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Temperature Effects on the Swelling and Bentonite Extrusion Characteristics of GCLs

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Abstract

This investigation was conducted to evaluate effects of temperature on swelling and bentonite extrusion properties of GCLs. The swelling characteristics were determined using standardized test procedures and extrusion characteristics were determined using a new test method developed by the authors. Tests were conducted on a conventional medium-weight woven/nonwoven GCL. The range of test temperatures was 2 to 98°C (swelling tests) and -5 to 100°C (extrusion tests). The extrusion tests were conducted under stresses between 100 and 400 kPa and moisture contents between 50 and 150%. Temperature had significant effects on both swell and extrusion. The swell index ranged from 21 mL/2g at 2°C to 36.5 mL/2g at 98°C, with the largest increase occurring from 20 to 40°C. The amount of extrusion ranged from nearly 0 to 40.5 g/m^2 with generally decreasing extrusion with temperature from 2 to 100°C. At a given temperature, extrusion increased with increasing stress and moisture content.

INTRODUCTION

Geosynthetic Clay Liners (GCLs) experience a wide range of temperature conditions during service life in various containment applications. Service temperatures vary due to local climatic conditions and also due to biological, biochemical, and chemical processes and reactions that occur within the contained materials. Low temperatures occur due to air temperatures in cover systems and in exposed bottom liner systems prior to waste placement. Barrier systems in cold regions or regions with sufficient seasonal temperature variation have undergone freezing in service conditions (e.g., Hanson et al. 2005, Yesiller et al. 2008, McWatters et al. 2015, Yesiller et al. 2015). Elevated temperatures occur in barrier systems due to heat generation in overlying wastes (e.g., Hanson et al. 2010). Engineering properties and behavior of natural and geosynthetic barrier materials including GCLs are affected by temperature (e.g., Ishimori and Katsumi 2012, Hanson et al. 2015). Therefore, characterization under representative temperature conditions is necessary to establish appropriate parameters for use in predicting behavior of these materials. A laboratory test program was conducted to evaluate the effects of temperature on swelling and bentonite extrusion properties of GCLs.

BACKGROUND

Transfer of fluids through GCLs and shear strength characteristics of GCLs are affected by swelling and hydration of the bentonite component. Hydraulic conductivity decreases considerably for bentonite that has undergone complete hydration and swelling (Yesiller and Shackelford 2011), whereas hydrated GCLs exhibited very low internal as well as interface shear strength resistance (Fox and Stark 2004). Swelling capacity of bentonite can be assessed experimentally using the swell index test. Swell index test results have been directly correlated to hydraulic conductivity of GCLs (Jo et al. 2001, Scalia and Benson 2011, Ishimori and Katsumi 2012, Chen et al. 2015). Hydraulic conductivity of GCLs increased by up to over 5 orders of magnitude (10^{-6} to 10^{-11} m/s) as swell index decreased from approximately 40 to 5 mL/2g.

Extrusion of bentonite from GCLs has been reported in the literature. In general observations and measurements were made in investigations of interface shear strength behavior. Bentonite extrusion from GCLs has been observed in interface shear strength tests between GCLs and geomembranes (GMs) (Gilbert et al. 1997, Triplett and Fox 2001, Vukelic et al. 2008, Hanson et al. 2015). The bentonite extruded from GCLs is dependent on many factors, including type of geotextiles (woven versus nonwoven), roughness of GM surface, type of hydration fluid, hydration condition of the GCL, stress level applied, sequence of hydration and loading, loading rate, and shearing rate (Chen et al. 2010). Vukelic et al. (2008) reported bentonite extrusion to be more extensive during shearing of prehydrated GCL/GM than for non-prehydrated GCL/GM interfaces. Hanson et al. (2015) identified threshold water contents and normal stress levels for onset of significant bentonite extrusion. In addition, fluid transfer characteristics of GCLs (i.e., containment effectiveness) are expected to be affected by bentonite extrusion due to the resulting reduction in the amount of bentonite in GCLs. While systematic/dedicated studies have not been reported in the literature, hydraulic and gas conductivity of GCLs and fluid flux are expected to increase due to decreased bentonite thickness and associated reduced swelling and hydration.

