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Strength Envelopes from Single and Multi Geosynthetic Interface Tests

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Abstract This paper presents a comparison of single- and multi-interface strength tests for a proposed landfill liner system configuration. The comparison includes peak and large displacement combination strength envelopes from single- and multi-interface direct shear tests for the same geosynthetic/geosynthetic, geosynthetic clay liner (GCL)/geomembrane, and soil/geosynthetic interfaces. This comparison shows relative agreement between strength envelopes derived from single- and multi-interface tests for the materials tested. Single-interface test results appear to be generally more conservative. Potentially significant differences in the large-displacement strength envelopes were noted that could be a result of the increased strain required to mobilize peak stresses in the multi-interface tests compared to the single-interface tests in combination with the limited maximum displacement allowed by the direct shear testing devices. The test results are also used to illustrate the effect of different soil types and GCL hydration on the peak and large displacement strength envelopes.

Keywords Geosynthetics design · Direct shear test · Interface shear resistance · Slope stability · Shear strength · Strength envelope

Abbreviations

CSL	Compacted soil liner
GCL	Geosynthetic clay liner
GM	Geomembrane
HDPE	High density polyethylene
k	Hydraulic conductivity
LCRS	Liquid collection and recovery system
LD	Large displacement
MSW	Municipal solid waste
NWGT	Nonwoven geotextile
t_{100}	Theoretical time for 100 % primary consolidation
τ	Shear strength

1 Introduction

The usual design objective for waste containment facilities is to maximize disposal capacity. Thus, it is important to design and construct landfill slopes as

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steeply as possible and increase the maximum elevation as high as possible (Stark and Choi 2004). A composite liner system consisting of multiple geosynthetic components, Liquid Collection and Recovery System(s) (LCRS), and an operations layer is usually installed prior to waste placement to reduce/eliminate leakage from these facilities. An important characteristic of these composite liner systems with respect to slope stability is the shear resistance available along the various component interfaces as well as the internal shear strength of each component. A number of case histories (Byrne et al. 1992; Seed and Boulanger 1991; Seed et al. 1990; Stark et al. 1998; Stark 1999) show that an overestimate of the interface or material shear resistance can lead to slope instability and substantial remedial costs. Many researchers, e.g., Karademir and Frost (2011), Bove (1990), Dove and Frost (1999), Fox and Kim (2008), Jones and Dixon (1998), Koerner et al. (1986), Li and Gilbert (2006), Martin et al. (1984), Mitchell et al. (1990), Negussey et al. (1989), O'Rourke et al. (1990), Saxena and Wong (1984), Stark and Poeppel (1994), Stark et al. (1996), Takasumi et al. (1991), Williams and Houlihan (1987), and Yegian and Lahlaf (1992) have studied the shear behavior of geosynthetic materials and interfaces, primarily using single-interface tests. However, little has been published on a comparison with multi-interface shear tests.

Consequently, the results of single- and multi-interface direct shear tests on a liner system configuration are presented herein to investigate the comparability of single- and multi-interface test results. The test results also include the outcome of investigations on the critical interface(s) within the liner system. The peak strength is the highest measured value of shear strength (τ) that commonly occurs at low shear displacements. After the peak strength is mobilized, a loss in shear strength typically occurs and yields a lower strength with increasing shear displacement until the residual shear strength is reached at much larger displacements and beyond which no further strength reduction occurs. If shear displacement is insufficient to reach the residual condition, a large displacement (LD) strength is often defined. For example, the shear strength at a shear displacement of 75 mm (3 in.) is a common limit for geosynthetic direct shear devices and is referred to as a LD strength.

This study shows multi-interface tests are indicative of liner system performance, however, it is beneficial to compare the multi-interface test results with at least one single-interface test, such as the critical interface for a given normal stress. This comparison is considered beneficial because of previously gained experience and expertise with single-interface tests where fewer variables are involved (Stark and Choi 2004).

2 Multi-Interface Tests

This section describes the advantages and disadvantages of multi-interface tests in laboratory testing and design for the composite liner systems. This section can be used to also assess the advantages and disadvantages of single- interface tests.

2.1 Advantages of Multi-Interface Tests Over Single-Interface Tests

- The main problem with single-interface tests is a composite liner system contains many interfaces that require testing. Thus to understand the shear behavior of the entire liner system, a number of single-interface tests have to be conducted which requires substantial project time and cost and the installed liner system is not tested as a single unit.
- Multi-interface tests allow multiple interfaces and materials to be tested simultaneously and do not force the failure surface to occur through a specific material or along a specific interface which better simulates field configuration of a composite liner or cover system, but possibly not field shearing because of the gap between the upper and lower shear boxes.
- The peak and LD strength envelopes are determined directly from multi-interface tests instead of developing combination peak and LD failure envelopes from the results of a number of single-interface tests as described by Stark and Choi (2004).

2.2 Disadvantages of Multi-Interface Tests Over Single-Interface Tests

- Multi-interface tests are more difficult to perform than single-interface tests, which require the design engineer and testing laboratory to be experienced in specifying and performing these tests, respectively.

- Multi-interface tests are limited in that strength parameters are obtained only for the critical failure surface of the system being tested and no other interface.
- Single-interface tests are assumed to be more reliable because each interface is tested individually and one can characterize the shear strength of the interface for the full range of normal stresses. These results can be used to develop peak and LD combination strength envelopes for the appropriate range of normal stresses for each interface tested as illustrated herein, whereas multi-interface tests only provide peak and LD strength envelopes for the critical failure surface of the system identified at each normal stress.
- Because each interface in a multi-interface test has to mobilize at least the same shear strength as the peak shear strength of the critical interface, it is possible that the location of the critical interface is obfuscated when the sample is dismantled for inspection when there are large numbers of interfaces involved.
- In single-interface tests, it is possible to find which other interfaces might have strengths that are "close" to the critical interface strength. This could affect judgment based on evaluations of durability and manufacturing variability. Conversely, in the "stacked" multi-interface tests, there is no feedback on this issue.
- Another disadvantage suggested by a reviewer is a large amount of shear displacement being required to engage all of the interfaces which can reduce the amount of post-peak shear displacement that can be applied to the critical interface in displacement limited shear boxes.

3 Proposed Liner System and Testing

Liner system design and materials have evolved with the increase in environmental regulations, siting hearings, and increased public awareness. Accordingly, various multi-component systems are being used for the bottom liner systems in Subtitle D Waste Containment Facilities. A possible liner system configuration is considered herein and the various conditions for testing these systems are discussed.

3.1 Proposed Liner System

The Composite Liner System tested is shown in Fig. 1 and consists of, from top to bottom, a 410 g/m^2 geotextile filter, granular LCRS material, a 410 g/m^2 geotextile cushion, primary 1.5 mm thick textured both sides high density polyethylene (HDPE) geomembrane, a needle-punched reinforced GCL, secondary 1.5 mm thick textured both sides HDPE geomembrane, and a subgrade material. The laboratory shear testing program for both the single- and multi-interface configurations focused on the following interfaces and materials:

- Geotextile cushion and primary 1.5 mm textured HDPE geomembrane interface
- 1.5 mm textured HDPE geomembrane and GCL interface
- Internal GCL
- 1.5 mm textured HDPE geomembrane and Subgrade interface.

