Proceedings of the 9ICEG
9th International Congress on Environmental Geotechnics
25-28 June, 2023 | Chania, Greece
© Authors: All rights reserved, 2023
https://doi.org/10.53243/ICEG2023-238

Evaluation on Interface Shear Strength of a Bentonite-Polymer Geosynthetic Clay Liner and a Smooth Geomembrane

Hanrui Zhao[1], and Kuo Tian[2]

1Ph.D. Student, Dept. of Civil, Environmental, and Infrastructure Engineering, George Mason Univ., Fairfax, VA. Email: hzhao25@gmu.edu

2Assistant Professor, Dept. of Civil, Environmental, and Infrastructure Engineering, George Mason Univ., Fairfax, VA. Email: ktian@gmu.edu

ABSTRACT

Interface shear tests were conducted to investigate the interface shear strength between bentonite-polymer (B-P) geosynthetic clay liners (GCL) with a smooth geomembrane (GMBS). One B-P GCL consisted of linear polymer and one sodium (Na-B) GCL was used as a control. Tests were conducted at displacement rate of 0.1 mm/min under four normal stress levels. Free hydration conditions were used to represent the worst field condition during the service life of GCL, whereas dry conditions were used as control. The shear strength envelop under free hydration conditions for Na-B GCL was liner whereas for B-P GCL was non-liner. In addition, the peak shear strength for B-P GCL and Na-B GCL under dry conditions was similar. The peak shear strength for B-P GCL was significantly lower than that for Na-B GCL. The polymer hydrogel was visible in the interface after shearing, suggesting the polymer in the interface was like to cause the lower shear strength.

Keywords: Geosynthetic clay liners (GCL), Bentonite-polymer (B-P), Geomembrane (GMB), Interface shear tests,

1 INTRODUCTION

Geosynthetic clay liner (GCL) consists of a layer of sodium bentonite (Na-B) sandwiched by two layers of geotextiles. GCL placed below geomembrane (GMB) are used as a barrier liner system in the side-slope of a variety of environmental containment applications (GMB/GCL) (Stark et al., 1996; Triplett & Fox, 2001; Chiu & Fox, 2004; Fox & Stark, 2004, 2015; Mccartney et al., 2009; Fox & Ross, 2011; Feng et al., 2022). With increasing up-covered waste, GMB/GCL liner system experiences increasing in shear stress. Thus, the stability of GMB/GCL becomes a concern in the landfill operation (Fox & Stark, 2004, 2015). The physical mechanism of the strength of the textured GMB/GCL interface is controlled by the friction mechanism between the GCL and GMB interface, as well as the interlocking between the reinforcement fiber of GCL and the surface of GMB (Hebeler et al., 2005; Mccartney et al., 2009, Fox & Stark, 2004, 2015; Feng et al., 2022). On the other hand, the strength of the smooth GMB/GCL interface is mainly controlled by the friction mechanism. For example, Triplett & Fox, 2001 concluded that peak strength failure envelopes for laminated textured GMB/woven GCL was bilinear whereas peak strength failure envelopes for smooth GMB/woven GCL was linear.

Bentonite-polymer (B-P) GCL was developed to improve chemical compatibility due to three-dimensional (3D) polymer-clay structure clogging the inter-aggregate pores when permeating with aggressive leachates(Chen et al., 2017, 2021; Scalia et al., 2014; Tian et al., 2019; Tian & Benson, 2019; Li et al., 2021; Du et al., 2021; Gastelo et al., 2023; Wireko et al., 2022), e.g., coal combustion product (CCP) (Chen et al., 2019; Li et al., 2021; Zainab et al., 2021), and low-level radioactive waste (LLW)(Tian et al., 2016). However, the 3D polymer-clay structure is physically unstable and easily eluted from B-P GCL(Tian et al., 2019; Chen et al., 2021; Norris et al., 2022). The polymer elution into GMB/B-P GCL interface decreases physical mechanism of the strength of GMB/B-P GCL interface (Vukelić et al., 2008; Fox & Stark, 2015; Chen et al., 2017; 2022).

