Na-Mg and Li-Na-Ca-Mg solutions to free swell in Li-Ca solutions for solutions prepared with the same ionic strength and RMD

often correspond to the lowest  $d_{001}$  for each ionic strength, reflecting suppression of osmotic swelling due to the preponderance of divalent cations.

#### Effect of Cation Species

The influence of cation species on free swell is illustrated in Fig. 5 using data from the Li-Ca, Na-Mg, and Li-Na-Ca-Mg solutions. Swell in the Na-Mg and Li-Na-Ca-Mg solutions is essentially equal to the swell in the Li-Ca solutions at the same ionic strength and RMD. No discernable effect of cation species is evident. The tendency of divalent cations to suppress osmotic swelling, combined with the insensitivity of free swell to type of divalent cation species (i.e., as in Jo et al. 2001), probably muted any sensitivity to species for the monovalent cations. The single-species tests by Jo et al. (2001) also show that free swell in monovalent solutions is only slightly sensitive to cations species. Thus, free swell is likely to be insensitive to cation species for most monovalent-divalent cation mixtures.

#### Results of Hydraulic Conductivity Tests

##### Effect of Concentration and Relative Abundance of Monovalent and Divalent Cations

Hydraulic conductivity tests were conducted using multispecies aqueous solutions listed in Table 1. The ionic strength of the test solutions ranged from 0.05 M to 0.5 M, and the RMD ranged from 0 to 1.97  $\text{mM}^{1/2}$ . Hydraulic conductivities obtained from these tests are summarized in Table 3.

Hydraulic conductivity is shown in Fig. 6 as a function of ionic strength ( $I$ ). As in Fig. 2, the solutions have been characterized as primarily divalent ( $\text{RMD} < 0.35 \text{ mM}^{1/2}$ ), comparable mixtures ( $0.35 \text{ mM}^{1/2} < \text{RMD} < 0.90 \text{ mM}^{1/2}$ ), and primarily monovalent ( $\text{RMD} > 0.90 \text{ mM}^{1/2}$ ). The hydraulic conductivity is sensitive to the composition of the permeant solution, ranging from  $5.6 \times 10^{-10} \text{ cm/s}$  ( $I=0.05$  M and  $\text{RMD}=0.66 \text{ mM}^{1/2}$ ) to  $1.0 \times 10^{-5} \text{ cm/s}$  ( $I=0.5$  M and  $\text{RMD}=0$ ), and varies exponentially

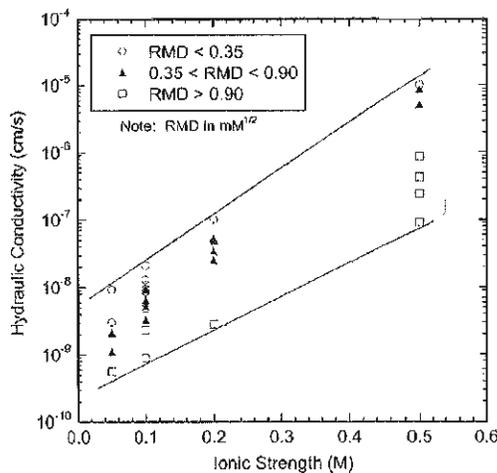
**Table 3.** Summary of Hydraulic Conductivities

Ionic strength (M)	RMD (mM <sup>1/2</sup> )	Hydraulic conductivity (cm/s)		
		Li-Ca solutions	Na-Mg solutions	Li-Na-Ca-Mg solutions
0.05	0.93	5.6 × 10 <sup>-10</sup>	---	---
	0.45	1.1 × 10 <sup>-9</sup>	2.1 × 10 <sup>-9</sup>	---
	0.20	3.0 × 10 <sup>-9</sup>	---	---
	0.00	9.2 × 10 <sup>-9</sup>	---	---
0.1	1.32	2.4 × 10 <sup>-9</sup>	8.9 × 10 <sup>-10</sup>	---
	1.12	2.3 × 10 <sup>-9</sup>	---	4.8 × 10 <sup>-9</sup>
	0.88	3.3 × 10 <sup>-9</sup>	---	---
	0.64	5.2 × 10 <sup>-9</sup>	6.5 × 10 <sup>-9</sup>	---
	0.38	9.3 × 10 <sup>-9</sup>	---	---
	0.16	9.5 × 10 <sup>-9</sup>	---	2.1 × 10 <sup>-8</sup>
	0.06	1.1 × 10 <sup>-8</sup>	8.5 × 10 <sup>-9</sup>	---
	0.00	1.3 × 10 <sup>-8</sup>	---	---
0.2	1.67	2.8 × 10 <sup>-9</sup>	---	---
	0.89	2.5 × 10 <sup>-8</sup>	3.4 × 10 <sup>-8</sup>	---
	0.40	4.9 × 10 <sup>-8</sup>	---	5.2 × 10 <sup>-8</sup>
	0.00	1.0 × 10 <sup>-7</sup>	---	---
0.5	1.97	2.4 × 10 <sup>-7</sup>	---	9.1 × 10 <sup>-8</sup>
	1.24	8.5 × 10 <sup>-7</sup>	4.2 × 10 <sup>-7</sup>	---
	0.64	5.0 × 10 <sup>-6</sup>	---	8.5 × 10 <sup>-6</sup>
	0.00	1.0 × 10 <sup>-5</sup>	---	---

