

Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids

Charles D. Shackelford^{a,*}, Craig H. Benson^b,
Takeshi Katsumi^c, Tuncer B. Edil^b, L. Lin^c

^a*Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523, USA*

^b*Department of Civil and Environmental Engineering, University of Wisconsin-Madison, Madison, WI 53706, USA*

^c*Disaster Prevention Research Institute (DPRI), Kyoto University, Kyoto 611 011, Japan*

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Abstract

Fundamental factors and testing considerations affecting the evaluation of the hydraulic conductivity of geosynthetic clay liners (GCLs) permeated with non-standard liquids (i.e., liquids other than water) are discussed and supported with test data. Both aggregate-size distribution and montmorillonite content of the bentonite portion of the GCL have a potential effect on the hydraulic conductivity of GCLs. Other factors affecting the hydraulic conductivity of GCLs permeated with non-standard liquids include thickness of the adsorbed layer, prehydration of the GCL, void ratio of the GCL, and test duration. Results show that non-standard liquids containing both high concentrations of monovalent cations (e.g., 0.6 M NaCl) as well as low concentrations of divalent cations (e.g. 0.0125 M CaCl₂) can cause significant increases (≥ 1 order of magnitude) in hydraulic conductivity provided the test is performed sufficiently long to allow for exchange of adsorbed cations. Results also indicate that termination of hydraulic conductivity tests involving prehydrated GCLs before chemical equilibrium is established may result in measured hydraulic conductivities that do not represent equilibrium and may be unconservatively low. Finally, control of average effective stress is more important than

* Corresponding author.

E-mail addresses: shackel@engr.colostate.edu (C.D. Shackelford), chbenson@facstaff.wisc.edu (C.H. Benson), katsumi@geotech.dpri.kyoto-u.ac.jp (T. Katsumi), edil@engr.wisc.edu (T.B. Edil)

control of hydraulic gradient when evaluating the hydraulic conductivity of GCLs. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Geosynthetic clay liners (GCLs) are factory-manufactured hydraulic barriers consisting of a thin layer of bentonite ($\sim 5.0 \text{ kg/m}^2$) sandwiched between two geotextiles or bonded to a geomembrane. The structural integrity of GCLs is maintained by stitching or needle-punching, and/or by binding the geotextile or geomembrane to the bentonite by adding an adhesive to the bentonite (Estornell and Daniel, 1992). Significant usage of GCLs began around 1990, and today GCLs are used widely in hydraulic containment applications (e.g., landfills, surface impoundments, and waste piles) because they often have very low hydraulic conductivity to water ($k_w < 10^{-8} \text{ cm/s}$) and relatively low cost.

Five GCL brands currently are available (Bentofix[®], Bentomat[®], Claymax[®], Gundseal[®], and NaBento[®]), and there are several variations within each brand (Koerner, 1994; Rowe, 1998). The primary differences between GCLs are the mineralogy and form of bentonite (e.g., powder versus granular, sodium versus calcium, etc.) used in the GCL, the type of geotextile (e.g., woven versus non-woven geotextiles) or the addition of a geomembrane, and the bonding methods. The thickness and bentonite content of all GCLs are similar.

In nearly all cases, the hydraulic performance of GCLs depends on the hydraulic conductivity of the bentonite. The only exceptions are GCLs containing a geomembrane where the geomembrane is seamed during construction (e.g., with a cap strip). As a result, the primary basis for assessing the technical equivalency of GCLs and other barrier layers has been the hydraulic conductivity of the GCL to water. However, GCLs often are used to contain liquids other than water and, thus, a fair assessment of equivalency should be based, in part, on the long-term hydraulic conductivity using the actual permeant liquid (Koerner, 1994). Hydraulic conductivity to the actual permeant liquid is usually assessed via a “compatibility test” where the specimen is permeated with the liquid to be contained or a liquid simulating the anticipated liquid. Herein, such liquids are referred to as “non-standard liquids” to distinguish them from more standard liquids such as deionized water, distilled water, tap water, or a “standard water”, such as the 0.05 N CaSO₄ solution prescribed in ASTM D 5084.

This paper discusses fundamental factors affecting the hydraulic conductivity of GCLs, and testing conditions and methods required for evaluating the hydraulic performance of GCLs permeated with non-standard liquids. The discussion is supported both by original data as well as previously published data re-plotted in an original manner. Discussion regarding the use of existing standard methods for

hydraulic conductivity testing, such as ASTM D 5084 (*standard test method for the measurement of the hydraulic conductivity of saturated porous materials using a flexible wall permeameter*) and ASTM D 5887 (*measurement of index flux through saturated geosynthetic clay liner specimens using a flexible wall permeameter*), to evaluate the compatibility of GCLs also is included.

2. Fundamental factors affecting hydraulic conductivity

2.1. Characteristics of the bentonite

2.1.1. Mineralogy

As shown in Table 1, the primary mineral in bentonites is montmorillonite. Montmorillonite often is referred to as smectite, although smectite is a group of clay minerals containing not only montmorillonite but also other similarly structured clay minerals (Grim, 1968; Moore and Reynolds, 1997). The mineralogical compositions reported in Table 1 were obtained by X-ray diffraction of bentonite samples from different GCLs. The montmorillonite content of these GCLs varies from 47 to 67%.

The large specific surface of montmorillonite ($800 \text{ m}^2/\text{g}$) combined with its large net negative charge result in adsorption of a large number of hydrated cations as well as adsorption and water molecules, and interlayer separation during hydration (Grim, 1968; Mitchell, 1993). These adsorbed water molecules and cations can comprise a significant fraction of the pore space, and are essentially immobile (Mesri and Olson, 1971; Mitchell, 1993; Shang et al., 1994). As a result, the portion of the pore space occupied by bulk water (i.e., non-adsorbed water that is free to flow) is relatively small, and the pathways formed by the bulk water have irregular shapes (Mesri and Olson,

Table 1
Mineralogy of bentonite portion of three GCLs

Mineral constituent(s)	Relative abundance (%) ^a		
	GCL Type 1	GCL Type 2	GCL Type 3
Quartz	16	15	15
Tridymite			4
Plagioclase feldspar	2	2	7
Calcite	3	1	1
Siderite			trace
Gypsum	trace		trace
Clinoptilolite	2	2	2
Illite/Mica	2	2	3
Montmorillonite	67	71	47
Mixed-layer Illite/Smectite	8	7	21
% Illite layer in mixed-layer	10–30%	10–30%	20–30%
Total	100	100	100

^aBased on x-ray diffraction analyses by Mineralogy Inc., Tulsa, Oklahoma.

1971). Consequently, the hydraulic conductivity of montmorillonite to water typically is very low ($\leq 10^{-8}$ cm/s). Also, the large affinity of montmorillonite for water molecules and hydrated cations results in significant swelling of montmorillonite (5–10 times the dry volume) when hydrated under low effective stress.

The montmorillonite content in bentonite also is reflected indirectly by the cation exchange capacity (CEC) of the bentonite. The CEC is a measure of the total adsorption capacity of a soil for cations, and increases with greater surface charge deficiency and greater specific surface of the clay mineral portion of the soil. As shown in Table 2, the CEC of bentonites typically is lower than the CEC of pure montmorillonite, the latter typically ranging from 80 to 150 meq/100 g (Grim, 1968; Mitchell, 1993). The difference between the CEC of bentonite and pure montmorillonite can be attributed, in part, to other non-adsorbing minerals in the bentonite, such as quartz (Table 1). Thus, as the montmorillonite content of bentonite increases, the CEC of the bentonite should approach the CEC of pure montmorillonite.

The low hydraulic conductivity of montmorillonite to water is responsible for the low hydraulic conductivity of bentonites and GCLs when permeated with water. As a result, the amount of montmorillonite should affect the hydraulic conductivity of a soil or GCL. For example, Stern and Shackelford (1998) permeated separate specimens of three different sand-clay soil mixtures with both distilled water and 0.5 M CaCl₂ solutions. Each specimen contained 80 percent sand (dry wt.) and 20% clay soil admixture (dry wt.). However, the composition of the clay portion was composed of three different mixtures of relatively inert attapulgite clay and active sodium bentonite. Stern and Shackelford (1998) found that, as the bentonite and, therefore, montmorillonite portion of the clay admixture increased, the hydraulic conductivity of the sand-clay mixture permeated with water decreased, whereas the hydraulic conductivity of the sand-clay mixture permeated the 0.5 M CaCl₂ solution increased. The hydraulic conductivity of GCLs should be affected by the montmorillonite content of the bentonite in a similar manner.