This paper investigated smooth GMB/GCL interface shear strength. The GCLs included one conventional GCL (Na-B GCL) and one bentonite-polymer GCLs (B-P GCL). Tests were conducted under normal stress ranging from 20kpa to 950kpa at displacement rate of 0.1 mm/min. The free

hydration processes are used to investigate the effect of polymer hydrogel into GMB/ GCL interface on the interface shear strength, and dry condition was used as a control test.

2 METERIALS AND METHOD

2.1 Materials

One high density polyethylene (HDPE) smooth geomembrane (GMBS) with the average thickness of 1.5 mm according to ASTM D5994 was used in this paper. The average yield strength and yield elongation of ten GMBS samples were 26.5 kN/m and 6.1% according to ASTM D6693. One conventional GCLs (named Na-B GCL) and one bentonite-polymer (B-P) GCLs with polymer loading of 4 percentage (named B-P-4 GCL) were used in this paper. Both Na-B and B-P-4 GCLs were needle-punched between two non-woven geotextiles. The peel strength (PS) of Na-B and B-P-4 GCLs was measured based on ASTM D6496 (ASTM 2009). Ten GCL samples from the same lots were measured and average were reported in Table 1. The average PS for Na-B and B-P-4 GCLs were very close (e.g., 1753.9 N/m vs. 1870.2 N/m). The mass per area of Na-B and B-P-4 GCLs was 5.6 kg/m^2 and 8.1 kg/m^2, respectively. The mass per area, thickness, the peel strength of GCLs is summarized in Table 1.

Table 1 *Summary of GCL properties*

Parameters	Method	Unit	Na-B	B-P-4
Dry mass per area	ASTM D3776	kg/m^2	5.6	8.1
Average height		mm	6.4	7.0
Polymer loading		%	-	4.0
Peel strength (PS)	ASTM D6496	N/m	1753.9 $\pm$ 230	1870.2 $\pm$ 270

2.2 Shear equipment and procedure

The large shear machine were used in this study according to ASTM D6243. The GMBS was placed below GCL fixed on the top box and moved horizontally during shearing. A gripping plate was placed above the GCL to uniform force during shearing. The gripping plate was built by using a 304 mm × 304 mm aluminium plate and 900 screws with a teeth height of 1.5 mm. A 304mm x 500mm piece of graded 36 3M commercial sandpaper was placed under the GMBS to prevent progressive failure during shear. The interface of GMBS/GCL is 304 mm × 304 mm and constant during the shear process.

All interface tests were conducted to a maximum displacement of 60 mm at displacement rate of 0.1 mm/min. Four stress levels of 20 kPa, 200 kPa, 500 kPa, and 950 kPa were used to represent increasing up-cover waste height (up to 60m) during landfill operation. Free hydration was used to represent the worst conditions during the service life of GCL, e.g., an accidental exposure of an uncovered GCL to short-duration rainfall reported by (Sawada et al., 2019). GCLs were trimmed and immerge into tap water under normal stress of 1 kPa for two days. Then hydrated GCLs were transported to shear machine. After GMB/GCL system was assembled, water was added into the water tank and GCLs were free to get water. The consolidation normal stress was gradually applied on the GCL to prevent bentonite extrusion from side of GCLs. The completion of consolidation was typically determined based on ASTM D2435 or by monitoring the vertical deformation rate, which is considered completion when it reduces to less than 0.2% per hour. Test were also conducted under dry condition to evaluate the effect of materials variabilities between Na-B and B-P-4 GCLs.

2.3 Polymer quantification

LOI tests were conducted to quantify the polymer loss after completion of shearing. Three grams of B-P composite and bentonite were extracted from the B-P-4 GCL and Na-B GCL before and after interface shear tests to evaluate the pre-test and post-test polymer loading. All samples were oven dried at temperature of 105°C to evaporate the free water in the samples. And then, the dried samples were transported to furnace and ignited at temperature of 550°C. All polymer was assumed to burn during this process. The polymer loading can be calculated by subtracting the LOI of Na-B from the LOI of B-P composite.

