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Joseph Scalia IV[1] *and Craig H. Benson*[2]

Effect of Permeant Water on the Hydraulic Conductivity of Exhumed GCLs

ABSTRACT: Hydraulic conductivity tests were performed on geosynthetic clay liners (GCLs) exhumed from composite barriers (i.e., geomembrane over GCL) in four landfill covers using three dilute permeant waters: type II deionized water (DW), 0.01*M* $CaCl_2$ (so called "standard water" (SW)), and a typical water having average characteristics of eluent from cover soils ("average water" (AW)). Depending on the exhumed state of the GCL, very different (up to four orders of magnitude) hydraulic conductivities were obtained with DW, AW, and SW. When macroscopic features were present in the GCL, similar hydraulic conductivities (1×10^{-9}–2×10^{-7} m/s) were obtained with SW and AW, but lower hydraulic conductivities were obtained with DW (1×10^{-11}–3×10^{-10} m/s). For GCLs without macroscopic features, much higher hydraulic conductivities were obtained with SW (1×10^{-9}–2×10^{-7} m/s) than AW or DW ($<2\times10^{-11}$ m/s) if the exhumed GCL had lower water content (<46 %), whereas similar hydraulic conductivities ($<5\times10^{-11}$ m/s) were obtained with all three waters if the GCL had higher water content (>53 %). For GCLs with lower water contents, permeation with AW or DW had minimal effect on the composition of bound cations. In contrast, permeation with SW reduced the mole fraction of monovalent bound cations. These findings demonstrate that the chemistry of the permeant water can have a significant effect on the hydraulic conductivity of exhumed GCLs even when the permeant water is dilute. To simulate typical conditions, a solution containing 1.3 mM NaCl and 0.8 mM $CaCl_2$ is recommended as the permeant water (73.8 mg of anhydrous NaCl and 87.0 mg of anhydrous $CaCl_2$/L DW). A conservative assessment of hydraulic conductivity can be obtained using 0.3 mM NaCl and 1.9 mM $CaCl_2$ (15.5 mg of anhydrous NaCl and 214.6 mg $CaCl_2$/L DW).

KEYWORDS: geosynthetic clay liner, landfill, cover, cation exchange, permeant water, hydraulic conductivity

Introduction

Geosynthetic clay liners (GCLs) are factory-manufactured hydraulic barriers used in waste containment systems. In a final cover, a new GCL containing sodium (Na) bentonite typically will have a saturated hydraulic conductivity of $\sim1\times10^{-11}$ m/s (Shan and Daniel 1991; Shackelford et al. 2000; Jo et al. 2001, 2005; Kolstad et al. 2004). However, recent studies on GCLs exhumed from final covers have shown that the initially low hydraulic conductivity can increase appreciably while a GCL is in service. For example, Melchior (2002), Meer and Benson (2007), and Benson et al. (2007) reported hydraulic conductivities in the range of 1×10^{-7}–1×10^{-6} m/s for GCLs exhumed from final covers having service lives ranging from 2.0 to 11.0 years.

The hydraulic conductivity of new or exhumed GCLs is strongly affected by conditions during hydration (Jo et al. 2001, Meer and Benson 2007, Benson et al. 2007, Benson and Meer 2007). Bentonite in a GCL hydrates in two distinct phases: the crystalline phase and the osmotic phase (Norrish and Quirk 1954). Crystalline hydration occurs first as water molecules move into the interlayer space, hydrating the mineral surface and associated cations and forcing the interlayer to separate by a distance corresponding to several water molecules (McBride 1994). Osmotic hydration then follows as water molecules flow into the interlayer region in response to the concentration gradient between the interlayer region and the free pore water forcing the interlayer to separate much more than crystalline swelling alone (McBride 1994). When the bentonite in a GCL undergoes osmotic swell during hydration, GCLs have lower hydraulic conductivity ($<3\times10^{-10}$ m/s) and will maintain lower hydraulic conductivity in the presence of dilute solutions of inorganic chemicals provided that the bentonite does not dehydrate (Jo et al. 2001, 2005; Benson and Meer 2007). In contrast, if the bentonite only undergoes crystalline swelling during hydration, the hydraulic conductivity of the GCL can be three to four orders of magnitude higher (Lin and Benson 2000; Jo et al. 2001; Jo et al. 2004).

The state of hydration at the onset of permeation is controlled by the ionic strength (I) and the relative abundance of monovalent and multivalent cations in the hydrating liquid and how these chemical characteristics affect the distribution and composition of cations adsorbed on the clay surface (Jo et al. 2001; Kolstad et al. 2004). GCLs hydrated in strong solutions dominated by multivalent cations exhibit crystalline swell and higher hydraulic conductivity, whereas GCLs hydrated in dilute solutions exhibit greater osmotic swell and low hydraulic conductivity. GCLs exhumed from the field may be partially or fully hydrated. Thus, the chemistry of the permeant water may affect the outcome of a hydraulic conductivity test conducted on an exhumed GCL.

The potential importance of the chemistry of the permeant solution has been known for decades. For example, in their seminal paper on hydraulic conductivity testing of fine-grained soils, Olson and Daniel (1981) recommend using "a permeant of the same chemistry as the original pore water." Nevertheless, common test methods employed for hydraulic conductivity testing of GCLs (e.g., ASTM D5084 (2003), ASTM D5887 (2009), or ASTM D6766 (2009)) provide little guidance on appropriate permeant solutions, although they do acknowledge that the chemistry of the permeant solution may affect the outcome of the test. For example, ASTM D5887 stipulates deionized (DI) water (DW) as the permeant solution but indicates that the "flux through a GCL specimen

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[1] Graduate Research Assistant, Geological Engineering, Univ. of Wisconsin—Madison, Madison, WI 53706 (Corresponding author), e-mail: scalia@wisc.edu

[2] Wisconsin Distinguished Professor and Chair, Geological Engineering, Univ. of Wisconsin—Madison, Madison, WI 53706, e-mail: chbenson@wisc.edu