Since the low hydraulic conductivity of bentonite is primarily due to adsorbed molecules associated with the montmorillonite restricting the pore spaced active in flow, bentonites are particularly sensitive to changes in the composition of the pore fluid that influence the thickness of the adsorbed layer. In particular, liquids that cause the adsorbed layer to collapse also cause the hydraulic conductivity to increase (Mesri and Olson, 1971). Thus, GCLs containing bentonite with a greater montmorillonite content are potentially more vulnerable to chemical attack and incompatibility.

2.1.2. *Aggregate size*

Bentonites used in GCLs are crushed after mining. The size of the bentonite aggregates (i.e., agglomerations of bentonite comprised of numerous particles) in a GCL depends on the crushing process that is used. Aggregate-size distributions for three different GCLs are shown in Fig. 1 along with distributions for powdered bentonite (Super Gel-X) and bentonite “chips” (pure gold) commonly used for sealing the annulus in monitoring wells and for backfilling exploration holes. The aggregate-size distributions were obtained by dry sieving of the bentonites. Depending on the

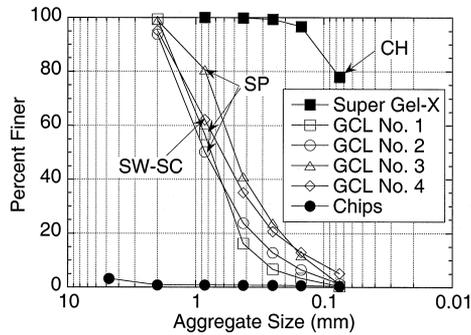


Fig. 1. Aggregate-size distributions for bentonites in different GCLs (classifications based on Unified Soil Classification System, ASTM D 2487).

amount of crushing, bentonite aggregates can have particle size distributions ranging from gravel to silt and clay.

Aggregate-size distribution has little effect on the steady-state hydraulic conductivity to water. However, aggregate-size distribution should affect the rate of swell, and can affect the hydraulic conductivity to non-standard liquids. Larger aggregates of bentonite should take longer to hydrate because the permeant liquid must migrate through the aggregates to reach particles in the interior of the aggregate. Moreover, if the permeant liquid forms a thin adsorbed layer (or no adsorbed layer at all), little or no swelling occurs, and the aggregates do not break down to form a monolithic layer of bentonite as occurs during hydration with water (Lin, 1998). If the aggregates are not broken down, the hydraulic conductivity of the GCL will be comparable to the hydraulic conductivity of a coarse-grained material with a particle-size distribution similar to the aggregate-size distribution of the bentonite.

The Unified Soil Classification System (ASTMD 2487) classifications of the dry bentonite in GCLs (i.e., classification based solely on the dry aggregate-size distribution) are indicative of the potential for high hydraulic conductivity when the bentonite in GCLs is not hydrated. Each of the bentonites from the four GCLs have aggregate-size distributions similar to sands (either SP or SW-SC) and, thus, should be very permeable if the bentonite does not hydrate and swell to form a monolithic layer of bentonite. As will be shown subsequently, the hydraulic conductivity of GCLs containing granular bentonite (i.e., as in Fig. 1) are in the silty sand range (10^{-5} to 10^{-4} cm/s) when permeated with aggressive liquids that prevent or limit development of the adsorbed layer.

2.1.3. Exchangeable metals

Although the bentonites normally used in GCLs are commonly referred to as sodium bentonites, the exchange complex (i.e., the cations in the adsorbed layer) of natural bentonites is comprised of several cations, as shown in Table 2. The relative abundance of the cations varies with the source of the bentonite, and affects the thickness of the adsorbed layer (see subsequent discussion). For example, the natural

Table 2
Chemical properties of two bentonites (data from Howell et al., 1997)

Property	Granular bentonite	Powdered bentonite
Cation exchange capacity, CEC (meq/100g)	63.9	72.3
Exchangeable metals (meq/100 g):		
Ca	18.6	26.6
Mg	7.4	4.2
Na	29.8	36.3
K	1.3	0.9
Al	< 0.1	0.2
Si	1.0	1.3
Sum	58.1	69.5
Soluble salts (mg/kg):		
Ca	140	80.2
Mg	48.8	18.3
Na	2,820	4,200
K	19.6	19.6
Soil pH	9.1	8.9
Soil electrical conductivity (mS/cm @ 25°C)	2.5	3.3

exchange complex of bentonites from Wyoming, USA, typically is dominated by sodium, as indicated in Table 2. Consequently, even if all other factors are equal, GCLs containing bentonite from different locations (or different mines at similar location) are expected to have different hydraulic conductivities and sensitivity to the composition of permeant liquids.

2.1.4. Chemically-resistant bentonite

Bentonites treated with stabilizing agents have been developed for applications where chemical interactions are likely to affect the adsorbed layer and, consequently, the hydraulic conductivity. The stabilizing agents used in these “chemically resistant” bentonites are usually proprietary, and data from independent, long-term testing conducted to assess the likelihood of satisfactory field performance under sustained severe conditions are scarce. However, some of the research results on chemically resistant bentonites appear promising.

For example, Onikata et al. (1996) developed a chemically resistant bentonite, called multi-swellable bentonite (MSB), that is made from a natural bentonite mixed with a swelling-activation agent. Results of free swell tests conducted on MSB and a natural sodium bentonite are shown in Fig. 2. The swell tests were conducted with a variety of solutions containing primarily inorganic compounds covering a broad range of electrical conductivity (EC). For all of the solutions, the MSB exhibits comparable or greater swell than the natural bentonite, even with aggressive liquids,

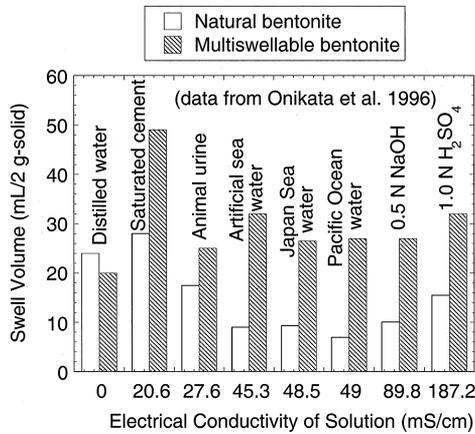


Fig. 2. Swell test results for multiswellable bentonite using various liquids.

such as saturated cement water, sea water, and sulfuric acid. Despite these positive findings, additional study is needed to verify that stabilized bentonites, such as MSB, will retain swelling capability and low hydraulic conductivity after long-term permeation.

2.2. Factors affecting thickness of the adsorbed layer

The adsorbed layer, referred to as the diffuse double layer (DDL) in colloid chemistry, is commonly described using the Stern-Guoy model (van Olphen, 1977; Mitchell, 1993; Shackelford, 1994; Shang et al., 1994). According to the Stern-Guoy model, a thin film called the “Stern layer” consisting of oriented water dipoles and fixed hydrated cations is directly adjacent to the clay surface, while a diffuse layer of hydrated cations attracted to the clay surface resides immediately adjacent to the Stern layer (Shang et al., 1994). The concentration of cations in the diffuse layer is a function of the electrical potential of the negatively charged clay surface, which decreases with distance from the clay surface. The Debye length, λ , corresponds approximately to the centroid of the diffuse layer, and is given by the following expression (e.g., Mitchell, 1993):

$$\lambda = \sqrt{\frac{\varepsilon\varepsilon_0 RT}{2v^2 F^2 \eta}}, \quad (1)$$

where ε is the dielectric constant of the pore water (also referred to as the relative permittivity), ε_0 is the permittivity in a vacuum, R is the Universal gas constant, F is Faraday’s constant, T is absolute temperature, v is the valence of the cation, and η is the electrolyte concentration. By convention, λ usually is used as the “thickness” of the diffuse double layer, although in reality a distinct boundary does not exist between the diffuse layer and the bulk pore fluid.

As indicated by Eq. (1), the electrolyte concentration, cation valence, and dielectric constant affect λ which, in turn, affects the hydraulic conductivity and swelling of bentonite. A decrease in λ will cause a corresponding increase in hydraulic conductivity by increasing the size of the flow paths (Mesri and Olson, 1971; Shang et al., 1994; Gleason et al., 1997; Stern and Shackelford, 1998). Dramatic reductions in λ caused by liquids with low ϵ have resulted in particle attraction, shrinkage, and cracking of clay with corresponding large increases in hydraulic conductivity (Bowders and Daniel, 1987; Mitchell and Madsen, 1987; Broderick and Daniel, 1990; Shackelford, 1994).