3 RESULTS AND DISCUSSION

3.1 Shear stress-displacement relationship horizontal

The typical shear stress(τ) versus displacement (δ) relationship is shown in Figure 1. The τ-δ curves increased to peak shear strength (τ_p) and then gradually decreased to large displacement shear strength (τ_l) at δ = 60 mm regardless of GCL types and hydration conditions. The displacement at peak shear strength (δ_p) for GMB/Na-B GCL and GMB/B-P-4 GCL interfaces under dry conditions had a similar value (e.g., 1.1 mm vs. 1.6 mm). It can be explained by the same friction mechanism between needle-punched nonwoven Na-B and B-P-4 GCLs with GMBS. This is likely because all the GCLs used in this study were with similar peel strength and manufactured by the same company. However, the δ_p for GMB/B-P-4 GCL interface was 3.5 time higher than that for GMB/Na-B GCL interface under free hydration conditions, e.g., 10.8 mm vs. 3.1 mm. The result suggests that polymer hydrogel in the interface acted as a lubrication and caused slippage between the B-P-4 GCL and GMBS during the shearing.

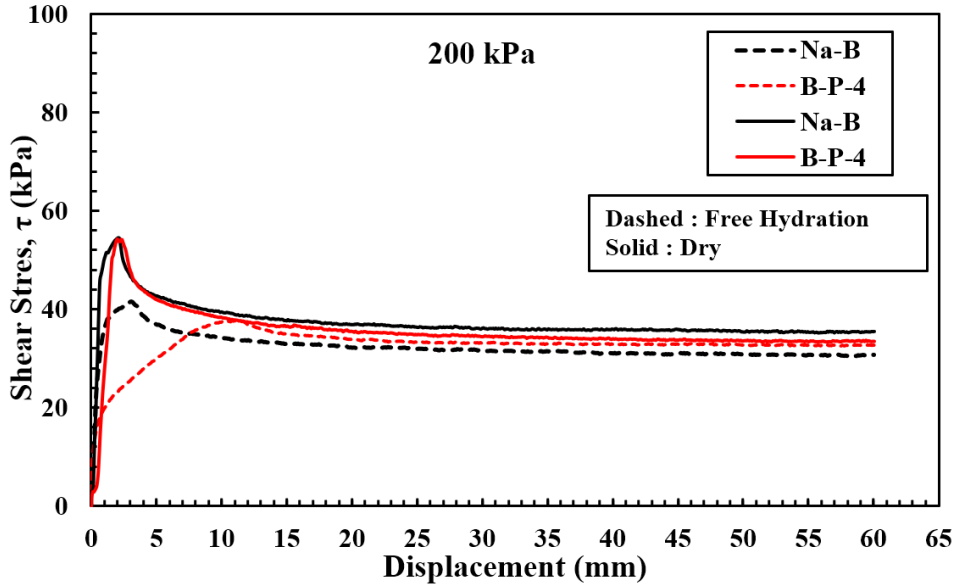


Figure 1. *Shear stress versus shear horizontal displacement relationships for GMB/Na-B GCL and GMB/B-P-4 GCL under dry and free hydration conditions at normal stress of 200 kPa*

3.2 Shear strength envelopes

Shear strength envelopes for GMB/GCL interfaces were shown in Figure 2. The friction angle (φ) for GMB/GCL interfaces can be extracted by using liner regression equations as proposed by (Triplett & Fox, 2001; Fox & Stark, 2015) following Eq. 1:

$$\tau = \sigma_n \tan \varphi \quad (1)$$

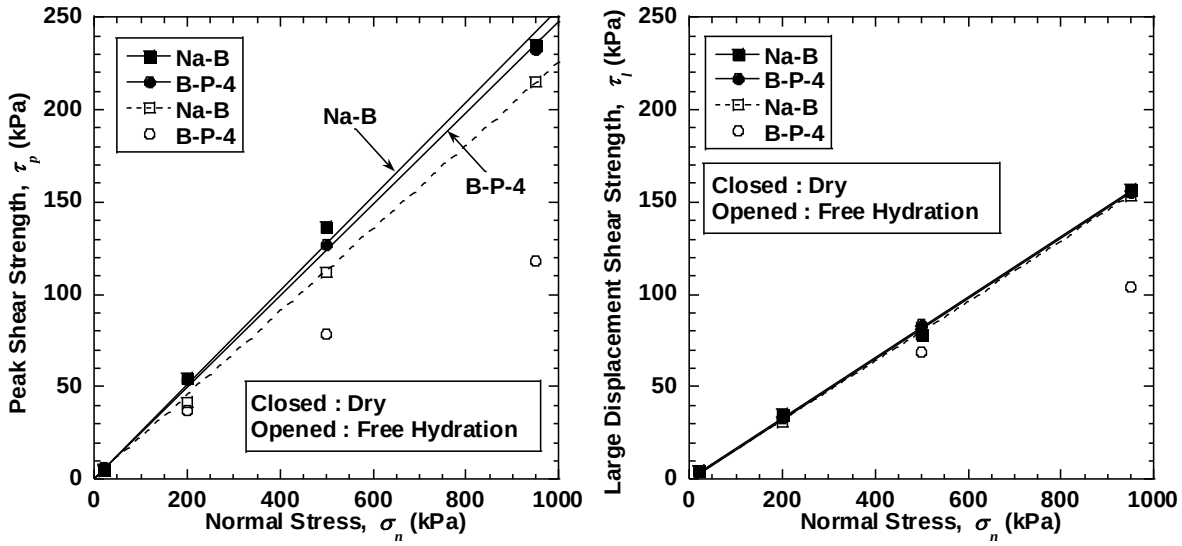
Where φ is equal to the interface friction angle (°); σ_n is equal to normal stress (kPa); τ is equal to shear strength (kPa). All interface friction angles were summarized in Table 2.

The peak strength angle (φ_p) for GMB/Na-B GCL and GMB/B-P-4 GCL interfaces under dry conditions was 14.2° and 13.9°, respectively (Figure 2a and Table 2). The result can be explained that Na-B and B-P-4 GCLs had a same reinforcement fiber intensity leading to similar peel strength (e.g., PS = 1753.9 N/m vs.1870.2 N/m). Thus, the same φ_p occurred as the same value of δ_p was observed. The φ_p for GMB/Na-B GCL under free hydration conditions was lower than that under dry conditions (e.g., 14.3° vs. 12.7°) (Table 2). The results illustrate that the extrusion bentonite and water in the interface decreased the shear resistance of the interface as proposed by Vukelić et al. (2008) and Fox & Stark (2015). The GMB/B-P-4 GCL interfaces under free hydration conditions were non-liner as shown in Figure 2a. And the τ_p for GMB/B-P-4 GCL interfaces was significantly lower than GMB/Na-B GCL, especially at medium to high normal stress (from 200 kPa to 950 kPa). For example, the τ_p for GMB/Na-B GCL and GMB/B-P-4 GCL interfaces at normal stress of 500 kPa were 112.0 kPa and 78.3

kPa, respectively. The lower interface shear strength for B-P-4 GCL was like to be the polymer hydrogel in the interface as shown in Figure 3.
The large displacement strength angle (φ_l) for GMB/Na-B GCL and GMB/B-P-4 GCL interfaces were summarized in Table 2. The same φ_l for GMB/Na-B GCL and GMB/B-P-4 GCL interfaces under dry conditions and free hydrations were same (e.g., 9.2°) (Figure 2b and Table 2). However, the exception was the GMB/B-P-4 GCL interfaces under free hydration condition. The τ_l for GMB/B-P-4 GCL interfaces under free hydration was lowest at the same normal stress. The result can be attributed to be the effect of polymer hydrogel in the GMB/B-P-4 GCL interface.