Temperature effects on swelling and hydration properties and interface strength of GCLs were reported in a limited number of studies in literature. Ishimori and Katsumi (2012) investigated the swelling capacity and hydraulic conductivity of GCLs at two test temperatures. The baseline swell index at 20°C was reported to be 30 mL/2g with the swell index increased to 35 mL/2g at 60°C. The calculated Debye length (describing the extent of electrostatic effects of ionic species in a solution away from a clay surface, related to characteristic thickness of diffuse double layer (Tournassat et al. 2015)) was slightly lower at 60°C than at 20°C. The hydraulic conductivity of the GCL increased by nearly an order of magnitude for temperature increasing from 20°C to 60°C (Ishimori and Katsumi 2012). Interface shear strength of GCLs against textured geomembranes was determined to be a function of temperature (Hanson et al. 2015). Tests were conducted at 20 and 40°C for bottom liner stress conditions and at 2, 20, and 40°C for cover liner stress conditions. Interface friction angle was higher at 20°C than 40°C (for bottom liner tests) and was higher at 20°C than at both 2°C and 40°C (for cover liner tests). Interface shear strength for a given normal stress decreased with increasing temperature with variations up to 18% and 54% for bottom liner and cover liner conditions, respectively (Hanson et al. 2015).

This test program was conducted to evaluate physical characteristics including swelling behavior of bentonite in GCLs and extrusion response of GCLs as a function of temperature. Service conditions in containment systems vary significantly from standard laboratory test temperatures. An assessment of temperature-dependent behavior of GCLs is required to improve understanding of GCL response under field conditions.

EXPERIMENTAL TEST PROGRAM

Materials. Tests were conducted on a GCL commonly used for containment applications in the U.S. The GCL was a mid-weight product consisting of a layer of bentonite encased between a lightweight slit-film woven geotextile and a heavier weight nonwoven geotextile. The GCL is held together by needlepunching the fibers of the nonwoven geotextile through the apertures of the woven geotextile. Properties of the GCL are presented in Table 1.

Table 1. Properties of GCL.

Property	Value	ASTM Test Method
Bentonite mass per unit area (g/m^2)[a]	3600	D5993
Total dry GCL mass per unit area (g/m^2)[a]	3905	D5993 and D5199
GT mass per unit area (g/m^2)[a]	105 (W), 200 (NW)	D5199
Bentonite mass per unit area (g/m^2)[b]	4590	D5993
Total dry GCL mass per unit area (g/m^2)[b]	4895	D5993
As received moisture content (%)[b]	20	D2216
80% by mass of particle diameter (mm)[a]	0.075 to 2	D421

[a]Manufacturer data, [b]Measured, W = woven, NW = nonwoven

Swell index tests. Swell index tests were conducted in accordance with ASTM D5890. In this method, 2 g of ground bentonite powder (passing 0.075 mm sieve) is added to DI water in a 100 mL graduated cylinder. The powder is added in 0.1 g increments every 10 minutes. The specimen is allowed to hydrate for 24 hours and a reading of swell index is recorded by observation. The swell index tests were conducted in thermally controlled environments for this test program. All materials were heated or cooled to target test temperatures. A convection oven and a temperature-controlled bath were used to heat and cool the GCLs to target temperatures, respectively.

Bentonite extrusion tests. The bentonite extrusion tests were conducted using the methodology developed by the authors (Hanson et al. 2014). The test involves measuring the amount of bentonite that is extruded through the geosynthetic component onto a series of fiberglass screens upon 1-D loading in a consolidometer. Circular test specimens with a diameter of 63.5 mm are used in the tests. A stack of 8 flexible screen disks is placed on each side (top and bottom) of the test specimen to create space for bentonite extrusion to occur. The GCL test specimens and spacer disks are cut using a rigid template. The extrusion spacer configuration allows for systematic determination of amount of bentonite that was extruded from the GCL specimens onto the screens. Fiberglass is selected as the screen material to: a) provide a somewhat flexible medium and b) to provide color contrast for imaging of the spatial distribution of bentonite extrusion after testing was complete.