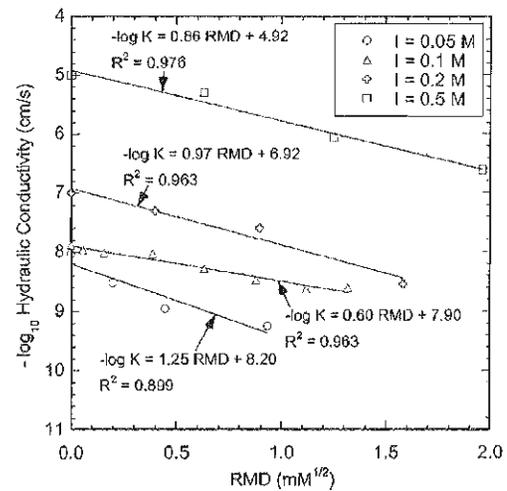
Note: Hydraulic conductivity to distilled water = 9.0 × 10<sup>-10</sup> cm/s; RMD = Relative abundance of monovalent and divalent cations.

with ionic strength (linearly on a semilogarithmic graph). The highest hydraulic conductivities at any ionic strength were obtained using the primarily divalent (RMD < 0.35 mM<sup>1/2</sup>) solutions, and the lowest for the primarily monovalent (RMD > 0.90 mM<sup>1/2</sup>) solutions.

The effect of RMD at constant ionic strength is shown in Fig. 7. The base-10 logarithm of hydraulic conductivity (log<sub>10</sub>K) is approximately linearly related to RMD. The trend lines relating



**Fig. 6.** Hydraulic conductivity of GCL as a function of solution ionic strength for low, intermediate, and high RMD



**Fig. 7.** Hydraulic conductivity of GCL as a function of RMD for ionic strengths of 0.05, 0.1, 0.2, and 0.5 M

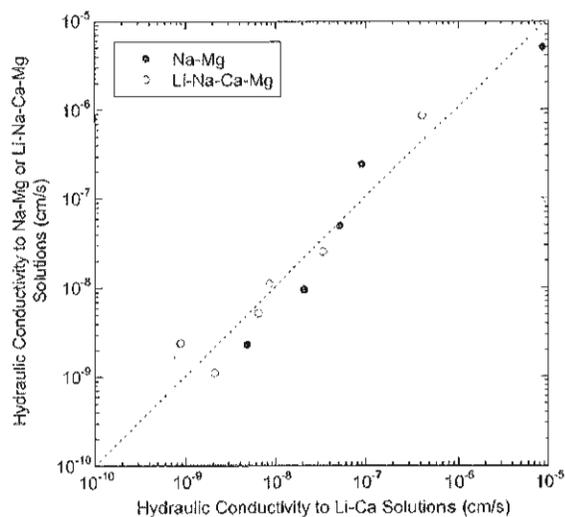
log<sub>10</sub>K and RMD in Fig. 7 were fit using least-squares linear regression. Their slope describes the sensitivity of hydraulic conductivity to RMD, and the intercept is the hydraulic conductivity to the divalent solution. The hydraulic conductivity exhibits greater sensitivity to RMD at lower ionic strength (i.e., slope = 1.25 at I = 0.05 M and 0.86 at I = 0.5 M). The data for the tests conducted at an ionic strength of 0.1 M are an exception to the trend. The reason for this deviation is unknown.

The trends in Figs. 6 and 7 are comparable to the trends reported by McNeal and Coleman (1966) for Gila clay. They found that the hydraulic conductivity increases with increasing concentration and decreasing SAR, and distinct curves relating hydraulic conductivity to SAR exists when the concentration is fixed. McNeal and Coleman (1966) report that SAR has a stronger influence on hydraulic conductivity at low concentrations, and that the effect of SAR diminishes at high concentrations. Jo et al. (2001) also report similar sensitivity to ionic strength and cation valence for single species solutions. At a given ionic strength, the highest hydraulic conductivities were obtained with divalent or trivalent solutions, and the lowest with monovalent solutions.

A diminished effect of ionic strength and RMD probably would have been observed had much lower or much higher ionic strengths been used. For example, DI water is the limiting case for dilute solutions (in this study, the hydraulic conductivity of the GCL to DI water was 9.0 × 10<sup>-10</sup> cm/s). In addition, Jo et al. (2001) report that the hydraulic conductivity of the GCL they tested leveled off between 10<sup>-5</sup> to 10<sup>-4</sup> cm/s for ionic strengths greater than 1 M. When the ionic strength is high, osmotic swelling becomes negligible, and the basal spacing is reduced to its smallest value in the hydrated state (≈ 2 nm). Once this compressed condition is reached, no further increase in hydraulic conductivity can occur. In fact, a decrease in hydraulic conductivity is possible due to the higher viscosity of concentrated solutions (Fernandez and Quigley 1988).

