

Hydraulic conductivity of two geosynthetic clay liners with different bentonite granule sizes

Yu Tan^{1*}, Craig H. Benson¹, Guangping Zhou¹, Sabrina L. Bradshaw¹, and Tuncer B. Edil¹

¹Geological Engineering, University of Wisconsin, Madison, WI, 53706, USA

Abstract. Experiments were conducted to evaluate the hydraulic conductivity of two commercially available geosynthetic clay liners (GCLs) with similar properties but different bentonite granule sizes ($D_{50}=1.0$ mm or 0.3 mm). A synthetic municipal solid waste (MSW) leachate prepared in the laboratory and four actual coal combustion product (CCP) leachates collected from the field were used as permeant solutions to represent different permeant chemical conditions for waste containment applications. The two GCLs had comparable hydraulic conductivity to dilute or moderate ionic strength (I) leachates (<0.1 M). With more concentrated leachates ($I > 0.1$ M), hydraulic conductivity of the GCL containing finer bentonite granules (FG) was 10 to 500 times lower than the hydraulic conductivity of the GCL containing coarser bentonite granules (CG) under the same equilibrium conditions. These results suggest that GCLs containing finer bentonite granules may be less vulnerable to permeant chemistry.

1 Introduction

Geosynthetic clay liners (GCLs) are factory-manufactured hydraulic barriers consisting of a thin layer of sodium bentonite (NaB) granules sandwiched between two geotextiles that are bonded by needlepunching or stitching [1]. GCLs are widely used as hydraulic barriers in waste containment facilities due to their low hydraulic conductivity to water ($<10^{-10}$ m/s) [2]. To achieve low hydraulic conductivity, the bentonite must swell sufficiently during hydration to close flow paths through intergranular pores and needlepunching fiber bundles [3, 4]. Thus, the hydraulic conductivity of GCLs containing larger intergranular pores and thicker needlepunching fiber bundles may be more sensitive to bentonite swelling.

The swelling of bentonite is sensitive to the chemical characteristics of the leachate. Leachates with higher ionic strength (I) or a preponderance of polyvalent cations suppress swelling and can result in GCLs having higher hydraulic conductivity ($>10^{-9}$ m/s) [5-7]. Chen et al. [8] permeated NaB GCLs with coal combustion product (CCP) leachates, and report that the hydraulic conductivity of the GCLs to CCP leachates was orders of magnitude higher ($\sim 10^{-10}$ to 10^{-7} m/s) than the hydraulic conductivity of the same GCLs to deionized (DI) water ($\sim 10^{-11}$ m/s). High hydraulic conductivity of NaB GCLs ($>10^{-9}$ m/s) has also been observed when GCLs are permeated with other solutions that suppress swelling, such as calcium chloride (CaCl_2) solutions [9, 10], bauxite liquors [11], and heap leach solutions [12].

* Corresponding author: ytan84@wisc.edu

Size of the bentonite granules can affect how a permeant solution affects the hydraulic conductivity of GCLs, as the intergranular pores are larger when the bentonite granules are larger and therefore may be more difficult to seal off during swelling. Gleason et al. [13] compared the hydraulic conductivity of bentonite with larger granules (90% > 0.425 mm) to the hydraulic conductivity of powdered bentonite (100% < 1 mm and 75% < 0.075 mm) when permeated with a 0.25 M CaCl₂ solution. Hydraulic conductivity of the bentonite with larger granules was approximately two orders of magnitude higher than the hydraulic conductivity of the powdered bentonite (6×10^{-7} vs. 9×10^{-9} m/s). Chen et al. [8] permeated two commercially available GCLs with different bentonite granule sizes ($D_{50} = 1$ mm vs. $D_{50} = 0.3$ mm) to CCP leachates. Hydraulic conductivities of the two GCLs to DI water were similar and low (2.6×10^{-11} and 3.6×10^{-11} m/s). When permeated with more aggressive CCP leachates ($I > 0.1$ M), however, the hydraulic conductivity of the GCL with finer bentonite granules was consistently lower than the hydraulic conductivity of the GCL with coarser bentonite granules.