Table 2 *Summary of friction angle of GMB/GCL interfaces*

Type of GCL	Normal stress, σ_n (kPa)	Hydration conditions	Peak strength angle, φ_p (°)	Large displacement strength angle, φ_l (°)
Na-B	20-950 kPa	Dry	14.2	9.2
Na-B		Free hydration	12.7	9.2
B-P-4		Dry	13.9	9.2
B-P-4		Free hydration	-	-



(a) *peak shear strength* *(b) large displacement shear strength*

Figure 2. *Shear strength envelopes for GMB/Na-B GCL and GMB/B-P-4 GCL under dry and free hydration conditions for: (a) peak shear strength; (b) large displacement shear strength*

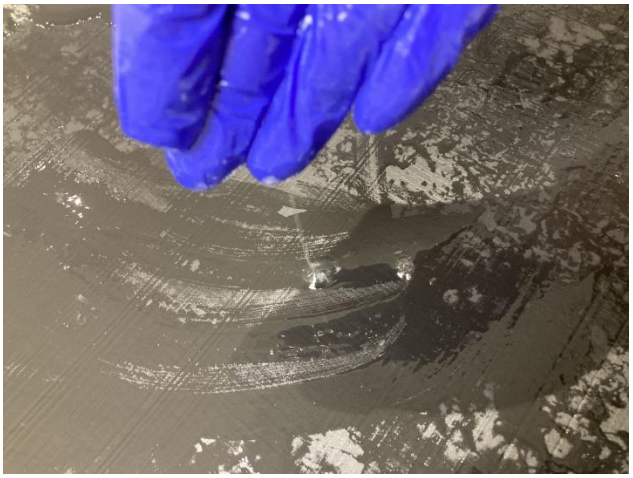


Figure 3. *Polymer hydrogel existed in the interface after shear test conducted by GMB/B-P-4 GCL at normal stress of 500 kPa under free hydration*

3.3 Post-peak strength ratio

Post-peak strength ratio was defined by the large displacement shear strength overs the peak shear strength (τ_l/τ_p). The post-peak strength ratio as a function of normal stress under free hydration is shown in Figure 4. The τ_l/τ_p for Na-B GCL under free hydration decreased as normal stress increased from 20 kPa to 200 kPa and leveled off after normal stress of 200 kPa. The results illustrate that an increase in normal stress causes closer contact between a GMBS and a GCL. This, in turn, leads to limited interface drainage for a GMBS, resulting in less extrusion bentonite and water at the interface. As displacement increased, closer contact led greater damage to the geotextile while shearing. Similar to Na-B GCL, τ_l/τ_p for B-P-4 GCL had a decrease and leveled off trend as increased of normal stress. However, the τ_l/τ_p for B-P-4 GCL was higher than that for Na-B GCL. For example, as tests conducted at normal stress of 950 kPa, τ_l/τ_p for B-P-4 GCL was 0.88 whereas τ_l/τ_p for Na-B GCL was 0.71. The higher value observed for B-P-4 GCL can be attributed to the presence of polymer in the interface. This polymer hydrogel likely acted as a protective layer for the geotextile during the shearing process.