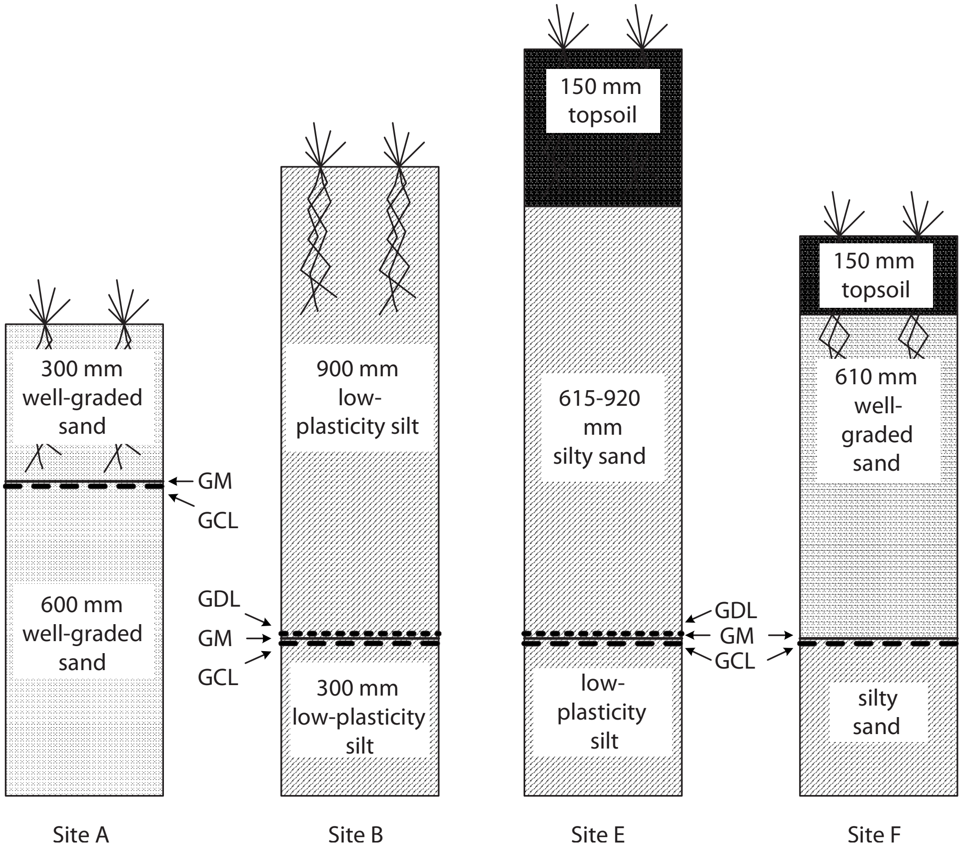

FIG. 1—*Profiles of final covers at landfills where GCLs were exhumed. GM = geomembrane, GCL = geosynthetic clay liner, and GDL = geosynthetic drainage layer.*

can be substantially influenced by the permeating fluid" and that "the flux value determined using this test method is not considered to be representative of the in-service flux of GCLs." ASTM D6766 states that "test liquids should be specified, and if necessary supplied along with a detailed chemical composition" by the requestor. ASTM D5084 states that "chemical interactions between a permeant liquid and the porous material may lead to variations in hydraulic conductivity" and that the "type of permeant water should be specified by the requestor." Additionally, ASTM D5084 cautions against using distilled or DW and indicates that "potable tap water shall be used for the permeant liquid" if the permeant water is not specified by the requestor. ASTM D5084 also recommends using $0.01M$ $CaCl_2$ "in areas with extremely hard or soft water." In practice, the $0.01M$ $CaCl_2$ solution cited in ASTM D5084 is commonly used for hydraulic conductivity testing and is often referred to as "standard water" (SW).

In this study, three permeant waters were evaluated when conducting hydraulic conductivity tests on GCLs exhumed from four landfill final covers: DW, SW, and a water having average characteristics of pore water eluted from cover soils placed adjacent to GCLs (i.e., the water that permeates the GCL in the field). The water with typical characteristics is referred to as average water (AW) henceforth. The impact of these permeant waters on the hydraulic conductivity of exhumed GCLs is presented along with the effect of permeation on bound cations (BCs). Based on these findings, recommendations are made regarding permeant waters for hydraulic conductivity testing of exhumed GCLs.

Sampling and Characterization

Geosynthetic Clay Liners

GCLs were exhumed from final covers at four landfills. Two of these landfills (sites A and B) were located in western coastal states of the United States, and two were located in upper Midwestern states (sites E and F). The cover profile at each site is shown in Fig.

TABLE 1—*Description of covers at field sites.*

	Site					
Property	A	B	E-01	E-02	F-03	F-05
Location	West		Midwest			
Installation date	5/2002	11/2000	8/2001	9/2002	9/2003	7/2005
Sampling date	3/2007	8/2007	6/2007	6/2007	8/2008	8/2008
Years in service (years)	4.9	6.7	5.8	4.7	4.9	3.1
Surface layer thickness (mm)	300	900	915–1145	915–1220	760	

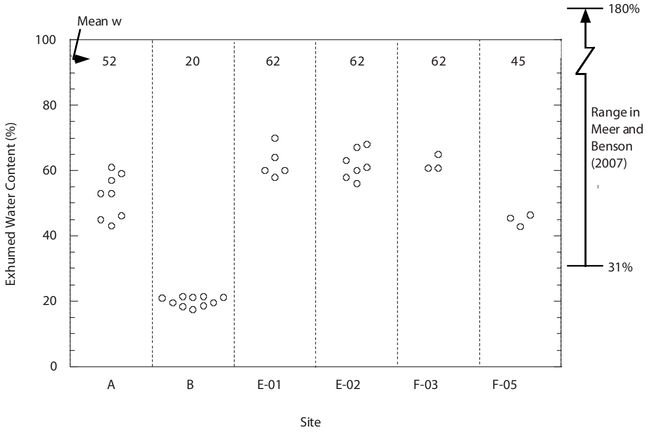

FIG. 2—*Water content of exhumed GCLs.*

1 and summarized in Table 1. At the time of exhumation, the GCLs had been in service for 3.1–6.7 years. At both Midwestern sites, GCLs were exhumed from two portions of the final cover constructed in separate years. Thus, data from these sites are designated with a suffix corresponding to the year when they were installed (see Table 1). All of the GCLs exhumed in this study were part of a composite barrier consisting of a GCL overlain by a geomembrane. Covers with composite barriers were selected for this study to complement data from studies by Melchior (2002), Meer and Benson (2007), and Benson et al. (2007), which focused primarily on covers where the GCL was the only barrier layer.

All GCLs were sampled in accordance with ASTM D6072 (2009), with a minimum of six square samples (0.3 m × 0.3 m) collected at each site. Soils over the geosynthetics were removed from an area of ~4 × 4 m^2 using a tracked excavator until the excavation was within ~0.15 m of the uppermost geosynthetic layer. The remaining soil was then removed by hand. Rectangular sections (0.2 m × 0.2 m) of geocomposite drainage layer (if present) and geomembranes (GM) were removed from the floor of the test pit by cutting the edges with a sharp utility knife. The perimeter of each GCL sample was scored and cut with a sharp utility knife, slid onto a rigid PVC plate, and sealed with plastic sheeting to prevent loss of moisture. All wrapped GCL samples were placed in plastic tubs and covered with at least 0.15 m of loose soil for protection during transport. No defects were observed in any of the overlying GMs. All evidence suggested that the GCLs were isolated hydraulically from the overlying cover soils.

Each of the GCLs was originally comprised of natural granular Na bentonite between two geotextiles bonded by thermally locked needle punching. These GCLs are typical of GCLs used in the United States. Water content of bentonite in each GCL sample was determined in accordance with ASTM D2216 (2005). Exhumed GCL water contents are shown by site in Fig. 2. At a given site, the water contents vary by at most 14 %, and overall the water contents fall within a band (17–70 %) that has less range than exhumed GCLs reported in past studies (31–180 %) (Meer and Benson 2007; Melchior 2002). GCLs in this study also had lower water contents, on average (mean w=52 %), than the GCLs exhumed by Meer and Benson (2007) (mean w=104 %) due to hydraulic isolation afforded by the overlying geomembrane. Thicknesses of the exhumed GCLs are presented in Table 2. A correlation between exhumed GCL thickness and water content was not evident.