### Effect of Cation Species

Li-Ca, Na-Mg, and Li-Na-Ca-Mg solutions having various RMD and ionic strengths were used to investigate how differences in cation species affect the hydraulic conductivity of GCLs



**Fig. 8.** Comparison of hydraulic conductivities of GCL obtained with Na-Mg and Li-Na-Ca-Mg solutions to hydraulic conductivities obtained with Li-Ca solutions for solutions prepared with the same ionic strength and RMD

permeated with mixed solutions. Composition of each solution is summarized in Table 1 and the hydraulic conductivities are in Table 3.

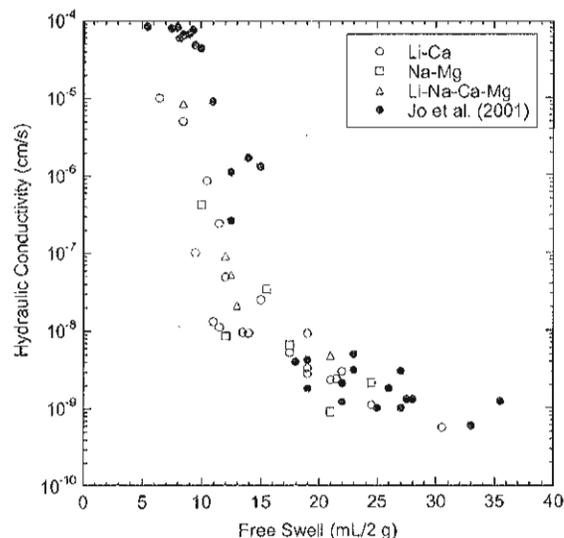
Hydraulic conductivities obtained using the Li-Ca solutions are compared with those obtained from the Na-Mg and Li-Na-Ca-Mg solutions in Fig. 8. At comparable ionic strengths and RMD, essentially the same hydraulic conductivities were obtained with the Na-Mg and Li-Na-Ca-Mg solutions as with the Li-Ca solutions. No discernable effect of cation species is apparent. The insensitivity of hydraulic conductivity to cation species is analogous to the insensitivity of free swell to cation species. Differences in preference of the montmorillonite for Ca over Mg and Na over Li appear to have a small effect compared to the effects of RMD and concentration. In addition, Jo et al. (2001) found that the hydraulic conductivity was insensitive to cation species for a given valence.

The insensitivity to cation species evident in Fig. 8, combined with the insensitivity to cation species observed by Jo et al. (2001) for single-species solutions, suggests that the hydraulic conductivity at fixed RMD is likely to be insensitive to cation species in most monovalent-divalent mixtures. Moreover, Jo et al. (2001) found that permeation with single-species solutions containing divalent and trivalent cations yielded essentially the same hydraulic conductivity at a given concentration. Thus, the insensitivity to cation species may extend to multispecies solutions in general, with ionic strength and RMD being the dominant variables controlling hydraulic conductivity. In this case, the denominator of RMD would include the total normality of the polyvalent (valence  $\geq +2$ ) cations in the solution. While this hypothesis is plausible, more testing is needed to confirm its validity.

## Practical Implications

### Free Swell and Hydraulic Conductivity

Jo et al. (2001) show that a strong relationship exists between free swell of bentonite and the hydraulic conductivity of GCLs ex-



**Fig. 9.** Hydraulic conductivity of GCL as a function of free swell of bentonite. Test data are from this study and from Jo et al. (2001)

posed to single-species solutions. A similar relationship could be expected for multispecies solutions as well because Figs. 2, 3, 6, and 7 show that ionic strength and RMD affect swell and hydraulic conductivity in a consistent and similar manner. McNeal et al. (1966) also report a strong correlation between swelling and hydraulic conductivity for Gila clay permeated with solutions having different ionic strengths and SAR.

Hydraulic conductivity of the GCL specimens permeated with the multispecies solutions is shown in Fig. 9 as a function of free swell along with the single-species data from Jo et al. (2001). A strong relationship exists between hydraulic conductivity and free swell for both data sets. The slight offset in the two data sets at lower swell volumes (and higher hydraulic conductivities) is most likely due to differences in the granule size distributions of the bentonites and not the use of multispecies versus single species solutions. The GCLs used in both studies were essentially identical, except the bentonite in the GCL used in this study has smaller granules than the bentonite in the GCL used by Jo et al. (2001) (Fig. 1). Mesri and Olson (1971) and McNeal et al. (1966) indicate that bentonites with larger “domains” (quasi-crystals) permit larger flow paths and higher hydraulic conductivity. In addition, Katsumi et al. (2002) show that nonprehydrated GCLs containing bentonite with larger granules are more permeable than GCLs with smaller granules when permeated using stronger ( $\geq 0.2$  M) salt solutions. Because the granules do not swell appreciably in strong solutions, bentonites with larger granules have larger intergranular pores, and higher hydraulic conductivity. That is, the hydraulic conductivity of granular bentonite permeated with strong solutions follows a similar relationship with particle size as do granular soils; i.e., the hydraulic conductivity increases as the particle size increases, all factors being equal (e.g., Lambe and Whitman 1969; Terzaghi et al. 1996). In contrast, granule size has no effect on free swell, because the bentonite is crushed to pass the No. 200 sieve prior to free swell testing.