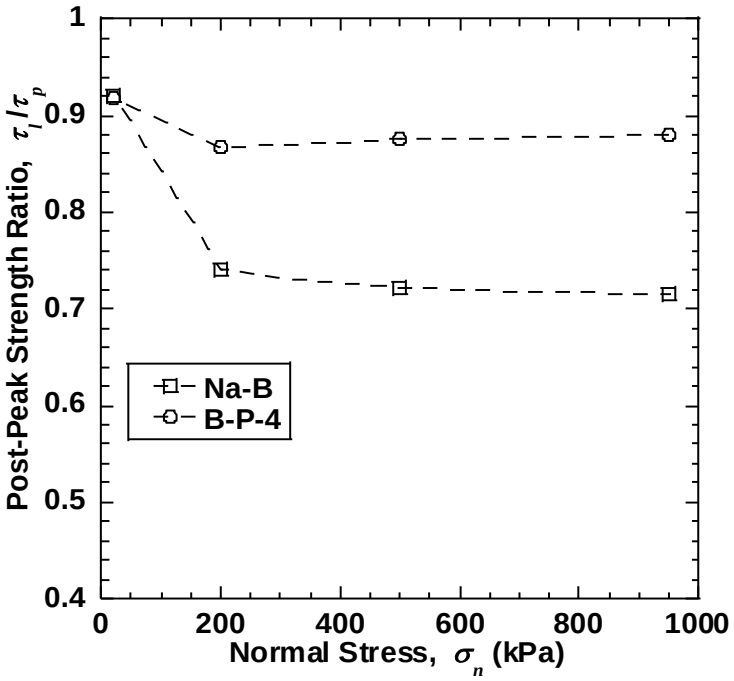


Figure 5. *Post-peak strength ratio as a function of normal stress under free hydration conditions.*

3.4 Polymer loss

The post-test polymer loading in B-P-4 GCL as a function of normal stress is shown in Figure 5. All B-P-4 GCLs after test had lower polymer loadings than the initial polymer loading (e.g., 4%), indicating polymer loss during the tests. In addition, post-test polymer loading in B-P-4 GCL decreased with increased of normal stress. For example, as normal stress increased from 20 kPa to 950 kPa, the post-test polymer of B-P-4 GCL decreased from 3.7% to 2.5%. The results can be explained that linear polymers are characterized by having long polymer chains which are free to move and slide past one another, leading to a dispersed behaviour when hydrated. Thus, the hydrated linear polymer can easily elute with dissipated water during the consolidation and shearing process.

4 CONCLUSIONS

Interface shear tests between a smooth geomembrane (GMB) and a bentonite-polymer (B-P) geosynthetic clay liners (GCLs) were conducted to evaluate the effect of polymer hydrogel on the interface shear strength. One sodium bentonite GCL (Na-B GCL) was used as a comparison. Interface tests were performed ranged from 20 kPa to 950 kPa at displacement rate of 0.1 mm/min. Free hydration was used to represent the worst condition during the service life of GCL. Dry GCL was used in the test to evaluate the variation from different lots. The following conclusions can be made based on the findings of the study:

1. All shear stress versus shear horizontal displacement relationship for GMB/GCL interfaces was similar. The displacement at peak shear strength of GMB/Na-B GCL and GMB/B-P-4 GCL interfaces was similar under dry condition; however, the displacement at peak shear strength of GMB/B-P-4 GCL interfaces was higher than that of GMB/Na-B GCL under free hydration testing condition.
2. GMB/GCL interfaces had the similar peak shear strength under dry conditions. However, the peak shear strength for GMB/B-P-4 GCL interfaces was lower than that of GMB/Na-B GCL interfaces. Meanwhile, post-peak shear strength ratio for GMB/B-P-4 GCL interfaces was higher than that for GMB/Na-B GCL interfaces.
3. The polymer hydrogel was visible in the interface after shearing. All post-test polymer loading of B-P-4 GCLs after shearing tests was lower than original polymer loading of B-P-4 GCLs and decreased with increased of normal stress. The lower shear strength and higher post-peak shear strength ratio for GMB/B-P-4 GCL interfaces was like to be the polymer hydrogel lubricating the shearing interface.

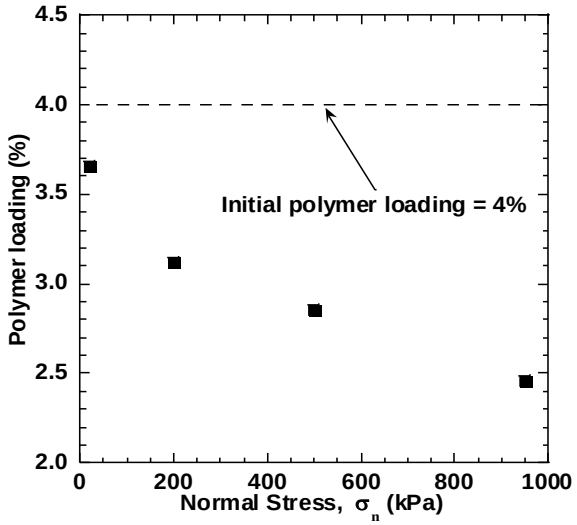


Figure 5. *Post-test polymer loading in B-P-4 GCL as a function of normal stress*

REFERENCES

ASTM. 2020. Standard Test Method for Determining Average Bonding Peel Strength Between Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners, ASTM D6496/D6496M-20, West Conshohocken, PA: ASTM.