In this study, hydraulic conductivity tests were conducted on two commercially available GCLs using a synthetic municipal solid waste (MSW) leachate prepared in the laboratory and four CCP leachates collected from the field. One GCL contained bentonite with coarser granules ($D_{50} = 1$) and the other GCL had bentonite with finer granules ($D_{50} = 0.3$ mm). Several of the hydraulic conductivity tests were conducted for more than ten pore volumes of flow (PVF) with the objective of understanding the long-term hydraulic conductivity of the GCLs.

2 Materials and Methods

2.1 Geosynthetic clay liners

Two NaB GCLs that are commonly used in North America were evaluated in this study: CG GCL and FG GCL. The CG GCL contains coarser bentonite granules with $D_{50} = 1$ mm. The FG GCL contains finer bentonite granules with $D_{50} = 0.3$ mm. Granule size distributions of the bentonite in the GCLs measured using dry sieve analysis [ASTM D6913, 14] are shown in Fig. 1.

The two GCLs have similar properties. Both GCLs have bentonite encapsulated between a woven and a nonwoven geotextile that are bonded by needlepunching. The average dry bentonite mass per unit area is 3.6 kg/m² for CG GCL and 3.7 kg/m² for FG GCL, and the hygroscopic moisture content of the bentonite is 8.5% for the CG GCL and 8.1% for the FG GCL. Montmorillonite content of the bentonite in both GCLs is greater than 77%. Cation exchange capacity (CEC) and concentrations of initial bound cations (Na⁺; potassium, K⁺; magnesium, Mg²⁺; and Ca²⁺) of the bentonite were determined following the method in ASTM D7503 [15]. The CEC is 94.2 cmol⁺/kg for CG GCL and 85.6 cmol⁺/kg for FG GCL (triplicates). The exchange complex of the CG GCL includes Na⁺ (38.5 cmol⁺/kg), K⁺ (2.1 cmol⁺/kg), Mg²⁺ (18.6 cmol⁺/kg), and Ca²⁺ (28.2 cmol⁺/kg). For the FG GCL, the exchange complex includes Na⁺ (34.6 cmol⁺/kg), K⁺ (1.4 cmol⁺/kg), Mg²⁺ (5.9 cmol⁺/kg), and Ca²⁺ (26.8 cmol⁺/kg).

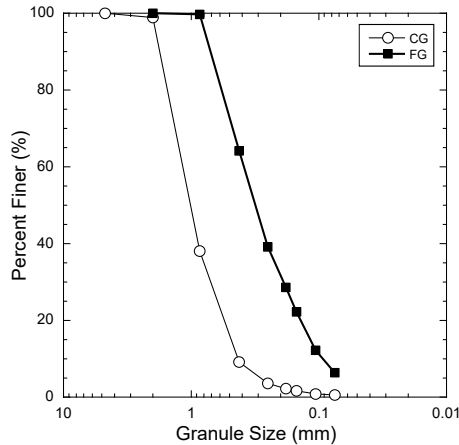


Fig. 1. Granule size distributions of the bentonite in the evaluated GCLs

2.2 Permeant liquids

A synthetic MSW leachate prepared in the laboratory and four actual CCP leachates (DE, WR, SP, and ST) collected from the field were evaluated in this study. The synthetic MSW leachate was developed by Bradshaw and Benson [16] to represent a typical inorganic chemistry for MSW leachates based on an extensive review of MSW leachates in the United States. The synthetic leachate was prepared by dissolving reagent-grade salts in DI water following the procedures in Benson et al. [12]. Chemical characteristics of the four CCP leachates collected from the field were analyzed following the method described in Tian et al. [17]. Ionic strength (I) and the relative abundance of monovalent and polyvalent cations (RMD) were computed to quantify the geochemistry of the leachates [4]:

