Hydraulic Conductivity of Geosynthetic Clay Liners Exhumed from Landfill Final Covers

Stephen R. Meer[1] and Craig H. Benson[2]

Abstract: Samples of geosynthetic clay liners (GCLs) from four landfill covers were tested for water content, swell index, hydraulic conductivity, and exchangeable cations. Exchange of Ca and Mg for Na occurred in all of the exhumed GCLs, and the bentonite had a swell index similar to that for Ca or Mg bentonite. Hydraulic conductivities of the GCLs varied over 5 orders of magnitude regardless of cover soil thickness or presence of a geomembrane. Hydraulic conductivity was strongly related to the water content at the time of sampling. Controlled desiccation and rehydration of exhumed GCLs that had low hydraulic conductivity (10^{-9} to 10^{-7} cm/s) resulted in increases in hydraulic conductivity of 1.5–4 orders of magnitude, even with overburden pressure simulating a 1-m-thick cover. Comparison of these data with other data from the United States and Europe indicates that exchange of Ca and/or Mg for Na is likely to occur in the field unless the overlying cover soil is sodic (sodium rich). The comparison also shows that hydraulic conductivities on the order of 10^{-6} to 10^{-4} cm/s should be expected if exchange occurs coincidently with dehydration, and the effects of dehydration are permanent once the water content of the GCL drops below approximately 100%. Evaluation of the field data also shows that covering a GCL with a soil layer 750–1,000 mm thick or with a geomembrane overlain by soil does not ensure protection against ion exchange or large increases in hydraulic conductivity.

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Introduction

Geosynthetic clay liners (GCLs) are factory-made clay liners that consist of a layer of bentonite sandwiched between two geotextiles that are held together by needle punching, stitching, or adhesives. In some cases, a geomembrane is included in addition to or in lieu of the geotextiles. The key component of a GCL is the sodium (Na) bentonite, which has a hydraulic conductivity $\approx 10^{-9}$ cm/s when permeated with deionized (DI) or tap water under stresses typical in final covers (Shan and Daniel 1991; Shackelford et al. 2000; Jo et al. 2001; 2005; Kolstad et al. 2004). GCLs present an attractive alternative to compacted clay liners as the hydraulic barrier layer in landfill cover systems because of their low hydraulic conductivity (10^{-9} cm/s), ease of installation, and limited thickness (Bouazza 2002). However, the bentonite in GCLs is sensitive to chemical interactions with the hydrating liquid, and ion exchange that occurs in bentonite can significantly alter its physical properties (Shan and Daniel 1991; Gleason et al. 1997; Ruhl and Daniel 1997; Shackelford et al. 2000; Jo et al. 2001, 2004; Vasko et al. 2001; Kolstad et al. 2004).

Recent studies have suggested that, under some circumstances, the combined effects of ion exchange and physical dehydration can significantly increase the hydraulic conductivity of a GCL (Melchior 1997, 2002; Lin and Benson 2000; Benson et al. 2006), rendering the GCL ineffective as a hydraulic barrier. However, field data confirming these effects have been limited. The focus of this study was to determine the hydraulic conductivity of GCLs used in four landfill final covers and to investigate field conditions influencing the hydraulic conductivity. GCLs from each cover were exhumed and tested for saturated hydraulic conductivity, water content, swell index, and composition of the exchange complex (the collection of cations adsorbed on the clay surface). Samples of the overlying cover soil from each field site were also tested for carbonate content, cations in the pore water, and index properties. Data from these tests were evaluated in conjunction with data reported by others to draw inferences regarding the likelihood of cation exchange and increases in hydraulic conductivity. Methods commonly assumed to protect GCLs from ion exchange and increases in hydraulic conductivity are also evaluated in the context of the field data.

Background

Laboratory Studies on Effects of Wet–Dry Cycling and Ion Exchange

Lin and Benson (2000) studied the effects of wet–dry cycling on the swell of bentonite and the hydraulic conductivity of a needle-punched GCL hydrated with DI water and a 12.5 mM $CaCl_2$ solution representing the pore water of vegetated surface layers in Wisconsin. A needle-punched GCL with a dry mass per unit area of 7.5 kg/m^2 was used. Hydraulic conductivity tests were con-

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ducted on GCL specimens that were repeatedly permeated and then allowed to air dry until the mass ceased changing (gravimetric water content ≈15–20%). Swell tests were conducted on bentonite that had been wetted and dried. Swelling decreased to levels typical of Ca bentonite within 4–5 wet–dry cycles for all specimens hydrated with the $CaCl_2$ solution, whereas swell of specimens hydrated with DI water increased slightly as the number of wet–dry cycles increased. All specimens retained low (10^{-9} cm/s) hydraulic conductivity through four wet–dry cycles. During the remaining wet–dry cycles, the specimen permeated with DI water retained low hydraulic conductivity, but all specimens permeated with $CaCl_2$ showed increases in hydraulic conductivity of approximately 3 orders of magnitude ($>10^{-6}$ cm/s). Lin and Benson (2000) conclude that the increase in hydraulic conductivity was the result of ion exchange in conjunction with dehydration of the bentonite, the latter giving rise to desiccation cracks that did not swell shut during rewetting.

Sporer and Gartung (2002) conducted wet–dry cycling on GCLs containing Na or Ca bentonite. The GCLs were hydrated with DI water or 9 mM $CaCl_2$ under a normal stress of 15 kPa, and then were dried under the same confining stress until the water content was ≈10–15%. Water content after each wetting cycle was determined and the bentonite was inspected visually for cracks after the final cycle. Sporer and Gartung (2002) report that desiccation impacts subsequent rehydration, reducing the hydrated water content by approximately 10–20% depending on the water used for hydration (DI water or $CaCl_2$ solution). No cracks were visible in the bentonite hydrated with DI water, but cracks were present in the bentonite permeated with the $CaCl_2$ solution. Hydraulic conductivity tests were also conducted on two GCLs containing Ca bentonite that had undergone one wet–dry cycle or no cycling. The hydraulic conductivity of the specimen that had undergone a single wet–dry cycle was 1 order of magnitude lower than the specimen that was not dried.

Field Studies of Hydraulic Properties of Geosynthetic Clay Liners in Landfill Final Covers

James et al. (1997) exhumed an adhesive-bonded GCL containing Na bentonite to determine why a cover with a GCL was leaking excessively. The GCL was placed on compacted clay and was overlain by a 150-mm-thick layer of gravel and a 300-mm-thick surface layer. The exhumed GCL contained finely cracked zones and had an average gravimetric water content of 116%. Na in the GCL was extensively replaced by Ca. The montmorillonite fraction of the bentonite in the exhumed GCL contained 10.3 $cmol^+/kg$ Na and 81.6 $cmol^+/kg$ Ca, on average, whereas 60.4 $cmol^+/kg$ Na and 40.9 $cmol^+/kg$ Ca were present when the GCL was new. Calcite in the bentonite (2%), rainfall percolating through overlying calcareous soil, and the water used to initially hydrate the GCL (Ca concentration ≈0.003 M) were suggested as the source of the Ca involved in exchange. Hydraulic conductivity tests were not conducted on the exhumed GCL.

Melchior (1997, 2002) studied five GCLs containing Na bentonite installed in a landfill cover near Hamburg, Germany. Two of the GCLs were underlain by a pan lysimeter (50 × 10 m) for measuring percolation. Three GCLs were installed in observation plots (3 × 2 m) without a lysimeter. A composite GCL containing a geomembrane was included in one of the observation plots, with the geomembrane oriented upward. All GCLs were covered with 150 mm of sandy gravel overlain by a 300-mm-thick surface layer of topsoil. For the conventional GCLs, daily percolation rates from the lysimeters were as high as 15 mm/day, and the average annual percolation rate ranged between 188 and 222 mm/year after 4 years. Root penetration of the GCL occurred within 5 months of installation, and extensive cracking of the bentonite was observed in slightly more than 1 year, with some cracks as wide as 2 mm. Moreover, complete exchange of Ca for Na occurred and the swell index of the bentonite was comparable to that of Ca bentonite. Hydraulic conductivities ranged between 1×10^{-5} and 3×10^{-4} cm/s and water contents ranged between 55 and 100% (average=60%). Desiccation cracks were observed in GCLs having a water content <100%. Properties of the composite GCL were notably different. Less cation exchange occurred in the composite GCL, and the bentonite retained had higher water content and swell index. However, cation exchange was not eliminated by the geomembrane.

Egloffstein (2001, 2002) summarizes the properties of GCLs exhumed from landfill covers in Germany. Gravimetric water contents of the GCLs ranged from 40 to 120% and complete exchange of Ca for Na occurred within as little as 2 years. Egloffstein (2002) reports that the GCLs had hydraulic conductivities on the order of 10^{-5} cm/s when first permeated, but the hydraulic conductivity decreased to approximately 10^{-7} cm/s after approximately 20 days. An effective stress of 20 kPa was applied during the hydraulic conductivity tests. No information was provided regarding the permeant liquid.