3.2 Test Details, Configurations, and Effective Normal Stresses

The main objectives of this paper are to: (a) develop combination peak and large displacement strength envelopes for the proposed liner system shown in Fig. 1 as suggested by Stark and Choi (2004), and

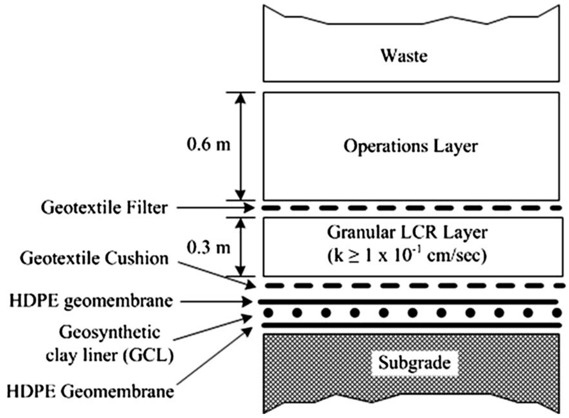


Fig. 1 General description of the proposed liner system

(b) compare single- and multi-interface test results for the proposed liner system. Figure 2 shows a general configuration of the laboratory testing apparatus used to accomplish these objectives. Both single-interface tests (see Fig. 3) and multi-interface tests (see Fig. 4) were conducted using the same direct shear device which satisfies the requirements of ASTM D5321 / D5321M-14.

The shear resistance of the various interfaces is a function of: (1) the aggressiveness of the geomembrane texturing, (2) the amount of bentonite that extrudes, migrates, or is squeezed from the GCL into the textured HDPE geomembrane interface, and (3) the internal shear strength of the GCL. Based on the list of potentially critical interfaces and materials, four series of single-interface and two series of multi-interface direct shear tests were designed and conducted. Each series consists of testing the interface(s)/composite system over a range of five different effective normal stresses. Tables 1 and 2 provide test details and normal stresses that were used in the single- and multi-interface direct shear tests, respectively. The details common to the single- and multi-interface tests are discussed here, while those specific to the respective tests are discussed in following sub-sections.

The geosynthetic interface tests were performed in accordance with ASTM Standard Test Method D5321 / D5321M-14. The normal stresses for this testing program were selected to represent the range of stresses under a Subtitle D [or municipal solid waste (MSW)] landfill having a unit weight of 12.55 kN/m^3 and a maximum height of 165 m. Accordingly, each series of tests was performed at normal stresses of 70, 170, 690, 1380, and 2070 kPa. The highest of these normal stresses (2070 kPa) is greater than the normal stress that can be applied in a 0.3 m $\times$ 0.3 m direct shear box because of the large normal force required to achieve a normal stress of 2070 kPa with a specimen area of 0.09 m^2. As a result, both 0.3 m $\times$ 0.3 m and 0.15 m $\times$ 0.15 m direct shear boxes were used at an effective normal stress of 1380 kPa. If these devices yielded similar results, the 0.15 m $\times$ 0.15 m shear box was used for the shear test at a normal stress of 2070 kPa instead of the 0.3 m $\times$ 0.3 m shear box. A shear box smaller than 0.3 m $\times$ 0.3 m is allowed under ASTM D5321 / D5321M-14, if it yields similar test results as the 0.3 m $\times$ 0.3 m shear box. One-fourth of the normal force is required to achieve the desired normal stress in a 0.15 m $\times$ 0.15 m shear box than in a 0.3 m $\times$ 0.3 m shear box, which allowed testing at a normal stress of 2070 kPa to simulate field conditions.

To better define the shear strength of the liner system at low normal stresses, a normal stress of 70 kPa was included in the testing program. The use of relatively low normal stresses (70 and 170 kPa) helped define the stress dependent nature of the strength envelopes at low effective normal stresses. All interface shear tests were continued to a shear displacement of about 75 mm unless the shear stress-displacement relationship had reached a constant minimum or residual strength condition. If the shear stress-displacement relationship did not reach a constant minimum strength before 75 mm, the resulting strengths are referred to as LD strengths and not residual strengths. As seen in Fig. 5, single and multi-interface tests shear strengths (peak and LD) are comparable for lower normal stresses (170 and 690 kPa). However, for higher normal stresses (1380 and 2070 kPa), multi-interface tests result in higher peak and LD strengths than the single interface tests.

The GCL, and subgrade interface tests were performed in accordance with ASTM Standard Test Method D6243-98), so a proper consolidation time and shear displacement rate were used (Fox and Stark 2004). The test configurations having a GCL were tested using the following two different states of hydration: un-hydrated, i.e., bentonite moisture content as received from the manufacturer, and hydrated, i.e., bentonite moisture content after soaking for 48 h

Fig. 2 General configuration of ASTM D5321 / D5321M-14 laboratory direct shear device

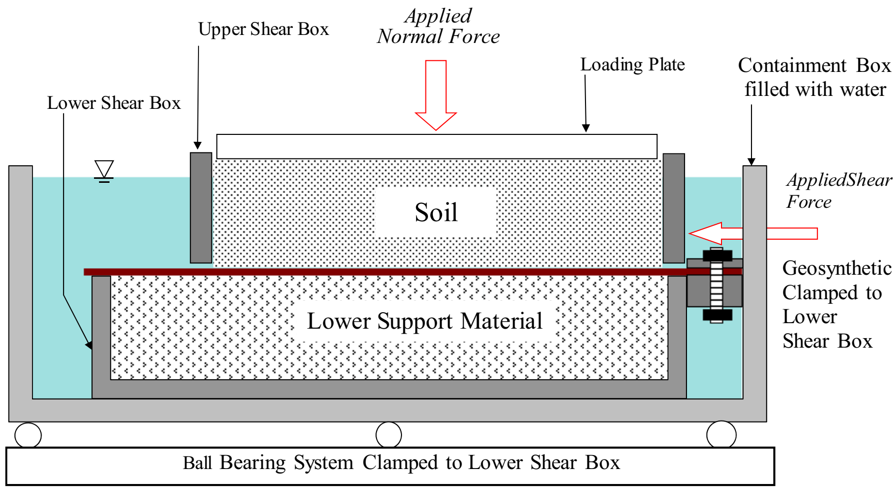


Fig. 3 Schematic diagram of laboratory single-interface direct shear test configuration

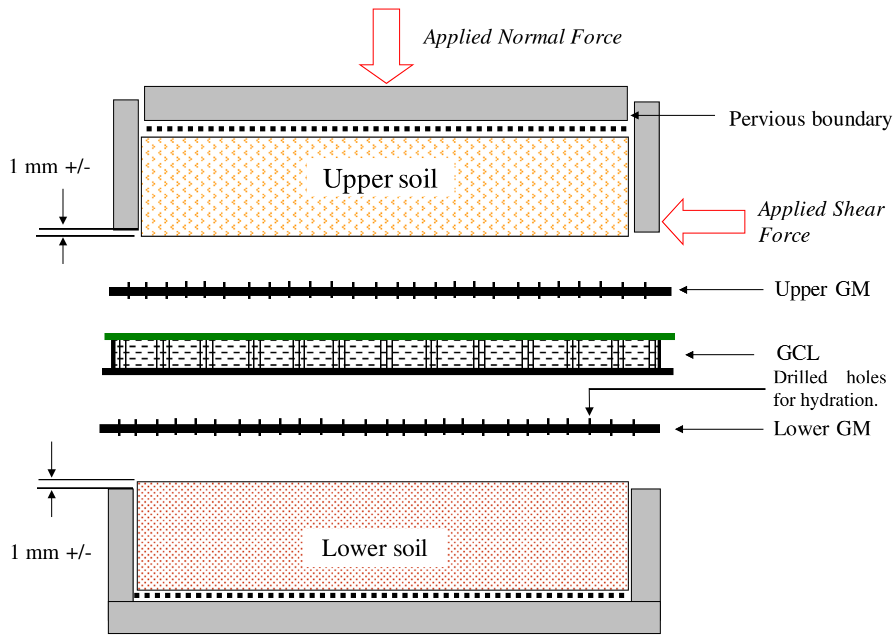


Fig. 4 Schematic diagram of laboratory multi-interface direct shear test configuration with five layers

under a normal stress of 70 kPa as per ASTM D6243-98. After GCL soaking, the multi-interface test specimens were consolidated to the desired shearing normal stress for at least 24 h or until the time for 100 % theoretical primary consolidation (t_{100}) was achieved, as determined by Taylor's square root of time fitting method (Taylor 1948). The soaking was performed in shear boxes outside of the shear machine to facilitate use of the shear machine. The vertical displacements were monitored during consolidation and shearing so the effect of specimen thickness could be investigated.