McNeal et al. (1966) conclude that swelling of expansive minerals such as montmorillonite is the dominant mechanism affecting the hydraulic conductivity. The results of this study, as well as those in Jo et al. (2001), support this conclusion. The trends shown in Fig. 9 also indicate that free swell tests can be a relatively simple and quick screening method to evaluate the compat-

ibility of GCLs permeated with inorganic salt solutions containing mixtures of cations. Although not a surrogate for chemical compatibility testing (direct testing is needed to demonstrate that a GCL is compatible with a liquid), free swell testing can be used to identify liquids that are incompatible with GCLs. The data in Fig. 9 also illustrate that the relationship between hydraulic conductivity and free swell is bentonite specific, and needs to be identified empirically.

### Estimating Hydraulic Conductivity

The approximately linear trends shown in Figs. 6 and 7 suggest that a relatively simple empirical model can be used to estimate hydraulic conductivity of GCLs as a function of ionic strength and RMD. A model relating these parameters was developed using stepwise regression (Draper and Smith 1998) using a significance level of 0.05:

$$\frac{\log K_c}{\log K_{DI}} = 1.085 - 1.097I + 0.0398I^2 RMD \quad (3)$$

In Eq. 3,  $K_c$ =hydraulic conductivity to the inorganic chemical solution and  $K_{DI}$ =hydraulic conductivity to deionized water. The  $R^2$  for Eq. (3) is 0.967 and the  $p$  statistic is less than 0.0001. Eq. (3) is linear in both  $I$  and RMD, and the product  $I^2 \times RMD$  reflects that the sensitivity to RMD varies nonlinearly with ionic strength (e.g., as in Fig. 7). Eq. (3) is valid for  $I=0.05-0.5$  M and  $RMD < 2.0$   $\text{mm}^{1/2}$ .

Eq. (3) is based on data from the GCL tested in this study under the state of stress that was employed (effective stress = 20 kPa). However, Eq. (3) can be used to estimate how inorganic solutions may affect the hydraulic conductivity of other GCLs provided they employ granular Na-bentonite consisting of approximately 80% montmorillonite. Many of the GCLs used in North America today fit this description. Even if the granule size or montmorillonite content differs from those in this study, the relative effects of ionic strength and RMD should be approximately correct. In addition, Petrov and Rowe (1997) show that the hydraulic conductivity of GCLs exhibits similar sensitivity to effective stress regardless of whether DI water or a salt solution is used as the permeant liquid. Thus, Eq. (3) can be used to estimate the hydraulic conductivity at different effective stresses if the hydraulic conductivity to DI water at these stresses is known.

A comparison of  $K_c$  predicted with Eq. (3) and the measured hydraulic conductivity is shown in Fig. 10(a). The contour lines in Fig. 10 correspond to Eq. (3), whereas the data points correspond to the  $I$  and RMD for the tests conducted in this study. Eq. (3) captures the data reasonably well. Hydraulic conductivities predicted with Eq. (3) are also shown as contours in Fig. 10(b) along with points corresponding to  $I$  and RMD for actual leachates from a variety of wastes and solid waste disposal facilities reviewed by Kolstad (2000). The ionic strength and RMD of each leachate is summarized in Table 4, along with the data source (literature and regulatory agency reports) and the type of containment facility. The points and contour lines in Fig. 10(b) illustrate what hydraulic conductivity likely would have been had the GCL used in this study been tested with these leachates.

Of the 50 points shown in Fig. 10(b), 37 fall below  $10^{-7}$  cm/s (74%) and 24 fall below  $10^{-8}$  cm/s (48%). Thus, GCLs with high hydraulic conductivities ( $>10^{-7}$  cm/s) should not be common in bottom liners where leachates similar to those in Table 4 are likely to be found. Moreover, many of the points in Fig. 10(b) associated with high hydraulic conductivities correspond to "young" (landfill age < 5 yr) municipal solid waste (MSW)