TABLE 2—*Average physical properties of exhumed GCLs.*

	Thickness (mm)		Water Content (%)	
Site	Mean	Std. Dev.	Mean	Std. Dev.
A	7.0	0.0	52	3
B	7.3	0.3	20	2
E-01	6.8	0.4	62	5
E-02	6.7	0.6	59	5
F-03	8.3	1.7	63	2
F-05	5.1	0.2	45	2

Swell index (SI) tests were performed on bentonite from the GCLs in accordance with the methods described in ASTM D5890 (2006) using DW as the hydrating solution. The SIs are summarized in Table 3 and are presented by site in Fig. 3. The upper shaded range corresponds to SI typical for Na bentonites (26–30+ mL/2 g), and the lower shaded range represents SI typical for Ca bentonites (5–10 mL/2 g). Even with an overlying GM in place to prevent downward flow from overlying soil pore water, the exhumed GCLs were not protected from loss of swell. GCLs from four of six sites in this study (E-01, E-02, F-03, and F-05) had SI in the range typical for Ca bentonite. Similar findings were reported by Meer and Benson (2007) for GCLs exhumed from covers with and without a geomembrane over the GCL. Greater SI were observed for GCLs from two sites (A and B), although these SI are less than the SI of a new GCL with Na bentonite. The observed reductions in SI are directly related to the extent of cation exchange in the bentonite (discussed subsequently).

BCs and cation exchange capacity (CEC) were determined following the method in the draft ASTM (2010), "Standard Test Method for Measuring Exchangeable Cations and Cation Exchange Capacity of Fine Grained Soils," which is being balloted by ASTM Subcommittee D18.04. This method uses extraction with ammonium acetate to determine BC and CEC as described by Thomas (1982). Tests were conducted on 10 g of air-dry bentonite crushed to pass the No. 20 U.S. standard sieve. BCs are defined as cations adsorbed (bound) to the mineral surface that may be exchanged. A chemical analysis of extracts was conducted using inductively coupled plasma optimal emission spectroscopy (ICP-OES) following USEPA Method 6010B (2007). BC mole fractions were calculated as the ratio of total charge associated with a specific BC to the CEC. BC mole fractions of the dominant exchangeable cations (Na, K, Ca, and Mg) are presented in Table 3.

Mole fractions of bound monovalent cations (X_m) are shown by site in Fig. 4. A typical new GCL has X_m between 0.65 and 0.80 (composed predominantly of Na) (Meer and Benson 2007), whereas the X_m of exhumed GCLs is <0.18 at four of the six sites and below 0.61 at all sites. Thus, even with a GM over the GCL, cation exchange occurs in the bentonite, which is consistent with the decrease in SI shown in Fig. 3 (Jo et al. 2004; Meer and Benson 2007). The Na was replaced primarily by Ca and Mg (Table 3), which most likely originated from the subgrade and/or from dissolution of carbonates within the GCL (James et al. 1997; Guyonnet et al. 2005; Meer and Benson 2007; Guyonnet et al. 2009). GCLs with the greatest cation exchange also had the highest water contents when exhumed (Fig. 5) regardless of the number of years in service. New GCLs were assigned the average water content for GCL rolls received from the manufacturer (mean=7 %) at the University of Wisconsin Geotechnics Laboratory. Greater exchange in the GCLs with higher water content probably occurred

TABLE 3—*Physical and chemical properties of exhumed GCLs.*

			Hydraulic Conductivity (m/s)			Initial Exchange Complex (mole fractions)			
Site ID	SI (mL/2 g)	Water Content (%)	SW	AW	DW	Na	K	Ca	Mg
New[a]	36[a]	···	1.2×10^{-11}[a]	···	1.1×10^{-11}[a]	0.74[a]	0.02[a]	0.22[a]	0.03[a]
	34[a]	···	1.7×10^{-11}[a]	···	1.0×10^{-11}[a]	0.65[a]	0.02[a]	0.27[a]	0.03[a]
Site A	20.5	53	1.1×10^{-11}	···	···	0.32	0.01	0.48	0.18
	18.0	55	1.0×10^{-11}	···	···	0.33	0.01	0.49	0.17
	22.0	53	9.3×10^{-12}	···	···	0.39	0.01	0.43	0.17
	19.8	56	1.3×10^{-11}	1.2×10^{-11}	1.0×10^{-11}	0.35	0.01	0.47	0.16
	13.0	53	1.5×10^{-11}	···	···	0.25	0.01	0.57	0.17
	20.5	61	1.2×10^{-11}	···	···	0.30	0.01	0.50	0.19
	20.0	57	1.4×10^{-11}	···	···	0.29	0.01	0.51	0.19
	16.5	59	1.6×10^{-11}	···	···	0.34	0.01	0.49	0.16
Site B	12.0	22	1.8×10^{-8}	2.1×10^{-11}	···	0.37	0.03	0.41	0.20
	14.0	21	2.0×10^{-8}	2.0×10^{-11}	···	0.45	0.03	0.52	0.00
	20.0	21	4.1×10^{-9}	1.9×10^{-11}	···	0.52	0.03	0.29	0.16
	16.5	21	1.5×10^{-8}	2.2×10^{-11}	···	0.59	0.03	0.24	0.14
	16.0	17	2.3×10^{-9}	1.4×10^{-11}	···	0.46	0.03	0.33	0.18
	14.0	20	8.5×10^{-9}	1.4×10^{-11}	···	0.46	0.03	0.33	0.18
	17.0	18	2.1×10^{-9}	1.5×10^{-11}	2.0×10^{-11}	0.43	0.03	0.35	0.19
	13.0	19	4.5×10^{-8}	1.2×10^{-11}	···	0.41	0.02	0.37	0.20
	15.0	20	1.5×10^{-9}	1.4×10^{-11}	···	0.54	0.03	0.28	0.15
	18.0	21	1.9×10^{-8}	1.3×10^{-11}	···	0.52	0.03	0.29	0.16
Site E-01	8.0	70	4.7×10^{-11}	···	···	0.06	0.01	0.71	0.21
	8.0	64	4.2×10^{-11}	···	···	0.06	0.01	0.70	0.22
	10.0	58	4.0×10^{-11}	···	···	0.05	0.01	0.69	0.25
	10.0	60	2.3×10^{-11}	···	···	0.05	0.02	0.72	0.22
	8.0	58	1.3×10^{-8}[b]	···	···	0.05	0.01	0.70	0.25
Site E-02	10.0	56	1.6×10^{-7}[b]	···	···	0.06	0.02	0.66	0.26
	10.0	56	1.3×10^{-7}[b]	8.9×10^{-8}	2.5×10^{-10}	0.03	0.01	0.70	0.26
	11.0	63	2.1×10^{-8}[b]	···	···	0.04	0.00	0.71	0.25
	9.0	60	1.5×10^{-8}[b]	···	···	0.04	0.01	0.69	0.25
	11.0	68	3.3×10^{-11}	···	···	0.05	0.01	0.67	0.27
	10.0	67	3.2×10^{-11}	···	···	0.05	0.01	0.69	0.25
	8.0	61	3.7×10^{-11}	···	···	0.05	0.02	0.72	0.21
Site F-03	8.0	61	6.5×10^{-9}[b]	6.1×10^{-9}	8.9×10^{-11}	0.03	0.03	0.95	0.00
	10.0	61	2.6×10^{-9}[b]	1.9×10^{-9}	9.3×10^{-11}	0.01	0.03	0.96	0.00
	10.0	65	3.3×10^{-9}[b]	3.7×10^{-9}	1.2×10^{-10}	0.01	0.02	0.97	0.00
Site F-05	13.0	43	3.8×10^{-9}	1.0×10^{-11}	1.3×10^{-11}	0.14	0.03	0.83	0.00
	12.0	46	2.1×10^{-7}	1.2×10^{-11}	1.4×10^{-11}	0.14	0.04	0.83	0.00
	13.0	45	1.1×10^{-8}	1.9×10^{-11}	1.3×10^{-11}	0.13	0.03	0.84	0.00

[a] Tests conducted by Meer and Benson (2007).