The key role the adsorbed layer plays in controlling the hydraulic conductivity of clay minerals and, in particular, bentonite is demonstrated convincingly by Mesri and Olson (1971). They permeated sedimented specimens of kaolinite, illite, and montmorillonite with nonpolar liquids (benzene and carbon tetrachloride, $\epsilon < 3$), salt solutions (NaCl and CaCl₂), and deionized water. Non-polar liquids were used to fully collapse the adsorbed layer, whereas salt solutions and deionized water were used to obtain adsorbed layers of varying thickness. At a given void ratio, the kaolinite, illite, and montmorillonite had identical hydraulic conductivity when permeated with non-polar liquids. In contrast, the three minerals had very different hydraulic conductivities when permeated with the salt solutions and deionized water. For all void ratios, the hydraulic conductivity was highest for kaolinite and lowest for montmorillonite when permeated with aqueous solutions, and the difference between the hydraulic conductivities of the minerals increased as the salt concentration decreased.

2.2.1. Effect of valence

As indicated by Eq. (1), replacement of sodium in the exchange complex with other ions should affect the thickness of the adsorbed layer and, thus, swelling and hydraulic conductivity of the bentonite in GCLs. As shown in Fig. 3, this effect is evident by the results of free swell tests conducted on bentonite from a needle-punched GCL that was hydrated with three different 0.025 M chloride solutions (LiCl, MgCl₂ and AlCl₃) and deionized water. The free swell tests were conducted following ASTM D 5890 (*standard test method for swell index of clay mineral component of geosynthetic clay*

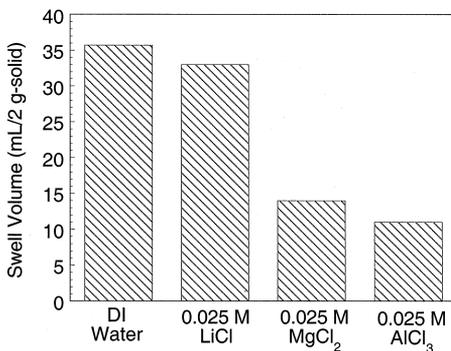


Fig. 3. Free swell for bentonite from a needle-punched GCL hydrated with deionized (DI) water or 0.025 M chloride solutions (LiCl, MgCl₂ and AlCl₃) conducted following ASTM D 5890.

liners), where 2 g of pulverized and air-dried bentonite is added to 100 mL of water in a graduated cylinder.

The smallest swell volume was obtained with the AlCl_3 solution, which is consistent with Stern-Gouy theory, and suggests that the thinnest double layer is obtained with the trivalent Al^{3+} . In contrast, the LiCl solution resulted in swell that was $> 90\%$ of the swell with deionized water because Li^+ is monovalent (as is Na^+) and, thus, has little effect on the thickness of the adsorbed layer relative to deionized water. As anticipated, the MgCl_2 solution resulted in swell that falls between the swell obtained with the LiCl and AlCl_3 solutions, because Mg^{2+} is divalent. Specimens of the GCL also were permeated with deionized water and 0.025 M solutions of LiCl or MgCl_2 . Hydraulic conductivities of 4.1×10^{-9} cm/s (LiCl) and 4.1×10^{-6} cm/s (MgCl_2) were obtained. As with the results of the free swell tests, these hydraulic conductivities are consistent with changes in the thickness of the adsorbed layer in accordance with Eq. (1).

The influence of valence also is evident from the data shown in Fig. 4 depicting hydraulic conductivities measured during a long-term compatibility test on a needle-punched GCL with a dilute (0.0125 M) CaCl_2 solution. The specimen has been permeated for more than 540 days in a flexible-wall permeameter using a backpressure of 324 kPa, an average effective stress of 18 kPa, and a hydraulic gradient of 80. No change in hydraulic conductivity occurred during the first 5 pore volumes of flow. However, after 5 pore volumes of flow, the hydraulic conductivity began to increase gradually. This test is still ongoing. Currently, the hydraulic conductivity has increased to 3×10^{-8} cm/s after 51 pore volumes of flow, and still appears to be increasing slightly. The Ca^{2+} from the dilute solution apparently is exchanging gradually for Na^+ on the exchange complex, resulting in a gradual compression of the adsorbed layer with a consequent gradual increase in hydraulic conductivity.

Field data from GCLs used in covers exhibit a similar phenomenon. For example, James et al. (1997) investigated the cause of leakage through GCLs that were used in a cover system for brick arches that served to protect water reservoirs. The exchange

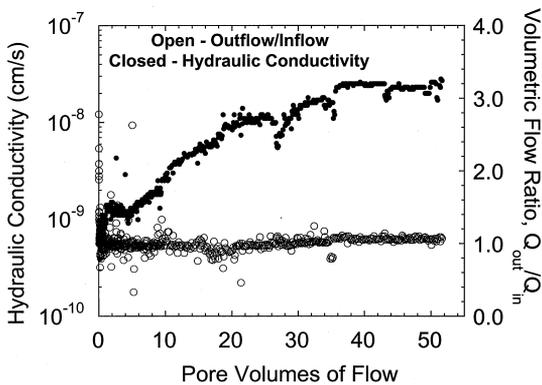


Fig. 4. Hydraulic conductivity versus time for a needle-punched GCL permeated with 0.012 M CaCl_2 solution.

complex of the bentonite in the GCL initially was dominated by sodium ($\text{Na}^+ = 65.0 \text{ meq}/100 \text{ g}$; $\text{Ca}^{2+} = 10.9 \text{ meq}/100 \text{ g}$; and $\text{Mg}^{2+} = 12.3 \text{ meq}/100 \text{ g}$) with a cation exchange capacity (CEC) of $90.2 \text{ meq}/100 \text{ g}$. After leakage was observed in the field, tests on exhumed specimens of the GCL indicated that the Ca^{2+} concentrations on the exchange complex increased to values ranging from $42.5 \text{ meq}/100 \text{ g}$ to $85.8 \text{ meq}/100 \text{ g}$, whereas the average Na^+ concentrations on the exchange complex had decreased to values ranging from $2.6 \text{ meq}/100 \text{ g}$ to $15.3 \text{ meq}/100 \text{ g}$ in five of the six samples. Based on this data and other tests, James et al. (1997) concluded that calcium from the foundation soil had migrated into the GCL and displaced the sodium from the exchange complex resulting in subsequent shrinkage and cracking of the bentonite.

Nearly identical scenarios are reported by Melchior (1997) for a GCL used as an earthen barrier in a test section in a landfill cover in Hamburg, Germany, and by Lin (1998) for GCLs subjected to wetting and drying using dilute CaCl_2 solutions. Similar results also have been reported for GCLs used at petroleum tank farms where calcium from adjacent soils exchanged for sodium (Aboveground Tank Update, 1992; Dobras and Elzea, 1993).

2.2.2. Influence of concentration

The influence of concentration is illustrated by the data shown in Fig. 5 depicting the hydraulic conductivities and swell volumes for a needle-punched GCL hydrated and permeated with deionized water or ZnCl_2 solutions ranging in concentration from 0.01 to 0.1 M. Hydraulic conductivities were measured in flexible-wall permeameters with an average effective stress of 20 kPa, hydraulic gradient of 100, and no backpressure. Swell volumes were measured on bentonite from the GCL following ASTM D 5890. As indicated by the data in Fig. 5, concentration affects the hydraulic conductivity and swell volume in a manner consistent with Eq. (1); i.e., as the concentration of the electrolyte increases, thickness of the adsorbed layer decreases. Thus, the swell volume decreases and the hydraulic conductivity increases.

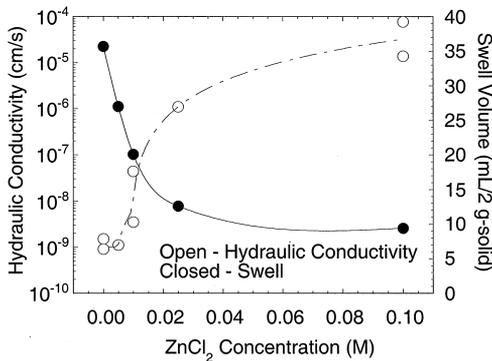


Fig. 5. Hydraulic conductivity and free swell of a needle-punched GCL permeated or hydrated with deionized (DI) water or ZnCl_2 solutions of various concentrations.

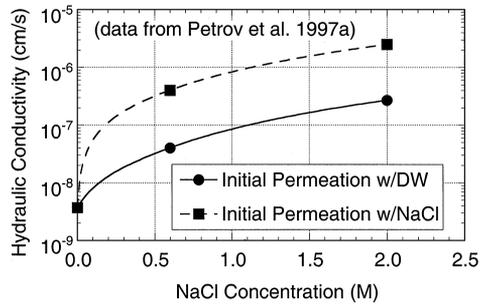


Fig. 6. Hydraulic conductivity of a needle-punched GCL versus NaCl concentration for specimens initially permeated with distilled water (DW) and specimens permeated directly with NaCl solutions.