Figure 4 is a schematic drawing showing a GCL between two geomembranes in a multi-interface test with five layers including the soil in the upper and lower shear boxes. Figure 4 shows many materials and interfaces provide shear resistance during a multi-interface direct shear test because the shear box is applying shear stress to all of the interfaces during the test.

In the liner system, the GCL is encapsulated by two geomembranes to simulate field conditions (see Fig. 4). As a result, field hydration can only occur through geomembrane defects. However for stability

Table 1 Single-interface direct shear test details

Test series	Interface test configuration	Specimen size (m)	GCL soaking		Minimum consolidation time (h)[a]	Normal stress during consolidation and shearing (kPa)[b]
			Normal stress during soaking (kPa)	Soaking time (h)		
1 (GMX)	1.5-mm HDPE and GCL and 1.5-mm HDPE-un-hydrated	0.3 × 0.3	N/A	N/A	24	70
		0.3 × 0.3	N/A	N/A	24	170
		0.3 × 0.3	N/A	N/A	24	690
		0.3 × 0.3	N/A	N/A	24	1380
		0.15 × 0.15	N/A	N/A	24	1380
		0.15 × 0.15	N/A	N/A	24	2070
2 (GMX)	1.5-mm HDPE and GCL and 1.5-mm HDPE-hydrated	0.3 × 0.3	70	48	72	70
		0.3 × 0.3	70	48	72	170
		0.3 × 0.3	70	48	72	690
		0.3 × 0.3	70	48	72	1380
		0.15 × 0.15	70	48	72	1380
		0.15 × 0.15	70	48	72	2070
3 (GMX)	410 g/m^2 cushion geotextile and 1.5-mm textured HDPE-pre-wetted	0.3 × 0.3	N/A	N/A	1	70
		0.3 × 0.3	N/A	N/A	1	170
		0.3 × 0.3	N/A	N/A	1	690
		0.3 × 0.3	N/A	N/A	1	1380
		0.15 × 0.15	N/A	N/A	1	1380
		0.15 × 0.15	N/A	N/A	1	2070
4 (GMX)	1.5-mm textured HDPE geomembrane and subgrade-pre-wetted	0.3 × 0.3	N/A	N/A	24	70
		0.3 × 0.3	N/A	N/A	24	170
		0.3 × 0.3	N/A	N/A	24	690
		0.3 × 0.3	N/A	N/A	24	1380
		0.15 × 0.15	N/A	N/A	24	1380
		0.15 × 0.15	N/A	N/A	24	2070

[a] A consolidation time of 1 h is used instead of 24 or 72 h for the 1.5 mm Textured HDPE/410 g/m^2 cushion geotextile interface because no soils had to undergo consolidation. The use of 1 h is to allow sufficient time for the geotextile and geomembrane to engage prior to shearing

[b] Shearing displacement rate of 1.01 mm/min (0.04 in./min) was used for all the tests in accordance with ASTM D5321 / D5321M-14 and D6243-98. For the normal stresses applied in these tests, Fox (2010) suggest a decrease in shearing displacement rate by one log cycle would show, at most, a 3–5 % decrease in peak and large displacement shear strengths, which is a negligible effect

purposes, the GCL should be completely hydrated to evaluate the lower bound GCL internal strength and geomembrane/GCL interface strength. In the shear box for the multi-interface tests, GCL hydration is a challenge because the GCL is encapsulated by two geomembranes; so hydration of the GCL can only occur from the edges of the specimen, which results in minimal hydration near the center of the GCL specimen even after substantial time. To facilitate GCL hydration herein, four (4) small (6.35 mm diameter) holes were drilled through the primary and secondary geomembranes to facilitate hydration (see Fig. 6a). These four holes allowed the inner portions of the GCL to hydrate at the same time as the edges without removing a significant amount of the textured surface from both geomembranes. One test was conducted on the same configuration without holes in the geomembrane and there was no significant difference in the measured shear resistance, and therefore, these four (4) small holes with an area of only 31.6 mm^2 (0.05 in.^{2}) were used for other shear tests. Four holes were selected to simulate the worst

Table 2 Multi-interface direct shear test details

Test series	Interface test configuration	Specimen size (m)	GCL soaking		Minimum consolidation time (h)	Normal stress during consolidation and shearing (kPa)[a]
			Normal stress during soaking (kPa)	Soaking time (h)		
5 (GMX Black/Black)[b]	410 g/m^2 cushion geotextile and 1.5-mm HDPE and GCL and 1.5-mm HDPE and subgrade soil (#4 Sieve minus)-un-hydrated	0.3 × 0.3	N/A	N/A	72	70
		0.3 × 0.3	N/A	N/A	72	170
		0.3 × 0.3	N/A	N/A	72	690
		0.3 × 0.3	N/A	N/A	72	1380
		0.15 × 0.15	N/A	N/A	72	1380
		0.15 × 0.15	N/A	N/A	72	2070
6 (GMX Black/Black)[b]	410 g/m^2 cushion geotextile and 1.5-mm HDPE and GCL and 1.5-mm HDPE and subgrade soil (#4 Sieve minus)-hydrated	0.3 × 0.3	70	48	72	70
		0.3 × 0.3	70	48	72	170
		0.3 × 0.3	70	48	72	690
		0.3 × 0.3	70	48	72	1380
		0.15 × 0.15	70	48	72	1380
		0.15 × 0.15	70	48	72	2070

[a] Shearing displacement rate of 1.01 mm/min (0.04 in./min) was used for all the tests in accordance with ASTM D5321 / D5321M-14 and D6243-98. For the normal stresses applied in these tests, Fox (2010) suggests a decrease in shearing displacement rate by one log cycle would show, at most, a 3–5 % decrease in peak and large displacement shear strengths, which is a negligible effect

[b] This geomembrane/GCL/geomembrane system was used for single-interface shear test instead of a two layer system to better simulate the situation in the field where the GCL is encapsulated by two geomembranes