[b] Preferential flow observed.

due to the higher aqueous-phase diffusion coefficient at higher water saturation (Quigley et al. 1987; Jury et al. 1991).

Subgrade Soils

A bulk sample of subgrade soil was collected directly beneath each GCL sample. Water contents (w) (ASTM D422 (2007)) and Unified Soil Classification System (USCS) classifications (ASTM D2487 (2006)) of the subgrade soils are summarized in Table 4. The subgrade soils range from well graded sand (site A) to low plasticity clayey silt (site E) and exhibit a wide range of water content, from 2.3 % (site B) to 15.9 % (site F-03).

Elution tests were conducted on each subgrade soil using the batch method described in ASTM D6141 (2009). Meer and Benson (2007) indicate that this procedure "provides a relatively simple and expedient method to generate a test liquid representative of flow-through conditions." DW was used as the eluent at a liquid-to-solid ratio of 1.3. The mixture was sealed in a 250 mL bottle and rotated for 24 h. The eluent was separated by centrifugation and vacuum filtered through 0.45 μm filter paper. Concentrations of the major cations (Ca, Mg, Na, and K) in the eluent were measured using ICP-OES following USEPA Method 6010 B.

The relative abundance of monovalent and multivalent cations in the eluents was characterized by the ratio of monovalent to divalent cations (RMD), defined as $M_m/\sqrt{M_d}$, where M_m is the total molarity of monovalent cations in solution and M_d is the total molarity of multivalent cations in the solution (Kolstad et al. 2004). Kolstad et al. (2004), Jo et al. (2005), and Benson and Meer (2007) show that RMD is the predominant variable affecting the hydraulic conductivity of GCLs at low ionic strengths (I). The average ionic

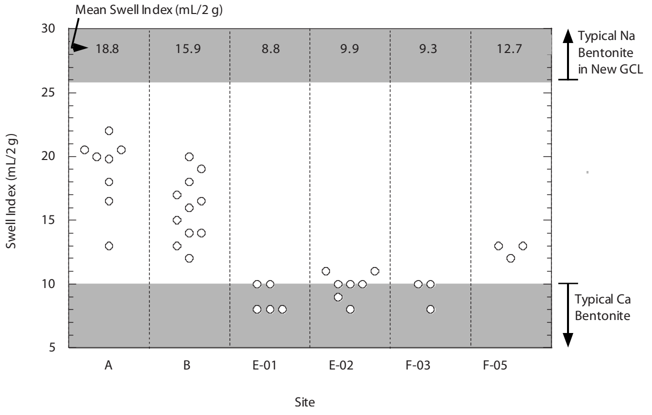

FIG. 3—*SI of bentonite from exhumed GCLs in DW.*

strength and RMD of the eluent from each subgrade soil are presented in Table 5. Ionic strength was computed using only the cation concentrations. Thus, the computed ionic strength is lower than the actual ionic strength of the solutions. Table 5 also includes I and RMD of eluents from cover soils (reported by Meer and Benson (2007)) and subgrades (reported by Bradshaw (2008)) that were generated using the same methods employed in this study.

Ionic strength and RMD of the eluents are shown in Fig. 6. Eluents in this study typically have higher ionic strength ($0.0030M-0.0056M$) than those reported by Meer and Benson (2007) ($0.0004M-0.0032M$) and Bradshaw (2008) ($0.0022M-0.0037M$). However, the RMD of the eluents in this study ($0.02-0.08M^{0.5}$) falls within the ranges reported by Meer and Benson (2007) ($0.01M^{0.5}-0.08M^{0.5}$) and Bradshaw (2008) ($0.006M^{0.5}-0.12M^{0.5}$). All eluents have RMDs less than $0.14M^{0.5}$, which Benson and Meer (2007) show is the threshold below which GCLs undergo appreciable increases in hydraulic conductivity when exposed to wet-dry cycling.

Hydraulic Conductivity Tests

Hydraulic conductivity tests were conducted on the GCL specimens in flexible-wall permeameters following the procedures in ASTM D5084. The falling headwater-constant tailwater method was employed. Backpressure was not applied to represent the field condition. An average effective stress between 15 and 24 kPa was applied based on the in situ cover thickness. To avoid washing of fines from specimens with low initial water content, in-cell hydration for 48 h was conducted prior to flow. After the permeameter was assembled and connected to the falling headwater apparatus, cell pressure was applied, and all tubing was saturated with the permeant liquid. The inflow line of the permeameter was then opened to allow the specimen to hydrate. After 48 h, flow under an average hydraulic gradient of 125 was initiated by opening the effluent lines. This hydraulic gradient is higher than in the field but is typical for GCL testing. In addition, Shackelford et al. (2000) showed that hydraulic gradient has negligible impact on the hydraulic conductivity of GCLs when the hydraulic gradient is less than 500.

Equilibrium hydraulic conductivity was established through the termination criteria detailed in ASTM D5084. Termination criteria based on chemical equilibrium were not used because the goal of testing was to determine the hydraulic conductivity of the GCL in the as-exhumed condition, rather than to evaluate incompatibility between the GCL and a liquid being contained.

Specimens were cut from the GCL field samples using a razor knife. The GCL sample was retained on the rigid plastic sampling plate during cutting to avoid disturbing structure within the bentonite. After cutting, geotextile fibers around the perimeter of the specimen were trimmed back with scissors. The mass of the specimen was measured, and the thickness of the GCL specimen was