$$I = \frac{1}{2} \sum_{i=1}^n C_i z_i^2 \tag{1}$$

$$RMD = \frac{M_M}{\sqrt{M_D}} \tag{2}$$

where C_i is the molar concentration of the i^{th} ion in solution, z_i is the valence of the i^{th} ion, M_M is the total molarity of monovalent cations in solution, and M_D is the total molarity of polyvalent cations in solution. The relationship between RMD and ionic strength of the leachates is shown in Fig. 2. Ionic strength of the leachates varies from 0.0042 to 2.1 M and RMD of the leachates varies from 0.014 to 1.8 $M^{0.5}$, corresponding to dilute and concentrated leachates that are expected to have varying effects on bentonite swelling and hydraulic conductivity. DI water was also used as a permeant solution.

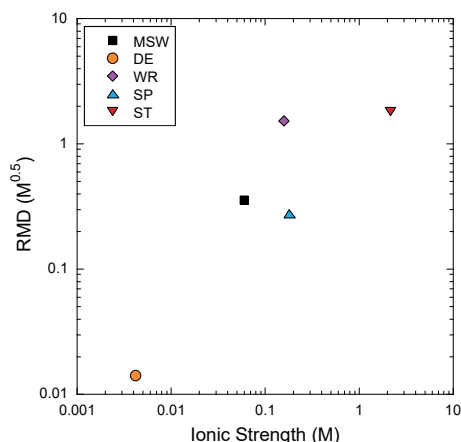


Fig. 2. RMD versus ionic strength of the permeant leachates used in this study.

2.3 Hydraulic conductivity

Hydraulic conductivity of the GCLs was measured in flexible-wall parameters using the falling headwater-constant tailwater method in ASTM D6766 [18]. All specimens were tested under an average effective stress of 20 kPa and an average hydraulic gradient of 150. The GCL was permeated directly with the permeant liquid (no prehydration) with the flow oriented upwards to facilitate saturation. The GCL was hydrated with the permeant liquid in the permeameter for 48 hr immediately prior to permeation with the cell pressure and influent head applied, and the effluent line closed. No backpressure was used to avoid unintended geochemical alterations [12].

GCL specimens were prepared using the procedures described in Benson et al. [12]. GCL disks (150-mm diameter) were cut from a GCL roll provided by the manufacturer using a razor knife. Geotextile fibers along the edge were removed using scissors and the perimeter was hydrated with DI water to prevent loss of bentonite during handling. A thin layer of bentonite paste prepared with DI water was smeared along the perimeter of the specimen to minimize the potential for sidewall leakage. The GCL was placed in the permeameter between two heavy nonwoven geotextiles (300 g/m²) to distribute flow during testing. When a GCL had high hydraulic conductivity (> 10⁻⁹ m/s), dye tests were conducted to evaluate whether sidewall leakage occurred. No sidewall leakage was encountered for the tests reported herein.

Permeation was continued for at least two PVF and until the termination criteria in ASTM D6766 [18] were satisfied. Hydraulic equilibrium was defined by steady hydraulic conductivity and volumetric flow continuity, and chemical equilibrium was defined as electric conductivity (EC) of the effluent comparable to EC of the influent (within ±10%), per D6766. The tests were continued as long as practical to evaluate the long-term hydraulic conductivity of the GCLs.

3 Results and discussion

3.1 Temporal behavior

Hydraulic conductivity of the GCLs at hydraulic equilibrium and at the time of preparing this paper (referred to as “end of paper” or “end”) are summarized in Table 1. The “end of paper” hydraulic conductivity is reported in Table 1 only for those tests where EC equilibrium was achieved.

Table 1. Summary of hydraulic conductivity (K) and PVF at hydraulic equilibrium and at time of preparing this paper. EC equilibrium was achieved for all tests in Table 1 except those marked with NA.