Specimens are hydrated with DI water to target moisture contents using an air-atomizing sprayer and are wrapped in thin plastic film. The specimens are placed in sealed plastic bags to prevent moisture loss and then hydrated for at least 16 hours. Upon hydration, the specimens are assembled by placing the stacks of screens on both sides of the GCL and wrapping the assembly in thin plastic film for the extrusion testing in a 1-D consolidometer. Temperature controlled

tests were conducted using a fluid circulation network consisting of copper tubing coiled tightly around the consolidometer cell. The tubing was connected to a thermal bath. The entire setup is encased in thermal insulation. A Type K thermocouple is embedded within a trial GCL specimen to establish temperature conditions before testing specimens. Loading is applied in a single load step to the target stress level. The load is left in place for 1 hour and then the testing assembly is removed from the consolidometer. The GCL specimen and the fiberglass screen stacks are disassembled. The bentonite extruded onto the thin plastic film is dried for 24 hours in an oven at 110°C. The extrusion spacer screens are weighed and oven dried for 21 hours. The drying time is highly controlled as preliminary tests indicated that the mass of the fiberglass screens decreased with heating due to apparent volatilization of a component or components of the screens. The mass loss of the screens was established to be 0.71% for 21 hours of drying at 110°C. This loss is incorporated into calculations related to quantities of bentonite extrusion. After oven drying, the screens are placed on a dark background for imaging to evaluate the spatial distribution and extent of the extruded bentonite. In the test program presented herein, extrusion was determined as a function of temperature, moisture content, and stress. The testing matrix is presented in Table 2. A schematic of the extrusion test setup is presented in Figure 1.

Table 2. Bentonite extrusion test matrix.

Temperature (ºC)	Moisture Content (%)	Stress (kPa)
-5	50	300
	100	100, 200, 300, 400
	150	300
2	50	300
	100	100, 200, 300, 400
	150	300
20	50	300
	100	100, 200, 300, 400
	150	300
40	50	300
	100	100, 200, 300, 400
	150	300
60	50	300
	100	100, 200, 300, 400
	150	300
80	50	300
	100	100, 200, 300, 400
	150	300
100	50	300
	100	100, 200, 300, 400
	150	300

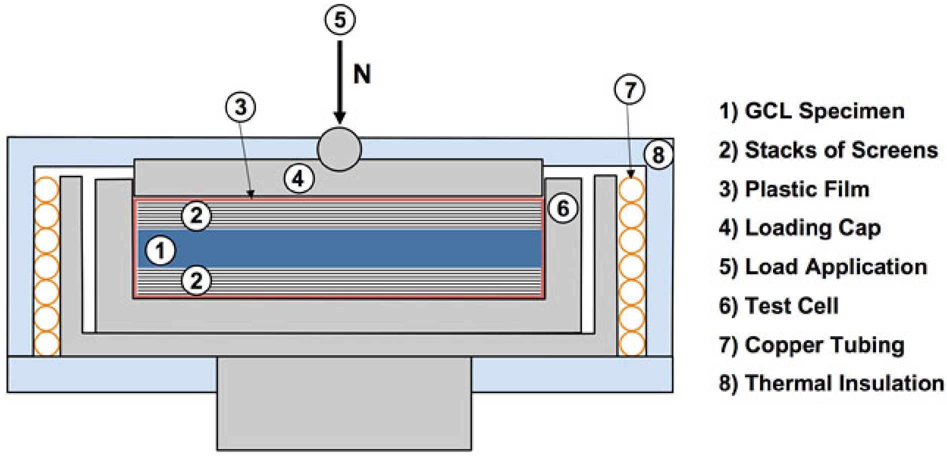

Figure 1. Schematic of extrusion test setup.

RESULTS AND DISCUSSION

Swell index tests. Swell index test results are provided in Table 3 and Figure 2. Swell index of the bentonite was affected by temperature. A linear curve fit was used to describe the increase in swell index with increasing temperature. The rate of increase of swell index was determined to be 0.16 mL/2g/°C.

Table 3. Swell index of bentonite.

Temperature (ºC)	Swell Index (mL/2g)	Average Swell Index (mL/2g)
2	20.5	21
	21	
	21.5	
20	24.5	25
	25	
	25.5	
40	29.5	30
	30	
	30.5	
60	31.5	32
	32	
	32	
80	33	33.5
	33.5	
	34	
98	36	36.5
	36	
	37	

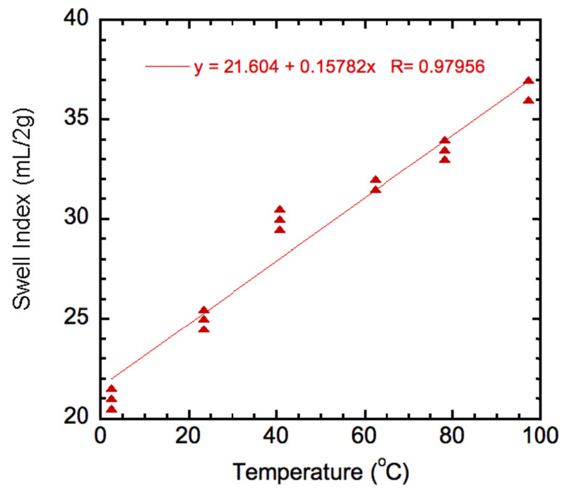

Figure 2. Swell index as a function of temperature.

