COMPARISON OF SINGLE AND MULTI GEOSYNTHETIC AND SOIL INTERFACE TESTS

Timothy D. Stark[1], Fawad S. Niazi[2], and Timothy C. Keuscher[3]

A technical paper submitted for review and possible publication in the
Geosynthetics International Journal

June 16, 2011

---

[1] Professor of Civil and Environmental Engrg., University of Illinois, Newmark Civil Engrg. Laboratory, 205 N. Mathews Ave., Urbana, IL 61801-2352, Telephone: +1 (217) 333-7394, Telefax: 1/(217)333-9464; E-mail: tstark@illinois.edu

[2] Graduate Research Assistant, Graduate Research Assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology, Room 243 Mason Building, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA, Telephone: 1/404-894-2282, Telefax: 1/(404)894-2281; E-mail: fniazi6@gatech.edu

[3] Principal Geotechnical Engineer, AMEC Geomatrix, Inc., 510 Superior Avenue, Suite 200, Newport Beach, CA 92663, Telephone: +1(949) 642-0245, Telefax: 1/; E-mail: Tim.Keuscher@amec.com

Technical Paper by T. D. Stark, F. S. Niazi, and T.C. Keuscher

COMPARISON OF SINGLE AND MULTI GEOSYNTHETIC AND SOIL INTERFACE TESTS

ABSTRACT: This paper presents a comparison of single- and multi-interface strength tests for two possible landfill liner system configurations. The paper provides a comparison of the 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 an agreement between the strength envelopes derived from single and multi-interface tests but there is a difference in the critical interface for some of the normal stresses and interfaces tested. The test results are also used to illustrate the effect of different types of geomembranes, soil type, 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

AUTHOR: T. D. Stark, Professor of Civil and Environmental Engineering, 2217 Newmark Civil Engineering Laboratory, University of Illinois, 205 N. Mathews Ave., Urbana, IL 61801, USA, Telephone: 1/217-333-7394, Telefax: 1/217-333-9464; E-mail: tstark@uiuc.edu. F. S. Niazi, Graduate Research Assistant, School of Civil and Environmental Engineering, Georgia Institute of Technology, Room 243 Mason Building, 790 Atlantic Drive, Atlanta, GA 30332-0355, USA, Telephone: 1/404-894-2282, Telefax: 1/404-894-2281; E-mail: fniazi6@gatech.edu. T.C. Keuscher, Principal Geotechnical Engineer, Principal Geotechnical Engineer, AMEC Geomatrix, Inc., 510 Superior Avenue, Suite 200, Newport Beach, CA 92663, Telephone: +1(949) 642-0245, Telefax: 1/949-642-4474; E-mail: Tim.Keuscher@amec.com.

PUBLICATION: *Geosynthetics International* is published by Thomas Telford Journals, Thomas Telford House, 1 Henon Quay, London, E14 4JD, United Kingdom, Telephone: 44/(0)20-7665-2461, E-mail: journals@thomastelford.com. *Geosynthetics International* is registered under ISSN 1072-6349.

DATES: Original manuscript received March 24, 2011, resubmitted December 27, 2011, and accepted ??. Discussion open until ??.

REFERENCE: Stark, T. D., Niazi, F.S., and Keuscher, T.C. (2011) Comparison of Single and Multi-Geosynthetics Interface Tests. Geosynthetics International, 15, No. ?, ??–??.

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 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'Rouke 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.

To date, substantial investigations have been conducted on the shear behavior of geosynthetic interfaces using single interface tests but little has been published on a comparison with multi interface shear tests. Consequently, the results of single and multi interface direct shear tests on two liner system configurations are presented to investigate the compatibility of single and multi interface test results. These test results are summarized herein as well as the critical interface(s) within each liner system and the resulting peak and large displacement (LD) strength envelopes for design. Another important aspect considered herein is the effect of geomembrane type and hydration on the shear behavior of an encapsulated geosynthetic clay liner (GCL) and its design peak and LD strength envelopes.

2 MULTI–INTERFACE TESTS

This section describes the advantages and disadvantages of multi-interface tests which are becoming more prevalent in laboratory testing and design.

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

The main problem with single-interface tests is that a composite liner system has 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 actually installed liner system is not tested as a single unit. Multi-interface tests allow multiple interfaces and multiple 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 shear behavior of a composite liner or cover system.