Permeant Leachate	GCL	Hydraulic Equilibrium			Paper Preparation		
		PVF	K (m/s)	K/K _{DI}	PVF	K (m/s)	K/K _{DI}
DI	CG	2.32	1.4x10 ⁻¹¹	-	17.41	2.8x10 ⁻¹¹	-
	FG	2.08	1.2x10 ⁻¹¹	-	12.41	1.4x10 ⁻¹¹	-
MSW	CG ^a	8.06	3.8x10 ⁻¹¹	2.7	22.41	9.5x10 ⁻¹¹	3.4
	CG (duplicate)	5.53	4.5x10 ⁻¹¹	3.2	7.46	NA ^c	NA
	FG ^a	2.17	2.8x10 ⁻¹¹	2.4	28.95	2.0x10 ⁻¹⁰	14.3
	FG (duplicate)	2.63	2.7x10 ⁻¹¹	2.3	8.71	NA	NA
	FG (triplicate)	2.04	2.4x10 ⁻¹¹	2.0	14.13	9.0x10 ⁻¹⁰	6.4
DE	CG	2.18	1.4x10 ⁻¹¹	1.0	5.36	NA	NA
	FG	2.01	1.8x10 ⁻¹¹	1.5	11.39	NA	NA
WR	CG ^b	2.15	1.5x10 ⁻⁸	1071.4	6.14	7.5x10 ⁻⁹	268
	FG ^b	2.52	8.8x10 ⁻¹⁰	73.3	6.72	1.2x10 ⁻¹⁰	8.6
SP	CG	2.51	1.5x10 ⁻⁸	1071.3	9.32	NA	NA
	FG	4.62	1.1x10 ⁻⁹	91.7	6.62	NA	NA
ST	CG	2.41	7.7x10 ⁻⁸	5500.0	9.96	1.0x10 ⁻⁷	3571
	FG	2.18	1.4x10 ⁻¹⁰	11.7	16.11	1.7x10 ⁻¹⁰	12.1
	FG (duplicate)	3.67	2.8x10 ⁻¹⁰	23.3	17.55	2.8x10 ⁻¹⁰	20.0

^aCorresponds to test for data reported in Fig. 3a.

^bCorresponds to test for data reported in Fig. 3b.

^cNA indicates EC equilibrium was not achieved at the time paper was prepared.

Examples of the temporal behavior of the hydraulic conductivity of GCLs permeated with MSW leachate and CCP leachate WR are shown in Fig. 3. Hydraulic conductivity of both GCLs to MSW leachate gradually decreases due to closure of intergranular pores and sealing of needlepunching fiber bundles as the bentonite swells (Fig. 3a). The hydraulic

conductivity then remains steady for a period, which is followed by a steady increase in hydraulic conductivity over many PVF, with a final higher hydraulic conductivity being reached after 20 PVF or more. Bradshaw et al. [16] report similar temporal behavior, including long-term increases in hydraulic conductivity during permeation for up to 40 PVF. Bradshaw et al. [16] attributed the gradual increases in hydraulic conductivity to the replacement of monovalent cations in the bentonite by divalent cations in the permeant solution, as evinced by comparing cation concentrations in the influent and effluent. This gradual exchange process suppressed swelling of the bentonite, resulting in larger flow paths and higher hydraulic conductivity.