The effect of an increase in salt concentration on the hydraulic conductivity of a needle-punched GCL also is illustrated in Fig. 6 using data reported by Petrov et al. (1997a). The tests were performed using similar hydraulic gradients ($144 < i < 162$) and a total confining stress of 3–4 kPa. Specimens either were permeated first with distilled water (DW) and then with NaCl solution, or were permeated directly with the NaCl solutions. An increase in the NaCl concentration results in an increase in the hydraulic conductivity of the GCL, regardless of whether the GCL is first permeated with DW or is permeated directly with NaCl solution. As with the data for ZnCl_2 in Fig. 5, the trend in Fig. 6 is consistent with the Eq. (1); i.e., increasing concentration shrinks the adsorbed layer and increases the hydraulic conductivity significantly, even when the permeant liquid contains only monovalent cations (Na^+).

2.2.3. Influence of dielectric constant

In some cases, permeating clays with solutions containing aqueous miscible organic solvents has resulted in large increases in hydraulic conductivity (Bowders and Daniel, 1987; Mitchell and Madsen, 1987; Fernandez and Quigley, 1988; Shackelford, 1994). This increase in hydraulic conductivity has been attributed primarily to shrinkage and cracking of the clay due to compression of the adsorbed layer by the low ϵ of pure phase organic compounds (typically $\epsilon < 40$) relative to water ($\epsilon \sim 80$). However, significant increases in hydraulic conductivity have been observed only when the concentration of the organic compound is $> 50\%$, since dilution with water results in an increase in the dielectric constant of the solution (e.g., Mitchell and Madsen, 1987; Bowders and Daniel, 1987; Fernandez and Quigley, 1988; Shackelford, 1994). Similarly, clays permeated with non-polar organic liquids also have been very permeable, primarily as a result of cracking caused by collapse of the adsorbed layer (Fernandez and Quigley, 1985; Broderick and Daniel, 1990; Shackelford, 1994).

For example, consider the data shown in Fig. 7 showing the effect of ethanol concentration on the hydraulic conductivity of a needle-punched GCL as reported by Petrov et al. (1997b). For ethanol concentration $\leq 50\%$, the hydraulic conductivity of the GCL actually decreases, whereas the hydraulic conductivity progressively increases as the ethanol concentration increases above 50%. Following an approach

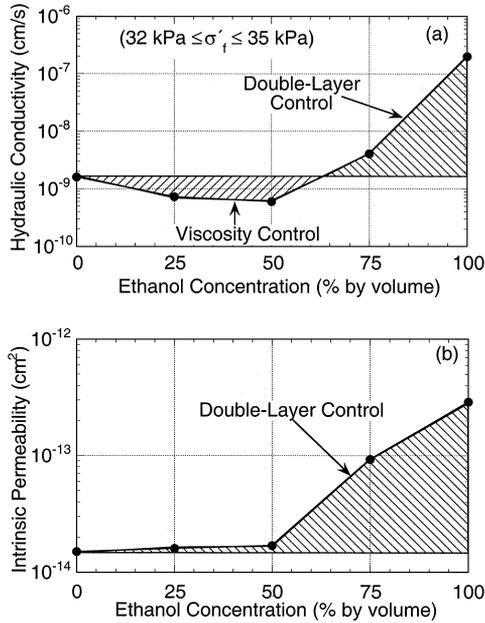


Fig. 7. (a) Hydraulic conductivity, and (b) intrinsic permeability, of a needle-punched GCL permeated with water-ethanol mixtures (data from Petrov et al., 1997b).

similar to Fernandez and Quigley (1988), Petrov et al. (1997b) explained this behavior in terms of contrasting effects of viscosity and thickness of the adsorbed layer, as follows.

The hydraulic conductivity to permeant liquid “l” (k_l) can be represented by (e.g., Mitchell, 1993):

$$k_l = K_1 \frac{\gamma_l}{\mu_l}, \tag{2}$$

where γ_l is the unit weight of the permeant liquid, μ_l is the absolute viscosity of the permeant liquid, and K_1 is the intrinsic permeability of the porous medium to the permeant liquid. Accordingly, the hydraulic conductivity to a particular chemical (c) relative to the hydraulic conductivity to water (w) is given by the following relationship:

$$\frac{k_c}{k_w} = \frac{K_c}{K_w} \frac{\mu_w}{\mu_c} \frac{\gamma_c}{\gamma_w}. \tag{3}$$

If $\gamma_c \cong \gamma_w$, then the hydraulic conductivity to the chemical relative to the hydraulic conductivity to water is proportional to the ratio of the intrinsic permeabilities (chemical relative to water) and the ratio of the viscosities (water relative to the chemical).

As shown in Fig. 7, permeation with solutions containing $\leq 50\%$ ethanol resulted in essentially no change in K_c , suggesting that ethanol concentrations $< 50\%$ have no effect on the pore structure of the bentonite. The decrease in hydraulic conductivity for ethanol concentrations $< 50\%$ was due to the increase in viscosity caused by addition of ethanol (Eq. (3)). However, for ethanol concentrations $> 50\%$, the decrease in ε apparently resulted in a thinner adsorbed layer, an increase in the size of the hydraulically active pores, and $K_c/K_w > 1$. As a result, the hydraulic conductivity was substantially higher when the ethanol concentration was $> 50\%$.

Petrov et al. (1997b) indicate that their results contradict the results of Shan and Daniel (1991) who reported a slight decrease in the hydraulic conductivity after permeating a GCL with 0.6 pore volumes of pure methanol. Petrov et al. (1997b) speculate that the test performed by Shan and Daniel (1991) was probably terminated before chemical equilibrium had been achieved, and that the decrease in hydraulic conductivity was due to the higher viscosity of methanol relative to water.

2.2.4. Influence of prehydration

Several investigators have reported that the order that permeant liquids are introduced to bentonitic barrier materials can have a significant effect on their final hydraulic conductivity (e.g., Daniel et al., 1993; Shackelford, 1994; Didier and Comeaga, 1997; Gleason et al., 1997; Petrov and Rowe, 1997; Petrov et al., 1997a; Quaranta et al., 1997; Ruhl and Daniel, 1997; Stern and Shackelford, 1998; Lin, 1998). In particular, hydrating the bentonite prior to permeation with a chemical solution generally results in a lower hydraulic conductivity than is obtained by direct permeation with the chemical solution. This effect is apparent in the data reported by Petrov et al. (1997a) as previously shown in Fig. 6. Also, Stern and Shackelford (1998) show that direct permeation of sand-bentonite mixtures with strong (0.5 M) CaCl_2 solutions results in hydraulic conductivities approximately one order of magnitude greater than those obtained by initial permeation with deionized water followed by permeation with the salt solution.

Results of hydraulic conductivity tests on prehydrated and non-prehydrated specimens of a needle-punched GCL are shown in Fig. 8 in terms of hydraulic conductivity and intrinsic permeability (Eq. (2)). The tests were conducted in flexible-wall permeameters using a backpressure of 324 kPa, effective stress of 18 kPa, and a hydraulic gradient of 80. One specimen was permeated directly with saturated CaCl_2 solution (6.7 M, $\mu = 1.75 \times 10^{-5}$ N-s/m², $\gamma = 15.1$ kN/m³). After 7 pore volumes of flow, the permeant liquid was switched to deionized water ($\mu = 1.01 \times 10^{-3}$ N-s/m², $\gamma = 9.85$ kN/m³) and permeation was continued for 16 additional pore volumes. The other specimen was permeated initially with deionized water for 1.2 pore volumes of flow, then the permeant liquid was switched to the saturated CaCl_2 solution and permeation continued for an additional 23 pore volumes of flow.

The saturated CaCl_2 solution affected the hydraulic conductivity and the intrinsic permeability of both specimens, although the effect was more dramatic on the specimen initially permeated with CaCl_2 solution. Data collected using the initial permeant liquids showed that the intrinsic permeability to deionized (DI) water was approximately four orders of magnitude lower than the intrinsic permeability to

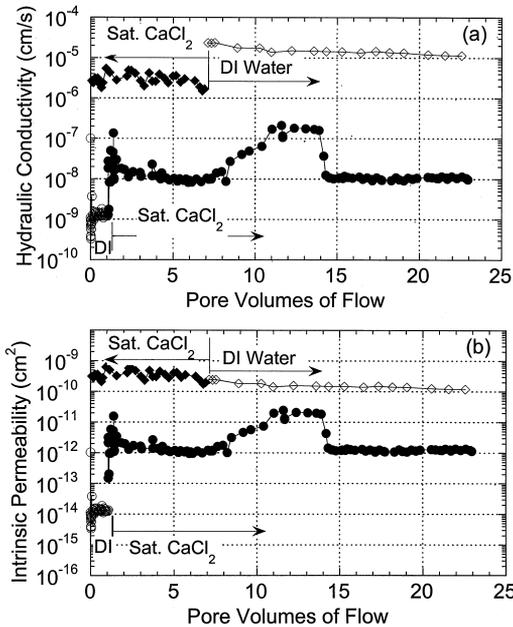


Fig. 8. (a) Hydraulic conductivity, and (b) intrinsic permeability, of needle-punched GCL specimens prehydrated with deionized (DI) water and then permeated with saturated CaCl₂ solution and initially permeated with saturated CaCl₂ solution followed by permeation with DI water.

saturated CaCl₂ solution when the GCL permeated with CaCl₂ solution was not prehydrated. After the permeant liquids were switched, the intrinsic permeability to DI water of the GCL initially permeated with CaCl₂ solution was 1.5 orders of magnitude higher than the intrinsic permeability to saturated CaCl₂ solution when the GCL was initially permeated with DI water (Fig. 8b).