Egloffstein (2001) also conducted a long-term hydraulic conductivity test on a new specimen of GCL that was initially permeated with DI water and then with a $CaCl_2$ solution. Permeation with the Ca solution caused the hydraulic conductivity to increase to 3×10^{-8} cm/s, which is considerably lower than the hydraulic conductivity of the exhumed specimens. Based on this observation, Egloffstein (2001) concludes that the higher hydraulic conductivities of exhumed GCLs are due to ion exchange combined with desiccation cracks that do not seal during rehydration, as suggested by Lin and Benson (2000). Egloffstein (2002) also reports that desiccation cracks in GCLs are finer and more abundant in needle-punched GCLs than in stitch-bonded GCLs. Egloffstein (2001) also suggests that the confining pressure afforded by 750 mm or more of cover soil is sufficient to seal desiccation cracks and prevent large increases in hydraulic conductivity, but provides no data to support this hypothesis.

Wagner and Schnatmeyer (2002) evaluated a landfill cover design containing a needle-punched GCL with Na bentonite at a field site in Luxembourg. Percolation from the cover was recorded with a 45-m^2 pan lysimeter over a 2-year period. The GCL was placed on a layer of sand and overlain by 250 mm of coarse electric furnace slag and 750 mm of silty sand. The slag provided lateral drainage at the surface of the GCL, and the sand and slag formed capillary breaks on both sides of the GCL that maintained moisture within the bentonite. Percolation collected in the lysimeter was minimal during the first year and 6 mm during the second year. Daily percolation rates typically were five times higher during the second year than the first year, and the peak daily percolation rate was 0.072 mm/day.

Mansour (2001) exhumed GCLs from a test section consisting of a 660-mm-thick surface layer of well-graded sandy soil with fines overlying a conventional GCL (characteristics not described) located in a semiarid area of California. The exhumation was conducted 5 years after the test section was constructed. Tests conducted on the exhumed GCL using DI water as the permeant liquid at a confining stress of 35 kPa yielded a hydraulic conductivity of 1.9×10^{-9} cm/s. Water content of the GCL was not reported, but the swell index was determined to be 33 mL/2 g, on average. These properties were reported as nearly

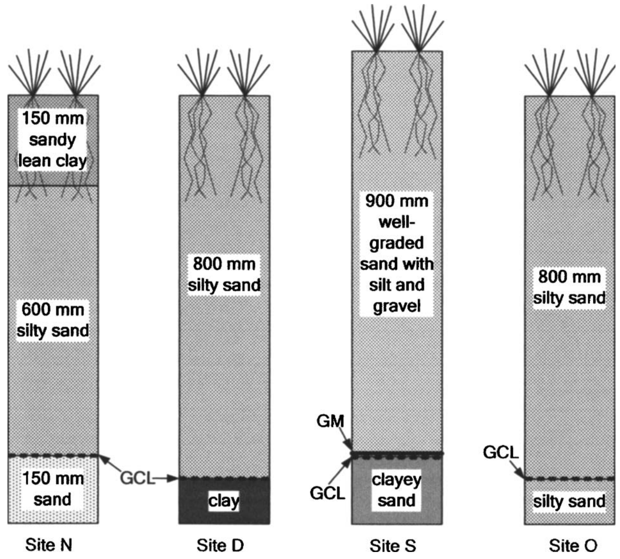

Fig. 1. Profiles of final covers at the field sites

identical to those measured on the GCL when it was installed. Analysis of soluble salts in the surface layer and the GCL indicated that the pore water in both materials was dominated by Na. The sodic (sodium rich) condition of the surface layer probably prevented cation exchange in the GCL, as evinced by the absence of change in swell index (Benson et al. 2006).

Henken-Mellies et al. (2002) conducted a 3-year field test of a GCL containing Ca bentonite in a landfill cover system underlain by a pan lysimeter. A geocomposite drainage layer was placed directly above the GCL and was overlain by a 1-m-thick surface layer. The average leakage rate for the 3-year observation period was 5.4 mm/year, although daily percolation rates as high as 1.7 mm/day (608 mm/year) were recorded. Henken-Mellies et al. (2002) also indicate that sensors installed in the GCL showed that the water content of the bentonite changed considerably, even with 1,000 mm of soil overlying the GCL. Higher water contents generally were observed in the spring and early summer, whereas lower water contents were observed over the rest of the year.

Mackey and Olsta (2004) exhumed GCLs from two landfills (A and B) on the coast of Florida where the final cover consisted of a surface layer overlying a needle-punched GCL. Both had been in service for more than 5 years. Clean sand (610–810 mm thick) was used for the cover soil at Landfill A and silty sand (460–860 mm thick) was used for the cover soil at Landfill B. Shell fragments (a potential source of Ca) were found in the surface layer at both sites. The bentonite was moist at both sites (water contents were not reported) and analysis of exchangeable cations showed that nearly all of the Na had been replaced by Ca and Mg at both sites. The swell index at both sites ranged between 7.5 and 14 mL/2 g, which is consistent with Ca and Mg being the dominant exchangeable cations. Hydraulic conductivity of the GCL exhumed from Landfill A ranged between 8.5×10^{-9} and 6.4×10^{-6} cm/s, with lower hydraulic conductivities being reported for tests conducted by the GCL manufacturer (average=1.4×10^{-8} cm/s) than independent laboratories (average=1.2×10^{-6} cm/s). Lower hydraulic conductivities were reported for the GCL exhumed from Landfill B (3.5×10^{-9} to 2.3×10^{-8} cm/s).

Benson et al. (2006) describe a case history of a final cover over a coal-ash landfill containing a GCL with Na bentonite. The GCL was covered with 760 mm of vegetated silty sand and underlain with two gravel-filled lysimeters to monitor percolation. Higher than anticipated percolation rates (up to 450 mm/year) were recorded within 4–15 months after installation of the GCL. The GCL was subsequently replaced with a composite GCL laminated with a polyethylene geofilm. Low percolation rates (2.6–4.1 mm/year) were maintained by the composite GCL for more than 5 years. Samples of the conventional GCL exhumed from the cover had hydraulic conductivities on the order of 5×10^{-6} cm/s. The high hydraulic conductivities were attributed to exchange of Ca and Mg for Na combined with dehydration of the bentonite. Ca and Mg from the surface layer were responsible for the cation exchange that occurred.

Table 1. Description of Covers at Field Sites

	Site			
Property	N	D	S	O
Location	Wisconsin	Wisconsin	Wisconsin	Georgia
Geosynthetic clay liner bonding	Needle punched	Adhesive bonded	Needle punched	Adhesive bonded (top deck); needle punched (slopes)
Installation date	11/1997	9/1991	9/1998	4/1997
Sampling date	7/2002	10/2002	10/2002	12/2002
Service life (year)	4.6	11.1	4.1	5.6
Surface layer thickness (mm)	750	800	900	800 (top deck) 400 (slopes)

Materials

GCLs

GCLs were exhumed from covers at four landfills. Three of the landfills are located in Wisconsin, and one is located in Georgia. The cover profiles at each site are illustrated in Fig. 1, and descriptions of each site are summarized in Table 1. None of the GCLs were laminated with a geomembrane (GM), but at one landfill (S), the GCL was overlain by a geomembrane to form a composite barrier. At each landfill, one or more test pits were excavated to a depth near the GCL in the cover profile. When the excavation approached the GCL, the remaining cover soil was removed by hand to prevent damage to the GCL. Once the GCL was exposed, samples were cut into square specimens (300×300 mm) using a razor knife and sealed in plastic for subsequent testing.

Tests were also conducted on a new (never in-service) GCL provided by a manufacturer. The new GCL contained granular Na bentonite encased by two geotextiles (a slit-film woven geotextile and a nonwoven geotextile) bonded by needle punching. The mass per unit area of air-dry bentonite in the GCL was 4.3 kg/m^2, the initial air-dry thickness of the GCL ranged from 5.8 to 7.0 mm, and the average initial air-dry water content of the bentonite was 7%. Bentonite in the GCL consisted of sand-size granules (0.075–2.0 mm). The clay-size fraction (particles finer than 0.002 mm) was 87%, the liquid limit was 504, and the plasticity index was 465.

Table 2. Properties of Cover Soils from Field Sites and Alternate Cover Assessment Program Sites

Site	Soil type	Water content (%)	Paste pH	$CaCO_3$ content (%)
N	Sandy lean clay (upper 150 mm)	11	7.4	2.6
	Silty sand (lower 600 mm)	13	7.2	2.2
S (surface layer)	Well-graded sand with silt and gravel	19	5.6	1.0
S (subgrade)	Clayey sand	13	5.1	1.0
D	Silty sand	24	5.8	1.0
O (top deck)	Silty sand	20	5.2	1.4
O (slope)	Silty sand	21	5.0	1.3
Alternate Cover Assessment Program D	Lean clay	—	7.9	0.9
Alternate Cover Assessment Program F	Sandy silt	—	7.8	1.9
Alternate Cover Assessment Program V	Silty sand with gravel	—	8.0	1.9
Alternate Cover Assessment Program A	Clayey sand	—	7.2	0.5

Although the new GCL was not identical to the GCLs used at each of the landfills, most of the GCLs used in North America contain bentonite from similar sources and have similar hydraulic properties, with hydraulic conductivities to DI water typically falling within 9×10^{-10} to 3×10^{-9} cm/s for stresses typical of covers (Shackelford et al. 2000; Thiel et al. 2001; Kolstad et al. 2004; Jo et al. 2001, 2004, 2005; Lee and Shackelford 2005). The new GCL was also provided by the same manufacturer that supplied the GCLs to each of the sites in this study. Therefore, except for bonding method, the new GCL used in this study is believed to be reasonably representative of the GCLs initially installed in the field.