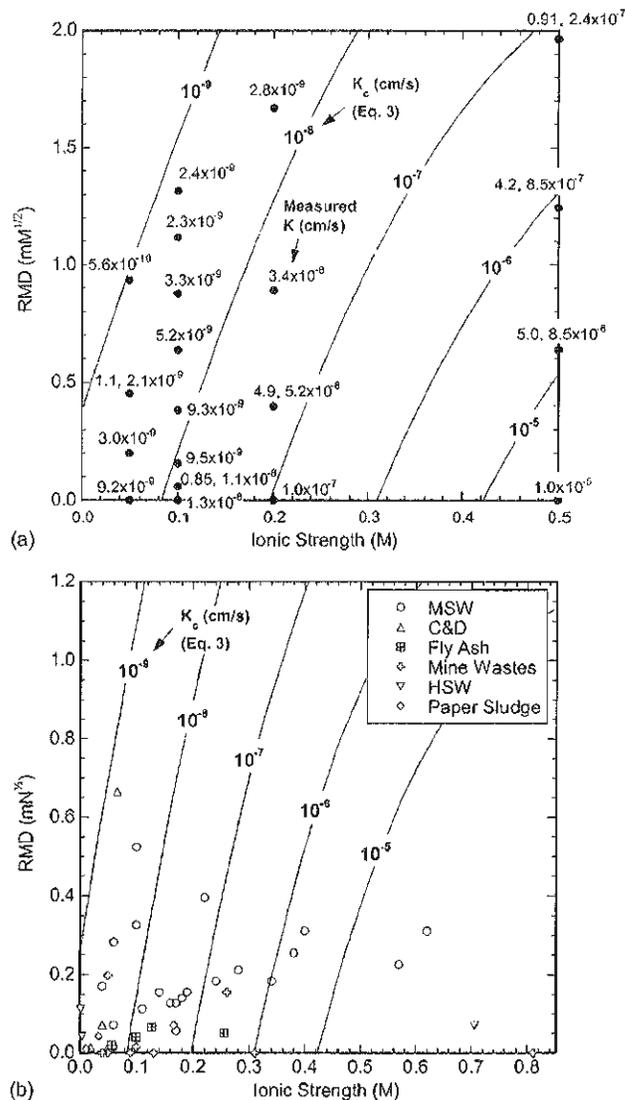


Fig. 10. Contours of hydraulic conductivity as a function of RMD and ionic strength predicted with Eq. (3) along with (a) measured hydraulic conductivities as solid circles and (b) points corresponding to ionic strength and RMD of various leachates. Data from Williams (1975) ( $I=1.87$  M and  $RMD=0$ ) and Kolstad (2000) ( $I=1.37$  M and  $RMD=2.52$   $\text{mm}^{1/2}$ ) are off the scale in (b).

leachates (Table 4). The composition of MSW leachate changes over time, and thus high hydraulic conductivities may not be realized because of the relatively long time required for a GCL and leachate to reach equilibrium under field conditions (Jo 2003). However, some of the points for mine waste, paper sludge, and fly ash disposal facilities are associated with high hydraulic conductivities, and the composition of leachates from these wastes can be persistent.

### Effect of Prehydration

The results of this study pertain specifically to nonprehydrated GCLs. Different results may have been obtained had the GCLs been completely prehydrated by permeation with DI or potable water for several pore volumes of flow. Comparisons between hydraulic conductivities of nonprehydrated and completely prehy-

**Table 4.** Summary of Ionic Strength and RMD of Various Leachates

Source	Leachate type	Ionic strength (M)	RMD (mM <sup>1/2</sup> )	
Ehrig (1983)	Young MSW leachate (<5 yr)	0.28	0.21	
Pohland (1980)		0.38	0.25	
Tchbanoglous et al. (1993)		0.14	0.16	
Chian and DeWalle (1976)		0.17	0.13	
Cheremisinoff (1983)		0.22	0.40	
Alker et al. (1995)		0.16	0.13	
Chian and DeWalle (1975)		0.57	0.23	
Chian and DeWalle (1975)		0.62	0.31	
Chian and DeWalle (1975)		0.34	0.18	
Farquhar (1989)		0.40	0.31	
Shams et al. (1994)	0.24	0.18		
Ehrig (1983)	Intermediate MSW leachate (5--10 yr)	0.10	0.52	
Pohland (1980)		0.10	0.33	
Chian and DeWalle (1975)		0.17	0.06	
Chian and DeWalle (1975)		0.11	0.11	
Farquhar (1989)		0.18	0.14	
Chian and DeWalle (1975)	Old MSW leachate (>10 yr)	0.06	0.01	
Chian and DeWalle (1975)		0.06	0.28	
Farquhar (1989)		0.06	0.07	
Alker et al. (1995)		0.04	0.17	
Kmet and McGinley (1982)	MSW leachate	0.19	0.16	
Ruhl and Daniel (1997)	C and D leachate	0.04	0.17	
Kolstad (2000)		0.05	0.01	
Kolstad (2000)		0.02	0.01	
WMNA (1993)		0.04	0.07	
Weber et al. (2002)		0.066	0.66	
Kolstad (2000)		Fly ash leachate	0.03	0.25
Kolstad (2000)		0.03	0.06	
Kolstad (2000)		0.02	0.10	
Kolstad (2000)	0.05	0.23		
Kolstad (2000)	0.06	0.13		
Kolstad (2000)	0.07	0.20		
Kolstad (2000)	0.37	2.52		
Kolstad (2000)	0.76	0.71		
Al et al. (1994)	Mine process water	0.05	0.00	
Shackelford (1998)		0.04	0.00	
Jordan et al. (1998)		0.05	0.20	

Table 4. (Continued.)