Increased energy of the clay-water electrolyte system at high temperatures may have resulted in the high swelling at high temperatures. The bentonite likely hydrated at a faster rate with water at higher temperatures than at lower temperatures. Observations made in the current test program agree with laboratory experimental results reported by Chevrier et al. (2012) where hydration of GCLs over two types of subgrade soils increased as the temperature increased from 5 to 20 to 45°C. Increasing rate of water vapor transfer with temperature was indicated to be the controlling mechanism for the GCL hydration tests conducted by Chevrier et al. (2015), whereas in the current test program, the increased swell was attributed to a combination of decreased viscosity of water and increased energy of the clay-water system at high temperatures, both mechanisms allowing rapid and effective hydration of the bentonite particles.

Bentonite extrusion tests. The results of the extrusion tests are presented in Table 4 and Figure 3. Data are presented in Figure 3a is for tests conducted at 100% moisture content and in Figure 3b for tests conducted at 300 kPa stress. Similar to previous observations by the authors (Hanson et al. 2014), bentonite extrusion generally increased with increasing stress and moisture content at a given temperature. Tests conducted at 2°C and 20°C demonstrated more sensitivity to changes in stress and moisture content than tests conducted at other temperatures (i.e., steeper slopes for curves in Figure 3). From 2 to 100°C, the amount of extrusion generally decreased with temperature. Due to complex coupled response of bentonite and geotextile components, the variations with temperature did not follow steady trends (with the exception of tests conducted at 150% moisture content where extrusion decreased with increasing temperature). Bentonite extrusion was very low at -5°C due to the relatively stiff (yet not solid) state of the hydrated bentonite core of the GCL. Highly increased extrusion was observed at 2°C likely due to continued stiff consistency of the geotextile fibers and the relatively softened state of bentonite with the highest extrusion (40.5 g/m^2) in the test program obtained at this temperature at 300 kPa stress and 150% moisture content.

In temperature-dependent (2, 20, 40, and 60°C temperatures) Atterberg limits tests on the bentonite obtained from the same GCL type analyzed in the current test program, the bentonite was observed to get softer through the 40°C temperature, yet observed to become tackier at the higher test temperature (Hanson et al. 2014). In addition, in temperature-dependent (2, 20, and

40°C temperatures) interface (GCL-textured geomembrane) shear strength tests on GCLs from the same manufacturer as that analyzed in the current test program, the interface shear strengths decreased with increasing temperature (Hanson et al. 2015) due to softening of the bentonite core of the GCL and increased flexibility of the geosynthetic components. Overall, bentonite extrusion likely was affected by a combination of variations in bentonite consistency and relative stiffness of the geotextile fibers and geotextile structure. Bentonite consistency varied with temperature from a stiff to a softer state between -5 and 40°C with increasing tackiness at higher temperatures. The polypropylene geotextile fibers were near the glass transition temperature at the low test temperatures (-5 and 2°C), whereas the fibers were softer and more ductile in the rubbery phase associated with the higher test temperatures, with increased stretching/flexure within the geotextile fiber matrix.

Table 4. Bentonite extrusion test results.

Temperature (ºC)	Moisture Content (%)	Extruded Mass at 100 kPa (g/m^2)	Extruded Mass at 200 kPa (g/m^2)	Extruded Mass at 300 kPa (g/m^2)	Extruded Mass at 400 kPa (g/m^2)
-5	50	x	x	0.0	x
	100	0.0	0.0	0.2	2.1
	150	x	x	0.0	x
2	50	x	x	9.7	x
	100	8.1	12.4	11.4	19.2
	150	x	x	40.5	x
20	50	x	x	0.0	x
	100	0.0	5.2	11.9	16.3
	150	x	x	30.8	x
40	50	x	x	9.1	x
	100	9.0	8.5	15.4	15.9
	150	x	x	16.5	x
60	50	x	x	3.5	x
	100	1.3	4.3	9.4	13.5
	150	x	x	22.6	x
80	50	x	x	2.6	x
	100	5.8	9.9	10.8	14.8
	150	x	x	14.8	x
100	50	x	x	3.8	x
	100	0.0	3.1	6.4	10.5
	150	x	x	11.7	x