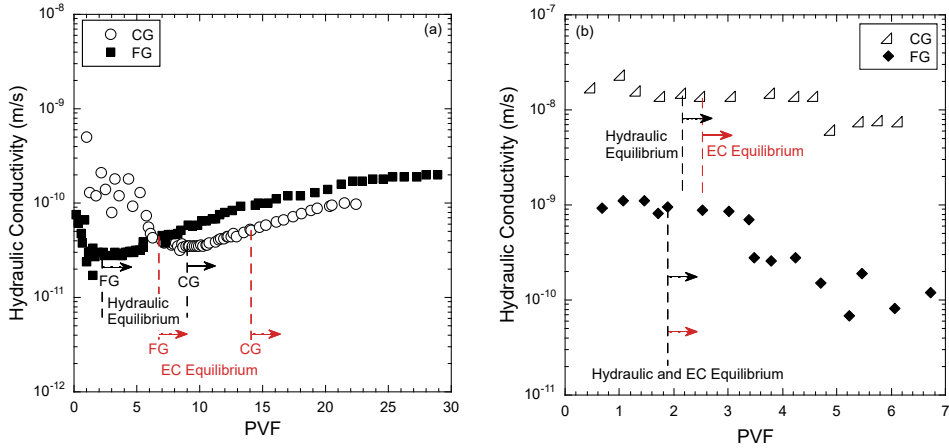


Fig. 3. Hydraulic conductivity versus PVF for CG and FG GCLs permeated with (a) MSW leachate and (b) CCP leachate WR.

Although the hydraulic conductivity of both GCLs to MSW leachate exhibited similar temporal behavior, the PVF over which the changes occurred, and the magnitude of the changes, differed between the FG and CG GCLs. Hydraulic equilibrium was established at 2.17 PVF for the FG GCL and 8.06 PVF for the CG GCL, as indicated by the black dashed lines in Fig. 3a. EC equilibrium was established at 6.36 PVF for the FG GCL and 14.02 PVF for the CG GCL, as indicated by the red dashed lines in Fig. 3a. Hydraulic conductivity of both GCLs increased after EC equilibrium was achieved, indicating that chemical interactions between the bentonite and permeant leachate were still occurring even though both tests were in chemical equilibrium per the criteria in ASTM D6766.

The FG GCL had lower initial hydraulic conductivity, reached hydraulic equilibrium in fewer PVF, and began increasing at lower PVF than the CG GCL. In addition, the gradual increase in hydraulic conductivity occurring after hydraulic equilibrium was established occurred over a greater number of PVF for the CG GCL, and the final hydraulic conductivity of FG GCL was higher than the final hydraulic conductivity the CG GCL.

Hydraulic conductivity of CG and FG GCLs permeated with CCP leachate WR are shown in Fig. 3b as a function of PVF. The hydraulic conductivities to the CCP leachate are higher than to the MSW leachate due to the higher ionic strength of the CCP leachate, which suppresses bentonite swelling and closure of intergranular pores. For both GCLs, hydraulic and EC equilibrium per ASTM D6766 are reached rapidly, in less than 3 PVF. The hydraulic conductivity of both GCLs subsequently undergoes a gradual decrease, becoming steady again by about 5 PVF. This unexpected decrease likely is due to the greater preponderance of monovalent cations in the CCP leachate relative to the MSW leachate, as indicated in Fig. 2 (higher RMD and higher ionic strength). Slow rate-limited cation exchange likely occurred

within the granules, with monovalent cations in the leachate replacing native polyvalent cations remaining on bentonite surfaces in the interior of the granules [19], promoting bentonite swelling and lower hydraulic conductivity. Nevertheless, the hydraulic conductivity remains higher than 1×10^{-10} m/s at the end of permeation (PVF > 6) due to the high ionic strength of CCP leachate WR (0.16 M).

The differences in temporal behavior for the FG and CG GCLs are likely due to differences in the rate of swelling and cation exchange. Coarser bentonite granules hydrate and swell more slowly than finer bentonite granules, and GCLs with coarser bentonite have larger intergranular pores and higher hydraulic conductivity at the onset of permeation (nearly 10x higher hydraulic conductivity at the onset in Fig. 3). The higher hydraulic conductivity of the CG GCL permits more PVF to pass through the GCL before low hydraulic conductivity is achieved. Cations in the permeant liquid also likely require more time to diffuse into the core of the larger bentonite granules in the CG GCL [19], resulting in slower cation exchange process and changes in hydraulic conductivity.

