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Stress-controlled direct shear testing of geosynthetic clay liners I: Apparatus development

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ABSTRACT

The use of geosynthetic clay liners (GCLs) in waste containment applications can induce long-term normal and shear stresses as well as expose GCLs to elevated temperatures and non-standard hydration solutions. Considering the importance of GCL internal shear strength to the design and integrity of waste containment barrier systems, innovative laboratory testing methods are needed to assess shear behavior of GCLs. There were two main objectives of this study: (i) develop a stress-controlled direct shear apparatus capable of testing GCLs exposed to elevated temperatures and hydrated in non-standard solutions; and (ii) assess internal shear behavior of GCLs under varying experimental conditions (e.g., stress, temperature, solution). These two objectives were partitioned into a two-paper set, whereby Part I (this paper) focuses on the shear box design and Part II focuses on an assessment of shear behavior. The direct shear apparatus includes a reaction frame to mitigate specimen rotation that develops from an internal moment within needle-punched reinforced GCLs. Rapid-loading shear tests were conducted to assess functionality of the apparatus and document baseline shear behavior for a heat-treated and a non-heat treated needle-punched GCL with comparable peel strength. These two GCLs failed at comparable applied shear stress; however, the heat-treated GCL yielded lower shear deformation and failure occurred via rupture of reinforcement fiber anchors, whereas the non-heat treated GCL yielded larger shear deformation and failure via pullout of reinforcement fibers.

1. Introduction

Geosynthetic clay liners (GCLs) are hydraulic barriers consisting of a layer of bentonite encapsulated between layers of geotextiles or adhered to a geomembrane (ASTM D 4439). The use of GCLs along steep slopes can subject the GCL to induced normal and shear stresses that must be resisted at the interfaces with adjacent layers (e.g., geosynthetics or soils) and internally within the GCL. The developed shear stress in a GCL should not lead to failure, but can induce long-term shear deformation (i.e., creep). The magnitude and rate of creep vary temporally due to changes in engineering properties of the geosynthetic components.

The use of GCLs in waste containment facilities (e.g., municipal solid waste, mine waste rock, mine tailings, and heap leach pads, etc.) can expose GCLs to elevated temperatures (i.e., higher than common laboratory temperatures) and non-standard chemical solutions (e.g., highly acidic or highly alkaline solutions) (Rowe, 2005; Koerner and Koerner, 2006; Hornsey et al., 2010; Bouazza et al., 2011; Stark et al., 2012; Bouazza and Gates, 2014; Jafari et al., 2014; Yeşiller et al., 2015; Touze-Foltz et al., 2016; Jafari et al., 2017). Exposure to these environmental stresses can induce hydrolytic degradation in polymeric materials (Mathur et al., 1994; Hsuan et al., 1993; Gulec et al., 2005; Jeon, 2006; Hornsey et al., 2010; Ewais et al., 2018) and reduce the mechanical properties, such as tensile modulus (Andrawes et al., 1984; Ariyama et al., 1997; Karademir and Frost, 2014). Thus, the coupled effects of elevated temperature and non-standard hydration solution may affect the long-term hydraulic and mechanical properties of GCLs. Fox and Stark (2015) reported that long-term strength of GCLs and GCL interfaces remains largely unknown and additional research is needed to assess long-term strength performance. These aforementioned factors support the development and evaluation of a direct shear apparatus to assess internal shear behavior of GCLs during exposure to environmental stresses that are representative of long-term field applications.

Displacement-controlled direct shear testing is the most common method used to evaluate peak and large-displacement shear strength of GCLs (Gilbert et al., 1996; Stark and Eid, 1996; Eid and Stark, 1997; Fox et al., 1998; Eid et al., 1999; Chiu and Fox. 2004; Fox and Stark, 2015; Theilmann et al., 2016). However, displacement-controlled direct shear may not be representative of long-term field conditions under which thermal, hydrolytic, and mechanical degradation can impact shear

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behavior and strength of GCLs (Müller et al., 2008; Zanzinger and Saathoff, 2012; Fox and Stark, 2015). Moreover, creep mechanisms in reinforced GCLs have not been fully evaluated, and displacement-controlled tests are not well-suited for this purpose. Thus, a stress-controlled direct shear box was designed to test GCLs exposed to elevated temperatures and/or hydrated in non-standard chemical solutions.

This study is presented in a two-paper set. In Part I (this paper), design of the direct shear apparatus is presented along with a description of stress-controlled shear behavior for non-heat treated and heat-treated, needle-punched reinforced GCLs (NP GCLs). In Part II (Ghazizadeh and Bareither, 2018), stress-controlled shear behavior is evaluated for specimen peel strength, normal stress, elevated temperature, non-standard solution hydration, and creep. Results from the stress-controlled direct shear tests also are compared to results from displacement-controlled direct shear tests to verify the apparatus and support the results.

2. Background

Stress-controlled direct shear tests on GCLs can be described as rapid loading shear (RLS) or stepwise shear (SWS) tests. In RLS tests, shear loads are successively increased until the specimen fails or until a desired shear stress is attained. In the latter case, the GCL may be allowed to creep under constant shear stress until the specimen fails or the test is terminated. In SWS tests, the specimen is subjected to target shear and normal stresses and allowed to creep. If failure does not occur within a certain time, shear stress is increased and creep is continued under the new shear stress. This stepwise procedure is repeated until the specimen fails or the test is terminated. Contrary to a RLS test, normal stress applied to a GCL specimen during a SWS test can be held constant or increased proportionally with the shear stress.