x: not tested

The extruded bentonite was measured separately through each geotextile component (i.e., each side of GCL). An example of extrusion of bentonite onto the spacer screen disks is presented in Figure 4. Screens were arranged left to right closest to farthest from the specific

geotextile component of the GCL. The bentonite extruded through the geotextile was more localized and extended to a further distance from the nonwoven geotextile side than the woven geotextile side. Data for geotextile-specific extrusion is presented in Figure 5 and Table 5. In general, the amount of bentonite extruded from the nonwoven side was equal or higher than the amount extruded from the woven side at all temperature levels. The extrusion through the nonwoven side ranged from 0.4 to 7.1 times the extrusion through the woven side for given testing conditions. At all tested temperatures, the extrusion through nonwoven side was greater than through woven side for w = 150% specimens. The lowest difference in extruded bentonite mass between nonwoven and woven geotextiles was observed for GCLs tested at 50% moisture content.

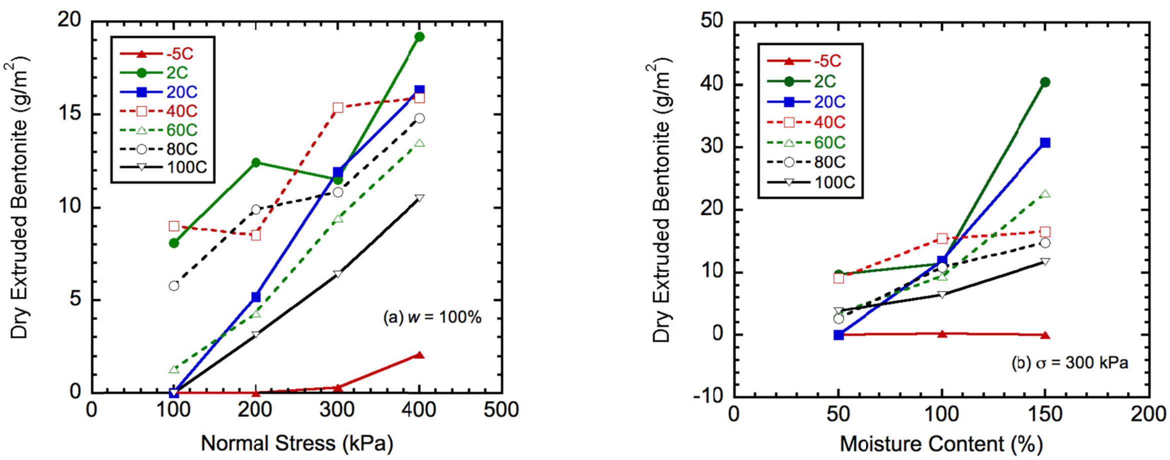

Figure 3. Bentonite extrusion test data.

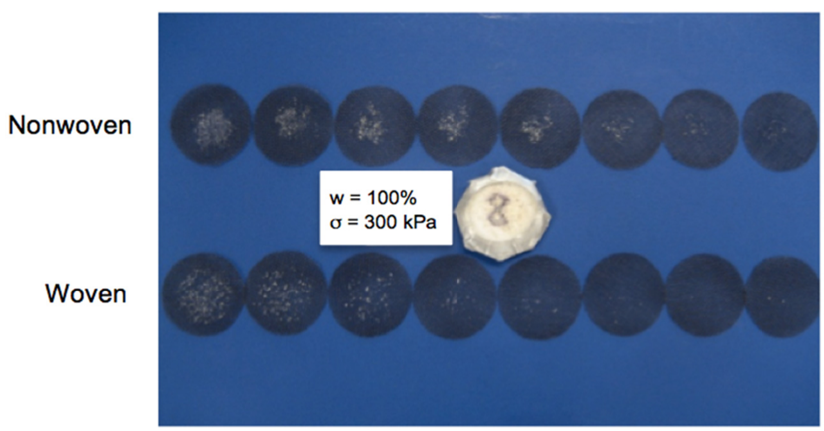

Figure 4. Spatial distribution of extruded bentonite (*w* = 100%, σ = 300 kPa, and *T* = 20°C).