3.2 Impact of ionic strength

Relative hydraulic conductivities (K_L/K_{DI}) of the FG and CG GCLs are shown in Fig. 4 as a function of ionic strength of the permeant leachates, where K_L/K_{DI} is the ratio of hydraulic conductivity of the GCL to leachate to the hydraulic conductivity of the same GCL to DI water. The data in Fig. 4 correspond to similar conditions: hydraulic equilibrium (HE) or the time of the paper was prepared (End). Relative hydraulic conductivity (K_L/K_{DI}) is indicative of the relative impact of the leachate on hydraulic conductivity of the FG and CG GCLs.

Relative hydraulic conductivity (K_L/K_{DI}) of both GCLs increases as the ionic strength of the leachate increases (Fig. 4), which is consistent with trends reported in the literature [3, 5, 6]. Higher ionic strength results in greater suppression of osmotic swelling of the bentonite, larger pores between bentonite granules, and higher hydraulic conductivity [20]. The K_L/K_{DI} for the FG and CG GCLs are similar at lower ionic strengths, with K_L/K_{DI} of the FG GCLs being modestly larger than those for the CG GCL in some cases. At higher ionic strengths, however, the CG GCL has considerably higher hydraulic conductivity than the FG GCL, regardless of whether the hydraulic conductivity is evaluated at the HE or End conditions. The hydraulic conductivities of the FG and CG GCLs are similar at low ionic strength because intergranular pores in both the FG and CG GCLs are readily closed by the high swelling of the bentonite in low ionic strength leachate or DI water. In contrast, swelling is suppressed with higher ionic strength leachates. Consequently, intergranular pores are not closed as effectively, resulting in greater differences in hydraulic conductivity.

3.3 Effect of granule size

The effect of granule size is shown explicitly in Fig. 5, as the hydraulic conductivity of the FG GCL relative to the hydraulic conductivity of the CG GCL for the same test conditions. Hydraulic conductivities are shown for the HE and End conditions. For the dilute leachates (DI water, MSW, CCP leachate DE), hydraulic conductivities of the FG and CG GCLs are comparable (within 2x) and relatively low ($< 2 \times 10^{-10}$ m/s). In contrast, for the leachates with higher ionic strengths (CCP leachate SP, WR, and ST), the FG GCL with fine granules has considerably lower hydraulic conductivity than the CG GCL with coarser granules for HE and End conditions. As indicated in the discussion of ionic strength, concentrated leachates suppress swelling of bentonite granules, impeding closure of intergranular pores that contribute to higher hydraulic conductivity. Intergranular pores are larger for bentonites with larger granules, which results in higher hydraulic conductivity when other factors are the

same [20]. These results suggest that GCLs containing finer bentonite granules may be less vulnerable to the chemistry of permeant liquids.

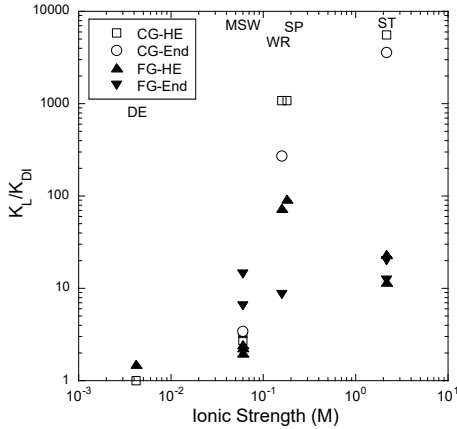


Fig. 4. Hydraulic conductivity to leachate relative to hydraulic conductivity to DI water (K_L/K_{DI}) as a function of the ionic strength of permeant liquids.