Relevant research on stress-controlled direct shear testing of GCLs is summarized in Table 1. Key differences between previous studies include test method (RLS versus SWS), temperature, GCL characteristics, hydration time, applied normal stress, and creep stress ratio. The creep stress ratio (τ_c/τ_p) is defined herein as the applied shear stress during creep (τ_c) divided by the peak shear strength (τ_p) obtained from a displacement-controlled test. Siebken et al. (1997) evaluated long-term shear strength of heat-treated (HT) NP GCLs subjected to high τ_c/τ_p. Trauger et al. (1997) performed similar experiments on HT NP GCLs at high and low normal stress. However, internal shear failure was not observed in either of these studies. Koerner et al. (2001) conducted RLS and SWS tests with $\tau_c/\tau_p < 0.5$ on NP and stitched-bonded (SB) GCLs. Koerner et al. (2001) also did not observe failure. Zanzinger and Alexiew (2000, 2002a,b) performed both RLS and SWS tests on SB GCLs at $\tau_c/\tau_p \le 0.9$ without reaching failure.

Müller et al. (2008) performed creep tests under constant shear stress to normal stress ratio on HT and non-heat treated (NHT) NP GCLs. Specimens were hydrated in de-ionized water (DIW) or tap water and subjected to temperatures of 20 °C, 50 °C, and 80 °C. Failure was observed for some specimens hydrated in DIW and tested at elevated temperature, which was attributed to reduced strength of polymeric reinforcement fibers as temperature increased. However, failure was not observed for any specimen hydrated in tap water, which was attributed to ion exchange in the sodium montmorillonite that increased the internal shear strength of hydrated bentonite in the GCLs. Zanzinger and Saathoff (2012) and Zanzinger (2016) conducted RLS tests on SB and NP GCLs at 80 °C and reported failure for specimens at $\tau_c/\tau_p \ge 0.4$ within a few days to months. They also observed an increase in the time to required reach failure with a decrease in the applied shear stress.

These previous studies imply that internal shear failure of GCLs can be achieved in stress-controlled direct shear tests. However, failure has been achieved with the aid of elevated temperatures, and additional testing is needed to assess and quantify temperature effects on GCL shear strength. In addition, hydration solution chemistry can alter the internal shear strength of bentonite and/or mechanical properties of reinforcement fibers. Thus, experimental conditions such as temperature and hydration solution chemistry need to be taken into account as to assess their influence on the internal shear behavior and shear strength of NP GCLs.

3. Shear box development

A schematic of the stress-controlled direct shear apparatus developed in this study is shown in Fig. 1. The external shear box (B in Fig. 1) was constructed of ultra-high molecular weight (UHMW) polyethylene for insulation and chemical resistant properties. The direct-shear apparatus consists of three main component systems: (i) shear stress system, (ii) normal stress system, and (iii) heating system. Each component system was subjected to an iterative design and analysis procedure through a series of preliminary experiments. Inspection of test specimens and comparison of shear behavior to literature was conducted to assess the effectiveness of a given experimental component and update the design as needed. Key aspects of the final shear box design are described subsequently. This GCL direct shear apparatus provides the following experimental capabilities:

- dead-weight loading on a 150 mm × 150 mm GCL specimen to achieve shear stresses (τ) up to 150 kPa and normal stresses (σ_n) up to 100 kPa;
- transfer of shear stress to the internal region of a GCL via pyramid-tooth gripping plates;

Table 1

Summary of previous studies on the internal shear strength and deformation behavior of geosynthetic clay liners evaluated in stress-controlled direct shear tests.

Reference	Test Type	Temp. (°C)	GCL Type	Hydration Solution	Hydration Time (h)	Normal Stress (kPa)	Specimen Size (mm)	Creep Stress Ratio[a]	Internal Failure
Zanzinger (2016)	RLS	80	NP, NHT	DIW	69–142	50	200 × 200	0.4–0.6	Yes
Zanzinger and Saathoff (2012)	RLS	80	SB	DIW	72	50	200 × 200	0.29–1.10	Yes
Müller et al. (2008)	RLS	R, 50, 80	NP, NHT & NP, HT	DIW, TW	48	43	230[b] x 120	0.39	Yes
Koerner et al. (2001)	SWS & RLS	R	NP, NHT	TW	240	17	300 × 300	0.2–0.5	No
Zanzinger and Alexiew (2000, 2002a,b)	SWS & RLS	R	SB	DIW	24	20	300 × 300	0.45–0.9	No
Seibken et al. (1997)	RLS	20	NP, HT	TW	120	441 to 621	300 × 300	0.93–0.97	No
Trauger et al. (1997)	RLS	R	NP, HT	TW	120	97 to 389	300 × 300	0.23–0.7	No

Notes: NP = needle punched; HT = heat treated; NHT = non-heat treated; SB = stitch-bonded; TW = tap water; DIW = de-ionized water; SWS = stepwise shear test; RLS = rapid Loading shear test; R = room temperature.

[a] Creep stress ratio = applied creep shear stress divided by peak shear strength from displacement-controlled direct shear.

[b] Dimension in the direction of shear.