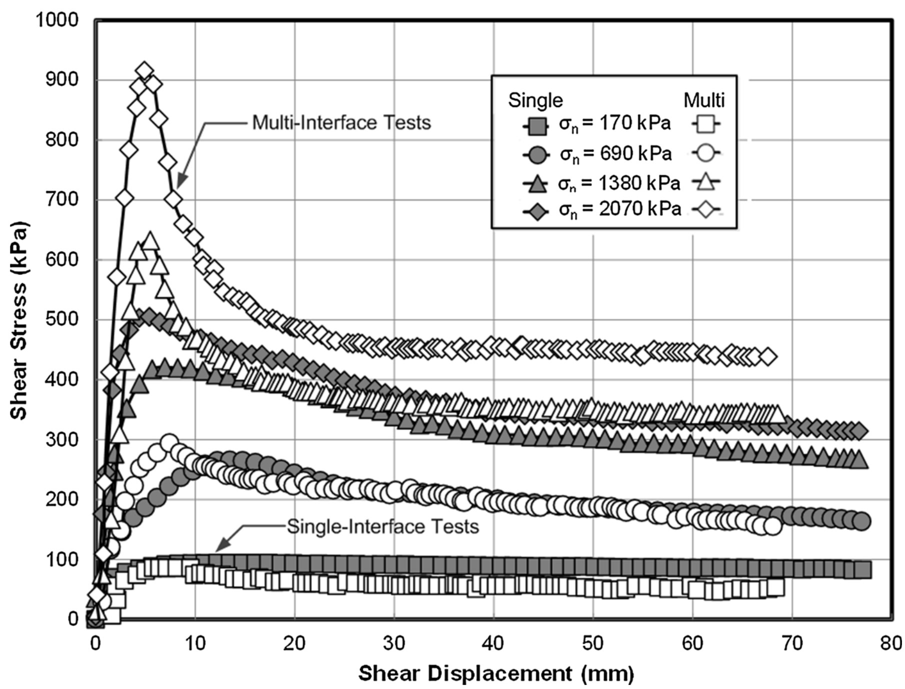


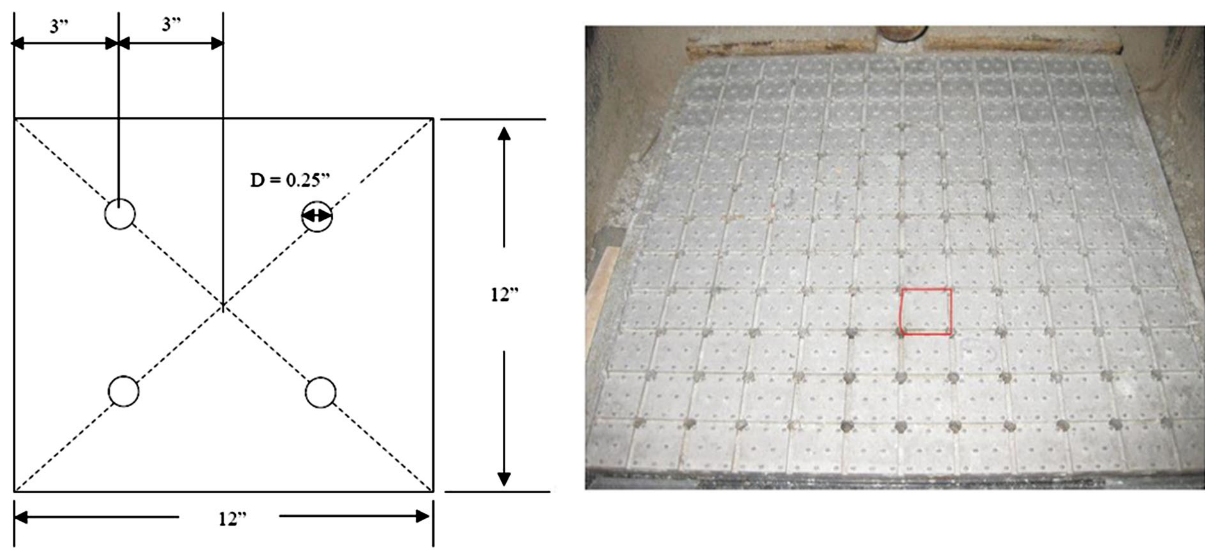
Fig. 5 Typical shear stress versus shear displacement relationship for single and multi-interface tests involving GM-X textured HDPE geomembrane

case scenario for defects in the geomembranes during installation. This is a conservative estimate because typically there are fewer than four defects per square meter of installed geomembrane but full hydration was the main objective in the laboratory testing to measure the lower bound GCL interface and material strength. After shearing, the upper geomembrane was removed and the area of hydration around each defect was determined and photographed to verify hydration. The moisture contents of the bentonite in the hydrated and possibly not hydrated areas of the soaked GCL were measured and compared to verify hydration had occurred throughout the entire GCL specimen. Full hydration was assumed when the vertical displacement versus time, i.e., the measured swell-time relationship, stopped increasing due to bentonite swelling. When the vertical displacement stops increasing, it is assumed that the equilibrium moisture content has been achieved with no water flowing in or out of the GCL specimen. This condition was subsequently verified by the post-test measurements of moisture content.

A summary of the geosynthetic materials, and their characteristics used for the different liner system components is given in Table 3. In all of the single- and multi-interface tests, the geosynthetics were orientated in the machine direction to simulate field conditions because the machine direction is usually installed parallel to the slope.

3.3 Single-Interface Tests

Table 1 provides the test details and effective normal stresses applied in the single-interface direct shear tests. Test Series No. 1 and 2 in Table 1, i.e., 1.5 mm HDPE geomembrane over GCL over 1.5 mm HDPE geomembrane interface configuration, consists of 1.5 mm textured HDPE geomembranes being fixed in the lower and upper halves of the shear boxes, respectively, and the needle-punched double-nonwoven GCL being placed between the geomembranes and aligned in the gap between the upper and lower halves of the shear boxes. The two geomembranes were clamped to the upper and lower shear boxes and the GCL was not clamped. Thus, the failure surface could only occur at the interfaces between either of the upper and the lower geomembranes and the GCL or through the GCL depending on the applied normal stress. Clamping the geomembrane to the lower shear box also prevents movement of the geomembrane as it is pushed past the top shear box. These interface test series evaluate the shear resistance of the two GCL/geomembrane interfaces and the internal strength of the GCL simultaneously. But these are



(a) (b)

Fig. 6 **a** Schematic diagram showing four small (6.35 mm diameter) holes through primary and secondary geomembranes to facilitate GCL hydration and **b** mini-spiked steel plate placed in lower half of *shear box*

Table 3 Material sources and characterization for proposed liner systems

Material	Manufacturer/placement condition	Material characterization
1.5 mm thick double-sided textured, Black/Black colored	Manufacturer X (GMX)	Specimens were cut and oriented in the shear device with the most consistent and uniform direction of texturing parallel to the direction of shear for all test series Mean asperity heights: GMX Black/Black = 0.30 and 0.38 mm
GCL	Manufacturer Y	Needle-punched high peel strength (7 kN/m according to ASTM D4632-08) Initial moisture content to be representative of manufactured moisture content of GCL
410 g/m^2 non-woven geotextile	Manufacturer X	Non-woven geotextiles
LCRS coarse Sand crushed to 19 mm minus material	Lightly tamped	Gradation analysis (ASTM D421-85)
Subgrade material	Relative compaction of 90 % based on laboratory modified proctor compaction test and a moisture content of 3 % wet of optimum (10 %) and dry unit weight (16.55–16.68 kN/m^3)to achieve the desired sub-grade behavior	Maximum dry unit weight and optimum moisture content (ASTM D1557-07) Gradation analysis (ASTM D421-85)

listed and analyzed as single-interface tests because of the following reasons:

- only the geomembrane-GCL interfaces and the GCL material are being sheared,
- the geomembrane over GCL over geomembrane represent the actual placing sequence of the proposed liner system, tested later as part of the overall composite stack, in the same placing sequence within the multi-interface tests, so the response of this sub-composite was expected to be same in both, and
- to economize on the number of single-interface tests on similar interfaces, based on the prior experience and knowledge already gained [e.g., Erickson and Theil (2002), Fox and Stark (2004), Fox (2010)].