Cover Soils

Grab samples of the overlying cover soils at each site were collected for particle size analysis (ASTM D 422, see ASTM 2004) and calcium carbonate content following the method described in Radd (1978). Paste pH was also measured following the method described in Sobek et al. (1978). Properties of the cover soils are summarized in Table 2. Four additional cover soils from the Alternative Cover Assessment Program (ACAP) (Albright et al. 2004, 2006) were also tested for comparative purposes, as was the subgrade soil from one of the field sites (Site S). Index properties of the ACAP soils and the subgrade from Site S are also summarized in Table 2. The cover soils are fine textured, ranging from silty sands to clays, have near neutral pH (5.1–8.0), and low carbonate content.

Methods

Cover Soil Elution Tests

Elution tests were conducted on the cover soils using a batch procedure and a column procedure. The batch procedure was conducted following the procedures described in ASTM D 6141 (ASTM 2004) using a solution mimicking synthetic rainwater as the eluent (see subsequent discussion for composition) with a liquid-to-solid ratio of 1.3. The mixture was blended using a high-speed mixer. The resulting slurry was sealed, allowed to equilibrate for 24 h, and then vacuum filtered using a Buchner funnel and Whatman GF-F filter paper. Concentrations of Ca, Mg, Na, and K in the test liquid were measured using atomic absorption spectroscopy (AAS) following USEPA Method 200.7.

Column elution tests were conducted on the cover soils in rigid-wall permeameters similar to those described in ASTM D 5856 (ASTM 2004). Specimens were prepared by compaction in a stainless steel compaction mold (diameter=105 mm, height=75 mm) to a dry unit weight corresponding to 85% relative compaction per standard Proctor. Both ends of the specimen were covered with disks of nonwoven geotextile, and a porous stone was placed on top of the upper geotextile to distribute the influent water. Synthetic rainwater was allowed to slowly drip (2 mL/h) onto the porous stone to simulate the slow unsaturated infiltration that might occur in the field. Effluent from the column was analyzed for concentrations of Ca, Mg, Na, and K by AAS, as described previously.

Ionic composition of the synthetic rainwater was based on an analysis of rainwater chemistry from 18 locations in North America, Europe, and Asia (Meer and Benson 2004). The analysis showed that average rainwater has an ionic strength of 0.8 mM, RMD of 0.02 $M^{1/2}$, and pH 7.1, on average, with Ca, Na, and NH_4 being the dominant cations. RMD is defined as $M_m/M_d^{1/2}$, where M_m=total molarity of monovalent cations and M_d=total molarity of polyvalent cations, and represents the relative abundance of monovalent and polyvalent cations in a solution. For inorganic aqueous permeant solutions, ionic strength and RMD

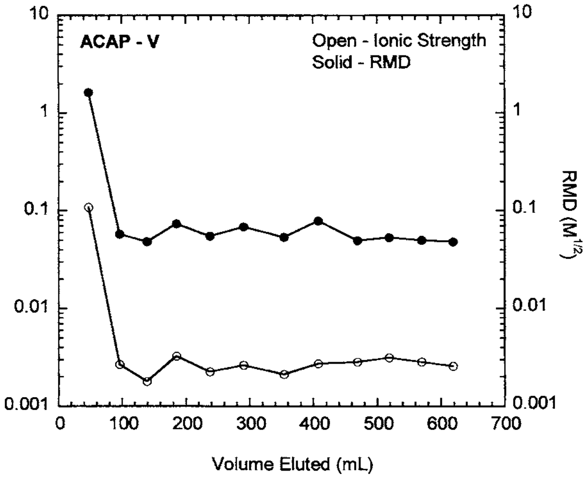

Fig. 2. Ionic strength and RMD for the leachate from column tests on surface layer soil from alternate cover assessment program (Site V)

Table 3. Steady-State Ionic Strength and RMD from Column Elution Tests on Cover Soils

		Column		Batch	
Site	Location	Ionic strength (M)	RMD ($M^{1/2}$)	Ionic strength (M)	RMD ($M^{1/2}$)
S	Surface layer	0.0005	0.0075	0.0005	0.0140
S	Subgrade	0.0009	0.0250	0.0007	0.0154
D	Surface layer	0.0006	0.0110	0.0004	0.0210
O	Surface layer (top deck)	0.0010	0.0600	0.0009	0.0535
O	Surface layer (slopes)	0.0011	0.0350	0.0009	0.0192
N	Surface layer (upper)	0.0042	0.0060	0.0010	0.0102
N	Surface layer (lower)	0.0015	0.0050	0.0009	0.0252
Alternate Cover Assessment Program D	Surface layer	0.0004	0.0180	0.0172	1.910
Alternate Cover Assessment Program F	Surface layer	0.0037	0.0950	0.0028	0.0713
Alternate Cover Assessment Program V	Surface layer	0.0028	0.0500	0.0015	0.0789
Alternate Cover Assessment Program A	Surface layer	0.0040	0.0300	0.0032	0.0299

are master variables controlling the hydraulic conductivity of GCLs for pH between 2 and 12 (Jo et al. 2001; Kolstad et al. 2004). The synthetic rainwater was prepared by dissolving NaCl and $CaCl_2$ salts in DI water to create a solution having the ionic strength and RMD noted above. NH_4 was not included to minimize the potential for chemical instability of the influent.

An example of how the ionic strength and RMD of the effluent varied is shown in Fig. 2 as a function of eluted volume (all data compiled in Meer and Benson 2004). The ionic strength and RMD typically decreased quickly and then leveled off, with steady ionic strength and RMD being obtained within 200 mL of elution. The steady ionic strengths and RMDs obtained from the column tests are summarized in Table 3 along with the ionic strengths and RMDs obtained from the batch tests. The column and batch test data are compared in Fig. 3.

The data from the batch and column tests are comparable. Ionic strengths from the column tests are slightly higher than those from the batch tests (1.5 times, on average) and the RMD is slight lower (0.85 times, on average). Thus, the batch test provides a relatively simple and expedient method to generate a test liquid representative of flow-through conditions. Graphs were also prepared to determine if ionic strength or RMD could be correlated to the $CaCO_3$ content of the cover soils. No trend with $CaCO_3$ content was observed for ionic strength or RMD.

Swell Index Tests

Swell index tests were conducted on bentonite from the new GCL and the exhumed GCLs according to methods described in ASTM D 5890 (ASTM 2004). Tests were conducted with DI water on all of the GCLs. Leachate obtained from the batch elution tests on the cover soils was also used to conduct swell index tests on bentonite from the new GCL. Tests were conducted with the batch test leachate to determine whether swell index tests can be used to assess compatibility of GCLs with cover soils. Results of the swell index tests are summarized in Table 4 (new GCL) and Table 5 (exhumed GCLs).

Hydraulic Conductivity Tests

Hydraulic conductivity tests were conducted on the GCLs in flexible-wall permeameters according to methods described in ASTM D 5084 using the falling headwater-constant tailwater

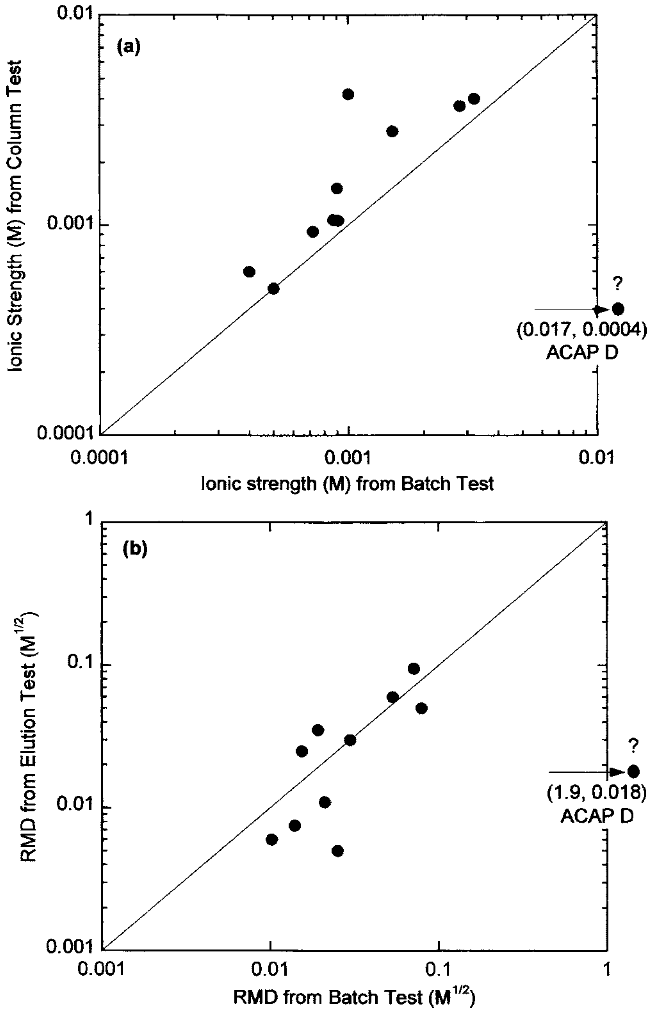

Fig. 3. Comparison of ionic strength (a) and RMD (b) from column and batch elution tests on cover soils using synthetic rainwater as the eluent