ASTM. 2020. Standard Test Methods for Mass Per Unit Area (Weight) of Fabric, ASTM D3776/D3776M-20, West Conshohocken, PA: ASTM.

ASTM. 2021. Standard Test Method for Determining Tensile Properties of Nonreinforced Polyethylene and Nonreinforced Flexible Polypropylene Geomembranes, ASTM D6693/D6693M-20, West Conshohocken, PA: ASTM.

ASTM. 2021. Standard Test Method for Determining the Internal and Interface Shear Strength of Geosynthetic Clay Liner by the Direct Shear Method, ASTM D6243/D6243M-20, West Conshohocken, PA: ASTM.

ASTM. 2021. Standard Test Methods for Loss on Ignition (LOI) of Solid Combustion Residues, ASTM D7348-21, West Conshohocken, PA: ASTM.

ASTM. 2021. Standard Test Method for Measuring Core Thickness of Textured Geomembranes, ASTM D5994/D5994M-10(2021), West Conshohocken, PA: ASTM.

Chen, J., Benson, C. H., Likos, W. J., & Edil, T. B. (2017). Interface shear strength of a bentonite-polymer geosynthetic clay liner and a textured geomembrane. In Geotechnical Frontiers 2017, (pp. 219-226).

Chen, J., Salihoglu, H., Benson, C. H., Likos, W. J., & Edil, T. B. (2019). Hydraulic conductivity of bentonite–polymer composite geosynthetic clay liners permeated with coal combustion product leachates. Journal of Geotechnical and Geoenvironmental Engineering, 145(9), 04019038.

Chen, J., Gustitus, S. A., & Benson, C. H. (2021). Effect of polymer elution on interface shear strength between bentonite-polymer composite geosynthetic clay liners and geomembranes. Japanese Geotechnical Society Special Publication, 9(2), 45-48.

Chen, J., Gustitus, S. A., Lin, H., & Benson, C. H. (2022). Shear strength of bentonite–polymer composite geosynthetic clay liners and geomembranes. Environmental Geotechnics, 40(XXXX), 1-10.

Chen, Y. M., Lin, W. A., & Zhan, T. L. (2010). Investigation of mechanisms of bentonite extrusion from GCL and related effects on the shear strength of GCL/GM interfaces. Geotextiles and Geomembranes, 28(1), 63-71.

Chiu, P., & Fox, P. J. (2004). Internal and interface shear strengths of unreinforced and needle-punched geosynthetic clay liners. Geosynthetics International, 11(3), 176-199.

Du, Y. J., Shen, S. Q., Tian, K., & Yang, Y. L. (2021). Effect of polymer amendment on hydraulic conductivity of bentonite in calcium chloride solutions. Journal of Materials in Civil Engineering, 33(2), 04020452.

Feng, S. J., Shen, Y., Zheng, Q. T., & Shi, J. L. (2022). Multi-functional direct shear apparatus for geosynthetic interfaces with its application on various GMB/GCL interfaces. Acta Geotechnica, 17(3), 993-1008.

Fox, P. J., & Ross, J. D. (2011). Relationship between NP GCL internal and HDPE GMX/NP GCL interface shear strengths. Journal of Geotechnical and Geoenvironmental Engineering, 137(8), 743-753.

Fox, P. J., & Stark, T. D. (2004). State-of-the-art report: GCL shear strength and its measurement. Geosynthetics International, 11(3), 141-175.