Multi-interface shear tests can reduce the amount of testing, and the time required for testing and design by testing a large portion of the liner system at one time. Also, the peak and LD design 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 (see Stark and Choi 2004).

The use of single interface shear tests can lead to an overestimation of the shear resistance of some geosynthetic interfaces and materials. For example, Eid and Stark (1997) show that the critical failure surface with an encapsulated geomembrane-backed GCL is the adhesive bond between the backing geomembrane and the granulated bentonite and not within the bentonite as indicated from single interface tests (Daniel and Shan, 1992).

In the field, shear displacement may occur on more than one interface as described by Stark et al. (1998). Stark et al. (1998) use a case history to show movement occurred at the bentonite/geomembrane interface as well as the overlying geomembrane/geonet interface. This possibility can be captured in multi-interface tests if these interfaces are included in the specimen.

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

The following are some disadvantages of multi-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 strength envelopes for the appropriate range of normal stresses for each interface tested, whereas multi-interface tests only provide peak and LD strength envelopes for the critical failure surface of the system identified at each normal stress.
- This study shows multi-interface tests are accurate but it is beneficial to compare the multi-interface test results with at least one test on a single interface, such as the critical interface for a given normal stress because most experience is with single interface tests and it has fewer variables. In this study, both the single and multi-interface tests were conducted using the same direct shear device.

3 PROPOSED LINER SYSTEMS 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. Two possible liner system configurations are considered herein.

3.1 Proposed Liner Systems

The two Composite Liner Systems tested are shown in Figure 1(a) and 1(b), respectively. Proposed Composite Liner System No. 1 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, a 0.3 m thick low hydraulic conductivity compacted fine-grained soil liner (CSL), and a subgrade material. Proposed Composite Liner System No. 2 consists essentially of the same components, in the same order, with the CSL being omitted so the geomembrane is in contact with a coarser-grained and less compacted subgrade material. In both liner systems, the HDPE geomembranes are textured on both sides to increase the shear resistance at the geotextile cushion, GCL, CSL, and subgrade interfaces. This texturing develops a hook-and-loop connection, also referred to by the Trademark name of Velcro, with the 410 g/m^2 cushion geotextile and the non-woven geotextile of the GCL because the GCL is manufactured with two non-woven geotextiles. The LCRS consists of granular drainage media with a hydraulic conductivity greater than or equal to 1x10^{-1} cm/sec and an overlying 410 g/m^2 geotextile filter fabric. The gradation of the LCRS gravel consists of between 8 to 10 percent passing 9.5 mm (3/8-inch) sieve and and no more than 5 percent passing #4 sieve.

A qualitative evaluation of the materials and interfaces in these two liner systems was used to identify the stronger interfaces and materials which could be excluded from the laboratory shear testing program. It was anticipated that the waste, operations layer, geotextile filter/operations layer interface, geotextile filter/granular LCRS material interface, granular LCRS material, granular LCRS material/geotextile cushion interface, CSL material, and subgrade material would not be critical in terms of slope stability for these two liner systems. Based on this qualitative evaluation, the laboratory shear testing program for both the single- and multi-face configurations focused on the following interfaces and materials:

- Geotextile cushion/primary 1.5 mm textured HDPE geomembrane interface
- 1.5 mm textured HDPE geomembrane/GCL interface
- Internal GCL

- 1.5 mm textured HDPE geomembrane/CSL interface (Liner System No. 1 only)
- 1.5 mm textured HDPE geomembrane/Subgrade interface (Liner System No. 2 only)

3.2 Test Details, Configurations and Normal Stresses

The two main objectives of the testing program were to identify the interface(s) or material(s) that exhibit the lowest shear resistance: (1) in either test configuration (single- vs. multi-interface testing), for different geomembranes; and (2) for different states of GCL hydration for the two liner systems shown in Figure 1. The shear resistance of these interfaces is a function of the aggressiveness of the geomembrane texturing, the amount of bentonite that extrudes, migrates, or is squeezed from the GCL into the textured HDPE geomembrane interface, and the internal shear strength of the GCL. Based on the list of potentially critical interfaces and materials, nine series of single-interface and five 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 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 the different details are discussed in following sub-sections.