These tests were conducted under hydrated and un-hydrated conditions to measure the range of shear resistance for these GCL interfaces and material.

A two-layer system was used for the single-interface tests to simplify the testing. For example, single-interface Test Series No. 4 in Table 1, i.e., Subgrade and 1.5 mm HDPE geomembrane interface configuration, consists of the Subgrade in the upper half of the shear box and a 1.5 mm thick textured HDPE geomembrane adhered to a rigid substrate in the lower half of the shear box and not clamped. Adhered means the mini spikes of steel substrate slightly embed in the 60 mm textured HDPE geomembrane but do not penetrate the bottom surface of the geomembrane. The mini spikes have a height of about 40 mm and density of 1.2 spikes per square centimeter. This mini-spike layer is similar to a microspike geomembrane. The rigid substrate is a mini-spiked steel plate that was placed in the lower half of the shear box. A rigid substrate is allowed under ASTM D5321/D5321M-14 and may consist of "soil, wood, roughened steel plates or other rigid media." The gap of the shear box was set so the Subgrade and Geomembrane interface was exposed and subject to shearing. The low hydraulic conductivity soil was compacted in the bottom of shear box and thus confined by the shear box so it would not extrude laterally.

Single-interface Test Series No. 3 in Table 1, i.e., 410 g/m^2 geotextile cushion and 1.5 mm HDPE primary geomembrane interface configuration, consists of both geosynthetics being adhered to a rigid substrate. The gap of the shear box was set so the geotextile and geomembrane interface was subject to shearing.

The critical interface and/or material within each test configuration was identified after each test by observing the location(s) of shear displacement within the failed specimen.

3.4 Multi-Interface Tests

Table 2 provides the test details and effective normal stresses used in the multi-interface direct shear tests. Figure 7 illustrates the procedure followed to set up these direct shear tests. Multi-interface Test Series No. 5 and 6 in Table 2 consist, from upper half of the shear box to the lower half of the shear box of the following materials:

- Subgrade Soil
- 1.5 mm thick textured HDPE geomembrane
- Needle-punched reinforced double-non-woven GCL
- 1.5 mm thick textured HDPE geomembrane
- 410 g/m^2 non-woven cushion geotextile
- Granular LCRS soil

The gap of the shear box was set so all of the interfaces and materials were subject to the applied shear stresses. Multi-interface tests were conducted under hydrated and un-hydrated conditions. Test Series No. 5 and 6 were conducted to develop design strength envelopes for the proposed liner system. These two multi-interface test series evaluated the shear resistance of all of the geomembrane interfaces in the proposed liner system as well as the internal strength of the GCL in each test instead of testing each interface separately as shown in Table 1.

The critical interface and/or material within each multi-interface test configuration were identified after each shear test by observing the location(s) of the shear displacement within the failed specimen.

4 Single-Interface Test Results

The single-interface tests conducted initially helped identify the critical interfaces for the proposed liner system for the full range of effective normal stresses considered. The critical interface is the one with lowest shear strength for the given effective normal stress, and it can vary with increase in the effective normal stress because geosynthetic and soil interfaces exhibit stress-dependent shear resistance (Stark and Poeppel, 1994). Thus, it is necessary to construct a combination design strength envelope using segments of single-interface strength envelopes that represent the lowest peak strength for a range of given effective normal stresses (Stark and Choi 2004).

4.1 Peak Combination Strength Envelope

For comparison purposes, Fig. 8 presents the peak strength envelopes from single-interface Test Series No. 1 through 4. Figure 8 shows the strongest interface is the GMX/Subgrade Pre-wetted for the full range of normal stresses. The pre-wetting of the interface involved using a spray bottle to pre-wet the surface of the compacted soil for the geomembrane and compacted soil interface test prior to shearing to simulate moisture buildup below a geomembrane in the field due to heating especially with a black geomembrane. The weakest interface, representing the lowest shear strength, is a function of effective normal stress and it can possibly change with increasing normal stresses. To explain this point, results from an additional series of single-interface test involving compacted soil liner (CSL) and 1.5 mm HDPE geomembrane interface is also shown in Fig. 8. The configuration of this test series is similar to that of the Test Series No. 4, except that the Subgrade was replaced with CSL. Although, from the original single-interface test series 1 through 4, the weakest interface for the entire range of normal stresses is presented by the results of Test Series No. 2, i.e., GMX over GCL over GMX, Hydrated interface, however, it switches to GMX/CSL, Pre-wetted interface at an interpolated effective normal stress of about 870 kPa. It should be noted that the additional test series involving GMX/CSL, Pre-wetted has been presented only to explain that the weakest interface can possibly change at different normal stresses. In such cases, the strength envelope should be developed from a combination of the segments of the two interfaces which represent the lowest shear strength. As such, the GMX/CSL, Pre-wetted interface does not form part of the proposed liner system, nor was this interface included in the multi-interface tests. Thus, the peak combination strength envelope for the proposed liner system is defined by the GMX over GCL over GMX, Hydrated interface only.

4.2 Large Displacement Combination Strength Envelope

The peak combination strength envelope for one or more interface(s) determines the LD combination strength envelope (Stark and Choi 2004). Figure 9 shows the individual LD strength envelopes for all of the single-interfaces in Test Series No. 1 through 4. It