An attempt was made to correlate the swell index to bentonite extrusion. While lower extrusion was generally associated with higher swell index, the overall trend was not strong. The response of the GCL system during an extrusion test involves coupled phenomena including shear strength/consistency of the bentonite and mechanical response of the geosynthetic components and therefore trends cannot be entirely described with swell behavior alone.

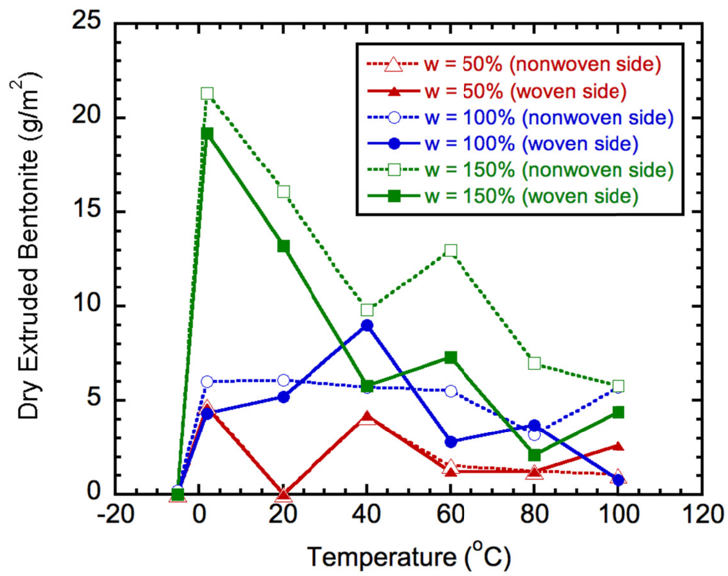

Figure 5. Bentonite extrusion from nonwoven and woven sides of test GCL.

Table 5. Extrusion from Nonwoven (NW) and woven (W) sides at σ = 300 kPa.

Temperature (°C)	Moisture Content (%)	NW Extruded Dry Mass (g/m^2)	W Extruded Dry Mass (g/m^2)
-5	50	0.0	0.0
	100	0.2	0.0
	150	0.0	0.0
2	50	4.7	4.6
	100	6.0	4.3
	150	21.3	19.2
20	50	0.0	0.0
	100	6.1	5.2
	150	16.1	13.2
40	50	4.1	4.2
	100	5.7	9.0
	150	9.8	5.8
60	50	1.5	1.2
	100	5.5	2.8
	150	13.0	7.3
80	50	1.2	1.2
	100	3.2	3.7
	150	7.0	2.1
100	50	1.0	2.6
	100	5.7	0.8
	150	5.8	4.4

CONCLUSIONS

Based on the experimental test program, the following conclusions were drawn:

1. The minimum swell index (21 mL/2g) was observed at 2°C and the maximum swell index (36.5 mL/2g) was observed at 98°C. Swell index increased monotonically with increasing temperature (0.16 mL/2g/°C). Swell index was more sensitive to temperature between 2 and 40°C than between 40 and 98°C.
2. Bentonite extrusion increased with increasing stress level and moisture content. Temperature affected both the consistency of the bentonite and the state of the geotextile fibers. The coupled mechanism is complex and resulted in the highest extrusion at 2°C (40.5 g/m^2 at 300 kPa stress and 150% moisture content). Extrusion at -5°C was significantly lower compared to other test temperatures with negligible values at normal stresses below 400 kPa.
3. Extrusion for GCLs tested at 150% moisture content was more sensitive to temperature than GCLs tested at 100% or 50% moisture content.
4. Generally, more extrusion occurred through the nonwoven geotextile side of the GCL than the woven geotextile side. The extrusion through the nonwoven side was up to 7.1 times the extrusion through the woven side for given testing conditions.
5. Temperature can have significant influence on both the individual bentonite properties as well as combined bentonite-geotextile response in GCLs.
6. The extrusion test methodology provides a means to investigate trends associated with the coupled response of GCLs.

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REFERENCES

Chen, J. N., Benson, C. H., and Edil, T. B. (2015). “Hydraulic conductivity of geosynthetic clay liners to coal combustion product leachates.” *Proceedings, Geosynthetics 2015,* IFAI, Roseville, MN, 173-180.

