Hydraulic conductivity of a geosynthetic clay liner (GCL) from a composite liner after 12-yr of atmospheric exposure

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ABSTRACT: A geosynthetic clay liner (GCL) was exhumed from a composite liner (geomembrane overlying GCL) in a landfill cell that had been exposed to the atmosphere for 12 yr because a leachate collection system had not been placed and the cell was never filled with waste. GCL samples were exhumed from locations along the top, middle, and toe of eastern and southern slopes, as well as from an anchor trench. Hydraulic conductivity of the GCL was less than 5.0 x 10^{-11} m/s or greater than 10^{-6} m/s, depending on sampling location. GCL samples exhumed from the top of slope had low hydraulic conductivities and contained bentonite with relatively high swell index (≥ 20 mL/2 g), whereas samples exhumed from the toe had high hydraulic conductivities and low swell index (≤ 10 mL/2 g). Hydraulic conductivity of GCLs exhumed from mid-slope and from an anchor trench varied. Five of six GCL samples with low hydraulic conductivity had exhumed gravimetric water contents < 20%, suggesting that these GCL samples may have remained relatively dry during the exposure period.

Keywords: Geosynthetics, geosynthetic clay liner, GCL, composite liner, geomembrane, hydraulic conductivity, bentonite migration, cation exchange, swell index

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are manufactured hydraulic barriers consisting of a thin layer of bentonite clay between two geotextiles. The bentonite clay swells appreciably when hydrated with water, enabling the GCL to act as a hydraulic barrier by constricting the pore space available for flow. Numerous studies have characterized the effects of the chemical properties of the hydrating solution and the predominant cation species in the exchange complex on the swelling behavior of bentonite (e.g., Jo et al. 2001; Kolstad et. al 2004; Meer and Benson 2007, 2009; Scalia and Benson 2010). Bentonite exposed to multivalent cations in solution undergoes cation exchange, with multivalent cations replacing the monovalent cations predominant in the original bentonite exchange complex. As the proportion of multivalent cations increases in the exchange complex, bentonite swelling diminishes and the hydraulic conductivity of the GCL increases.

Cation exchange in a GCL used in a lining system occurs when leachate contacts the bentonite or when cations in the subgrade migrate upward during GCL hydration (Bradshaw et al. 2013, 2015; Bradshaw and Benson 2014). In a composite liner comprised of a geomembrane (GM) over a GCL, the GCL is hydrated primarily by moisture in the underlying subgrade soil. The geochemistry of the subgrade affects the degree of hydration and cation exchange. Thus, the hydraulic conductivity of a GCL can be affected by the hydration condition (Scalia and Benson 2011).

Hydraulic conductivity of GCLs can also be affected by wet-dry cycling, especially if the GCL undergoes cation exchange and multivalent cations become predominant in the exchange complex of the bentonite. Several recent studies have shown that GCLs in composite liners that are left exposed (no leachate collection system or cover soils placed over the liner after construction) are susceptible to wet-dry cycling and internal erosion of bentonite within the GCL (Rowe et. al. 2014, 2016; Take et. al. 2015). In this study, GCL samples were exhumed from an exposed composite liner at a municipal solid waste landfill located in a temperate climate in California (Csb - temperate, Peel et al. 2007). The liner had been exposed to the atmosphere for 12 yr. The leachate collection system was never placed and the cell had not been filled. During this exposure period, cation exchange, wet-dry cycling, and erosion of the bentonite in the GCL occurred, affecting the properties of the GCL. These properties are described herein.

2 EXHUMATION AND TESTING METHODOLOGY

2.1 *Sample exhumation*

GCL samples were collected along the eastern and southern side slopes (2:1 slope) of the cell. The GCL had nonwoven geotextiles on both sides bonded by needlepunching. Samples were exhumed at the top of slope, mid-slope, toe of slope, and from an anchor trench. Designations, locations, and sizes of the exhumed samples are provided in Table 1. Narrower samples were collected at mid-slope and from the anchor trench due to difficult sampling conditions.

Table 1. Identifier, location, and size of samples.

Location and Sample Size	Identifiers for GCL Samples		
	East Slope	South Slope	Southeast Corner
Top of Slope (0.3×0.3 m)	ES-T-1	SS-T-1	P-T-1
Middle of Slope (0.3×0.15 m)	ES-M-1	SS-M-1	P-M-1
Toe of Slope (0.3×0.3 m)	ES-B-1	SS-B-1	P-B-1
Anchor Trench (0.3×0.15 m)	A1-1, A2-1	-	-

2.2 *Laboratory methods*

GCL samples were immediately wrapped in plastic, placed in air-tight bags following exhumation, and transported to the laboratory. Gravimetric water content of the bentonite was measured using ASTM D2216 on arrival in the laboratory (Table 2). Swell index (SI) of the bentonite from each GCL was measured using ASTM D5890 with deionized (DI) water as the hydrating liquid. Mass per unit area of the exhumed GCLs was measured using ASTM D5993 on 100 mm by 100 mm square specimens.