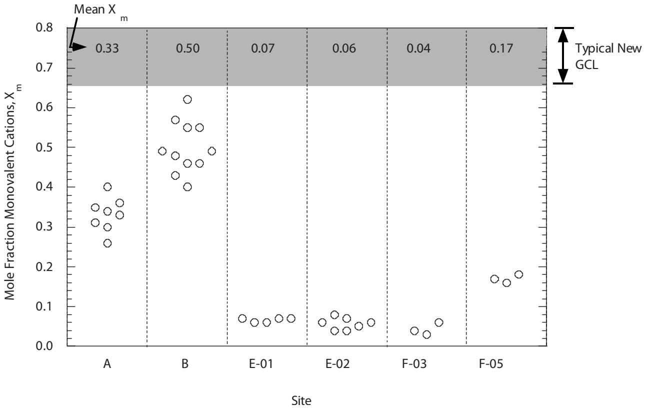

FIG. 4—*Mole fraction monovalent BCs for exhumed GCLs.*

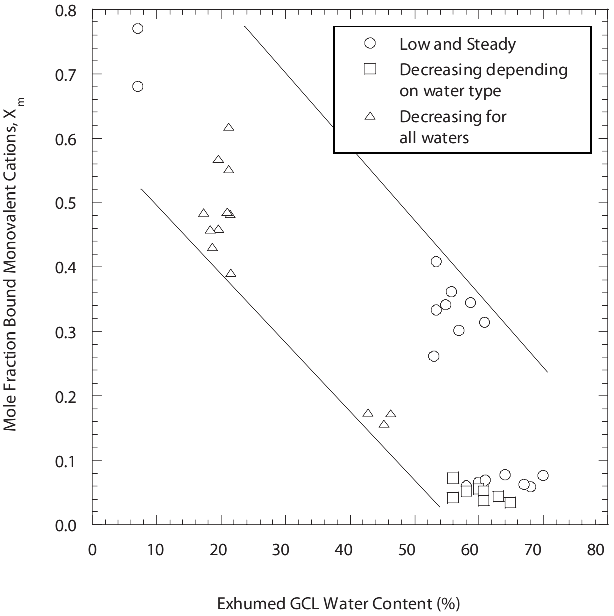

FIG. 5—*Mole fraction of bound monovalent cations versus exhumed GCL water content.*

TABLE 4—*Water content and USCS classification of subgrade underlying GCLs.*

Site	Water Content (%) Mean	Std. Dev.	USCS Classification Mean
A	9.8	0.0	SW
B	2.3	0.2	ML
E-01	14.9	1.6	CL-ML
E-02	15.6	1.2	CL-ML
F-03	15.9	0.0	SM
F-05	8.5	0.0	SM

TABLE 5—*Ionic strength and RMD of pore water in soils adjacent to GCLs as determined by batch elution.*

		Ionic Strength (*M*)		RMD ($M^{0.5}$)	
Site	Source	Mean	Std. Dev.	Mean	Std. Dev.
A	This study	0.0035	0.0007	0.0546	0.0109
B	This study	0.0045	0.0006	0.0657	0.0057
E-01	This study	0.0041	0.0021	0.0432	0.0097
E-02	This study	0.0031	0.0009	0.0333	0.0049
F-03	This study	0.0030	0.0006	0.0193	0.0009
F-05	This study	0.0056	0.0008	0.0730	0.0105
D	Meer and Benson (2007)	0.0004	⋯	0.0210	⋯
N	Meer and Benson (2007)	0.0010	0.0001	0.0177	0.0106
O	Meer and Benson (2007)	0.0009	0.0000	0.0364	0.0243
S	Meer and Benson (2007)	0.0006	0.0001	0.0147	0.0010
ACAP A	Meer and Benson (2007)	0.0032	⋯	0.0299	⋯
ACAP F	Meer and Benson (2007)	0.0028	⋯	0.0713	⋯
ACAP V	Meer and Benson (2007)	0.0015	⋯	0.0789	⋯
Torpedo sand	Bradshaw (2008)	0.0022	0.0000	0.0121	0.0040
Cedar rapids clay	Bradshaw (2008)	0.0033	0.0001	0.0065	0.0003
Red wing clay	Bradshaw (2008)	0.0027	⋯	0.0938	⋯
Boardman silt	Bradshaw (2008)	0.0037	0.0003	0.1150	0.0019

measured with calipers at six equidistant points around the GCL perimeter. Light pressure was applied with the caliper to compress the geotextiles while not deforming the bentonite layer. A thin frosting of Na bentonite (from a new GCL roll) paste hydrated in the permeant water was applied to the perimeter of the specimen to prevent sidewall leakage.

Three permeant waters were used in the hydraulic conductivity tests: SW (0.01*M* $CaCl_2$ solution), type II DW, and a synthetic pore water with an *I* and RMD at the arithmetic mean of the batch elution data (AW) (Table 5). These permeant waters were intended to represent waters typically used in practice (SW and DI) as well as representative soil eluent (AW) from soil contacting GCLs. SW and AW were created by dissolving reagent-grade NaCl and $CaCl_2$ salts in DW. Chemical characteristics of these permeant waters are summarized in Table 6 and are shown with the cover soil eluents in Fig. 6. Cover soil eluents are more dilute ($>4\times$) and more sodic than SW. In contrast, DW has a much lower ionic strength ($<3.7 \times 10^{-7} M$) than the soil eluents and has an undefined RMD. The $CaCl_2$ in SW (0.01*M*) is only slightly more dilute than the 0.0125*M* solution employed by Lin and Benson (2000) to evaluate the impacts of wet-dry cycling on GCLs and the 0.012*M* $CaCl_2$ solution employed by Egloffstein (2001) to evaluate the long-term hydraulic conductivity of GCLs. Benson et al. (2007) and Meer and Benson (2007) also used SW for permeating their GCLs. AW was incorporated into this study to provide a water type representing an average in situ condition.

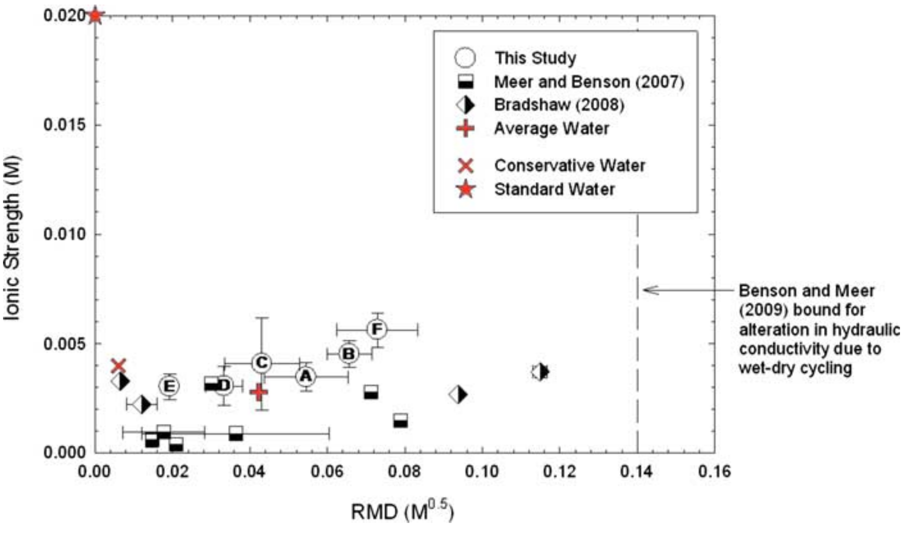

FIG. 6—*Ionic strength versus RMD of pore water eluent solutions from batch test procedure ASTM D6141. Error bars correspond to one standard deviation from the mean. Permeants used (AW and SW) or recommended (CW) for laboratory testing are also shown. Sites in this study are delineated as (a) site A, (b) site B, (c) site E-01, (d) site E-02, (e) site F-03, and (f) site F-05.*

TABLE 6—*Na and Ca concentrations, ionic strength, and RMD of permeant waters used in GCL testing or recommended for use.*

	Na		Ca		Ionic Strength	RMD
Water Type	mg/L	*M*	mg/L	*M*	*M*	$M^{0.5}$
Standard (SW)	0	0	401	0.01	0.02	0
DI (DW)	<0.005	$<2.2\times10^{-7}$	<0.005	$<1.3\times10^{-7}$	$<3.7\times10^{-7}$	undf
Average (AW)	29.0	0.0013	31.4	0.0008	0.002	0.045
Conservative (CW)	6.1	0.0003	77.5	0.0019	0.004	0.006

Results

Temporal Hydraulic Conductivity Behavior

Hydraulic conductivities of the exhumed GCLs are summarized in Table 3. For specimens that exhibited high hydraulic conductivity ($>10^{-9}$ m/s), rhodamine water tracing (WT) dye (5 mg/L) was added to the influent liquid at the conclusion of testing to determine if sidewall leakage was occurring. No indication of sidewall leakage was found in any test. The effluent lines and effluent were also inspected throughout testing for migration of bentonite particles. No particles were observed in the effluent lines or effluent.