The geosynthetic interface tests were performed in accordance with ASTM Standard Test Method D5321-02. 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, 1,380, and 2,070 kPa. The highest of these normal stresses (2,070 kPa) is greater than the normal stress that can be applied in a 0.3 m x 0.3 m direct shear box because of the large normal force required to achieve a normal stress of 2,070 kPa with a specimen area of 0.09 m^2. As a result, both 0.3 m x 0.3 m and 0.15 m x 0.15 m direct shear boxes were used at an effective normal stress of 1,380 kPa. If these devices yielded similar results, the 0.15 m x 0.15 m shear box was used for the shear test at a normal stress of 2,070 kPa instead of the 0.3 m x 0.3 m shear box because of difficulties in applying a large normal force to the large (0.3 m x 0.3 m) specimen area. A shear box smaller than 0.3 m x 0.3 m is allowed under ASTM D 5321, if it yields similar test results as the 0.3 m x 0.3 m shear box. One-fourth of the normal force is required to achieve the desired normal stress in a 0.15 m x 0.15 m shear box than in a 0.3 m x 0.3 m shear box, which allowed testing at a normal stress of 2,070 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 low normal stresses (70 and 170 kPa) helped define the stress dependent nature of the strength envelopes at low effective stresses. All interface shear tests were continued to a shear displacement of 0.65 to 0.75 m depending on whether or not the shear stress-displacement relationship was still decreasing significantly. If the shear stress-displacement relationship was still decreasing significantly at a shear displacement of 0.65 m, the tests were continued to a shear displacement of 0.75 m. Because the shear displacement is limited to 0.65 to 0.75 m, the resulting strengths are referred to as LD strengths and not residual strengths (Stark and Choi, 2004).

The GCL, CSL, 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 (selected single-interface and all multi-interface test configurations, see Figure 2) were tested using two different states of hydration, namely, un-hydrated i.e., bentonite moisture content being the moisture content received from the manufacturer and hydrated i.e., bentonite moisture content after soaking for 48 hours 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 hours or until the time for 100% 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 sample thickness could be investigated.

In both liner systems, the GCL is encapsulated by two geomembranes to simulate field conditions. As a result, field hydration can only occur through geomembrane defects. However, for stability purposes, the GCL should be completely hydrated to evaluate the lower bound GCL 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 because 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, five (5) small (6.35 mm diameter) holes were drilled through the primary and secondary geomembranes to facilitate hydration. These five 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 so these five (5) small holes with an area of only 31.6 mm^2 (0.05 in^2) were used for other shear tests. Five holes were selected to simulate the worst case scenario for defects in the geomembranes during installation. This is a conservative estimate because typically there are fewer than five 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. One of the geomembrane defects was located at the center of the specimen and the other four defects were spaced equally from the center to each corner of the specimen. 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. 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.

A summary of the geosynthetic materials, manufacturers, 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 parallel to the slope.

3.2.1 Single-Interface Tests

Table 1 provides the test details and normal stresses applied in the single-interface direct shear tests. Test Configurations No. 1 through 4 in Table 1, i.e., 1.5 mm HDPE geomembrane/GCL/1.5

mm HDPE geomembrane interface configuration, consist 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-non-woven GCL being placed between the geomembranes and aligned in the gap between the upper and lower halves of the shear boxes. This interface test evaluated the shear resistance of the two GCL/geomembrane interfaces and the internal strength of the GCL, but is still considered a single interface test because only the GCL interfaces and material is being sheared. This test was conducted under hydrated and un-hydrated conditions to measure the range of shear resistance for these geomembrane interfaces and the GCL. As noted in Fox and Stark (2004), gripping surfaces can result in an over-estimation of GCL interface and internal shear resistance because field conditions do not involve similar gripping surfaces. The use of the two geomembranes that will be installed in the field is a better simulation of field shearing condition in the laboratory test than one or two aggressive gripping surfaces. Thus, the two geomembranes were clamped to the upper and lower shear boxes and the GCL was placed between the geomembranes but not clamped as shown in Figure 2. Thus, the failure surface could only occur at a geomembrane/GCL interfaces or through the GCL depending on the applied normal stress. Clamping the geosynthetic layer to the lower shear box also prevents movement of the geomembrane during shearing. This three layer system was used for the 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.

Single Interface Test Configurations No. 5 and 6 in Table 1, i.e., CSL/1.5 mm HDPE geomembrane interface configuration, consist of the CSL 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. The gap of the shear box was set so the CSL/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 could not extrude laterally. In contrast, the GCL was exposed in the multi-interface test and some of the hydrated bentonite could migrate through the gap in the shear boxes. In the unhydrated GCL tests, little, if any, bentonite migration occurred.