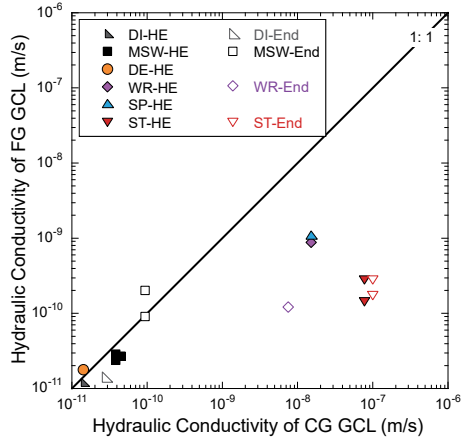


Fig. 5. Hydraulic conductivity of FG GCL vs. hydraulic conductivity of CG GCL permeated with same liquid at same termination criteria, i.e., at hydraulic equilibrium (HE) or at time of preparing paper (End).

4 Summary and Conclusions

Hydraulic conductivity tests were conducted on two commercially available needlepunched GCLs with coarser (CG) or finer (FG) bentonite granules. A synthetic MSW leachate prepared in the laboratory and four actual coal combustion product (CCP) leachates collected from the field were used as permeant liquids. The leachates varied from dilute to concentrated, and predominantly monovalent cations to predominantly polyvalent cations. Several of the tests were continued as long as practical to evaluate the long-term hydraulic conductivity of the GCLs.

Two types of temporal behavior were observed for both the CG and FG GCLs. One type consisted of the hydraulic conductivity decreasing for several pore volumes of flow (PVF) after initiating permeation, stable for several additional PVF, and then gradually increasing for many PVF, ultimately reaching a final equilibrium hydraulic conductivity. The gradual increase occurred after chemical equilibrium was established, which was based on the equality of electrical conductivity (EC) of the influent and effluent ($\pm 10\%$) as described in ASTM D6766. The final equilibrium hydraulic conductivity was attained after approximately 20 PVF. The other type of behavior consisted of the hydraulic conductivity stable for several PVF, followed by a decrease to a lower final equilibrium hydraulic conductivity. The long-term increasing hydraulic conductivity was associated with leachate in which polyvalent cations were predominant (low RMD), whereas the long-term decreasing hydraulic conductivity was associated with leachate where monovalent cations were predominant (high RMD). These long-term trends are likely associated with slow rate-limited cation exchange processes that suppress osmotic swelling (low RMD solutions with a gradual increase in hydraulic conductivity) or enhance osmotic swelling (high RMD solutions with a gradual decrease in hydraulic conductivity), thereby affecting the size of pores conducting flow and the hydraulic conductivity.

The effect of granule size on hydraulic conductivity varied with the characteristics of the permeant leachate. When the leachate was less concentrated (ionic strength, $I < 0.1$ M), hydraulic conductivities of the CG and FG GCLs were comparable and low ($< 2 \times 10^{-10}$ m/s). When permeated with more concentrated leachates ($I > 0.1$ M), the hydraulic conductivity of the FG GCL was consistently lower (10 to 500x) than the hydraulic conductivity of CG GCL. These results suggest that GCLs with finer bentonite granules may be less vulnerable to permeant chemistry than GCLs with coarser bentonite granules.

Financial support for this study was provided by the US Department of Energy (DOE) under cooperative agreement DE-FC01-06EW07053 (Consortium for Risk Evaluation with Stakeholder Participation III).