Table 4. Swell Index of Sodium Bentonite from New Geosynthetic Clay Liner in Liquid Produced by ASTM D 6141 Batch Tests Conducted with Cover Soils from Field Sites

Site	Soil used in batch test	Swell index (mL/2 g)
N	Surface layer—upper 150 mm	30
N	Surface layer—lower 600 mm	30
D	Surface layer	28
O	Surface layer—top deck	29
O	Surface layer—side slope	29
S	Surface layer	28
S	Subgrade	29
New geosynthetic clay liner	No soil—deionized water	35

method. An average hydraulic gradient of 100 and an average effective stress of 20 kPa were applied. Backpressure was not used to simulate field-satiated conditions. The hydraulic gradient that was used is higher than that in the field, but is typical of hydraulic gradients used when testing GCLs. Because GCLs are thin, relatively high hydraulic gradients can be used without the excessive increases in effective stress that are encountered when testing compacted clays with higher hydraulic gradients (Shackelford et al. 2000).

GCL test specimens were prepared using the method described in Jo et al. (2001). A razor knife was used to cut the GCL along the outer circumference of a stainless steel cutting ring with a sharpened edge. To prevent loss of bentonite around the perimeter, a small volume of permeant liquid was applied to the GCL along the inner circumference of the cutting ring prior to cutting. After the specimen was removed from the cutting ring, excess

Table 5. Physical and Chemical Properties of Geosynthetic Clay Liners

Site ID[a] and sample number	Exhumed water content (%)	Post-test water content (%)	Swell index (mL/2 g)	Hydraulic conductivity (cm/s)	Exchange complex (mole fraction) Na	Ca	Mg	K
New geosynthetic clay liner	—	209.1	36	1.2×10^{-9}	0.74	0.22	0.03	0.02
New geosynthetic clay liner	—	202.3	34	1.7×10^{-9}	0.65	0.27	0.03	0.05
N-1	30.9	55.0	9.5	4.3×10^{-5}	0.06	0.73	0.16	0.05
N-2	39.8	52.0	8.0	8.2×10^{-5}	0.03	0.70	0.18	0.08
N-3	44.5	73.0	8.0	6.0×10^{-5}	0.02	0.71	0.20	0.07
N-4	51.4	51.4	—	1.7×10^{-5}	0.02	0.74	0.18	0.05
N-5	38.4	44.0	—	1.2×10^{-6}	0.06	0.71	0.20	0.03
N-6	55.1	54.0	8.0	1.2×10^{-5}	0.03	0.71	0.21	0.05
N-7	48.8	42.0	—	1.5×10^{-6}	—	—	—	—
N-8	32.5	53.0	—	8.1×10^{-6}	—	—	—	—
N-9	52.0	47.0	—	2.1×10^{-5}	—	—	—	—
N-10	55.7	67.0	—	1.0×10^{-4}	—	—	—	—
N-11	58.5	60.0	—	9.1×10^{-5}	—	—	—	—
N-12	38.3	60.1	—	7.2×10^{-5}	—	—	—	—
N-12	—	—	—	4.6×10^{-5}	—	—	—	—
N-13	44.3	60.8	—	2.0×10^{-5}	—	—	—	—
N-14	53.4	53.4	—	1.9×10^{-5}	—	—	—	—
D-1	182.1	155.1	11.0	2.9×10^{-8}	0.15	0.72	0.12	0.01
D-2	170.2	135.9	—	3.0×10^{-8}	0.02	0.78	0.18	0.02
D-3	204.2	179.0	—	1.1×10^{-7}	0.03	0.78	0.18	0.01
D-4	165.9	179.0	10.5	7.5×10^{-8}	0.04	0.70	0.21	0.04
S-1	57.9	68.5	—	5.1×10^{-5}	0.21	0.68	0.09	0.01
S-2	59.2	94.4	9.5	9.4×10^{-5}	0.18	0.66	0.13	0.02
S-3	60.9	90.4	9.3	1.6×10^{-4}	0.29	0.61	0.09	0.01
S-4	60.8	98.0	—	1.3×10^{-4}	0.22	0.65	0.11	0.02
O-1[b]	98.5	102.0	—	1.2×10^{-4}	—	—	—	—
O-2	94.9	103.7	6.9	4.0×10^{-5}	0.11	0.53	0.19	0.18
O-3	108.0	118.1	9.2	5.2×10^{-9}	0.29	0.43	0.21	0.07
O-4	99.1	115.3	—	2.6×10^{-8}	0.09	0.75	0.12	0.04
O-5[c]	59.4	81.0	—	1.4×10^{-4}	0.16	0.56	0.17	0.12
O-6	61.4	72.7	—	7.5×10^{-5}	—	—	—	—
O-7	82.0	95.2	—	1.5×10^{-6}	—	—	—	—
O-8	86.1	96.1	—	1.8×10^{-8}	—	—	—	—

[a] Letter designates site.

[b] Needle-punched geosynthetic clay liner.

[c] Adhesive-bonded geosynthetic clay liner.

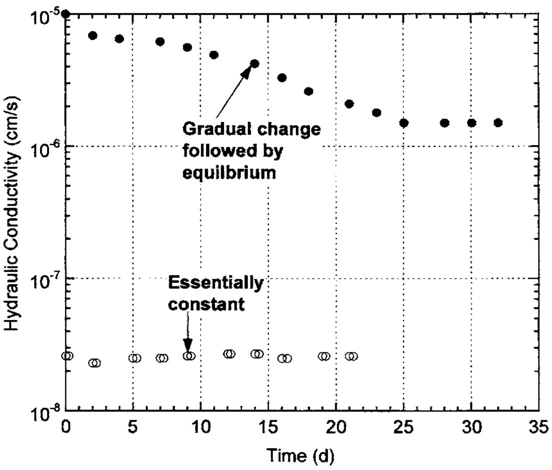

Fig. 4. Hydraulic conductivity records typifying the range of behavior observed in the hydraulic conductivity tests on exhumed geosynthetic clay liners. Data in this graph are from tests conducted on geosynthetic clay liners from Site 0.

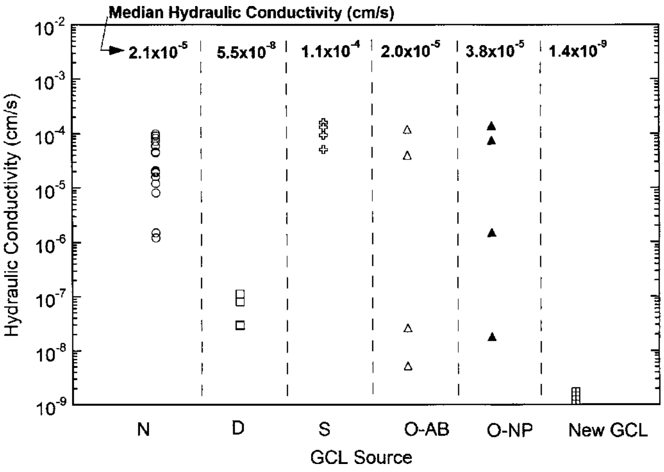

Fig. 5. Hydraulic conductivities of exhumed geosynthetic clay liners. Geosynthetic clay liners at Site O were adhesive bonded or needle punched. The geosynthetic clay liners from Sites N and D were adhesive bonded and the geosynthetic clay liners from Site S was needle punched. Hydraulic conductivity of new geosynthetic clay liners included for comparison.

geotextile fibers along the edge of the GCL were removed with scissors, and bentonite paste was applied around the perimeter to reduce the potential for sidewall leakage.

A 10 mM $CaCl_2$ solution was used as the permeant liquid, as suggested in ASTM D 5084 for regions with hard tap water (e.g., Madison, Wis.). Egloffstein (2001, 2002), Lin and Benson (2000), and Benson et al. (2006) have used similar solutions when permeating GCLs used for landfill cover applications. To evaluate the importance of the permeant liquid, comparative hydraulic conductivity tests were conducted using DI water as the permeant liquid on a GCL exhumed from Site S. The hydraulic conductivity obtained with DI water (1.4×10^{-5} cm/s) was 3.6 times lower than the lowest hydraulic conductivity (5.1×10^{-5} cm/s) measured from Site S specimens using 10 mM $CaCl_2$ solution as the permeant liquid. Thus, the choice of permeant liquid is believed to have only a modest effect on hydraulic conductivity. Benson et al. (2006) also conducted tests on exhumed GCLs with a pore water percolate and 10 mM $CaCl_2$ solution, and found similar hydraulic conductivities were obtained using both liquids. The lack of sensitivity to the permeant liquid reflects the abundance of exchangeable Ca in the exhumed GCLs (discussed subsequently).