Source	Leachate type	Ionic strength (M)	RMD (mM <sup>1/2</sup> )
Williams (1975)	Acidic mine waste drainage	1.87	0.00
Christensen and Laake (1996)		0.13	0.00
Christensen and Laake (1996)		0.09	0.00
Al et al. (1994)		0.81	0.00
Shackelford (1998)		0.31	0.00
Williams (1975)	Pyritic tailings leachate	0.26	0.16
Pettit and Scharer (1999)	Ur rock drainage	0.10	0.01
Kolstad (2000)	Hazardous waste leachate	0.001	0.11
		0.70	0.07
		0.003	0.04
Kolstad (2000)	Paper mill landfill leachate	0.17	0.07
		0.01	0.01
		0.03	0.04

Note: RMD=Relative abundance of monovalent and divalent cations; MSW=Municipal solid waste.

drated GCLs that have been permeated long enough to establish chemical equilibrium between the bentonite solid and the solution show that prehydration by permeation with DI water results in hydraulic conductivities an order of magnitude lower than those obtained without prehydration, even if cation exchange between the mineral surface and the permeant liquid is complete (Petrov and Rowe 1997; Jo et al. 2004).

Although the effect of complete prehydration is significant, complete prehydration is unlikely to occur in the field. Most GCLs in field applications hydrate as water is drawn to the bentonite from an underlying subgrade via vapor diffusion or gradients in matric potential (Daniel et al. 1993, 1998; Katsumi et al. 2003). The prehydration afforded by these processes does not appear to have the same effect as complete prehydration by direct permeation. Vasko et al. (2001) found that the hydraulic conductivity of GCLs prehydrated with DI water via capillary wetting and vapor diffusion and permeated with CaCl<sub>2</sub> solutions had essentially the same hydraulic conductivity as nonprehydrated GCLs unless the solution was very strong (concentration >0.1 M). Comparable findings are reported by Katsumi et al. (2003). These observations suggest that hydraulic conductivities reported in this study are likely to be more representative of most field conditions than hydraulic conductivities of completely prehydrated GCLs.

## Summary and Conclusions

This study dealt with the influence of multispecies inorganic salt solutions on swelling and hydraulic conductivity of nonprehydrated GCLs. Free swell and hydraulic conductivity tests were conducted on nonprehydrated specimens of a commercially available GCL using DI water and aqueous solutions of LiCl, NaCl, CaCl<sub>2</sub>, and MgCl<sub>2</sub> salts. The relative amounts of monovalent and

divalent cations in solution were quantified with the parameter RMD, which is the ratio of the total molarity of monovalent cations to the square root of the total molarity of divalent cations.

Results of the free swell tests show that swell is directly related to RMD and inversely related to ionic strength. RMD has a strong effect on swell in weaker solutions, and a modest effect in strong solutions. Similar findings were obtained from the hydraulic conductivity tests. Hydraulic conductivity was found to be directly related to ionic strength and inversely related to RMD, with RMD having a greater effect on hydraulic conductivity in weaker solutions. Tests were also conducted to determine if cation species affects swell or hydraulic conductivity. No discernable effect of cation species was evident in the free swell or hydraulic conductivity for tests conducted at a given ionic strength and RMD.

A strong relationship between hydraulic conductivity and free swell was found that is analogous to the relationship reported by Jo et al. (2001) for tests conducted using single-species salt solutions. However, the hydraulic conductivity-free swell relationship is not unique, and must be defined empirically for a particular bentonite if free swell tests are to be used for chemical compatibility screening.

The hydraulic conductivity data were also used to develop a regression model relating hydraulic conductivity of the GCL to ionic strength and RMD of the permeant solution. Predictions made with the model indicate that high hydraulic conductivities (i.e., >10<sup>-7</sup> cm/s) are unlikely for nonprehydrated GCLs in base liners in many solid waste containment facilities. However, for some wastes that transmit stronger leachates or leachates that are dominated by polyvalent cations (e.g., fly ash, paper sludge, and mine wastes), high hydraulic conductivities may be realized provided adequate time exists for the bentonite and leachate to reach chemical equilibrium.