Hydraulic conductivity of the exhumed GCL samples was measured in flexible-wall permeameters using the falling headwater and constant tailwater method in ASTM D5084-16a (Method B). No backpressure was applied to simulate the field condition. An average effective stress of 21 kPa was applied, and the hydraulic gradient varied between 100 to 320 depending on specimen thickness. Specimens were cut from the exhumed GCL samples with a razor knife to a diameter of 102 mm, and the thickness was measured with calipers (average of three measurements). Average water (AW) was used as the permeant liquid to simulate typical porewater chemistry expected in the field (1.3 mM NaCl and 0.8 mM $CaCl_2$, Scalia and Benson 2010). Gravimetric water content was measured immediately after testing each specimen to assess hydration that occurred during permeation.

3 RESULTS AND DISCUSSION

A summary of the properties of the exhumed GCLs is provided in Table 2. The footnotes provide additional context.

3.1 *Exhumed water content*

The subgrade soil is the primary source of moisture when a GCL in a composite liner hydrates (Bradshaw et al. 2013). For the GCLs in this study, the GCL water content increased with increasing subgrade soil water content (Fig. 1). Except for Sample P38-B-1, the exhumed water contents are less than 40%, which is low relative to water contents reported in previous studies of exhumed GCLs from composite barriers (Meer and Benson 2007, Scalia and Benson 2011). However, none of the past studies evaluated GCLs from exposed composite liners. Moreover, the exhumed water contents may not reflect the entire range of water content for each specimen while in service, as the GCLs may have been undergoing wet-dry cycling. Overall, GCLs exhumed from the toe of slope had the highest water contents (2-86%), whereas GCLs exhumed from the middle and top of slope had comparable water contents (11-15%). GCLs from the anchor trench had intermediate water contents (32-37%).

Table 2. Characteristics of exhumed GCL samples.

GCL Sample ID[a]	GCL Water Content (%)	Subgrade Water Content (%)	GCL Mass Per Area (kg/m^2)[b]	Swell Index (mL/2 g)	Hydraulic Conductivity (m/s)	Post-Permeation Water Content (%)
ES-T-1	14	8.1	4.5	20.1	3.9×10^{-11}	148
ES-M-1	14	3.5	6.2	10.0	2.6×10^{-6}	77
ES-B-1	39	8.5	4.9	10.0	1.3×10^{-6}	98
SS-T-1	13	1.0	4.4	22.0	2.5×10^{-11}	184
SS-M-1	11	1.1	6.1	20.0	3.1×10^{-11}	151
SS-B-1	2	4.4	1.6	3.0	2.6×10^{-6}	NM
P-T-1	15	0.8	4.5	23.0	2.9×10^{-11}	163
P-M-1	14	1.3	4.8	18.5	2.4×10^{-11}	124
P-B-1	86	16	5.8	8.0	1.6×10^{-6}	113
A1-1	11	8.1	5.4	11.0	1.3×10^{-6}	91
A2-1	16	8.1	5.2	16.0	3.9×10^{-11}	133

[a] ES = east slope, SS = south slope, A = anchor trench, P = southeast corner slope, T = top, M = middle, B = bottom; [b] includes geotextiles and bentonite, initial mass per unit area of installed GCL ~ 5 kg/m^2. NM indicates not measured.

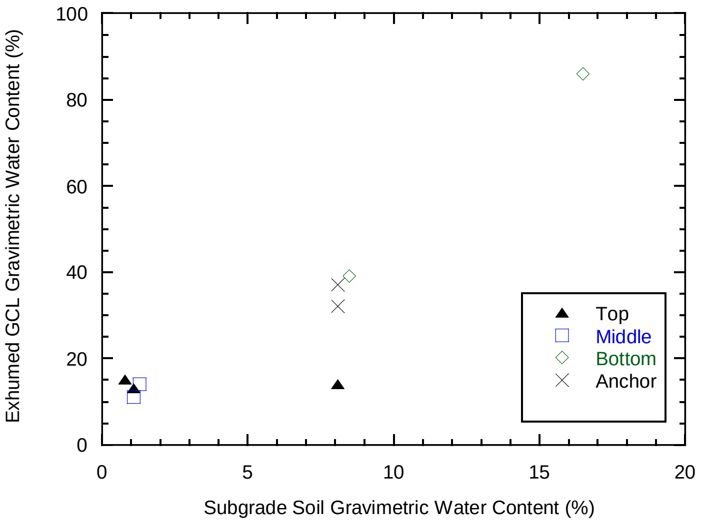

Figure 1. GCL water content vs. subgrade soil water content at various sampling locations.