Hydraulic conductivities of the GCLs are summarized in Table 5. Typical permeation times ranged between 20 and 45 days, even though the termination criteria in ASTM D 5084 generally were met in much shorter periods. Longer permeation times were used to determine if decreases in hydraulic conductivity would occur as reported by Egloffstein (2002). Two types of behavior were observed during the hydraulic conductivity tests on the exhumed GCLs (see examples in Fig. 4). For most of the tests on the exhumed GCLs, the hydraulic conductivity remained essentially constant from the beginning of the test. However, for some of the test specimens, the hydraulic conductivity increased or decreased gradually during the test period, and then stabilized. All tests were conducted long enough so that steady hydraulic conductivity was obtained and inflow equaled outflow, as defined in ASTM D 5084.

If specimens had high hydraulic conductivity ($>10^{-6}$ cm/s), rhodamine WT dye (5 mg/L) was added to the permeant liquid to verify that sidewall leakage was not occurring as recommended by Jo et al. (2001). No indication of sidewall leakage was found in any of the tests. The effluent lines were also inspected periodically for bentonite particles that may have piped from the GCL. No bentonite particles were observed visually in the effluent.

Soluble Salts and Exchangeable Cations

Exchangeable cations present on the bentonite of the exhumed GCLs and the new GCL were determined by extraction using the ammonium acetate method (Thomas 1982). Each test was conducted with 10 g of dry bentonite crushed to pass a No. 20 U.S. standard sieve. Chemical analysis of the extracts was conducted by AAS, as described previously. Mole fractions of exchangeable Na, K, Ca, and Mg are summarized in Table 5.

Results and Discussion

Hydraulic Conductivity

Hydraulic conductivities of the exhumed GCLs are shown in Fig. 5. The median hydraulic conductivity of the GCL from each site is also shown along the top of the graph (Fig. 5). The exhumed GCLs have a broad range of hydraulic conductivities, spanning nearly five orders of magnitude (5.2×10^{-9} to 1.6×10^{-4} cm/s). Greater variability was obtained at sites where GCL samples were taken from multiple test pits (2 orders of magnitude at Site N, nearly 5 orders of magnitude at Site O) than those where the GCLs were obtained from single test pits (less than 1 order of magnitude for Sites D and S). All of the exhumed GCLs also have higher hydraulic conductivity than the new GCL (1.2×10^{-9} to 1.7×10^{-9} cm/s). For example, the median hydraulic conductivity of the GCL from Site D (5.5×10^{-8} cm/s), which has lowest overall hydraulic conductivity of the four sites, is 39 times higher than the median hydraulic conductivity of the new GCL (1.4×10^{-9} cm/s).

At Site O, a needle-punched GCL was used on the side slopes and an adhesive-bonded GCL was used on the top deck. Comparison of the hydraulic conductivities (Fig. 5, Table 5) indicates that there is no apparent difference between the hydraulic conduc-

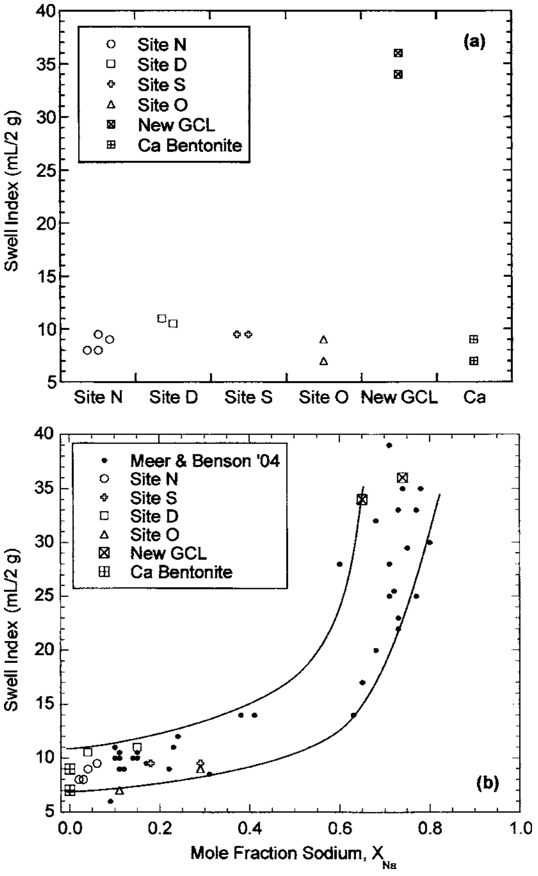

Fig. 6. Box plots of index swell of bentonite from exhumed geosynthetic clay liners, new geosynthetic clay liners, and Ca bentonite: (a) index swell versus mole fraction of exchangeable sodium (b). Smooth curve and solid points in (b) are from parametric laboratory tests conducted by Meer and Benson (2004). Index swell of Ca bentonite is from Jo et al. (2004).

tivity of the needle-punched (labeled O-NP) or adhesive-bonded (labeled O-AB) GCLs at Site O. Both types of GCL had hydraulic conductivities near the upper end ($\sim 1 \times 10^{-4}$ cm/s) and the lower end ($\sim 3 \times 10^{-8}$ cm/s) of the range. A *t* test was conducted on the data at the 5% significance level to confirm that the two sets of hydraulic conductivities are similar. The data were transformed logarithmically prior to testing, so that the assumption of normality in the *t* test would be satisfied. A *p* statistic of 0.66 was obtained, indicating that there is no statistically significant difference between the hydraulic conductivity of both data sets at the 5% level ($0.66 \geqslant 0.05$). The similarity of the hydraulic conductivities of the needle-punched and adhesive-bonded GCLs (collected from the slopes and top deck, respectively) also suggests that the slope had no systematic effect on hydraulic conductivity of the GCL.

Swell Index and Exchangeable Cations

The swell index data are shown in Fig. 6(a). DI water was used as the hydrating liquid for these swell tests; thus, ion exchange did not occur during these tests and the data in Fig. 6(a) reflect the swell index of the bentonite in its in-service condition. Swell indices for the new GCL are also shown in Fig. 6(a) along with swell indices for Ca bentonite reported by Jo et al. (2004) for bentonite from the new GCL homoionized following the procedure in Mesri and Olson (1971). For each site, there is little variability (<4 mL/2 g) in the swell index of the exhumed GCLs and all of the swell indices fall within a narrow range (6.9–11.0 mL/2 g). The swell indices for the exhumed GCLs are similar to those for the calcium bentonite (6–10 mL/2 g) and much lower than the swell index for the new GCL (34–36 mL/2 g).

The exchangeable cation data, summarized in Table 5, are consistent with the low swell indices for the exhumed GCLs shown in Fig. 6(a). For all of the exhumed GCLs, much of the Na originally sorbed to the bentonite has been replaced primarily by Ca, but also by Mg. The Na mole fraction of the exhumed GCLs ranges from 0.02 to 0.29 (average=0.11), the Ca mole fraction ranges from 0.43 to 0.78 (average of 0.68), and the Mg mole fraction ranges from 0.09 to 0.21 (average=0.16). In contrast, for the new GCL, the Na mole fraction is 0.65–0.74, the Ca mole fraction is 0.22–0.27, and the Mg mole fraction is 0.03. The preponderance of exchangeable Ca and Mg in the exhumed GCLs is not surprising given that the leachates from the column tests on the cover soils contained primarily divalent cations ($0.0050 < \mathrm{RMD} < 0.095\ \mathrm{M}^{1/2}$). The abundance of divalent exchangeable cations in these GCLs is also consistent with the findings reported by James et al. (1997), Melchior (1997, 2002), Egloffstein (2001, 2002), Mackey and Olsta (2004), and Benson et al. (2006).

The correspondence between swell index and mole fraction of exchangeable Na is shown in Fig. 6(b). Also included are data from Meer and Benson (2004), which span a broad range of Na mole fraction, and the data from Jo et al. (2004) for Ca bentonite. Meer and Benson (2004) created bentonites with varying Na and Ca mole fractions by batch mixing bentonite from the new GCL with aqueous solutions having varying concentrations of Na and Ca. Replacement of Na by Ca (i.e., a decrease in the Na mole fraction) corresponds directly to a decrease in swell index. Moreover, when the Na mole fraction is less than 0.3, the bentonite has a swell index comparable to that of fully exchanged Ca bentonite. Thus, complete replacement of Na by divalent cations is not necessary for a bentonite to have the swelling properties of Ca bentonite.