Three different types of temporal behavior were observed when permeating the exhumed GCLs with SW, AW, and DW: low and steady hydraulic conductivity (Fig. 7(*a*)), high and steady or decreasing hydraulic conductivity depending on water type (Fig. 7(*b*)), and decreasing hydraulic conductivity for all water types (Fig. 7(*c*)). The records shown in each graph in Fig. 7 are from separate specimens cut from the same GCL sample that were permeated with different waters. Steady or decreasing hydraulic conductivity was observed in all tests (hydraulic conductivity increasing over time was not observed).

Low and steady hydraulic conductivities with all waters (Fig. 7(*a*)) were observed for all (eight of eight) GCLs exhumed from site A and for seven of the 12 GCLs from Site E. In all cases with low and steady hydraulic conductivity, the hydraulic conductivity was on the order of 10^{-11} m/s regardless of the type of permeant water (Table 3). These GCLs had both the highest and lowest SI in the entire data set, and six of the 20 samples had SI typical of Ca bentonite (Fig. 8(*a*)). GCLs with low and steady hydraulic conductivity also had water contents on the wetter end of all exhumed GCLs (>53 %; Fig. 8(*b*)).

Decreasing hydraulic conductivity depending on water type (Fig. 7(*b*)) was observed for five of the 12 GCL samples from site E and for all (three of three) of the GCLs from site F-03. These GCLs also exhibited preferential vertical flow along bundles of needle-punched fibers. Mechanisms causing these preferential flow paths are outside the scope of this paper. However preferential flow paths are noted as they are influential in GCL-permeant water sensitivity (discussed subsequently). GCLs with preferential flow paths had high and steady hydraulic conductivity of the order of $10^{-9}-10^{-6}$ m/s when permeated with SW or AW but decreasing hydraulic conductivity that ultimately equilibrate at approximately 10^{-10} m/s when permeated with DW. All but one (seven of eight) of these GCLs had SI in the range typical of Ca bentonite (Fig. 8(*a*)), and all had water contents on the wetter end ($w>56$ %) of the data set (Fig. 8(*b*)).

Decreasing hydraulic conductivity for all water types (Fig. 7(*c*)) was observed for all (ten of ten) GCLs from site B and all (three of three) GCLs from site F-05. These GCLs had high hydraulic conductivity ($>10^{-7}$ m/s) initially, which then decreased rapidly to $\sim10^{-11}$ m/s when permeated with AW or DW or gradually to $10^{-9}-10^{-8}$ m/s when permeated with SW. All of these GCLs had lower water contents ($w<46$ %), and ten of the 13 GCL samples had water contents <22 % (Fig. 8(*b*)). SIs of these GCLs (Fig. 8(*a*)) were intermediate between the Na bentonite and Ca bentonite end states.

Effect of Permeant Water on Bound Cations

The key factor differentiating the GCLs with low and steady hydraulic conductivity (Fig. 7(*a*)) from the GCLs that had decreasing hydraulic conductivity with all water types (Fig. 7(*c*)) is the water content of the exhumed GCL (Fig. 8(*b*)). Exhumed GCLs with higher water content have undergone osmotic swell and have low hydraulic conductivity. Consequently, permeation with dilute permeant water for a testing period typical of ASTM D5084 or ASTM D6766 (generally <2 pore volumes of flow) has little effect on BCs in the bentonite and therefore little effect on hydraulic conductivity. This is illustrated in Fig. 9, which shows X_m before and after permeation with AW, DW, and SW for a GCL sample from site A that exhibited low and steady hydraulic conductivity. Each bar in Fig. 9 corresponds to a separate identical specimen from the same GCL sample. The fraction of monovalent BCs (Fig. 9) was essentially the same regardless of the permeant water used in the hydraulic conductivity test. Moreover, many of these GCLs had undergone complete replacement of Na and K by Ca while in service (Table 3). Thus, an alteration in hydraulic conductivity due to permeation with a dilute solution containing multivalent cations should not be expected.

For exhumed GCLs with lower water content that have undergone appreciable (but not complete) cation exchange while in service, the hydraulic conductivity decreases in response to osmotic swelling induced by hydration of the bentonite during permeation. Alterations in the pore water chemistry and the BCs during this hydration process influence the amount of osmotic swell that occurs and the rate of decrease in hydraulic conductivity (Jo et al. 2001; Kolstad et al. 2004). For example, permeation with all three waters reduced X_m in the GCL from site B (Fig. 9). The reduction in X_m was small when the GCL was permeated with AW or DW, whereas SW caused a much larger reduction in bound Na due to replacement by Ca. Consequently, permeation with SW inhibited osmotic swell (SI=13 mL/2 g), which resulted in a gradual reduction in hydraulic conductivity (Fig. 7(*c*)), and ultimately higher hydraulic conductivity at equilibrium ($2\times10^{-9}-5\times10^{-8}$ m/s). In contrast, permeation with AW or DW resulted in osmotic swell (SI=13 mL/2 g), a rapid reduction in hydraulic conductivity (Fig. 7(*c*)), and a low hydraulic conductivity at equilibrium ($<2.2\times10^{-11}$ m/s).