The data in Fig. 8 suggest that permeation with CaCl₂ solution affected the thickness of the adsorbed layer and the volume of pore space effective in flow, but that the adsorbed layer and pore space underwent smaller changes when the GCL was prehydrated with DI water. The data also show that collapse of the double layer caused by initial permeation with saturated CaCl₂ solution is not reversed by subsequent permeation with DI water. The intrinsic permeability to DI water was only slightly lower than the intrinsic permeability to the saturated CaCl₂ solution when the GCL was initially hydrated in the saturated CaCl₂ solution.

The effect of prehydration is illustrated further by the data shown in Fig. 9, for a needle-punched GCL permeated with a simulated mine tailings solution. The GCL was being considered for use in a bottom lining system at a mine waste disposal site. The prehydrated specimen was back-pressure saturated with water (pH = 6.7, electrical conductivity, EC = 0.32 mS/cm @ 25°C) for 23 days prior to permeation with a permeant liquid that was made to simulate an actual disposal solution (pH = 8.6, EC = 4.0 mS/cm @ 25°C, Ca = 330 mg/L), whereas the non-prehydrated specimen

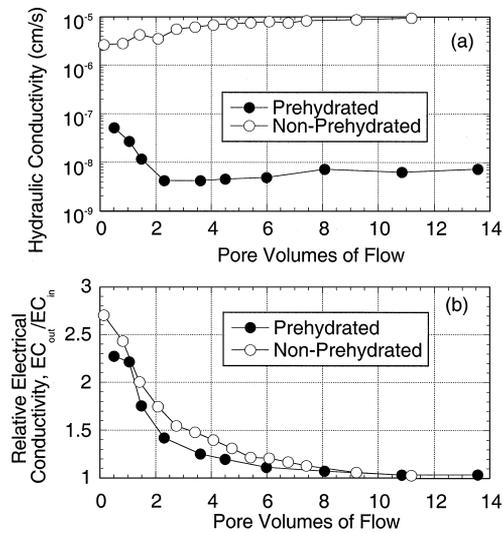


Fig. 9. Effect of prehydration on the hydraulic conductivity of a needle-punched GCL permeated with a simulated mine tailings solution: (a) hydraulic conductivity; (b) relative electrical conductivity.

was permeated directly with the simulated solution without backpressure saturation. Both tests were conducted at an average effective stress of 27.6 kPa and in general accordance with the procedures outlined in ASTM D 5084 except the hydraulic gradients for the tests ranged from ~ 330 to ~ 380 .

The data shown in Fig. 9a indicate that the hydraulic conductivity of the prehydrated specimen stabilized at 7×10^{-9} cm/s, whereas the final hydraulic conductivity of the non-prehydrated specimen was significantly higher (1280 times) at 9×10^{-6} cm/s. Neither test was terminated before the relative electrical conductivity between the effluent and influent solutions had equilibrated (Fig. 9b) indicating that complete chemical breakthrough had been achieved.

Daniel et al. (1993) performed tests where the bentonite portion of a GCL was prehydrated to initial gravimetric water contents (w) of 50%, 100%, and 125% before being permeated in flexible-wall permeameters. After prehydration, the specimens were permeated with benzene, gasoline, methanol, methyl tert-butyl ether (MTBE), or trichloroethylene (TCE) for approximately two months using hydraulic gradients ranging from 80 to 120. Air-dried ($w = 17\%$) and saturated ($w = 145\%$) bentonite specimens also were tested. The hydraulic conductivities are shown in Fig. 10. Hydraulic conductivities for the specimens prehydrated to initial water contents of 125% and 145% are not shown in Fig. 10 because no flow was observed.

The results in Fig. 10 indicate that the hydraulic conductivity of the non-prehydrated (i.e., air-dried) specimens and the specimens hydrated to $w < 50\%$ range from 3 to 5 orders-of-magnitude higher than the hydraulic conductivities of identical specimens prehydrated to an initial water content $\geq 100\%$. Moreover, the specimens prehydrated to $w < 50\%$ are all $> 10^{-5}$ cm/s. These results suggest that the

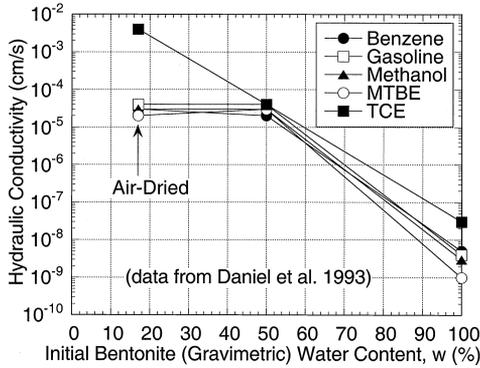


Fig. 10. Effect of initial bentonite water content on the hydraulic conductivity of a GCL permeated with different non-standard liquids.

hydraulic conductivity of GCLs is a function of the extent of prehydration, which is likely to be influenced by the stress condition and amount of water available (Daniel et al., 1993).

Although much of the existing data suggest that prehydration with water protects GCLs against large increases in hydraulic conductivity, nearly all of the tests have had limited durations. Consequently, the long-term effectiveness of prehydration is unknown long-term testing of prehydrated GCLs certainly is needed.

2.3. Void ratio effect

Mesri and Olson (1971) showed that a direct linear relationship exists between the logarithm of hydraulic conductivity ($\log k$) and the logarithm of void ratio ($\log e$) for homoionized bentonites permeated with various aqueous solutions. As shown in Fig. 11, the data from the GCLs tested by Petrov and Rowe (1997) exhibit a similar relationship, although Petrov and Rowe (1997) indicated that an equally good linear relationship exists between $\log k$ and e . The $\log k$ versus $\log e$ lines shift towards higher hydraulic conductivity as the NaCl concentration increases and, for all but the strongest NaCl solutions, the lines have similar slope.

The data in Fig. 11 show that both void ratio and cation concentration influence the hydraulic conductivity. Void ratio, which is controlled by the state of stress, describes the total amount of void space in the specimen. The fraction of the total void space that conducts flow is controlled by the thickness of the adsorbed layer, which is influenced by the cation concentration (Eq. (1)). The data in Fig. 11 suggest that changes in void ratio have similar effect on hydraulic conductivity regardless of the cation concentration or the thickness of the adsorbed layer. That is, the effect of varying the total void space appears to be independent of the effect of changing the thickness of the adsorbed layer.

The effect of the adsorbed layer can be ascertained by plotting hydraulic conductivity versus NaCl concentration at constant void ratio, as shown in Fig. 12. For GCL

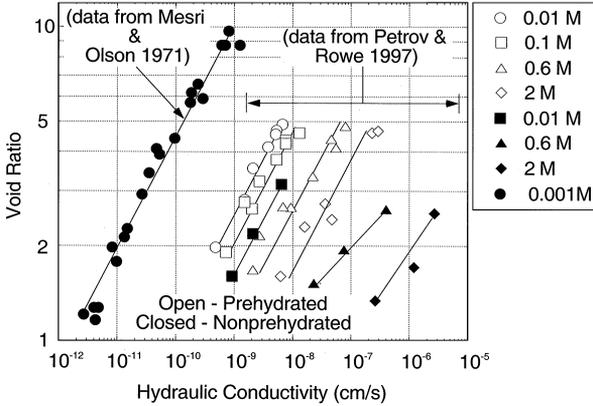


Fig. 11. Hydraulic conductivity of bentonites permeated with various NaCl solutions as a function of the logarithm of void ratio.

