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Stress-controlled direct shear testing of geosynthetic clay liners II: Assessment of shear behavior

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ABSTRACT

This paper is the second of a two-paper set on stress-controlled direct shear testing of geosynthetic clay liners (GCLs). Design of the apparatus, preliminary experiments, and shear deformation mechanisms in heat-treated and non-heat treated needle-punched (NP) GCLs were discussed in Part I. The objective of Part II (this paper) was to evaluate the effects of physical factors (i.e., peel strength and initial normal stress, σ_{ni}), environmental factors (i.e., temperature and hydration solution), and creep on the internal shear behavior of NP GCLs. In addition, failure conditions of GCLs in the stress-controlled direct shear tests were compared to displacement-controlled direct shear tests to verify results. An increase in internal shear strength developed from increased GCL peel strength or increased normal stress. Elevated temperatures were observed to decrease internal shear strength for both non-heat treated and heat-treated NP GCLs. Specimens hydrated with a calcium-rich synthetic mining solution experienced increased internal shear strength due to cation exchange in the bentonite, whereas specimens hydrated with a highly alkaline synthetic mining solution experienced decreased internal shear strength. Creep tests revealed an increase in time-to-failure with decrease in applied shear stress. Finally, stress states at failure from stress-controlled and displacement-controlled shear tests corresponded to a unique failure envelope, which validates the efficacy of using stress-controlled direct shear tests to assess internal shear behavior and shear strength of NP GCLs.

1. Introduction

Barrier systems for waste containment (i.e., liners and covers) are generally designed and constructed without the intent to remove or replace system components in the future. Over the lifespan of a barrier system, components (e.g., mineral layers, geosynthetics, etc.) can experience long-term shear deformation from induced normal and shear stresses (i.e., creep), fluctuations in temperature, and hydration from non-standard chemical solutions. The influence of factors such as creep, temperature, and non-standard hydration solution on the mechanical behavior of geosynthetic clay liners (GCLs) is of particular interest considering these factors can influence the longevity of GCLs. Thus, assessments of exposure to temperature and non-standard hydration solutions as well as creep deformation are needed to improve GCL design.

Geosynthetic clay liners used in liner systems can experience elevated temperatures from exothermic chemical and biological processes within the contained material. For example, temperatures in heap leach pads can be as high as 45–50 °C in copper leaching and 75 °C in nickel leaching (Thiel and Smith, 2004; Smith, 2008; Brierly, 2008; Steemson and Smith, 2009). The temperature in municipal solid waste landfills has been reported in excess of 60 °C (Rowe, 2005; Yeşiller et al., 2005; Bouazza and Bowders, 2009; Bouazza et al., 2011; Stark et al., 2012; Jafari et al. 2014, 2017; Yesiller et al., 2015; Touze-Foltz et al., 2016), and in specific cases involving the disposal of aluminum waste in municipal solid waste, temperatures exceeding 100 °C have been observed (Stark et al., 2012). Geosynthetic clay liners used in cover systems also experience elevated temperatures depending on geographical location and climatic conditions (Yeşiller et al., 2015; Koerner and Koerner, 2006; Hanson et al., 2010).

Liquid wastes and leachates in waste containment systems can come into contact and hydrate GCLs used in barrier systems. Non-standard solutions can be encountered in containment systems for mining, municipal solid waste, and coal combustion wastes, among others. These chemical solutions can have a broad range of ionic strength, pH, chemical constituents, and ratio of monovalent to divalent cations (Bouazza and Gates, 2014). For example, heap leach operations in copper mining generate extremely acidic solutions containing high sulfate, chlorine, phosphate, and oxidizing agents (USEPA, 1999; USEPA, 2008; Theil and Smith, 2004; Hornsey et al., 2010; Shackelford

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Table 1
Characteristics and properties of geosynthetic clay liners used in this study.

Properties	GCL 1	GCL 2	GCL 3	GCL 4
Carrier geotextile type[a]	NW	W	W	W
Carrier geotextile mass/area (g/m^2)[b]	280 (14.6)	270 (9.0)	130 (4.9)	180, (12.0)
Cover geotextile type[a]	NW	NW	NW	NW
Cover geotextile mass/area (g/m^2)[b]	240 (14.9)	140 (6.8)	110 (5.2)	420 (9.7)
Number of fiber bundles per 10 mm in machine direction[c]	2.3 (0.50)	2.0 (0.46)	1.4 (0.14)	2.7 (0.32)
Peel strength (N/m)[d]	2170	1490	720	740
Heat Treatment Method[e]	NHT	NHT	NHT	HT
Average bentonite water content (%)	10.0	9.8	9.8	11.0
Bentonite Type	Granular	Granular	Granular	Powder
Bentonite mass per area (g/m^2)[f]	5620 (109)	4530 (42)	5222 (93)	3410 (35)
Bentonite Liquid Limit (%)	396	411	405	493
Bentonite Plastic Limit (%)	29	36	31	48