GCLs that had preferential flow paths (Fig. 7(*b*)) behaved differ-

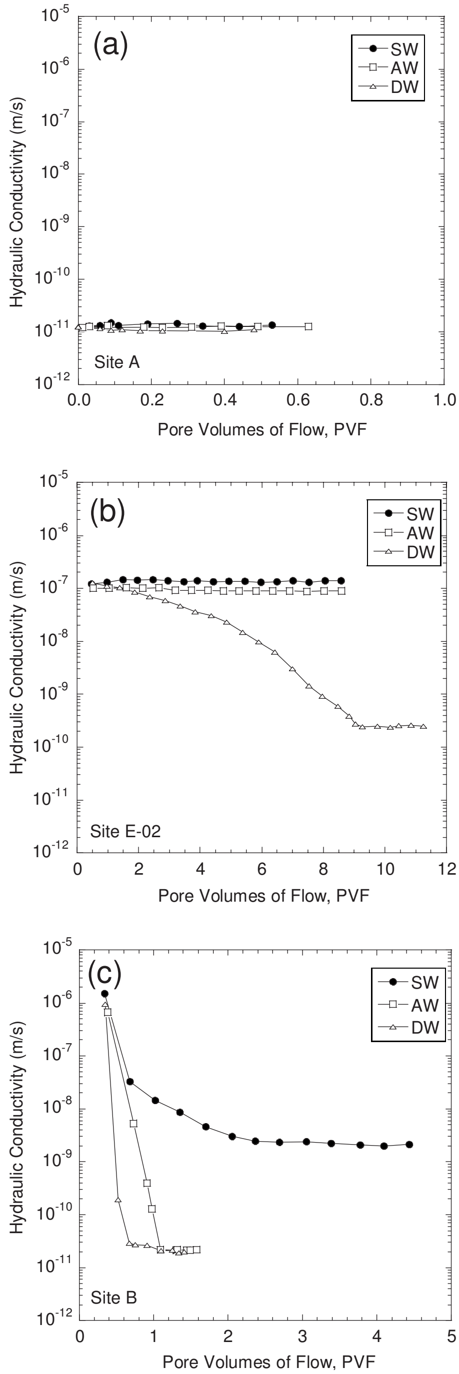

FIG. 7—*Hydraulic conductivity records typifying low and steady hydraulic conductivity (a) (total test durations ≈25 days), high and steady hydraulic conductivity with SW or AW, and gradually decreasing hydraulic conductivity with DW (b) (total test durations ≈5–35 days), and temporally decreasing hydraulic conductivity regardless of permeant chemistry (c) (total test durations ≈15–45 days).*

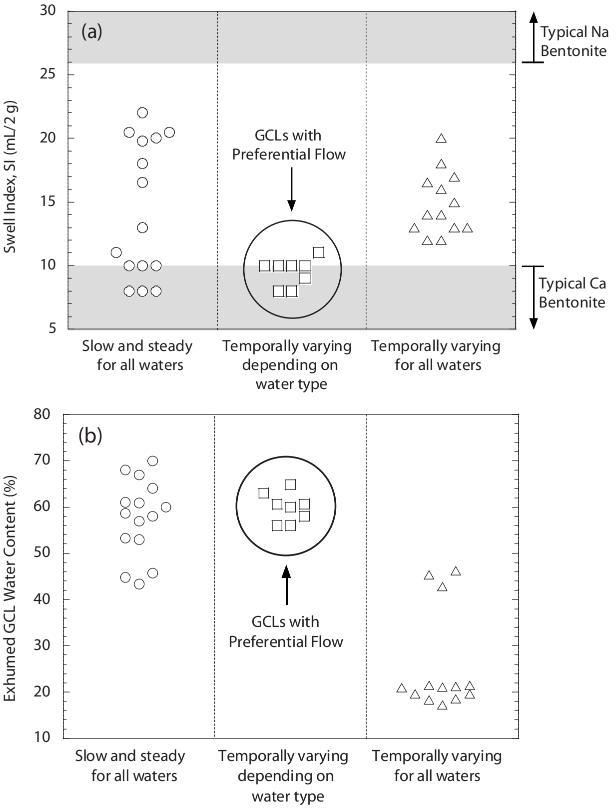

FIG. 8—*SI (a) and water content (b) for different temporal variations in hydraulic conductivity of exhumed GCLs.*

ently than the other GCLs. Regardless of the solution used for permeation, flow through these GCLs occurred preferentially along bundles of needle punching fibers (Fig. 10). In these GCLs, Ca and Mg replaced nearly all of the monovalent cations while the GCLs were in service. Thus, permeation with SW or AW had little impact on the composition of BCs (Fig. 9). Permeation with DW probably caused gradual swelling of bentonite around the needle punching fibers (due to lower ionic strength), which would constrain flow in the preferential flow paths and result in a reduction in hydraulic conductivity. SI tests (ASTM D5890 (2006)) performed on bentonite removed from GCLs with preferential flow paths had slightly greater swell in DW (8–11 mL/2 g) than in AW or SW (7–8 mL/2 g).

Implications for Hydraulic Conductivity Testing

Equilibrium hydraulic conductivities of GCLs permeated with DW or AW are shown in Fig. 11 as a function of the corresponding equilibrium hydraulic conductivities obtained with SW. The 1:1 line in Fig. 11 corresponds to cases where the same hydraulic conductivity was obtained with AW or DW as was obtained with SW. Figure 11 also contains data from Benson et al. (2007) for exhumed GCLs that had undergone extensive cation exchange and contained visible desiccation cracks and macroscopic features that served as preferential flow paths.

The comparison in Fig. 11 shows that similar hydraulic conductivities are generally obtained using AW or SW when GCLs contain preferential flow paths. Additionally, similar hydraulic conductivities are obtained with DW and SW when the GCL contains desiccation cracks or other visible macroscopic features (e.g., data from Benson et al. 2007 in Fig. 11). GCLs that have undergone osmotic swell and have low hydraulic conductivity ($\approx 10^{-11}$ m/s) also have similar hydraulic conductivity to SW, AW, and DW. This insensitivity to permeant water for GCLs that have undergone osmotic swell is well documented in the literature (Jo et al. 2001; Jo et al. 2005; Benson and Meer 2007). In other cases, however, testing with SW can result in much higher hydraulic conductivity than AW or DW.

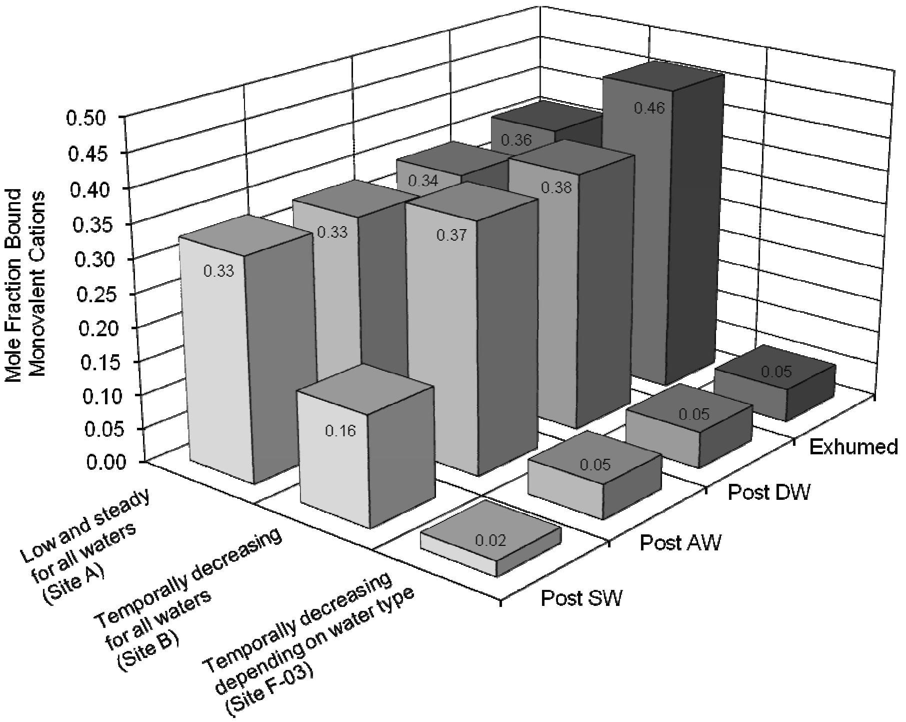

FIG. 9—*Mole fraction bound monovalent cations before and after permeation with DW, AW, and SW for GCL specimens from the same samples exhumed from sites A, B, and F-03. The mole fraction of bound monovalent cations in a new GCL is typically 0.65–0.75.*

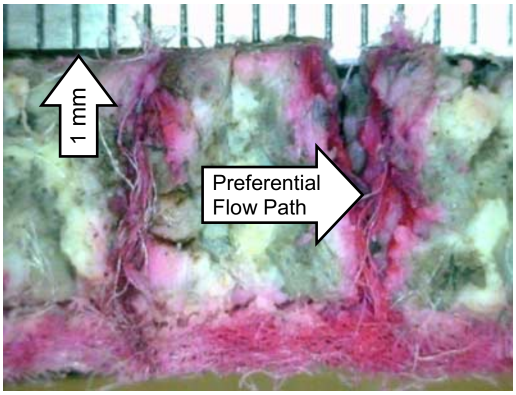

FIG. 10—*Cross section of GCL from site F-03 GCL after permeation with SW followed by SW containing 5 mg/L rhodamine WT dye. Vertical preferential flow paths are stained magenta.*

GCLs exhibiting this sensitivity also exhibit temporally varying hydraulic conductivity regardless of permeant water (Fig. 7(*c*)).