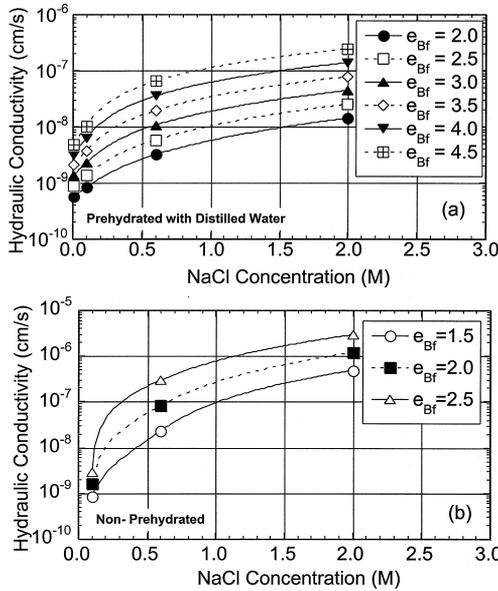


Fig. 12. Hydraulic conductivity as a function NaCl concentration for various final bulk void ratios (e_{Bf}) (data from Fig. 11): (a) prehydrated with distilled water and (b) permeated directly with NaCl solution.

specimens prehydrated with distilled water (Fig. 12a), the hydraulic conductivity of the GCL increases by approximately 1.5 to 2 orders of magnitude as the NaCl concentration increases from 0.01 M to 2.0 M, with the increase in hydraulic conductivity being slightly greater for GCLs with higher void ratios. This increase in hydraulic conductivity due to concentration is approximately the same order as the overall

effect of void ratio. In contrast, for the GCL specimens prehydrated with NaCl solution (Fig. 12b), the hydraulic conductivity of the GCL increases approximately 2.5 to 3 orders of magnitude as the NaCl concentration increases from 0.1 M to 2.0 M. Thus, the effect of thickness of the adsorbed layer is more influential than void ratio when the GCL is permeated directly with NaCl solution relative to initial permeation with distilled water.

3. Testing considerations

3.1. Swell tests

Free swell tests (i.e., at no overburden stress) can be used to assess the potential for incompatibility between a GCL and a permeant liquid. In general, the greatest swell occurs when the hydrating liquid is deionized or distilled water because the adsorbed layer is at maximum thickness. A decrease in the free swell relative to that obtained with deionized water is indicative of shrinkage of the adsorbed layer and a potential incompatibility between the bentonite and the non-standard liquid. This effect is evident in the data previously reported in Fig. 5 for bentonite hydrated with different $ZnCl_2$ solutions.

Two standard methods have been used for free swell testing of the bentonite from GCLs: GRI GCL-1 (*free swell of the clay component of geosynthetic clay liners*) and ASTM D 5890. Although GRI GCL-1 is no longer accepted by the industry as a standard, reference is still made to test results previously performed in accordance with GCL GRI-1. A swell test conducted in accordance with GRI GCL-1 consists of placing 100 g of bentonite into a California Bearing Ratio (CBR) mold, applying a 0.7-kPa vertical stress on the bentonite using a porous steel loading plate, submerging the CBR mold in a container filled with deionized water or a non-standard liquid, and recording the swell as a function of time. The swell at 24 hrs is reported as the free swell. The procedure used in ASTM D 5890 was described previously. As with GRI GCL-1, the free swell reported in ASTM D 5890 is the swell at 24 hours.

Narejo and Memon (1995) provide an example of the use of free swell tests to assess compatibility. They used GRI GCL-1 to evaluate three types of GCLs with three municipal solid waste leachates characterized as mild, medium, and harsh. Their results, shown in Fig. 13, suggest that GCL Type 3 is less sensitive to type of leachate than GCL Type 1 or 2. However, since the free swell results are not correlated with hydraulic conductivity, no definitive conclusion regarding compatibility can be made.

The measured swell may be affected by several factors including inconsistency in the hydration procedure, failure to spread the clay evenly, and friction between the loading plate (GCL-1) or the bentonite and the graduated cylinder (D 5890). Also, swell may not be complete after 24 hours. For example, Lin (1998) measured swell of bentonite from a needle-punched GCL in deionized water, tap water, and 0.012 M $CaCl_2$ using GCL-1. The swell at 24 hours was 11.0, 11.5, and 11.0 mm for the

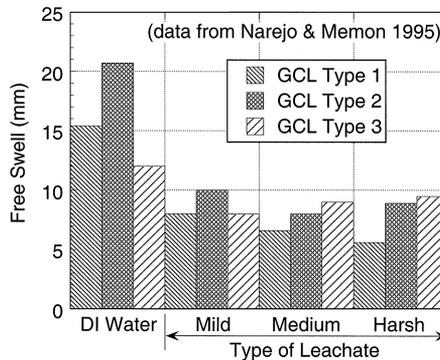


Fig. 13. Free swell at 24 hrs for three GCLs hydrated with deionized (DI) water and three leachates based on GRI GCL-1.

deionized water, tap water, and the CaCl_2 solution. However, swelling continued for more than 400 hrs, at which time the swell was 33.1, 25.9, and 19.5 mm for deionized water, tap water, and the CaCl_2 solution. Thus, the long-term swell data suggest that the GCL may be incompatible with the CaCl_2 solution, whereas the 24-hr data suggest that the GCL will behave similarly in all three solutions. The long-term hydraulic conductivity tests described previously (Fig. 4) were conducted using specimens of this same GCL. The measured long-term hydraulic conductivity of the GCL to deionized water was 1×10^{-9} cm/s (Lin, 1998), whereas the hydraulic conductivity to the CaCl_2 solution was 3×10^{-8} cm/s after 51 pore volumes of flow (Fig. 4).

The lesson to be learned from the results of the aforementioned studies is clear, viz., free swell tests can be used as an indicator of incompatibility, but free swell tests should not be used as a substitute for long-term hydraulic conductivity testing using the actual or anticipated liquid.

3.2. Hydraulic conductivity tests for evaluating GCL compatibility

3.2.1. Permeameter type

Petrov et al. (1997a) evaluated the use of fixed-ring, double-ring, and flexible-wall permeameters for measuring the hydraulic conductivity of a needle-punched GCL permeated with distilled water, tap water, or either 0.6 M NaCl or 2.0 M NaCl solutions. Their results indicate that similar hydraulic conductivities can be measured for a given permeant liquid and stress condition regardless of the type of permeameter, provided consistent specimen preparation and installation procedures are used.

Despite the findings of Petrov et al. (1997a), concern inevitably exists regarding the potential for sidewall leakage when rigid-wall permeameters are used, particularly when the non-standard liquid causes shrinkage of the specimen. In some cases, sidewall leakage has been detected by the use of double-ring rigid-wall permeameters (e.g., Daniel, 1994; Shackelford, 1994). However, since contact between the membrane and the test specimen generally is ensured when flexible-wall

permeameters are used, flexible-wall permeameters are recommended for compatibility testing of GCLs.

3.2.2. Termination criteria

Typical termination criteria used during compatibility testing are (1) equality of the inflow and outflow rates ($\pm 25\%$), (2) measurement of a steady hydraulic conductivity (four or more consecutive measurements within 25% to 50% of the mean), (3) permeation of a minimum of two pore volumes of flow through the specimen, and (4) similarity between the chemical composition of the effluent and the influent (Daniel, 1994). In addition, Petrov et al. (1997a) recommend that the height of the GCL be constant before terminating compatibility tests.

Ensuring similarity in the chemical composition of the effluent and influent is important because chemical equilibrium may not be established with only two pore volumes of flow (Shackelford, 1994). For example, Bowders (1988) reports that the hydraulic conductivity of a compacted kaolin permeated with acetic acid suddenly increased by a factor of 17 after more than six pore volumes of flow, even though the hydraulic conductivity appeared to be stabilized after six pore volumes of flow. Imamura et al. (1996) report that the hydraulic conductivity of a compacted sand-bentonite specimen permeated with $\text{Ca}(\text{OH})_2$ solution increased more than two orders of magnitude after more than 25 pore volumes of flow corresponding to three years of permeation. The long-term test data shown in Fig. 4 support these observations in that the hydraulic conductivity began to increase only after 5 pore volumes of flow.

The difficulty, expense, and time associated with measuring the chemical composition of the influent and effluent can be prohibitive. Thus, more practical indicators of chemical composition are used in some cases. Shackelford et al. (1998) suggest that electrical conductivity (EC) measurements, which are simple, inexpensive, and rapid, can be used as an index of the chemical composition of electrolyte solutions. For example, EC data were used as a criterion for terminating the test data previously reported in Fig. 9. Similarly, pH measurements are simple and useful indices of chemical composition.

Both EC and pH data from the GCL previously described in Fig. 4 are shown in Fig. 14. For the first 5 pore volumes, the effluent pH and EC are significantly higher than the influent pH and EC, suggesting that chemical equilibrium has not yet been established. If these parameters were not measured and equilibrium had been based only on the hydraulic conductivity data and the outflow/inflow ratio, the test probably would have been terminated before five pore volumes of flow and the hydraulic conductivity erroneously would have been reported as 1.2×10^{-9} cm/s (Fig. 4).