[a] W = woven; NW = non-woven.
[b] Average and standard deviation (in parentheses) based on 10 measurements (ASTM D5261).
[c] Average and standard deviation (in parentheses) based on 40 measurements.
[d] Peel strength reported as minimum value for a given roll by the manufacturers. Measurements were based on ASTM D6496/6496M.
[e] HT = heat treated; NHT = non-heat treated.
[f] Average and standard deviation (in parentheses) based on ASTM D5993.

et al., 2010; Plumb, 1999) whereas highly alkaline solutions are characteristic of bauxite mining (Gräfe et al., 2011). Leachates usually encountered in municipal solid waste systems have a semi-neutral pH and contain a variety of organic and inorganic chemicals with divalent and monovalent cations (Bradshaw and Benson, 2013; Bradshaw et al., 2016), and coal combustion leachate can have extreme pH and high ionic strength (Salihoglu et al., 2016; Chen et al., 2018).

The effects of elevated temperature and exposure to non-standard hydration solutions have been shown to influence polymers (e.g., polypropylene, polyethylene, and polyester) and bentonite commonly used in GCLs. Studies have documented reduced tensile strength, reduced tensile modulus, increased elongation at failure, and increased rate and magnitude of creep deformation, which were linked to changes in physical and chemical properties of polymeric materials and geosynthetics (Mathur et al., 1994; Farrag, 1998; Ariyama et al., 1997; Rahman and Alfaro, 2004; Gulec et al., 2005; Jeon et al., 2005; Rowe et al., 2009; Hornsey et al., 2010; Karademir and Frost, 2014; Ewais et al., 2018). Results from the aforementioned studies raise a concern regarding detrimental effects of high temperature and non-standard solutions on internal shear strength of GCLs, particularly for needle-punched (NP) and stitch-bonded GCLs derive a considerable fraction of shear strength from reinforcement fibers.

This is the second paper (Part II) of a two-paper set on the development (Part I) and assessment (Part II) of stress-controlled direct shear testing of NP GCLs. A detailed description of the stress-controlled shear apparatus is in Part I (Ghazizadeh and Bareither, 2018) and a brief summary of the direct shear apparatus is presented herein. The main objectives of Part II were to (i) evaluate physical (GCL peel strength and normal stress), environmental (temperature and hydration solution), and creep effects on the internal shear behavior of GCLs and (ii) compare failure conditions from stress-controlled direct shear tests to failure conditions from displacement-controlled direct shear tests to verify viability of the stress-controlled apparatus.

2. Materials and methods

2.1. Stress-controlled direct shear apparatus

The stress-controlled direct shear apparatus included a normal stress system, shear stress system, temperature-control system, and data acquisition system. Normal force was applied via dead weight. A reaction force generated from mitigation of specimen rotation during shear acted to increase the total normal force applied to a given test specimen. The reaction force was measured with an S-type load cell with maximum load capacity of 2.2 kN (Omega, LC101-500). The dead weight and reaction force were summed and divided by the initial area of the GCL shear plane to compute the total normal stress (σ_{nt}) during shear.

Shear force was generated via dead weight and transferred to the upper shear platen on a GCL test specimen via a pulley system and shear loading rod. Shear force was transferred to shear stress (τ) within the internal region of a GCL via 2-mm-tall pyramid-tooth gripping plates constructed from either stainless steel or titanium. Horizontal deformation was measured with a 75-mm linear potentiometer (Novotechnik TR 75) and vertical deformation was measured with two 25-mm linear potentiometers (Novotechnik TR 25) positioned at the front and back of the normal loading plate.

Temperature of the hydration fluid in the shear box was increased for select experiments using two submersible electronic cartridge heaters. The heaters were turned on and off to control temperature via a solid-state relay switch and thermocouple. Three hermetically-sealed, tip-insulated type-T thermocouples (Omega, HSTC-TT-T-20S-120) were used to monitor and control temperature of the hydration fluid.

Measurements of horizontal and vertical deformation, reaction load, and temperature inside the hydration box were monitored for all experiments. Sensors were connected to R3000 Campbell Scientific datalogger that was interfaced with an AM25T thermocouple multiplexer. Measurements were recorded every 1 s to 1 min based on user preference. Detailed characteristics of the shear apparatus are described in Part I (Ghazizadeh and Bareither, 2018).

2.2. Geosynthetic clay liners

Characteristics and properties of the NP GCLs used in this study are tabulated in Table 1. Differences between these GCLs included bentonite type (granular versus powder), dry bentonite mass per area (3400–5600 g/m^2, based on ASTM D5993), carrier and cover geotextiles (mass per area and geotextile type, based on ASTM, D5261), minimum peel strength for the GCL roll (720–2170 N/m, based on ASTM, D6496/6496M), and heat treatment (heat treated versus non-heat treated). Material specific characterization of the GCLs was conducted on ten, 100 mm × 100 mm specimens cut from each GCL roll. The number of reinforcement fiber bundles per length was counted on each side in machine direction. Geotextile reinforcement fibers were cut to separate carrier and cover geotextiles, extract bentonite, and measure geotextile and bentonite mass per area (Table 1). Water content