Given that the hydraulic conductivity of exhumed GCLs can be very sensitive to the permeant water used for testing, a realistic permeant solution should be used whenever possible. Ideally, hydraulic conductivity testing of exhumed GCLs should be conducted with water matching the field condition, as recommended in ASTM D5084. When testing to define chemical characteristics of pore water in the field is not practical, or when field conditions are unknown, realistic surrogate water is needed for testing. Using a permeant water having RMD near the lower bound of the observed field data and average ionic strength should yield a conservative measurement of hydraulic conductivity. A water having these characteristics is shown as "conservative water" (CW) in Fig. 6. A hydraulic conductivity corresponding to typical conditions should be obtained using AW as the permeant water. Chemical characteristics of these waters are summarized in Table 6. CW can be prepared by dissolving 15.5 mg of NaCl and 214.6 mg of $CaCl_2$ into 1 L of DW. AW can be prepared by dissolving 73.7 mg of NaCl and 87.0 mg of $CaCl_2$ into 1 L of DW.

When surrogate permeant waters are used, the temporal trends in hydraulic conductivity during permeation should be examined. If CW is used as the permeant water, if there is no temporal trend, and if the hydraulic conductivity is high ($>1 \times 10^{-10}$ m/s), then an additional test on a duplicate specimen should be conducted with AW to determine if the hydraulic conductivity is sensitive to the type of permeant water. If similar hydraulic conductivities ($<2.2 \times$ different, the reproducibility limit reported from the round robin study by Daniel et al. (1997)) are obtained with AW and CW, then the hydraulic conductivity of the exhumed GCL can be reliably reported as the hydraulic conductivity to either water (or the average). If different hydraulic conductivities ($>2.2\times$) are obtained with CW and AW, then both hydraulic conductivities should be reported to illustrate sensitivity to water type. In contrast, if the hydraulic conductivity to CW is steady and low, or permeation with CW results in decreasing hydraulic conductivity that equilibrates to a low value ($<5 \times 10^{-11}$ m/s), then hydraulic conductivity of the exhumed GCL should not be sensitive to type of permeant water. In such cases, the hydraulic conductivity of the exhumed GCL to CW can be reported as a reasonable but conservative estimate of the actual hydraulic conductivity of the GCL.

Summary and Conclusions

Hydraulic conductivity tests were conducted on GCLs exhumed from final covers where the GCL was installed as part of a composite barrier (i.e., geomembrane over GCL). Each GCL was perme-

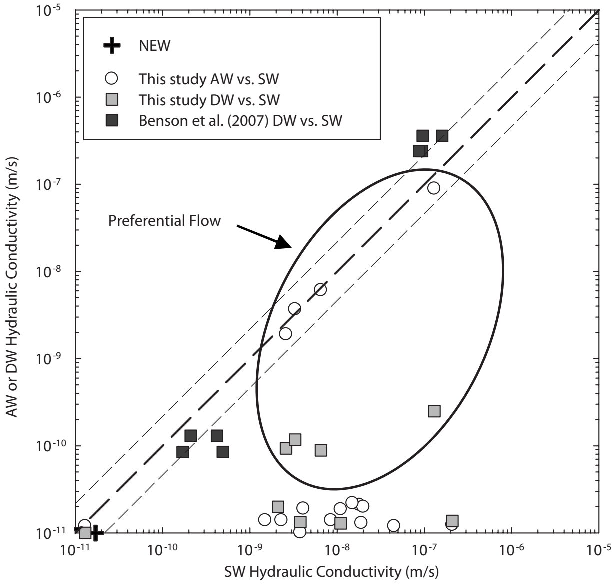

FIG. 11—*Hydraulic conductivity of exhumed GCLs permeated with AW or DW versus SW. Closed symbols represent GCLs that were the sole barrier layer. Open symbols represent GCLs from composite barriers.*

ated with type II DW, SW (0.01*M* $CaCl_2$), and water with characteristics of average eluent from cover soils (AW). Water content and SI in the bentonite from the exhumed GCLs were determined after exhumation. The relative abundance of BCs from the bentonite before and after permeation was also determined. Batch tests were conducted on samples of subgrade collected from beneath the GCLs to define the distribution of cations in water contacting the GCLs.

Results of the hydraulic conductivity tests showed that the hydraulic conductivity of exhumed GCLs from composite barriers can be sensitive to the permeant water used for testing and that this sensitivity is manifested in temporal trends in hydraulic conductivity during testing. GCLs that have higher exhumed water content (>53 %) and have undergone osmotic swell generally are insensitive to the type of permeant water used regardless of the amount of cation exchange that occurred when the GCL was in service. GCLs that have low water content (<46 %) (i.e., not fully hydrated when exhumed) and had a portion of the Na in the bentonite replaced by Ca or Mg while in service tend to be sensitive to type of permeant water, with much higher hydraulic conductivities (1×10^{-9}–2×10^{-7} m/s) obtained with SW (and some cases AW) and low hydraulic conductivities ($<5\times10^{-11}$ m/s) obtained with DW (and sometimes AW).

Based on the tests performed in this study, hydraulic conductivity tests on exhumed GCLs should be conducted using permeant water that reflects the field condition as closely as practical. If the chemical characteristics in the field are unknown, tests can be conducted using CW and/or AW. These waters have chemical characteristics corresponding to soil eluents with the greatest preponderance of divalent cations (CW) or an average relative abundance of monovalent and divalent cations (AW). CW can be prepared by dissolving 15.5 mg of NaCl and 214.6 mg of $CaCl_2$ into 1 L of DW. AW can be prepared by dissolving 73.7 mg of NaCl and 87.0 mg of $CaCl_2$ into 1 L of DW.

When testing GCLs with CW or AW, the temporal trend and hydraulic conductivity at equilibrium should be observed and reported. If no temporal trends are present and the hydraulic conductivity is high ($>1\times10^{-10}$ m/s) when permeating with CW, tests should be conducted on duplicate specimens using AW. In contrast, if the hydraulic conductivity to CW is steady and low ($<5\times10^{-11}$ m/s), or permeation with CW results in decreasing hydraulic conductivity that equilibrates to a low value, then this hydraulic conductivity can be reported as a reasonable but conservative measurement.

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