3.2 *Hydraulic conductivity*

Hydraulic conductivity of the exhumed GCL varied with location along the slope, with a similar trend on both slopes (Fig. 2). Low hydraulic conductivities (<5.0 x 10^{-11} m/s) were obtained near the top of slope, and high hydraulic conductivities (>10^{-6} m/s) from the toe of slope. GCL samples from the middle of the slopes and the anchor trench had variable hydraulic conductivity.

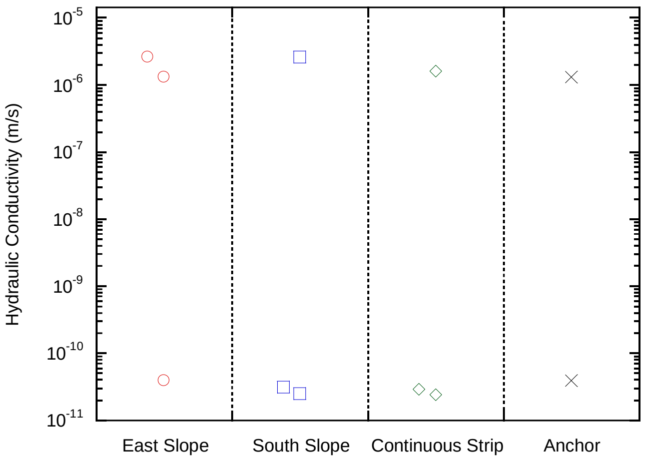

Figure 2. Hydraulic conductivity at various sample locations.

No relationship exists between hydraulic conductivity and water content of the bentonite of the exhumed GCLs (Fig. 3). Exhumed GCLs with high hydraulic conductivities had bentonite water contents between 2% and 86%, whereas all but one of the GCLs with low hydraulic conductivity (<5.0 x 10^{-11} m/s) had water contents < 20%. The lack of correspondence with water content may indicate that wet-dry cycling affected the GCLs. The cluster of low hydraulic conductivities and low water contents may indicate that some of these GCL samples never hydrated substantially or went through wet-dry cycling.

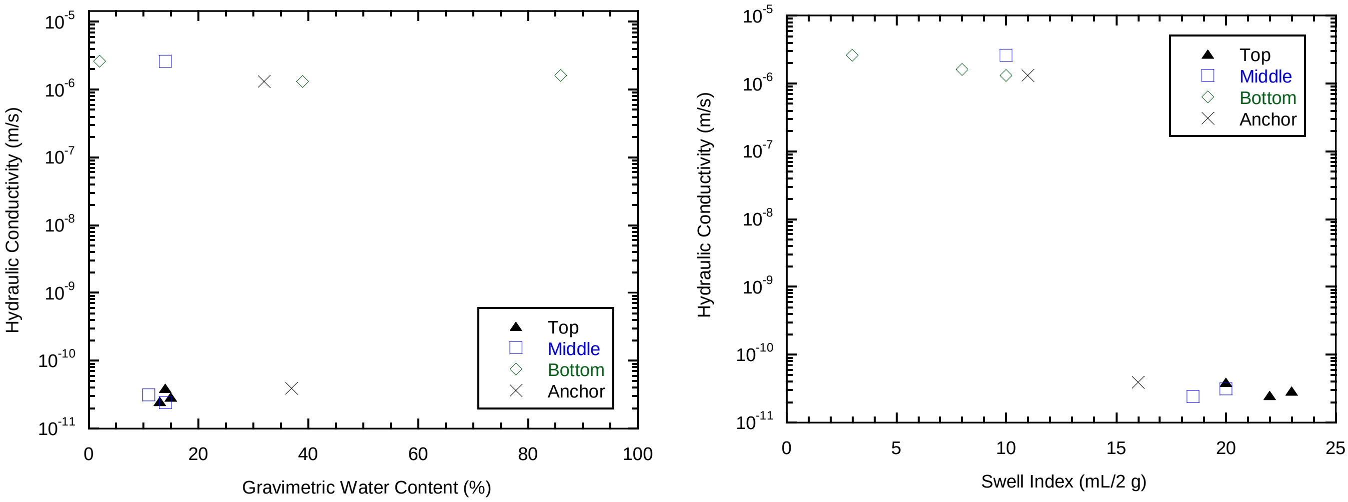

Figure 3. Hydraulic conductivity vs. gravimetric water content (left) and swell index (right) of bentonite from exhumed GCLs at different locations on slope.