The least amount of cation exchange occurred in the GCL from Site S (Na mole fraction=0.18–0.29). The presence of the geomembrane above the GCL at Site S probably slowed the exchange process, as was also observed by Melchior (2002), but the GCL at Site S was also in service for the shortest time (4.1 years) of all GCLs exhumed. Despite the reduction in exchange, the geomembrane was ineffective in protecting the GCL from alterations in hydraulic conductivity. In fact, the GCL from Site S had the highest median hydraulic conductivity of all the GCLs that were sampled. The source of the exchanging cations at Site S is also unclear, considering that the overlying geomembrane probably blocked most of the cations migrating from the overlying cover soils. Diffusion from the underlying subgrade may have been responsible for the exchange, as the leachate from the column tests on the subgrade soil was primarily divalent ($\mathrm{RMD}=0.025\ \mathrm{M}^{1/2}$). The distance over which diffusion would need to occur in the GCL is short enough (<10 mm) to permit influx of sufficient Ca and Mg within 4.1 years to provide the mass required for near complete exchange. However, the contributions of diffusion have not been confirmed experimentally, and additional study is needed to determine if diffusion from the underlying subgrade was a key factor contributing to exchange.

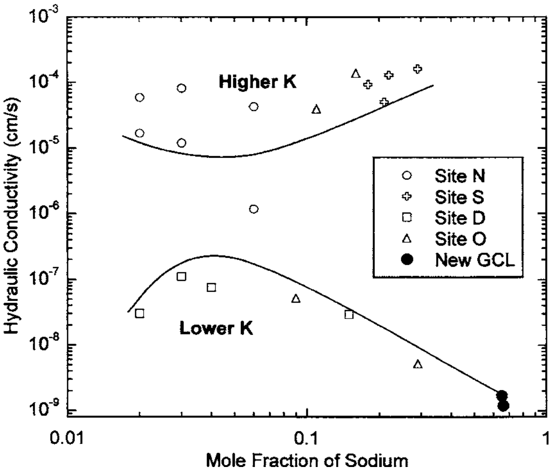

Fig. 7. Hydraulic conductivity of exhumed geosynthetic clay liner and new geosynthetic clay liner versus Na mole fraction in the exchange complex of the bentonite

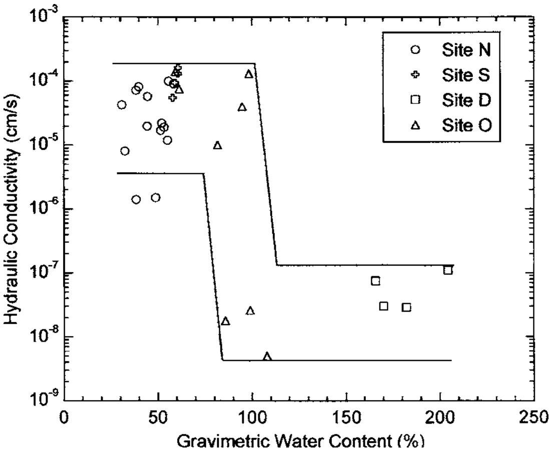

Fig. 8. Hydraulic conductivity of exhumed geosynthetic clay liners versus gravimetric water content at the time of exhumation

Hydraulic Conductivity and Exchangeable Cations

Hydraulic conductivity versus mole fraction of exchangeable Na is shown in Fig. 7 for the exhumed GCLs and the new GCL. There is no apparent relationship between hydraulic conductivity and Na mole fraction, although the lowest hydraulic conductivities correspond to the highest Na mole fraction (and are for the new GCL). However, all of the GCLs (except the new GCL) have swell indices comparable to that of Ca bentonite and a Na mole fraction low enough (<0.3) to result in swelling properties similar to Ca bentonite. Thus, because the Na mole fraction was low on all of the exhumed GCLs, a strong relationship between Na mole fraction and hydraulic conductivity should not be expected.

Except for one point, the data can be segregated into two groups regardless of the Na mole fraction: GCLs with higher hydraulic conductivity ($>10^{-5}$ cm/s) and GCLs with lower hydraulic conductivity ($<10^{-7}$ cm/s) (Fig. 7). The lower hydraulic conductivities are similar to those obtained from long-term hydraulic conductivity tests conducted by Egloffstein (2001) and Jo et al. (2005) using dilute Ca solutions (10 mM). Their tests, which were conducted long enough for complete replacement of Na by Ca under continuously saturated conditions, show that the long-term equilibrium hydraulic conductivity of saturated bentonite to dilute Ca solutions is approximately 2×10^{-8} cm/s for stresses similar to those observed in covers. In fact, a very long-term hydraulic conductivity test on a specimen of the new GCL that was continuously permeated over a period of 4.4 years and 1,108 pore volumes of flow with a 10 mM $CaCl_2$ solution yielded a hydraulic conductivity of 2.3×10^{-8} cm/s (Benson et al. 2006). Thus, the very high hydraulic conductivities of some of the exhumed GCLs must be caused by other factors in conjunction with ion exchange.

Hydraulic Conductivity and Water Content

Lin and Benson (2000), Egloffstein (2001, 2002), and Benson et al. (2006) suggest that the high hydraulic conductivities of GCLs exhumed from covers is due to replacement of Ca and Mg for Na combined with dehydration of the bentonite. For example, Lin and Benson (2000) found that Ca-for-Na exchange combined with desiccation resulted in hydraulic conductivities comparable to those in the group of higher hydraulic conductivities shown in Fig. 7.

Dehydration induces two physical changes in saturated bentonite that alter hydraulic conductivity: (1) removal of strongly bound water molecules in the interlayer region present from the initial hydration when Na was the dominant exchangeable cation; and (2) formation of desiccation cracks that do not heal during rehydration, due to the low swelling capacity of Ca and Mg bentonites. Strongly bound water molecules in the interlayer are responsible for the lower hydraulic conductivity of bentonites that have undergone Ca-for-Na exchange by permeation with dilute solutions (Jo et al. 2004, 2006; Benson et al. 2006). Removing these water molecules results in irreversible shrinkage of bentonite granules, resulting in larger intergranular pores and higher hydraulic conductivity (Benson et al. 2006). Similarly, desiccation cracks act as preferential flow paths that also contribute to higher hydraulic conductivity.

Hydraulic conductivity of the GCLs is shown in Fig. 8 as a function of gravimetric water content of the bentonite at the time of sampling. There is an abrupt change in hydraulic conductivity that occurs when the gravimetric water content is approximately 80–100%. GCLs with gravimetric water contents less than 85% typically have high hydraulic conductivities (10^{-6} to 10^{-4} cm/s), whereas GCLs with gravimetric water contents greater than 100% have lower hydraulic conductivities (10^{-8} to 10^{-7} cm/s). The GCLs exhumed by Melchior (2002) that contained desiccation cracks also had gravimetric water contents less than 100%. In contrast, water contents exceeding 200% were obtained for the new GCL (Table 5).

Comparison of the gravimetric water contents following termination of the hydraulic conductivity tests with the water contents at the time of exhumation (Table 5) indicates that this segregation of the data set remained after the specimens were permeated. GCLs with high hydraulic conductivity typically had gravimetric water contents less than approximately 125%. The largest increase in gravimetric water content during permeation was 37%, in most cases the gravimetric water content increased 10–15%, and in some cases the gravimetric water content decreased. Moreover, none of the exhumed GCLs had gravimetric water contents comparable to the new GCL. Thus, the dehydration effect is per-

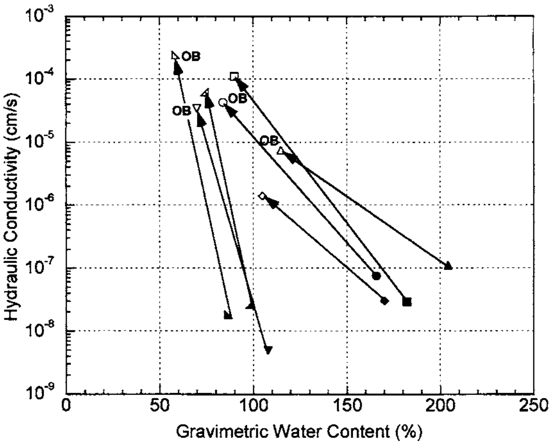

Fig. 9. Hydraulic conductivity of exhumed geosynthetic clay liners as a function of gravimetric water content before and after a controlled desiccation treatment. Solid symbol corresponds to in situ water content (before condition). Open symbol is water content after controlled desiccation. The label OB indicates that 20 kPa stress was applied during desiccation.

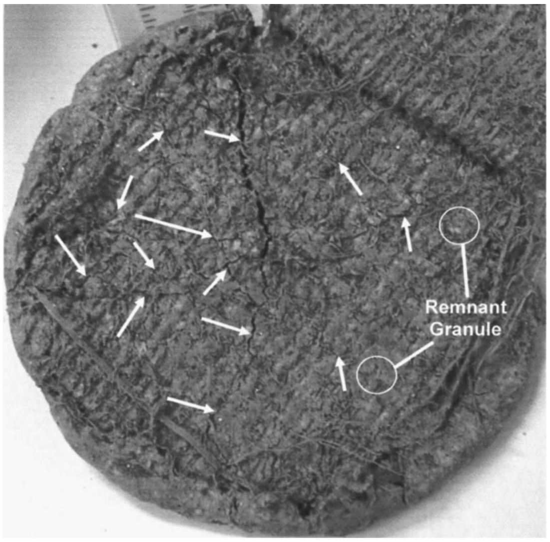

Fig. 10. Exposed surface of bentonite in exhumed geosynthetic clay liner desiccated to water content of 75% and then rehydrated and permeated. Note desiccation cracks in bentonite (white arrows) and examples of remnant bentonite granules.

manent, which is expected given that Ca and Mg bentonites do not undergo osmotic swelling during hydration (Norrish and Quirk 1954).