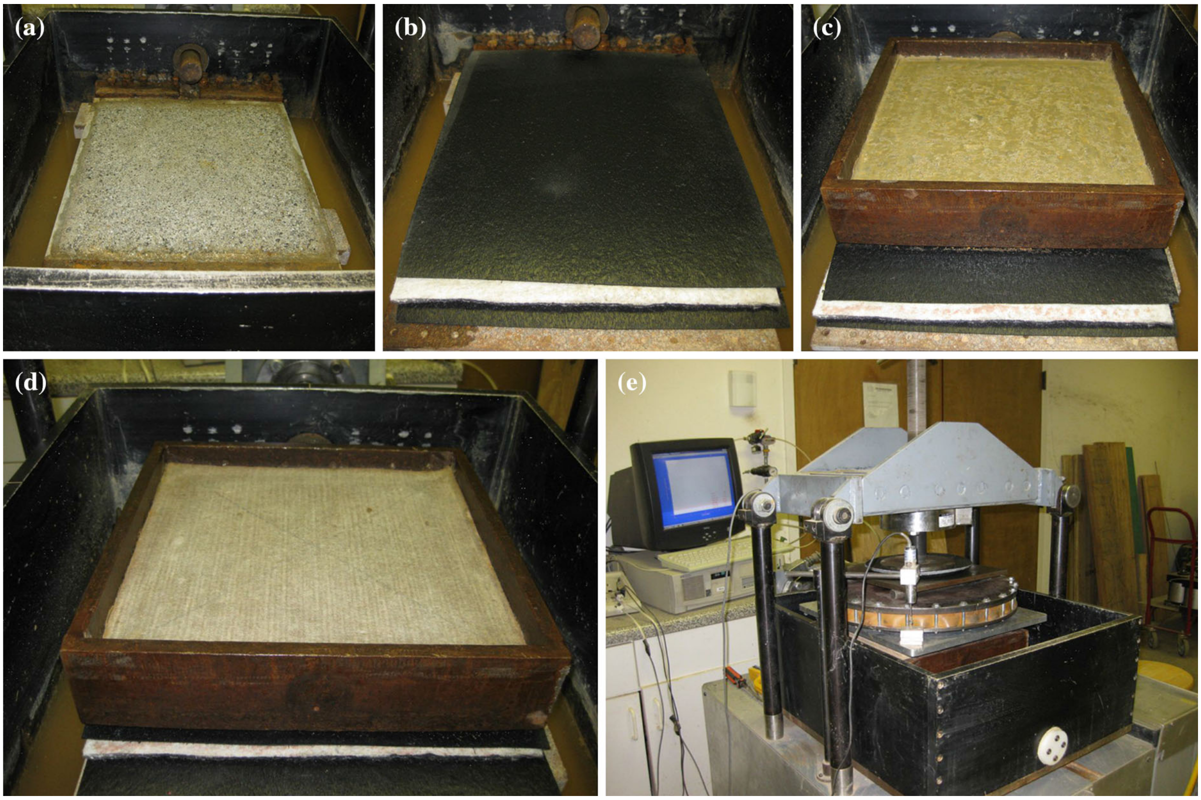


Fig. 7 Multi-interface direct shear test procedure: **a** compact soil in lower shear box, **b** place lower geomembrane, GCL, and *upper* geomembrane on top of compacted soil in the *lower shear box*, **c** compact the upper soil in the *upper shear box*, **d** place a drainage layer and nonwoven geotextiles (NWGT) on *top* of compacted soil to provide a pervious boundary, **e** place loading plates on top of the drainage layer and assemble the normal load reaction system, and then place an LVDT on top loading plate to monitor vertical deformation during consolidation and shearing

also shows the LD strength envelope from the additional test series on GMX/CSL, Pre-wetted.

Because the peak combination strength envelope defines the LD combination envelope, therefore, the GMX over GCL over GMX, Hydrated interface strength envelope should be the LD combination strength envelope for the proposed liner system. Interestingly, Fig. 9 shows that out of the interfaces considered for the proposed liner system, the GMX over GCL over GMX, Hydrated interface yields the lowest LD strengths for the entire range of effective normal stresses. In this case, the results of the LD strength envelope displaying the lowest shear strengths for the entire range of normal stresses are compatible with those of the peak strength envelope. This may not always be the case, i.e., the critical peak strength envelopes may not always correspond to the lowest LD failure envelope. Since, the LD strength envelope should be determined based on the lowest peak strengths over a range of different normal stresses (Stark and Choi 2004), it may result either from a single interface over the entire range of normal stresses (as determined from test series 1 through 4), or a combination of segments from different interfaces being the lowest in peak shear strength over different ranges of normal stresses (as determined by including the additional test series on GMX/CSL, Pre-wetted).

Interestingly, it may also be noticed from the LD strength envelopes shown in Fig. 9 that the results of the additional test series on GMX/CSL, Pre-wetted interface present an example of change in the weaker interfaces over different ranges of the effective normal stresses. If this interface was to be made part of the proposed liner system, the critical LD combination strength envelope should switch from GMX over GCL over GMX, Hydrated interface to GMX/CSL, Pre-

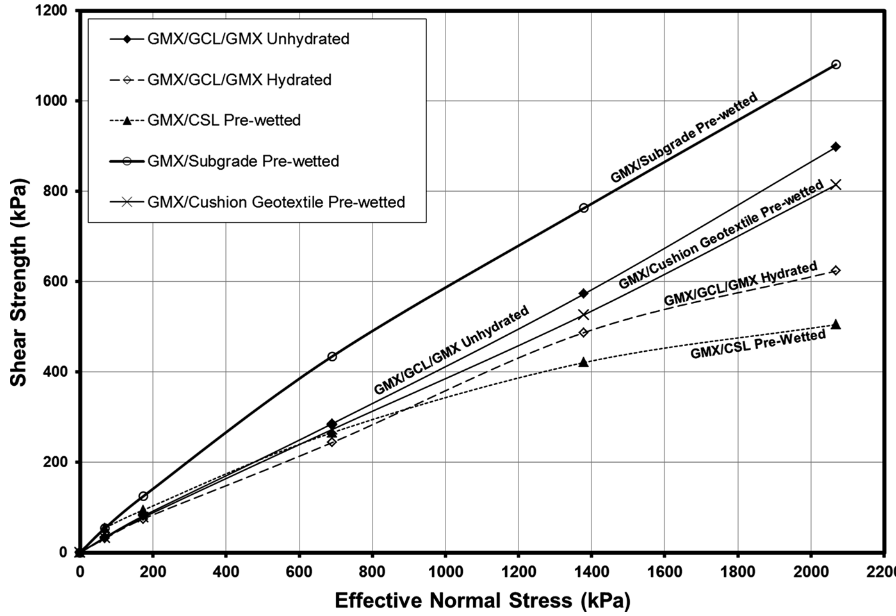


Fig. 8 Peak strength envelopes from single-interface tests on proposed liner system

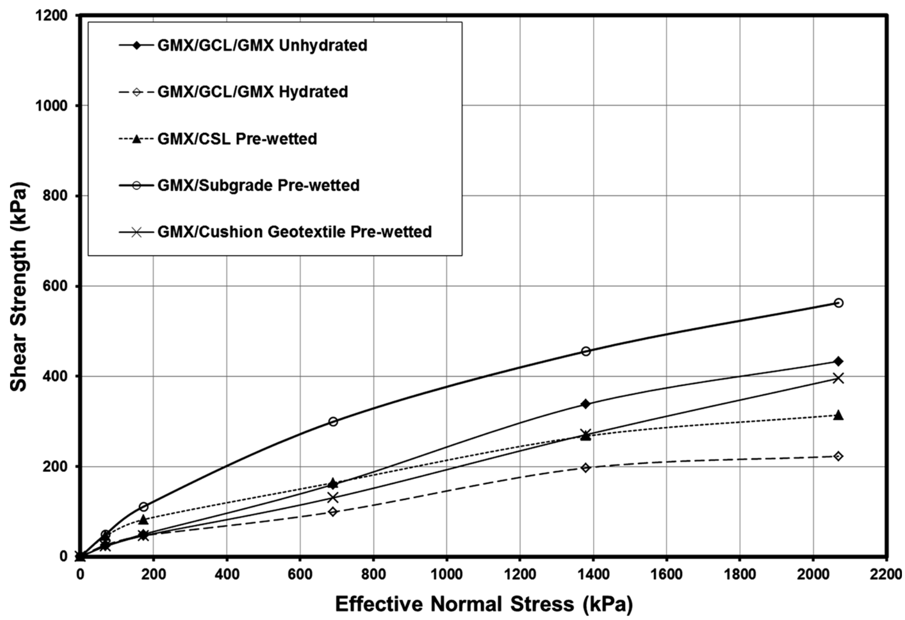


Fig. 9 LD strength envelopes from single-interface tests on proposed liner system

wetted interface for the interpolated effective normal stress of about 870 kPa and higher, as determined from its corresponding peak combination strength envelope. Again, the results of this additional test series have only been presented in order to explain how different segments of strength envelopes from different interface tests may be combined to determine the LD combination strength envelope based on the results of peak combination strength envelope.

5 Multi-Interface Test Results

The Black/Black colored GMX geomembrane exhibited mean asperity heights of 0.30 and 0.38 mm for the two sides of the geomembrane. Asperity height is defined as the individual projections of polyethylene that extend above the core surface of a textured geomembrane resulting in textured surface profile ASTM D7466-08). The standard deviation for these mean asperity heights is about 0.038 mm.