Fox, P. J., & Stark, T. D. (2015). State-of-the-art report: GCL shear strength and its measurement–ten-year update. Geosynthetics International, 22(1), 3-47.

Gastelo, J., Li, D., Tian, K., Tanyu, B. F., & Guler, F. E. (2023). Hydraulic conductivity of GCL overlap permeated with saline solutions. Waste Management, 157, 348-356.

Hebeler, G. L., Frost, J. D., & Myers, A. T. (2005). Quantifying hook and loop interaction in textured geomembrane–geotextile systems. Geotextiles and Geomembranes, 23(1), 77-105.

Li, D., Zainab, B., & Tian, K. (2021). Effect of effective stress on hydraulic conductivity of bentonite–polymer geosynthetic clay liners to coal combustion product leachates. Environmental Geotechnics, 40, 1-12.

Li, Q., Chen, J., Benson, C. H., & Peng, D. (2021). Hydraulic conductivity of bentonite-polymer composite geosynthetic clay liners permeated with bauxite liquor. Geotextiles and Geomembranes, 49(2), 420-429.

McCartney, J. S., Zornberg, J. G., & Swan Jr, R. H. (2009). Analysis of a large database of GCL-geomembrane interface shear strength results. Journal of Geotechnical and Geoenvironmental Engineering, 135(2), 209-223.

Norris, A., Aghazamani, N., Scalia, J., & Shackelford, C. D. (2022). Hydraulic Performance of Geosynthetic Clay Liners Comprising Anionic Polymer–Enhanced Bentonites. Journal of Geotechnical and Geoenvironmental Engineering, 148(6), 04022039.

Sawada, Y., Nakazawa, H., Take, W. A., & Kawabata, T. (2019). Full scale investigation of GCL damage mechanisms in small earth dam retrofit applications under earthquake loading. Geotextiles and Geomembranes, 47(4), 502-513.

Scalia IV, J., Benson, C. H., Bohnhoff, G. L., Edil, T. B., & Shackelford, C. D. (2014). Long-term hydraulic conductivity of a bentonite-polymer composite permeated with aggressive inorganic solutions. Journal of Geotechnical and Geoenvironmental Engineering, 140(3), 04013025.

Tian, Kuo, Craig H. Benson, and William J. Likos. "Hydraulic conductivity of geosynthetic clay liners to low-level radioactive waste leachate." Journal of Geotechnical and Geoenvironmental Engineering 142.8 (2016).

Tian, K., & Benson, C. H. (2018, October). Containing bauxite liquor using bentonite-polymer composite geosynthetic clay liners. In The International Congress on Environmental Geotechnics (pp. 672-678). Springer, Singapore.

Tian, K., Likos, W. J., & Benson, C. H. (2019). Polymer elution and hydraulic conductivity of bentonite–polymer composite geosynthetic clay liners. Journal of Geotechnical and Geoenvironmental Engineering, 145(10), 04019071.

Stark, T. D., Williamson, T. A., & Eid, H. T. (1996). HDPE geomembrane/geotextile interface shear strength. Journal of Geotechnical Engineering, 122(3), 197-203.

Triplett, E. J., & Fox, P. J. (2001). Shear strength of HDPE geomembrane/geosynthetic clay liner interfaces. Journal of Geotechnical and Geoenvironmental Engineering, 127(6), 543-552.

Vukelić, A., Szavits-Nossan, A., & Kvasnička, P. (2008). The influence of bentonite extrusion on shear strength of GCL/geomembrane interface. Geotextiles and Geomembranes, 26(1), 82-90.

Wireko, C., Abichou, T., Tian, K., Zainab, B., & Zhang, Z. (2022). Effect of incineration ash leachates on the hydraulic conductivity of bentonite-polymer composite geosynthetic clay liners. Waste Management, 139, 25-38.

Zainab, B., Wireko, C., Li, D., Tian, K., & Abichou, T. (2021). Hydraulic conductivity of bentonite-polymer geosynthetic clay liners to coal combustion product leachates. Geotextiles and Geomembranes, 49(5), 1129-1138.