The importance of maintaining water within the bentonite is also evident in the thickness of the GCLs, which is an index of the degree of swelling of the bentonite. The GCL from Site D, which had the highest water content and the lowest median hydraulic conductivity (5.5×10^{-8} cm/s), was thicker (average=13.4 mm) than the GCLs from Site N (average =6.0 mm) and Site S (average=9.0 mm), which had the lowest water contents ($<60\%$) and the highest hydraulic conductivities (median hydraulic conductivity $>10^{-5}$ cm/s). The exhumed GCLs from Site O with high hydraulic conductivity also were somewhat thinner than the GCLs with low hydraulic conductivity (7.5 versus 8.6 mm, on average).

The abrupt change in hydraulic conductivity shown in Fig. 8 suggests that there is a critical gravimetric water content below which the hydraulic conductivity remains high after the bentonite rehydrates. Thus, exhumed GCLs that had low hydraulic conductivity (10^{-7} to 10^{-9} cm/s) were subjected to a controlled desiccation treatment to achieve water contents between 58 and 90% or between 105 and 115% (i.e., above and below 100%). After drying, the specimens were repermeated (only one dry–wet cycle was applied). To determine if overburden pressure had any influence on the effect of desiccation, four exhumed GCLs having low hydraulic conductivity (10^{-7} to 10^{-9} cm/s) were dried under an overburden pressure of 20 kPa (applied dead load) to simulate the stress applied by approximately 1 m of cover soil. Hydraulic conductivities of these specimens are shown in Fig. 9 as a function of the gravimetric water content (exhumed water content or water content after desiccation treatment). Specimens that had overburden pressure applied during desiccation are labeled as "OB" in Fig. 9.

Controlled desiccation resulted in an increase in hydraulic conductivity in all cases. Desiccation to gravimetric water contents greater than 100% caused an increase in hydraulic conductivity of 1–2 orders of magnitude, whereas desiccation to gravimetric water contents less than 100% increased the hydraulic conductivity by 3–4 orders of magnitude. Thus, a critical water content below which the hydraulic conductivity did not change was not identified. Nevertheless, these findings suggest that drying to a lower water content has a more dramatic effect on hydraulic conductivity.

The increase in hydraulic conductivity during controlled desiccation was unaffected by the application of overburden pressure, regardless of the range of water contents used for drying (Fig. 9). The hydraulic conductivity following desiccation ranged from 8.0×10^{-6} to 2.4×10^{-4} cm/s for specimens that had overburden pressure applied during desiccation, whereas the specimens dried without overburden pressure had hydraulic conductivities ranging from 1.3×10^{-6} to 1.1×10^{-4} cm/s. A *t* test conducted at the 5% significance level on the logarithmically transformed data confirmed that the hydraulic conductivities of the specimens desiccated with and without overburden pressure were not statistically different ($p=0.57 \geqslant 0.05$). Moreover, a specimen that was desiccated to a gravimetric water content of 105% without overburden pressure applied had lower hydraulic conductivity (1.3×10^{-6} cm/s) than a specimen desiccated to water content of 115% (8.0×10^{-6} cm/s) with overburden pressure applied (Fig. 9). Thus, application of overburden pressure corresponding to 1 m of soil appears insufficient to prevent large increases in hydraulic conductivity during drying.

Formation of desiccation cracks appears to be a key factor contributing to the increase in hydraulic conductivity. A specimen of GCL from Site O (exhumed gravimetric water content=99%, hydraulic conductivity=2.6×10^{-8} cm/s) was desiccated to a gravimetric water content of 75%. Following desiccation, the hydraulic conductivity increased to 6.2×10^{-5} cm/s. After removal of the specimen from the permanent, the upper geotextile was carefully peeled back, and the bentonite examined for signs of structural changes due to desiccation. A photograph of the specimen illustrating the desiccation cracks (noted with white arrows) is shown in Fig. 10. Remnant bentonite granules are also evident in the photograph, suggesting that intergranule flow may also have contributed to the high hydraulic conductivity.

Table 6. Field Hydraulic Conductivity, Cover System, and Other Related Data from Literature and This Study

Source	Cover thickness (mm)	Service life (years)	Mole fraction sodium	Mole fraction calcium	Swell index (mL/2 g)	Hydraulic conductivity (cm/s)[a]
James et al. (1997)	450	1.5	0.16	0.69	NR	NR
Melchior (2002)	450	2.0	0.09	0.80	11	1.5×10^{-4} [b]
	450	4.0	0.04	0.81	9	3.5×10^{-5} [b]
	450	2.0	0.05	0.70	8	9.4×10^{-4} [b]
	450	4.0	0.02	0.83	7	1.0×10^{-5} [b]
Mansour (2001)	660	5.0	NR	NR	33	1.9×10^{-9} [b]
Mackey and Olsta (2004)	610–810	7.2	0.01	0.64	8.3	1.2×10^{-6} [c]
						1.4×10^{-8} [d]
	460–860	5.5	0.02	0.49	10.8	1.1×10^{-8}
Wagner and Schnatmeyer (2002)	1000	2.0	NR	NR	NR	8.3×10^{-8} [e]
Henken-Mellies et al. (2002)	1000	3.0	NR	NR	NR	2.3×10^{-6} [e]
Benson et al. (2006)	760	4.1	0.10	0.67	12	5.0×10^{-5} [b]
	760	2.0	0.09	0.55	8	4.8×10^{-5} [b]
This study—Site N	750	4.6	0.04	0.72	9	3.9×10^{-5} [b]
This study—Site D	800	11.1	0.06	0.74	11	6.2×10^{-8} [b]
This study—Site S	900	4.1	0.22	0.65	10	1.1×10^{-4} [b]
This study—Site O	800	5.6	0.16	0.56	8	4.7×10^{-5} [b]

[a] NR=not reported in previous study.

[b] Mean reported hydraulic conductivities measured on exhumed geosynthetic clay liners.

[c] Hydraulic conductivity of exhumed geosynthetic clay liner reported by independent testing laboratory.

[d] Hydraulic conductivity of exhumed geosynthetic clay liner reported by geosynthetic clay liner manufacturer.

[e] Computed based on peak daily percolation rate assuming unit gradient flow.

Practical Implications

Anticipated Field Conditions

Data from previous field studies are summarized in Table 6 along with the data from this study. Service life of the GCL, swell index of the bentonite, and mole fractions of exchangeable cations on the bentonite (if available) are reported in Table 6 along with hydraulic conductivities. Data from Egloffstein (2001, 2002) are not included in Table 6, because too little information was provided in these publications to complete the table entries reliably.

Hydraulic conductivity of the GCL in the field study conducted by Henken-Mellies et al. (2002) was computed from the reported peak daily percolation rate. A unit hydraulic gradient was used in the computations, because a geocomposite drainage layer having hydraulic conductivity several orders of magnitude higher than the overlying cover soils was placed above the GCL. Hydraulic conductivity of the GCL in the study by Wagner and Schnatmeyer (2002) was also computed using a unit hydraulic gradient and the peak daily percolation rate because of the lateral drainage provided by the coarse slag placed above the GCL.

The data summarized in Table 6 suggest that increases in the hydraulic conductivity of GCLs used in covers may be common, and that the contributing factors are cation exchange combined with desiccation (or lack of initial hydration, as discussed in the following section). The data reported in other studies generally are consistent with this conclusion (the exception being the study by Mansour 2001). Of the 15 GCLs included in Table 6, 9 have hydraulic conductivities greater than 10^{-5} cm/s, and 11 are greater than 10^{-6} cm/s. Four GCLs have hydraulic conductivities on the order of 10^{-8} cm/s. One GCL has a hydraulic conductivity less than 10^{-8} cm/s (Mansour 2001), and only this GCL has a hydraulic conductivity comparable to that of a new GCL ($\approx 2\times10^{-9}$ cm/s). Moreover, the soil placed over this GCL was sodic (Mansour 2001; Benson et al. 2006), which is atypical of most surficial soils (Sposito 1989), as is illustrated by the low RMDs of the column test leachates (Table 3).