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**Errata for “Hydraulic Conductivity and Swell of Nonprehydrated Geosynthetic Clay Liners Permeated with Multispecies Inorganic Solutions” by D. Kolstad, C. Benson, and T. Edil**

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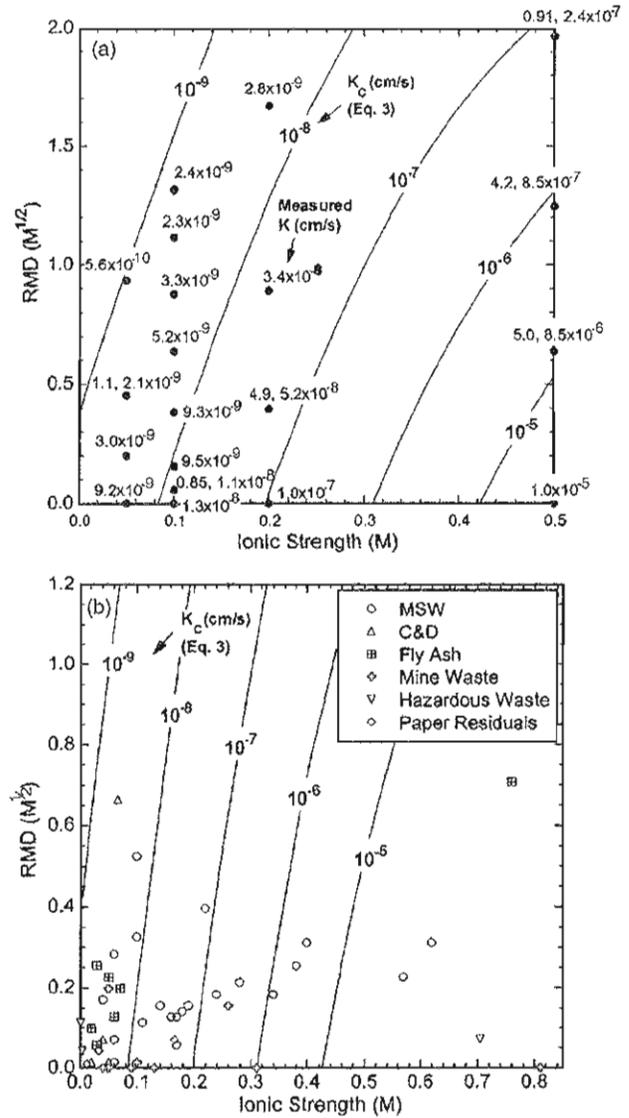
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The following corrections should be noted.

The units for RMD in the text and graphs in this paper should be  $M^{1/2}$  rather than the units of  $mM^{1/2}$  shown in the published version. Eq. (3) also contained typographical errors. The correct version is

$$\frac{\log K_c}{\log K_{DI}} = 0.965 - 0.976I + 0.0797RMD + 0.251I^2RMD \quad (3)$$

In addition, the plotting positions for the fly ash leachates were reversed in Fig. 10(b) (i.e., the fly ash leachate data were plotted as  $I$  versus RMD instead of RMD versus  $I$ ). A correct version of Fig. 10(b) is presented here. These errors do not affect any of the conclusions or inferences in the paper.



**Fig. 10.** Contours of hydraulic conductivity as a function of RMD and ionic strength predicted with Eq. (3) along with (a) measured hydraulic conductivities as solid circles and (b) points corresponding to ionic strength and RMD of various leachates. Data from Williams (1975) ( $I=1.87$  M and  $RMD=0$ ) and Kolstad (2000) ( $I=1.37$  M and  $RMD=2.52M^{1/2}$ ) are off the scale in (b).

**TABLE 3  
NEW LANDFILL CELL 1 ANALYSIS RESULTS  
INTERNATIONAL PAPER  
RIEGELWOOD, NORTH CAROLINA**

Client Sample ID:			Primary Leachate Collection System		Secondary Leachate Collection System		Under-Drain Leachate Collection System		2L Standard	SW/SL
Collect Date:			8/12/09		8/12/09		8/12/09			
Method	Parameter	Units	Value	Q	Value	Q	Value	Q		
EPA 200.7	Arsenic	ug/l	137		2.7	U	5.4		50	10
EPA 200.7	Barium	ug/l	210		68.8		110		2,000	100
EPA 200.7	Cadmium	ug/l	0.5	U	0.5	U	0.5	U	1.75	1
EPA 200.7	Chromium	ug/l	94.5		7.1		32.6		50	10
EPA 200.7	Copper	ug/l	0.3	U	0.3	U	0.3	U	1,000	10
EPA 200.7	Iron	ug/l	7980		1780		12000		300	300
EPA 200.7	Lead	ug/l	4	U	4	U	4	U	15	10
EPA 200.7	Manganese	ug/l	520		510		680		50	50
EPA 200.7	Selenium	ug/l	3.8	U	3.8	U	3.8	U	50	10
EPA 200.7	Silver	ug/l	0.73	J	0.23	J	0.42	J	17.5	10
EPA 200.7	Vanadium	ug/l	667		14.6		81.9		NE	25
EPA 200.7	Zinc	ug/l	31.9		7.9	B	0.4	U	1,050	10
EPA 245.1	Mercury	ug/l	0.22		0.07	U	0.07	U	1.05	0.2
ASTM D516-90	Sulfate	ug/l	344000		112000		6900		250,000	250,000
EPA 120.1	Specific Conductance	umhos/cm	6150		2870		3880		NE	NE
EPA 353.2	Nitrate	ug/l	100	U	100	U	100	U	10,000	10,000
EPA 365.1	Orthophosphate	ug/l	1300		2100		420		NE	NE
SM 2540C	Total Dissolved Solids	ug/l	5100000		2200000		2990000		500,000	NE
SM 4500Cl	Chloride	ug/l	153000		52700		221000		250,000	NE
SM 4500F	Fluoride	ug/l	190		850		190		2,000	2,000
SM 5210B	Biochemical oxygen demand	ug/l	33,600	J	3,600	J	3,600	J	NE	NE
SM 5220D	Chemical oxygen demand	ug/l	862000		148000		290000		NE	NE
SM 5310B	Total Organic Carbon	ug/l	292000		42500		105000		NE	NE
SW-846 9020	Total Organic Halides	ug/l	2000		1600		3000		NE	NE
SW-846 9040	pH	s.u.	7.2	J	6.7	J	6.8	J	6.5-8.5	NE