Hydraulic conductivity of the GCLs falls in two distinct groups when graphed vs. swell index (Fig. 3). Hydraulic conductivities <5×10^{-11} m/s correspond to SI > 15 mL/2 g and hydraulic conductivities > 10^{-6} m/s correspond to SI < 12 mL/2 g. All of the SIs in Table 2 and Fig. 3 are less than the SI of the bentonite in the new GCL (26.0 mL/2 g), indicating that some or most of the native Na^+ in the exchange complex was replaced with polyvalent cations, as observed by others for in-service GCLs (Meer and Benson 2007, 2009; Scalia and Benson 2011; Scalia et al. 2017). The swell index data suggest that GCL samples from the top of slope underwent the least multivalent cation exchange, GCL samples from the toe underwent more extensive exchange, and GCL samples from mid-slope and the anchor trench had variable amounts of exchange.

The hydraulic conductivity and SI correspond strongly with the post-permeation water content (Fig. 4), which reflects different degrees of cation exchange and wet-dry cycling. High post-permeation water contents (> 120%) are indicative of Na^+ being predominant in the exchange complex, promoting osmotic swelling and low hydraulic conductivity regardless of whether the GCL underwent wet-dry cycling. The bentonite in GCLs with lower post-permeation water content did not swell sufficiently to block pores that control hydraulic conductivity. Sampling location was also important as was shown in Fig. 3; GCL samples from top of slope had the highest post-permeation water content, SI, and low hydraulic conductivity; samples from toe of slope had variable water content, low SI, and high hydraulic conductivity, and samples from mid-slope fell in between. The post-permeation water content of sample P38-B-1 (113%) was high given the low SI, but the hydraulic conductivity was high due to the low propensity for bentonite to swell.

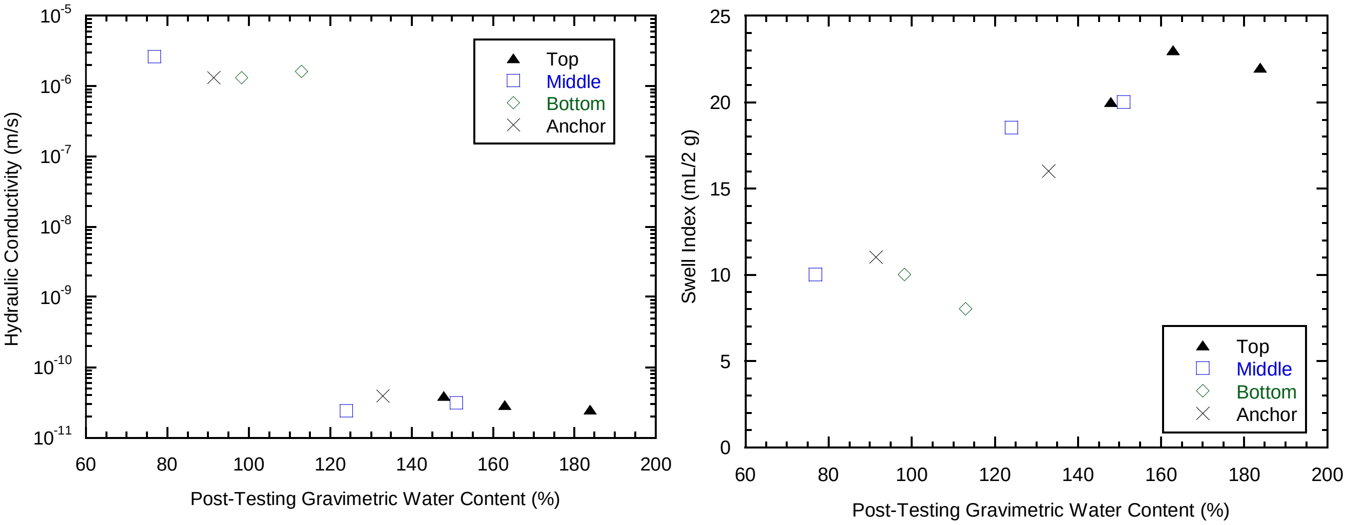

Figure 4: Hydraulic conductivity versus post-permeation water content (left) and swell index versus post-test water content (right) at varying positions along the slope lengths.