Except for the site described by Mansour (2001), the sites having GCLs with lower hydraulic conductivity ($\approx 10^{-8}$ cm/s, or lower) tend to be in wet and humid areas or have been in service for only a short period. The sites evaluated by Mackey and Olsta (2004) are on the coast of Florida, and Site D in the present study is located in a densely wooded area in northern Wisconsin that is surrounded by wetlands. Desiccation at these sites probably is less likely than at other sites. The study by Wagner and Schnatmeyer (2002) was only conducted for 2 years and even in this short duration, the hydraulic conductivity of the GCL had already reached 8.3×10^{-8} cm/s. If Wagner and Schnatmeyer (2002) had conducted their study over a longer period of time, higher hydraulic conductivity of the GCL may have been realized.

Protective Methods

Egloffstein (2001, 2002) recommends that at least 750 mm of cover soil (and preferably 1,000 mm) be placed above a GCL to prevent the changes in hydraulic conductivity associated with cation exchange and dehydration. Egloffstein (2002) suggests that GCLs covered with surface layers this thick are under sufficient overburden pressure to prevent large changes in hydraulic conductivity and will have long-term hydraulic conductivities of approximately 10^{-8} cm/s even if Ca replaces Na on the bentonite. Lin and Benson (2000) indicate that a geomembrane can be used to protect GCLs from desiccation and changes in hydraulic conductivity caused by cation exchange combined with desiccation.

Review of the data in Table 6 indicates that neither of these recommendations may be adequate to ensure that the low hydrau-

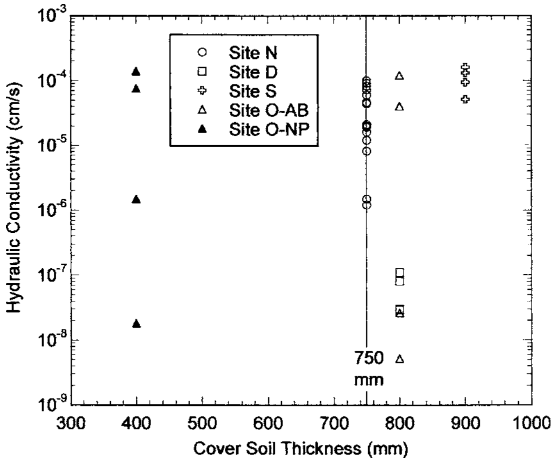

Fig. 11. Hydraulic conductivities of exhumed geosynthetic clay liners as a function of the thickness of the surface layer. Vertical line corresponds to Egloffstein's recommended minimum thickness (750 mm) to prevent changes in hydraulic conductivity caused by cation exchange and dehydration.

lic conductivity of a GCL is maintained. Hydraulic conductivities exceeding 10^{-6} cm/s were obtained for seven of the nine cases in Table 6 that have cover soils at least 750 mm thick, and the hydraulic conductivities exceeding 10^{-6} cm/s include the GCL evaluated by Henken-Mellies et al. (2002), which was overlain by 1,000 mm of soil. In addition, the highest hydraulic conductivity was obtained for Site S, which was covered with 900 mm of soil and a geomembrane. As illustrated in Fig. 11, there is no relationship between cover soil thickness and hydraulic conductivity of the exhumed GCLs. Whether any cover soil thickness is adequately protective remains unknown and deserves further study.

The data from Site S illustrate that covering a GCL with a geomembrane does not necessarily preclude increases in hydraulic conductivity or cation exchange, as this GCL had the highest median hydraulic conductivity of all the GCLs evaluated in this study, a Na mole fraction between 0.18 and 0.22, and a Ca mole fraction between 0.61 and 0.68. The reasons why the GCL from Site S were so permeable has not been determined conclusively, and the generality of this finding is unknown (only one site with a geomembrane over the GCL was evaluated). However, one possible explanation is that minimal hydration of the GCL occurred beneath the geomembrane before cation exchange occurred, a condition known to preclude osmotic swelling of the bentonite (Norrish and Quirk 1954; Jo et al. 2004; Kolstad et al. 2004). Consequently, water molecules were not bound in the interlayer and low hydraulic conductivity may never have been achieved, even when the GCL was first hydrating. Rapid exchange relative to the rate of hydration is known to result in bentonite having a hydraulic conductivity on the order of 10^{-5} cm/s for stresses typical of covers (Jo et al. 2005), which is similar to the hydraulic conductivity of the GCL at Site S.

Uncertainty exists regarding the mechanism responsible for exchange at Site S. However, as mentioned previously, the exchangeable Ca and Mg on the bentonite may have originated in the subgrade and migrated upward into the GCL via diffusion. The high hydraulic conductivity of the GCL at Site S may also have implications for linear applications where a composite liner consisting of a geomembrane overlying a GCL is placed on a subgrade soil where divalent cations are predominant.

Evaluating Compatibility of Cover Soils with Swell Index Tests

The batch elution procedure described in ASTM D 6141 is one method of creating synthetic pore water for evaluating the compatibility of cover soils and GCLs. The ASTM D 6141 batch test produced leachates having similar ionic strength as the elution tests when synthetic rainwater was used as the eluent. The leachate from ASTM D 6141 also had RMDs similar to, but slightly higher than the RMDs produced by the elution tests (average ratio of RMD for batch test to column test of 1.17). Thus, ASTM D 6141 appears to be a reasonable method to create synthetic pore water. More research is necessary, however, to verify that the ASTM D 6141 batch test with synthetic rainwater yields pore waters typical of field conditions.

The eluent from ASTM D 6141 is often used as the hydrating liquid for swell index tests to diagnose the compatibility of cover soils and bentonite in GCLs. As shown in Table 4, the swell indices for the batch test liquids range between 28 and 30 mL/2 g. This range is slightly lower than swell index of the new GCL in DI water (34–36 mL/2 g), but is not atypical of swell indices associated with Na bentonites (Jo et al. 2001; Kolstad et al. 2004; Katsumi and Fukagawa 2005; Lee and Shackelford 2005; Lee et al. 2005). In contrast, bentonite from GCLs exhumed from the field sites had swell indices ranged between 7 and 11 mL/2 g (Table 5), which are typical of Ca bentonite. This comparison, along with the hydraulic conductivities reported in Table 5, suggests that swell index tests conducted using the leachate from ASTM D 6141 batch tests are not reliable indicators of incompatibility between a GCL and a cover soil.

Summary and Conclusions

GCL samples were exhumed from four landfills and tested for water content, swell index, saturated hydraulic conductivity, and exchangeable cations. Tests were also conducted on a new GCL that had never been in service. Samples of the overlying cover soil from each landfill were also obtained and subjected to batch and column elution tests.

Most of the exchangeable Na initially on the bentonite in the exhumed GCLs was replaced by Ca and Mg, and the bentonites had swell indices typical of Ca bentonite (~10 mL/2 g). Hydraulic conductivities of the exhumed GCLs varied over a wide range (5.2×10^{-9} to 1.6×10^{-4} cm/s), and exhibited no relationship with cover soil thickness or mole fraction of exchangeable Na. Very high hydraulic conductivities (5.6×10^{-5} to 1.6×10^{-4} cm/s) were even obtained for a GCL that had been covered by a geomembrane and 900 mm of soil. The exchangeable cations, swell indices, and hydraulic conductivities of the exhumed GCLs in this study are similar to those reported in several other field studies in the United States and Europe. The similarity of these findings suggests that Ca-for-Na exchange in the bentonite of GCLs is likely to occur at most field sites (unless the overlying soil is sodic, which is unusual) and that large increases in hydraulic conductivity are likely to occur, unless the water content of the GCL can be maintained above 100%. None of the conventional means assumed to protect a GCL (cover soil at least 750 mm thick, overlying geomembrane) appears effective in preventing large increases in hydraulic conductivity.

Hydraulic conductivity of the exhumed GCLs was strongly related to the gravimetric water content at the time of sampling. GCLs with gravimetric water contents less than 85% had high hydraulic conductivities (10^{-6} to 10^{-4} cm/s), whereas GCLs with gravimetric water contents greater than 100% had lower hydraulic conductivities (10^{-8} to 10^{-7} cm/s). Controlled desiccation of exhumed GCLs that had low hydraulic conductivity (10^{-9} to 10^{-7} cm/s) resulted in increases in hydraulic conductivity of 1.5–4 orders of magnitude, even with an applied overburden pressure simulating 1 m of cover soil. The results of the controlled desiccation treatment indicate that desiccation (or lack of hydration) is a key factor controlling the hydraulic conductivity of GCLs once Ca-for-Na exchange has occurred.

If GCLs are to be considered as effective hydraulic barrier layers in landfill cover systems, the ability to protect GCLs from ion exchange and desiccation must be demonstrated. The hydraulic conductivity data reported in the literature for GCLs used in landfill covers, in conjunction with the data from this study, imply that commonly used protective measures (cover soil thickness >750 mm, overlying geomembrane) may be inadequate in many cases. Moreover, the common test method used to assess compatibility between bentonite and cover soils (i.e., ASTM D 6141) is unable to discriminate between conditions that cause long-term alterations in the exchange complex and hydraulic conductivity of GCLs. These findings indicate that more research is needed regarding installation methods that will ensure rapid hydration of GCLs, protective measures that will prevent dehydration, and test methods that can be used to diagnose whether a GCL is likely to undergo large increases in hydraulic conductivity when used in a landfill cover.

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