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

Chevrier, B., Cazaux D., Didier G., Gamet M., and Guyonnet, D. (2012). “Influence of subgrade, temperature and confining pressure on GCL hydration.” *Geotextiles and Geomembranes*, Vol. 33 (2012), 1-6.

Fox, P. J. and Stark, T. D. (2004). “State of the art report: GCL shear strength and measurement.” *Geosynthetics International*, Vol. 11 (3), 141-171.

Gilbert, R. B., Scranton, H. B., and Daniel, D. E. (1997). “Shear strength testing for geosynthetic clay liners.” *Testing and Acceptance Criteria for Geosynthetic Clay Liners*, STP 1308, L.W. Well, Ed., ASTM, West Conshohocken, PA, 121-135.

Hanson, J. L., Yesiller, N., and Swarbrick, G. E. (2005). "Thermal analysis of GCLs at a municipal solid waste landfill." *Waste Containment and Remediation, ASCE GSP 142*, A. Alsawabkeh et al., Eds., ASCE, 1-15.

Hanson, J. L., Yesiller, N., and Oettle, N. K. (2010). "Spatial and temporal temperature distributions in municipal solid waste landfills." *Journal of Environmental Engineering*, Vol. 136 (8), 804-814.

Hanson, J. L., Yesiller, N., Ethier, C., and Chrysovergis, T. S. (2014). "Bentonite extrusion from GCLs as a function of moisture content, stress application, and temperature." *Proceedings, 7th International Conference on Environmental Geotechnics,* 512-519.

Hanson, J. L., Chrysovergis, T. S., Yesiller, N., and Manheim, D. (2015). "Temperature and moisture effects on GCL and textured geomembrane interface shear strength." *Geosynthetics International*, Vol. 22 (1), 110-124.

Ishimori, H. and Katsumi, T. (2012). "Temperature effects on the swelling capacity and barrier performance of geosynthetic clay liners permeated with sodium chloride solutions." *Geotextiles and Geomembranes*, Vol. 33 (2012), 25-33.

Jo, H. Y., Katsumi, T., Benson, C. H., and Edil, T. B. (2001). "Hydraulic conductivity and swelling of nonprehydrated GCLs permeated with single-species salt solutions." *Journal of Geotechnical and Geoenv. Eng.*, Vol. 127 (7), 557-567.

McWatters, R., Rowe, R. K., and Jones, D. (2015). "Co-extruded geomembranes in barrier systems in extreme environments – from high temperature in laboratory tests to Antarctica field sites." *Proceedings, Geosynthetics 2015*, 1245-1253.

Mitchell J. K. (1993). *Fundamentals of Soil Behavior*, 2nd Ed. Wiley, New York.

Tournassat, C., Steefel, C. I., Bourg, I. C., and Bergeya, F. (Eds.) (2015). *Natural and Engineered Clay Barriers, Developments in Clay Science,* Vol. 6, Elsevier, Amsterdam.

Triplett, E. J. and Fox, P. J. (2001). "Shear strength of HDPE geomembranes/ geosynthetic clay liner interfaces." *Journal of Geotechnical and Geoenv. Eng.,* Vol. 127 (6), 543-552.

Scalia, J. and Benson, C. H. (2011). "Hydraulic conductivity of geosynthetic clay liners exhumed from landfill final covers with composite barriers." *Journal of Geotechnical and Geoenv. Eng.,* Vol. 137 (1), 1-13.

Vukelic, A., Szavits-Nossan, A. and Kvasnicka, P. (2008). "The influence of bentonite extrusion of shear strength of GCL/geomembrane interface." *Geotextiles and Geomembranes*, Vol. 26 (1), 82-90.

Yesiller, N., Hanson, J. L., Oettle, N. K., and Liu, W.-L. (2008). "Thermal analysis of cover systems in municipal solid waste landfills." *Journal of Geotechnical and Geoenv. Eng.*, Vol. 134 (11), 1655-1664.

Yesiller, N. and Shackelford, C. D. (2011). "Geoenvironmental Engineering." Chapter 13 in *Geotechnical Engineering Handbook*, B. M. Das Ed., J.Ross Publishing, 13.1-13.61.

Yesiller, N., Hanson, J. L., and Yee, E. H. (2015). "Waste heat generation: A comprehensive review." *Waste Management*, Vol. 42, 166-179.