3.3 *Bentonite migration*

During exhumation of the GCLs, significant accumulation of soil was observed at the toe of the slopes. X-ray diffraction (XRD) analysis of the accumulated soil at one location confirmed that the soil was mostly montmorillonite (>70%), suggesting that bentonite from the GCL had eroded in a manner similar to that described in Rowe et al. (2016). They attribute down-slope bentonite erosion to repeated daytime heating and nighttime cooling of the exposed geomembrane overlying the GCL. Temperature cycling results in evaporation of moisture from the GCL during the day, followed by condensation of this moisture on the underside of the GM at night. The condensate accumulates, eventually forming drips and rivulets that erode the bentonite as the water flows down slope.

At this site, bentonite accumulated between the overlying GM and the upper black geotextile of the GCL. For example, the upper (black) geotextile of exhumed GCL sample ES-B-1 was covered by a layer of accumulated material ~10 mm thick (Fig. 5). Several thin stripes of relatively dry bentonite were observed on the upper surface of GCL sample P38-M-1 (Fig. 6), likely corresponding to bentonite deposited from rivulets of water flowing down slope.

Erosion from GCL sample SS-B-1, exhumed near the toe of the slope, was particularly severe. The entire 0.30×0.30 m GCL sample contained scarcely sufficient bentonite to conduct swell and water content tests. XRD analysis on bentonite-like material extracted from the SS-B-1 GCL indicated the montmorillonite fraction was 57%, significantly lower than the montmorillonite content in the other GCL samples (73% to 81% montmorillonite). Thus, some of the finer montmorillonite particles may have been carried away with the flowing water, or subgrade soil may have migrated into the GCL.

Figure 5. Photograph of accumulated material on upper surface of GCL sample ES-B-1.

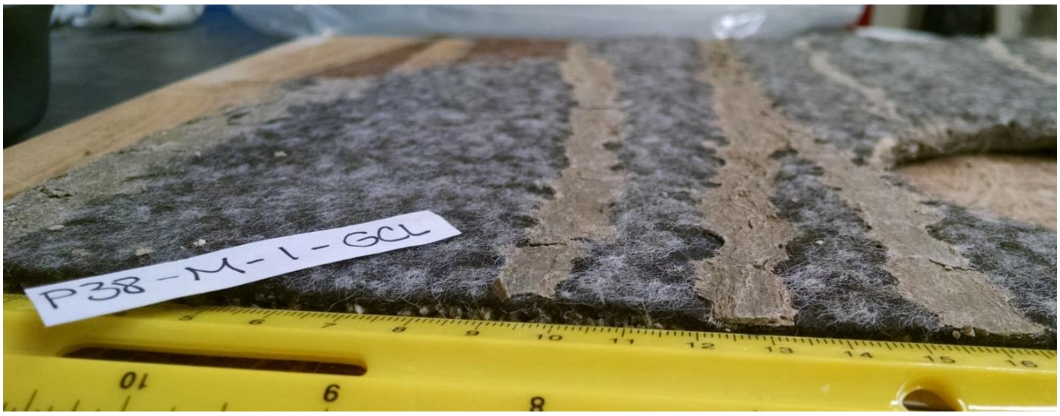

Figure 6. Photograph of stripes of eroded bentonite on upper surface of GCL sample P38-M-1.

4 SUMMARY AND CONCLUSIONS

GCL samples were collected from a composite liner (GM overlying GCL) left exposed to the atmosphere for 12 yr without a leachate collection system or other overlying materials. GCL samples collected from top of slope, mid-slope, and toe of slope were evaluated for exhumed water content, swell index, mass per unit area, hydraulic conductivity, and post-permeation water content. Properties of the exhumed samples indicate that GCLs in composite barriers left exposed without surcharge are vulnerable to long-term degradation. GCL samples from the exposed liner contained bentonite with low water content, lower swell index, and higher hydraulic conductivity than new GCLs. Wet-dry cycling that occurs as the surface of the GM in the composite liner heats during the day and cools at night induces bentonite erosion and migration down slope, resulting in areas where the GCL is nearly devoid of bentonite. Hydraulic conductivity and swell index of the GCL samples indicate that the degree of degradation varies along the slope, with GCLs near the toe undergoing the greatest degradation. These findings indicate that exposure of a composite liner without overlying layers should be minimized as much as practical. Installation of a protective surcharge or ballast layer (e.g., leachate collection system or cover soil) immediately after construction of the lining system is recommended to reduce the potential for degradation.

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