The peak and LD strength envelopes for the two series of multi-interface tests are presented in Figs. 10 and 11, respectively. Thus, each series of multi-interface tests provides its respective critical strength envelope and identifies the weakest geosynthetic interface(s)/material in the respective liner system for the full range of normal stresses via careful inspection of the interfaces after shearing. As a result, a critical peak strength envelope is generated directly from the results of multi-interface tests for the full range of normal stresses and the process of determining a peak combination envelope is not required. Moreover, unlike the single-interface tests, LD combination strength envelopes are not required that correspond to the peak strength envelopes. Instead, the LD strength envelope is determined from the actual test results, because large shear displacements occur on the interface that yields the lowest peak strengths. Thus, the LD strength envelope is determined by plotting the measured shear stress at the end of the test, i.e., the largest shear displacement.

The composite liner system tested in multi-interface Test Series No. 5 and 6 contain all of the interfaces/materials tested in the single-interface tests that were considered to determine combination envelopes for the proposed liner system. Hence, the results of these two series allow a direct comparison between the single- and multi-interface tests for the proposed liner system. These comparisons are discussed in the next section.

Table 4 presents a summary of critical interfaces for the two multi-interface test series for the range of normal stresses considered. In all of the single- and multi-interface tests, the geosynthetics and geonets or overlying LCRS material embedding in adjacent geonets were oriented in the machine direction being placed down sideslopes where a large displacement condition can develop. On the floor or base of the landfill the orientation of the geosynthetics varies.

Figures 10 and 11 show the results of Test Series Nos. 5 and 6 for the proposed liner system. Table 4 shows the un-hydrated critical interface may be stress dependent while the hydrated may not. Thus, the critical un-hydrated interface for the proposed liner system may change from one interface to another with increasing normal stresses. The critical interface switches to the geomembrane and un-hydrated GCL interface for normal stresses of 2070 kPa. Thus, the critical interface in the multi-interface tests may also be a function of the geomembrane type.

Comparison of the critical interfaces at different normal stresses for Test Series No. 5 and 6 in Table 4 shows that upon hydration of the GCL, the critical interface shifts to one of the GCL and Geomembrane

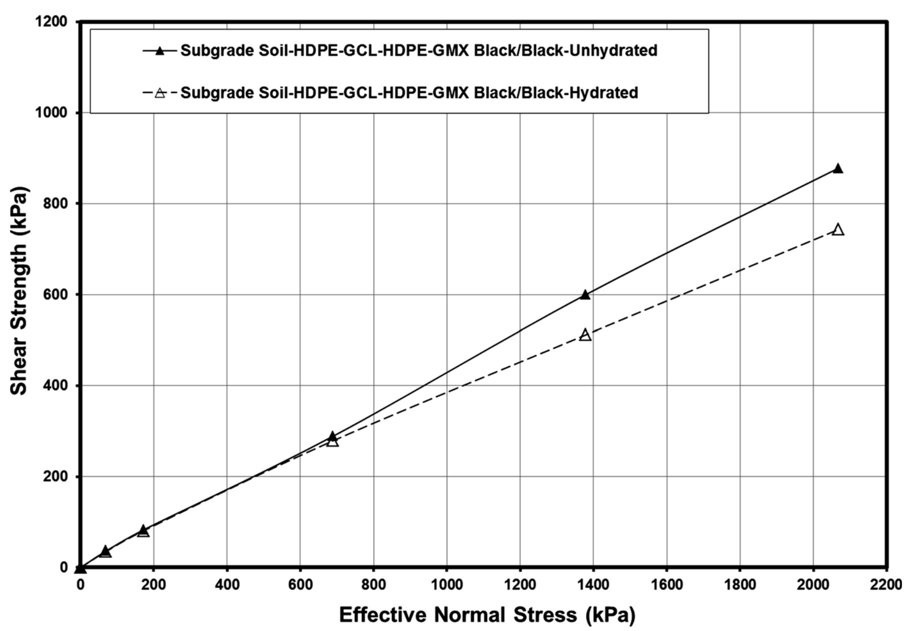


Fig. 10 Peak strength envelopes from multi-interface tests for proposed liner system

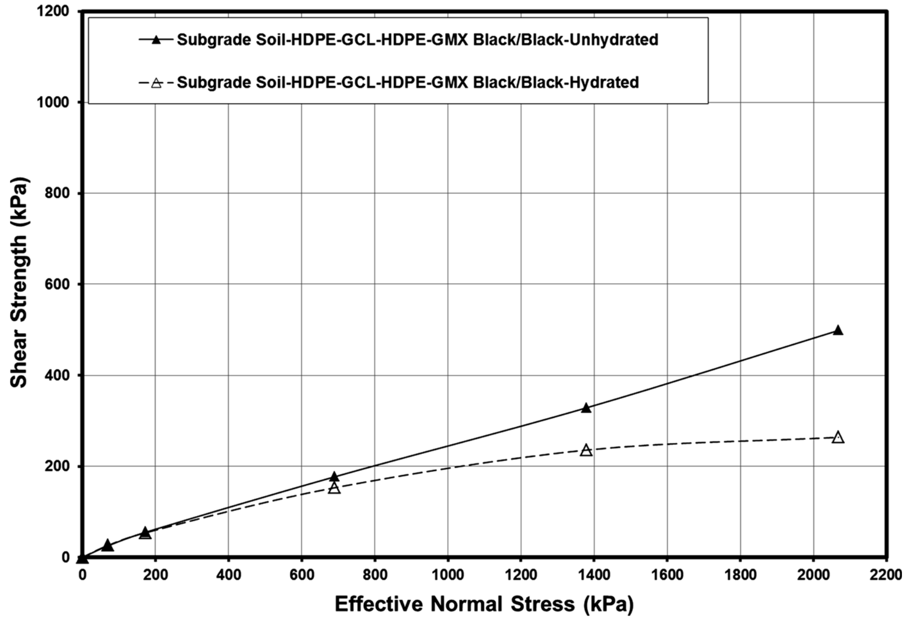


Fig. 11 LD strength envelopes from multi-interface tests for proposed liner system

Table 4 Summary of critical interfaces at different normal stresses from multi-interface tests

Effective normal stresses (kPa)	Test series	
	5 GMX-Black/Black-subgrade soil, un-hydrated	6 GMX-Black/Black-subgrade soil-hydrated
70	Cushion geotextile/GMX-pre-wetted	GMX/GCL hydrated
170	Cushion geotextile/GMX-pre-wetted	GMX/GCL hydrated
690	Cushion geotextile/GMX-pre-wetted	GMX/GCL hydrated
1380	Cushion geotextile/GMX-pre-wetted	GMX/GCL hydrated
2070	GMX/GCL un-hydrated	GMX/GCL hydrated

interfaces. Thus, if the GCL hydrates in an encapsulated design, a GCL interface will become critical depending on the normal stress.

The peak and LD strength envelopes obtained from multi-interface Test Series No. 5 and 6 represent two different states of GCL hydration in the proposed liner system. As expected, these results show that hydration of the GCL yields lower values of peak and LD strengths than the un-hydrated GCL for the normal stresses and geomembranes considered in these test series (see Figs. 10, 11).

6 Analysis and Comparison of Test Results

Peak and LD combination strength envelopes obtained from the results single-interface Test Series No. 2, 3, and 4 are compared with the results of multi-interface Test Series No. 6 for the proposed liner system. This comparison is appropriate because the combinations mentioned above involve all of the interfaces/materials tested in the two multi-interface tests for the respective liner system. These comparisons are presented in Figs. 12 and 13.