As shown in Fig. 14, the EC of the effluent and influent were not equal until 32 pore volumes passed through the specimen, at which time the hydraulic conductivity had increased to 1.4×10^{-8} cm/s and the majority of the change in hydraulic conductivity occurred (Fig. 4). However, as shown in Figs. 4 and 14, the hydraulic conductivity continues to increase, albeit very gradually, even after the effluent EC equaled the influent EC. Thus, equality between the effluent and influent

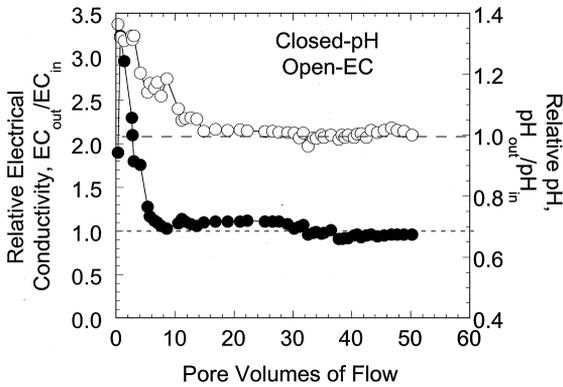


Fig. 14. Electrical conductivity (EC) and pH data for GCL specimen permeated with 0.012 M CaCl₂ (see Fig. 4) (EC_{out} = EC of outflow, EC_{in} = EC of inflow; pH_{out} = pH of outflow, pH_{in} = pH of inflow).

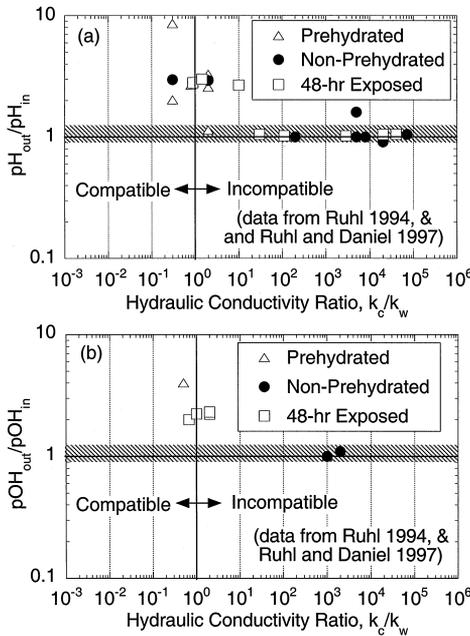


Fig. 15. Ratio of hydraulic conductivity to non-standard liquid to hydraulic conductivity to water (k_c/k_w) versus (a) ratio of outflow to inflow pH or (b) ratio of outflow to inflow pOH for different GCLs and different prehydration conditions.

EC and pH is a necessary, but not a sufficient, condition for termination of compatibility tests.

For many of the GCL compatibility test results reported in the literature, chemical equilibrium was not established before termination. As a result, some of the data may

not be representative of long-term conditions. For example, consider the data from Ruhl (1994) and Ruhl and Daniel (1997) from tests performed using several different GCLs and 5 different permeant liquids: (1) 0.1 M HCl (pH = 1), (2) a simulated hazardous waste (pH = 3), (3) a simulated municipal hazardous waste (pH = 4.4), (4) a simulated fly ash leachate (pH = 11.5), and (5) 0.1 M NaOH (pH = 13). Results for permeant liquids with $\text{pH} \leq 7$ are shown in Fig. 15a in terms of the hydraulic conductivity ratio (chemical to water, k_c/k_w) and the ratio of outflow pH to inflow pH ($\text{pH}_{\text{out}}/\text{pH}_{\text{in}}$), whereas the results for permeant liquids with $\text{pH} > 7$ are shown in Fig. 15b in terms of k_c/k_w versus and the ratio of outflow pOH to inflow pOH ($\text{pOH}_{\text{out}}/\text{pOH}_{\text{in}}$), where $\text{pOH} = 14 - \text{pH}$. The shaded zone corresponds to conditions where pH equilibrium was established (defined here as either $\text{pH}_{\text{out}}/\text{pH}_{\text{in}} = 1.0 \pm 0.1$ or $\text{pOH}_{\text{out}}/\text{pOH}_{\text{in}} = 1.0 \pm 0.1$).

As shown in Fig. 15, all of the GCL specimens permeated until either pH or pOH equilibrium conditions were achieved were incompatible ($k_c/k_w > 1$) with the permeant liquids. Also, none of the GCL specimens that show compatibility ($k_c/k_w \leq 1$) were permeated until either pH or pOH equilibrium was established. Also seven of the eight prehydrated specimens were terminated before either pH or pOH equilibrium was achieved. Similarly, seven of the twelve tests on GCLs exposed to the permeant liquid for 48 hours prior to permeation without prehydration were terminated before either pH or pOH equilibrium was achieved. In contrast, pH or pOH equilibrium was achieved before terminating seven of the ten non-prehydrated specimens.

These data, along with those shown in Figs. 4 and 14, demonstrate that chemical equilibrium must be established before terminating a compatibility test, which may require a significantly greater number of pore volumes of flow than commonly is considered acceptable. For example, the data reported by Ruhl and Daniel (1997) indicate that more than 15 pore volumes of flow may be required for prehydrated GCLs, whereas more than 51 pore volumes of flow will be required for the test represented by the data shown in Fig. 4.

3.2.3. *Methods of prehydration*

Three methods are commonly used to prehydrate GCLs: (1) backpressure saturation, (2) preliminary permeation with water prior to permeation with chemicals (e.g., Shan and Daniel, 1991; Ruhl and Daniel, 1997; Petrov et al., 1997a,b), or (3) imbibition of water before or after assembling the GCL in the permeameter (e.g., Didier and Comega, 1997). Although the importance of prehydration conditions is not well understood, some factors that probably affect the measured hydraulic conductivity are the stress condition during prehydration, the methods of backpressure saturation and permeation, and whether hydration occurs through one or both sides of the GCL. More research on the influence of these factors is warranted.

Petrov and Rowe (1997) assessed the effect of sequence of confinement and hydration on hydraulic conductivity. They considered two sequences: (i) confinement followed by hydration with deionized water and then permeation with NaCl solution, and (ii) hydration at low confining stress (6 kPa) with deionized water followed by confinement at the target stress and then permeation with NaCl solution. Results of their tests are shown in Fig. 16. Slightly higher hydraulic

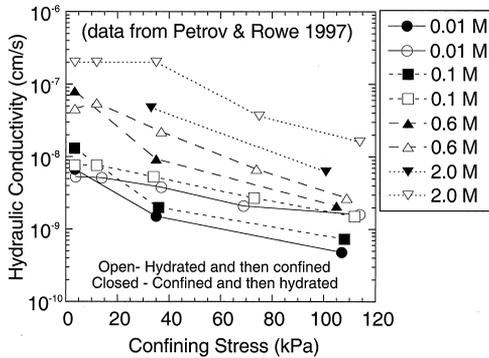


Fig. 16. Hydraulic conductivity of GCL specimens either hydrated and then confined to the target stress or confined to the target stress and then hydrated.

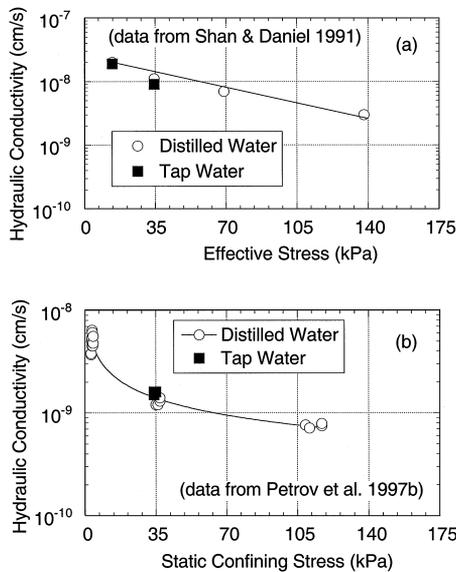


Fig. 17. Hydraulic conductivity of GCLs versus confining stress: (a) adhesive bonded GCL; (b) needle-punched GCL.

conductivities were obtained when the GCL was hydrated at low stress and then the target confining stress was applied. Hydration prior to confinement apparently results in higher void ratio at all effective stresses, resulting in slightly higher hydraulic conductivities.

These findings imply that more representative hydraulic conductivities are obtained by sequencing hydration and confinement to simulate the field condition. However, the effect of sequence is minor, since the hydraulic conductivities obtained using the two different sequences varied by no more than a factor of 3.