**Notes:**

Bold values indicate concentrations in excess of NC Groundwater quality standards for the protection of the groundwater.

2L Standard - 15A NCAC 2L Groundwater Standards

SWSL - Solid Waste Section Limits

NE = Not Established

s.u. = Standard unit

ug/L = Micrograms per Liter

umhos/cm = Micromhos per centimeter

**Qualifiers (Q):**

U The analyte was analyzed for, but was not detected above the associated detection limit.

B The analyte was detected in a laboratory blank at a similar concentration.

J The analyte was positively identified; the associated numerical value is the approximate concentration of the analyte in the sample

**TABLE 3  
NEW LANDFILL CELL 1 ANALYSIS RESULTS  
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RIEGELWOOD, NORTH CAROLINA**

Client Sample ID:			Primary Leachate Collection System		Secondary Leachate Collection System		Under-Drain Leachate Collection System		2L Standard	SWSL
Collect Date:			2/25/09		2/25/09		2/25/09			
Method	Parameter	Units	Value	Q	Value	Q	Value	Q		
SW-846 6010B	Aluminum	ug/l	1,170		45.5	B	490		NE	NE
SW-846 6010B	Arsenic	ug/l	29.3		2.7	U	7.4		50	10
SW-846 6010B	Barium	ug/l	207		60.4		105		2,000	100
SW-846 6010B	Cadmium	ug/l	0.5	U	0.5	U	0.5	U	1.75	1
SW-846 6010B	Chromium	ug/l	18.6		10.6		31.6		50	10
SW-846 6010B	Cobalt	ug/l	1.5	J	0.6	U	1.5	J	NE	10
SW-846 6010B	Copper	ug/l	0.3	U	0.43	J	0.3	U	1,000	10
SW-846 6010B	Lead	ug/l	4	U	4	U	4	U	15	10
SW-846 6010B	Manganese	ug/l	<b>681</b>		<b>647</b>		<b>614</b>		50	50
SW-846 6010B	Molybdenum	ug/l	1.1	U	1.1	U	1.1	U	NE	NE
SW-846 6010B	Silver	ug/l	1.3	B	0.56	B	0.95	B	17.5	10
SW-846 6010B	Zinc	ug/l	14.2		9.7	J	0.4	U	1,050	10
SW-846 7470	Mercury	ug/l	0.97		0.76		0.82		1.05	0.2
ASTM D516-90	Sulfate	ug/l	<b>623,000</b>		166,000		7,700		250,000	250,000
EPA 120.1	Specific Conductance	umhos/cm	5,220		3,040		4,370		NE	NE
EPA 353.2	Nitrate	ug/l	100	U	100	U	100	U	10,000	10,000
EPA 365.1	Orthophosphate	ug/l	280	J	1,200		510		NE	NE
SM 2540C	Total Dissolved Solids	ug/l	<b>3,870,000</b>		<b>2,010,000</b>		<b>2,920,000</b>		500,000	NE
SM 4500CL	Chloride	ug/l	119,000		53,000		239,000		250,000	NE
SM 4500F	Fluoride	ug/l	130		660		180		2,000	2,000
SM 5210B	Biochemical oxygen demand	ug/l	5,500	J	5,200	J	6,300	J	NE	NE
SM 5220D	Chemical oxygen demand	ug/l	366,000		121,000		277,000		NE	NE
SM 5310B	Total Organic Carbon	ug/l	179,000		106,000		157,000		NE	NE
SW-846 9020A	Total Organic Halides	ug/L	270		130		280		NE	NE
SW-846 9040	pH	s.u.	7	J	6.8	J	6.8	J	6.5-8.5	NE

**Notes:**

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