Figure 12 compares the peak combination strength envelope from the single-interface tests with the corresponding peak strength envelope from multi-interface Test Series No. 6 for the proposed liner system. For this liner system comparison, the critical interface is the same for both methods of testing, i.e., GMX/GCL, Hydrated, for the range of normal stresses considered. This result suggests that multi-interface tests can yield similar strengths and critical interfaces as single-interface tests for certain liner system configurations and geosynthetics. However, Fig. 12 also shows the peak strengths are slightly lower for the single-interface tests for the range of normal stresses considered, especially at high normal stresses. This difference may be attributed to single-interface tests being conducted in isolation and not influenced by surrounding geosynthetics, such as geonets embedding in multiple geosynthetics.

Comparisons of LD strength envelopes from the single- and multi-interface tests for the proposed liner system are presented in Fig. 13. This figure shows a larger difference in the LD envelopes than the peak envelopes for the single- and multi-interface test results. The multi-interface tests yield higher LD envelopes than the single-interface tests. The higher LD strengths in the multi-interface tests are consistent with higher peak strengths in the multi-interface tests shown in Fig. 12 and may be due to differences in shear displacement on the critical interface between single and multi-interface tests.

7 Summary

Based on the results obtained from the testing program described herein, the following observations can be derived:

- Peak and LD strengths, i.e., identification of the critical interface, of a composite liner system are dependent on the effective normal stress, geomembrane type, test procedure, and manufacturer. So, site specific testing should be performed. The limited data herein suggest that single-interface tests may exhibit slightly lower peak strengths than multi-interface tests because they have more planar surfaces and less dimpling but this probably depends on test setups. The relevant dimpling effects have been discussed in the past by Breitenbach and Swan (1999).
- Multi-interface tests herein yielded similar peak strengths as those from single-interface tests.
- LD strengths might generally be less for single-interface tests. The reason for this might be the reduced displacement on the critical interface for multi-interface tests, where the cumulative strains have to be mobilized along all the interfaces of the composite system. Thus, in general, it appears that single-interface tests may be slightly more conservative than multi-interface tests. These findings are consistent with previously published data in Triplett and Fox (2001).
- Several complicating factors are associated with multi-interface tests including: contemporaneous straining on multiple interfaces to mobilize peak

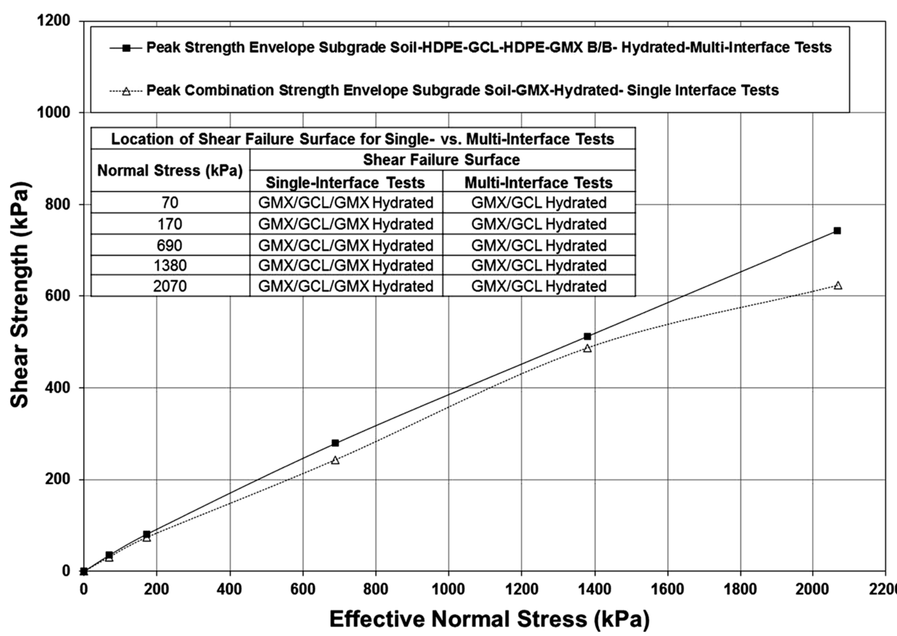


Fig. 12 Comparison of peak strength envelopes from single- and multi-interface tests for proposed liner system

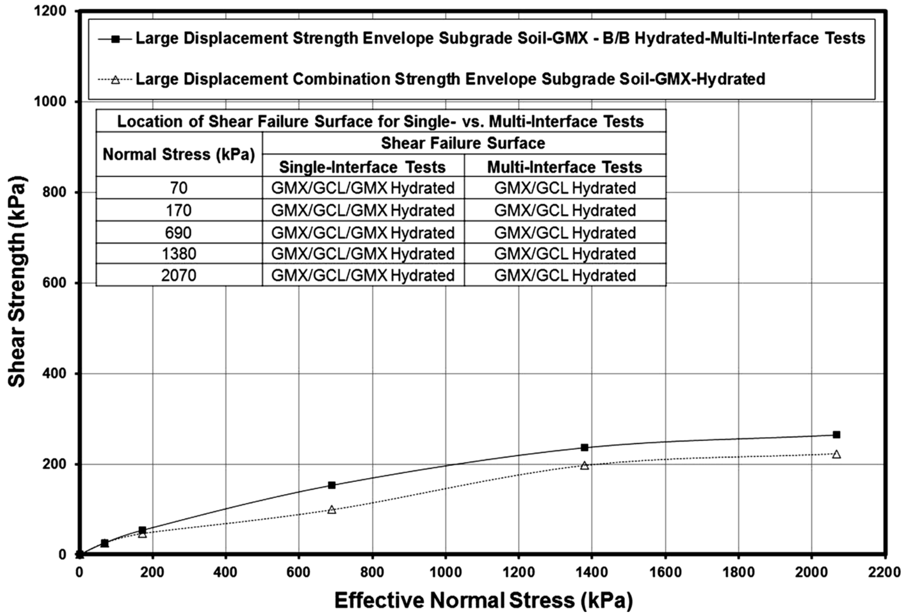


Fig. 13 Comparison of LD strength envelopes from single- and multi-interface tests for proposed liner system

strength, potential obfuscation of critical interface due to multiple displacements, possible complications arising from non-uniform application of normal stress that is unknown and endemic to the test method, complications with soil plowing being more difficult to manage with more layers, lack of knowledge about how close the strength of other interfaces might be to the strength of the critical interface, and overall difficulty and complexity of multi-interface test setup.

- The magnitude of strength loss for the liner system considered herein is more pronounced in single-interface tests than multi-interface tests for the entire range of effective normal stresses. The lower LD strengths observed in single-interface tests are probably caused by the rigid clamping of the geosynthetics which results in some tensile strains in the geosynthetics. Single-interface tests yielded a conservative estimate of the LD strength for the geosynthetics tested herein. As suggested by a reviewer, this may also be attributed to the greater displacement along the critical interface in single-interface tests than those in the multiple-interface tests by way of the explanation provided under the disadvantages of the multi-interface tests.
- Peak strengths are slightly lower for the single-interface tests for the range of normal stresses considered, especially at high normal stresses. Single-interface tests are performed in isolation and not influenced by dimpling effects created by the adjacent consolidated soils or surrounding geosynthetics, such as geonets. The components of a composite liner system behave more as a single entity in a multi-interface test, which can result in adjacent soil and surrounding geosynthetics influencing multiple layers and shear displacement occurring at different normal stresses.
- The data from these results is limited as only one geomembrane was tested so additional testing is required to present a complete comparison of single- and multi-interface tests.

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