3.2.4. Confining stress

The effects of confining stress on the hydraulic conductivity of an adhesive-bonded GCL and a needle-punched GCL are shown in Fig. 17. As shown in Fig. 17a, the hydraulic conductivity of the adhesive-bonded GCL decreases approximately one half order of magnitude as the effective stress increases from ~ 14 kPa to ~ 140 kPa. A slightly greater effect of static confining stress is indicated by the data for the needle-punched GCL shown in Fig. 17b. Accordingly, compatibility tests should be conducted at the effective stress anticipated in the field.

3.2.5. Hydraulic gradient

Higher hydraulic gradients often are used when testing soils with low hydraulic conductivity to reduce the test duration. However, hydraulic gradients much higher than those expected in the field can result in a measured hydraulic conductivity that is too low due to consolidation by high seepage forces. Although ASTM D 5084 recommends a maximum hydraulic gradient of 30 for media with low hydraulic conductivity ($k < 10^{-7}$ cm/s), hydraulic gradients ranging from 50 to 550 typically are used for measuring the hydraulic conductivity of GCLs (e.g., Shan and Daniel, 1991; Daniel et al., 1993; Didier and Comeaga, 1997; Petrov and Rowe, 1997; Petrov et al., 1997a,b; Quaranta et al., 1997; Ruhl and Daniel, 1997; Lin, 1998).

The effect of hydraulic gradient on the hydraulic conductivity of a needle-punched GCL tested by Petrov et al. (1997a) is shown in Fig. 18. The data cover a wide range of hydraulic gradients (17 to 546) for permeation with distilled water (DW) as well as permeation with 0.6 M NaCl or 2.0 M NaCl solutions. In contrast to the effect of type of permeant liquid, hydraulic gradient has a relatively minor effect on hydraulic conductivity provided the mean effective stress is constant. In most cases, the effect of hydraulic gradient is less than a factor of 2. Rad et al. (1994) also show that the hydraulic conductivity of a GCL to water essentially was unaffected by hydraulic gradients as large as 2800.

The insensitivity to hydraulic gradient can be explained, in part, by the relationship between hydraulic gradient and effective stress. For example, consider two specimens permeated with water under constant-head conditions using flexible-wall

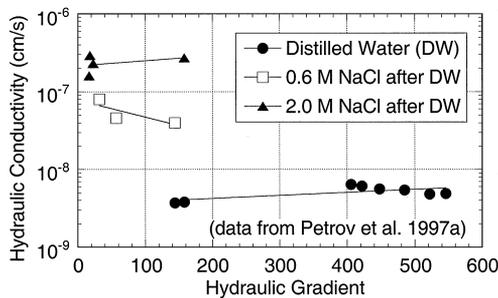


Fig. 18. Hydraulic conductivity versus hydraulic gradient for a needle-punched GCL permeated with distilled water (DW) and NaCl solutions at constant mean effective.

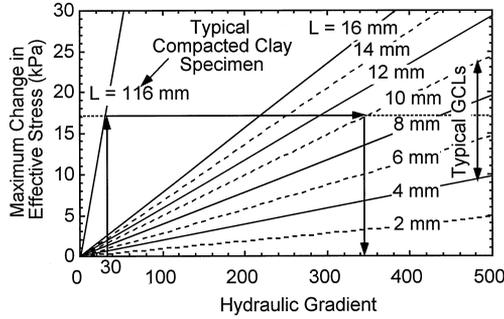


Fig. 19. Change in effective stress due to applied hydraulic gradient for different specimen thicknesses.

permeameters and backpressure saturation. Assume that the average effective stress during backpressure and permeation is the same. This condition requires simultaneously increasing the headwater pressure and decreasing the tailwater pressure by an equal amount to induce flow. In this case, the maximum and minimum effective stresses ($\sigma'_{\max,\min}$) that occur during permeation at the tailwater and headwater ends of the specimen, respectively, are given by

$$\sigma'_{\max,\min} = (\sigma_c - u_b) \pm \Delta\sigma' = \sigma'_b \pm \frac{i\gamma_w L}{2}, \quad (4)$$

where σ_c , u_b , and σ'_b are the cell pressure, backpressure, and effective stress, respectively, existing at the end of back-pressure saturation, i is the applied hydraulic gradient, $\Delta\sigma'$ is the change in effective stress resulting from the applied hydraulic gradient, γ_w is the unit weight of water, and L is the length or thickness of the specimen. The product $i\gamma_w$ in Eq. (4) is the seepage force per unit volume of the specimen.

The increase in effective stress ($\Delta\sigma'$) at the effluent end caused by the hydraulic gradient is shown in Fig. 19 for various L . The effective stress is far less sensitive to the hydraulic gradient for thin GCLs ($L = 5$ to 15 mm) than for thicker soil specimens. For a specimen of compacted clay prepared in a Proctor mold ($L = 116$ mm), applying a hydraulic gradient of 30 (i.e., the maximum gradient in D 5084) causes a 17 kPa increase in effective stress at the effluent end of the specimen (Fig. 19). For the same increase in effective stress, a hydraulic gradient of 342 can be applied to a 10 mm-thick GCL.

3.2.6. Using existing hydraulic conductivity testing standards

Neither ASTM D 5084 nor ASTM D 5887 requires an evaluation of chemical equilibrium as a criterion for terminating the hydraulic conductivity test. In addition, the backpressure saturation procedures in both of these standards result in prehydration if water is used for backpressuring. The prehydration effect may radically influence the test results, particularly if the test is not continued until chemical equilibrium is established. Other aspects of each standard, such as the recommended

maximum hydraulic gradients in ASTM D 5084 or the application of an initial effective stress of 69 kPa in ASTM D 5887, may not be appropriate for GCL compatibility testing. Thus, compatibility testing of GCLs solely in accordance with the procedures in these two standards is not recommended, particularly given the importance of chemical equilibrium in compatibility testing.

4. Conclusions and recommendations

The hydraulic performance of GCLs that do not contain a geomembrane depends on the hydraulic conductivity of the bentonite. The characteristically low hydraulic conductivities ($< 10^{-8}$ cm/s) often reported for bentonites are primarily due to restriction of the pore spaces effective in flow by adsorbed cations and water molecules associated with montmorillonite in the bentonite. Thus, the hydraulic conductivity of bentonites is particularly sensitive to changes in the composition of the pore fluid that influences the thickness of the adsorbed layer. In particular, liquids that cause the adsorbed layer to expand and the bentonite to swell, such as water, result in relatively low hydraulic conductivities. Liquids that cause the adsorbed layer to collapse and the bentonite to shrink cause the hydraulic conductivity to increase.

The amount of swell and the hydraulic conductivity of GCLs that do not contain a geomembrane can be predicted, at least qualitatively, on the basis of factors that affect the thickness of the adsorbed layer in accordance with the Guoy–Stern theory. High concentrations of monovalent cations (e.g., 0.6 M NaCl) as well as low concentrations of divalent cations (e.g., 0.0125 M CaCl_2) can cause a significant increase in hydraulic conductivity provided the test is performed sufficiently long to allow for exchange of adsorbed cations. Prehydrating GCLs with water before permeation with non-standard liquids appears to mute these effects. However, tests conducted on prehydrated GCLs have largely been terminated before chemical equilibrium was established. Thus, the long-term effectiveness of prehydration in maintaining relatively low hydraulic conductivity remains unknown.

In some cases, results of free swell tests can provide a relatively rapid, but qualitative, indication of the potential for incompatibility between a GCL and a non-standard liquid. Nevertheless, confirmation that a GCL and liquid are compatible requires long-term hydraulic conductivity testing with the actual or anticipated liquid and ensuring that chemical equilibrium has been established before termination. Preliminary termination may result in unconservative (low) hydraulic conductivities being reported. Checking for equality between influent and effluent electrical conductivity and pH is a reasonably reliable technique to determine if chemical equilibrium has been achieved and the major changes in hydraulic conductivity have occurred.

Hydraulic gradients well in excess of those typically considered suitable for hydraulic conductivity testing of compacted clay soils have been used in testing of GCLs without a significant effect on the test results. Hydraulic gradient has much less effect on GCLs than on common specimens of compacted clay because GCLs are much thinner, which makes the effluent effective stress less sensitive to the hydraulic gradient. Hydraulic gradients applied to GCLs can be more than ten times larger than

those typically applied to specimens of compacted clay, while maintaining the same effluent effective stress. Thus, control of average effective stress is more important than the control of the hydraulic gradient when evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids.

Neither ASTM D 5084 nor ASTM D 5887 requires an evaluation of chemical equilibrium as a criterion for terminating the hydraulic conductivity test. In addition, other procedures in these two standards, such as the backpressure saturation and the use of maximum hydraulic gradients, may not be appropriate when evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids. Thus, compatibility testing of GCLs solely in accordance with the procedures in these two standards is not recommended.

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