References

1. C. Shackelford, C. Benson, T. Katsumi, T. Edil, L. Lin, Evaluating the hydraulic conductivity of GCLs permeated with non-standard liquids, *Geotextiles and Geomembranes*, 18(2), 133-161 (2000).
2. R. Rowe, Geosynthetic clay liners: Perceptions and misconceptions, *Geotextiles and Geomembranes*, 48(2), 137-156 (2020).
3. H. Jo, T. Katsumi, C. Benson, T. Edil, Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions, *J. Geotech. Geoenviron. Eng.*, 127(7), 557-567 (2001).
4. D. Kolstad, C. Benson, T. Edil, Hydraulic conductivity and swell of nonprehydrated geosynthetic clay liners permeated with multispecies inorganic solutions, *J. Geotech. Geoenviron. Eng.*, 130(12), 1236-1249 (2004).
5. H. Jo, C. Benson, C. Shackelford, J. Lee, T. Edil, Long-term hydraulic conductivity of a geosynthetic clay liner permeated with inorganic salt solutions, *J. Geotech. Geoenviron. Eng.*, 131(4), 405-417 (2005).
6. Y. Tan, J. Chen, C. Benson, Predicting hydraulic conductivity of geosynthetic clay liners using a neural network algorithm, *Geo-Congress 2022*, ASCE, Reston, VA, 21-28 (2022).
7. K. Tian, C. Benson, W. Likos, Hydraulic conductivity of geosynthetic clay liners to low-level radioactive waste leachate, *J. Geotech. Geoenviron. Eng.*, 142(8), 04016037 (2016).
8. J. Chen, C. Benson, T. Edil, Hydraulic conductivity of geosynthetic clay liners with sodium bentonite to coal combustion product leachates, *J. Geotech. Geoenviron. Eng.*, 144(3), 04018008 (2018).
9. J. Scalia, C. Benson, G. Bohnhoff, T. Edil, C. Shackelford, Long-term hydraulic conductivity of a bentonite-polymer composite permeated with aggressive inorganic solutions, *J. Geotech. Geoenviron. Eng.*, 140(3), 04013025 (2014).
10. T. Katsumi, H. Ishimori, A. Ogawa, K. Yoshikawa, K. Hanamoto, R. Fukagawa, Hydraulic conductivity of nonprehydrated geosynthetic clay liners permeated with inorganic solutions and waste leachates, *Soils and Foundations*, 47(1), 79-96 (2007).
11. Q. Li, J. Chen, C. Benson, D. Peng, Hydraulic conductivity of bentonite-polymer composite geosynthetic clay liners permeated with bauxite liquor, *Geotextiles and Geomembranes*, 49(2), 420-429 (2020).
12. C. Benson, Y. Tan, J. Youngblood, S. Bradshaw, Bentonite-polymer composite geosynthetic clay liners for heap leach liners, *5th International Conference on Heap Leach Mining Solutions*, Sparks, NV, (2022).
13. M. Gleason, D. Daniel, G. Eykholt, Calcium and sodium bentonite for hydraulic containment applications, *J. Geotech. Geoenviron. Eng.*, 123(5), 438-445 (1997).

14. ASTM, Standard Test Methods for Particle-Size Distribution (Gradation) of Soils Using Sieve Analysis, ASTM D6913, *Annual Book of Standards*, ASTM International, West Conshohocken, PA (2017).
15. ASTM, Standard Test Method for Measuring the Exchange Complex and Cation Exchange Capacity of Inorganic Fine-Grained Soils, ASTM D7503, *Annual Book of Standards*, ASTM International, West Conshohocken, PA (2018).
16. S. Bradshaw, C. Benson, Effect of *Municipal Solid Waste Leachate on Hydraulic Conductivity and Exchange Complex of Geosynthetic Clay Liners*, *J. Geotech. Geoenviron. Eng.*, 140(4) 04013038 (2014).
17. K. Tian, C. Benson, J. Tinjum, Chemical characteristics of leachate in low-level radioactive waste disposal facilities, *J. Hazardous, Toxic, and Radioactive Waste*, 21(4) 04017010 (2017).
18. ASTM, Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Aqueous Solutions, ASTM D6766, *Annual Book of Standards*, ASTM International, West Conshohocken, PA (2020).
19. H. Jo, C. Benson, T. Edil. Rate-limited cation exchange in thin bentonitic barrier layers, *Canadian Geotech. J.*, 43 370-391 (2006).
20. J. Hou, R. Sun, C. Benson. Hydrodynamic assessment of bentonite granule size and swelling on hydraulic conductivity of geosynthetic clay liners, *Geotextiles and Geomembranes*, 51 93-103 (2023).