Test Configurations No. 7 and 8 in Table 1, i.e., 410 g/m^2 geotextile cushion/1.5 mm HDPE primary geomembrane interface configuration, consist of both geosynthetics being adhered to a rigid substrate. The gap of the shear box was set so the geotextile/geomembrane interface was subject to shearing. Figure 3 shows typical shear stress-displacement relationships for single-interface Test Series No. 7 between Nonwoven Cushion Geotextile against GM-A Textured HDPE Geomembrane under Hydrated and Consolidated Conditions.

Single Interface Test Configuration No. 9 in Table 1, i.e., subgrade/1.5 mm HDPE geomembrane interface configuration, consists of the soil subgrade being placed in the upper half of the shear box and a 1.5 mm thick textured HDPE geomembrane being adhered to a rigid substrate in the lower half of the shear box. The gap of the shear box was set so the subgrade/geomembrane interface was subject to shearing. This test is similar to the CSL/geomembrane test except a coarser soil and a low degree of compaction was used.

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

3.2.2 Multi-Interface Tests

Table 2 provides the test details and normal stresses used in the multi-interface direct shear tests. Multi-interface Test Configurations No. 10 through 14 in Table 2 consist, from upper half of the shear box to the lower half of the shear box of:

- 12-in thick CSL or Subgrade Soil
- 1.5 mm thick textured HDPE geomembrane
- Needle-punched reinforced double-non-woven GCL
- A 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 Configuration No. 10 represents proposed Liner System No. 1, whereas, Test Configurations No. 11 through 14 were conducted to develop design strength envelopes for Proposed Liner System No. 2, which was the preferred design. These five multi-interface test series evaluated the shear resistance of all of the geomembrane interfaces in the two proposed liner systems as well as the internal strength of the GCL in each test instead of testing each interface separately as shown in Table 1. To reduce the number of multi-interface tests and due to other factors, such as availability of adequate quality samples, economics, and GM-B having a less aggressive texturing than GM-A, only geomembrane GM-B was used for the multi-interface tests because it provided a conservative estimate of interface strength. Conversely, geomembranes GM-A and GM-B were both used for the single interface tests for comparison purposes. The critical interface and/or material for the multi-interface tests was identified after shear testing by observing the location of the shear displacements within the tested specimen. Figure 4 shows typical shear stress-displacement relationships for multi-interface Test Series No. 11 involving a Cushion Geotextile above Black/White GM-B Textured HDPE Geomembrane underlain by GCL and GCL underlain by another Black/White GM-B Textured HDPE Geomembrane underlain by Subgrade Soil minus No. 4 sieve under unhydrated, which is Test Series No. 11 in Table 2.

4 SINGLE-INTERFACE TEST RESULTS

The single-interface test series helped identify the weakest interfaces for both proposed liner systems for the full range of normal stresses considered. The weakest/critical interface varies with normal stress because geosynthetic and soil interfaces exhibit stress-dependent shear resistance. Thus, it is necessary to construct a combination design strength envelope using segments of single interface strength envelopes that represent the lowest strength for a given normal stress (Stark and Choi, 2004).

For comparison purposes, Figure 5 presents the peak combination strength envelopes from Single Interface Test Configurations No. 1 through 9. Figure 5 shows the strongest interface is the GM-B/Subgrade, Pre wetted for the full range of normal stresses. The weakest interface is a function of normal stress and thus changes with increasing normal stresses. The weakest interface changes from GM-A/GCL/GM-A, Hydrated to GM-A/CSL, Pre-wetted at an effective normal stresses of about 360 kPa as discussed in the next section. The weakest interface for GM-B involves similar interfaces, i.e., GM-B/GCL/GM-B, Hydrated to GM-B/CSL, Pre-wetted, but at an effective normal stresses of about 870 kPa instead of 360 kPa as discussed in the next section.

4.1 Peak Combination Strength Envelopes

Using the data in Figure 5, Figure 6 presents peak strength envelopes for the two GM-A geomembrane interfaces that yielded the lowest peak strength envelopes for the proposed liner systems, i.e., (1) GM-A/GCL/GM-A, Hydrated and (2) GM-A/CSL, Pre-wetted. For normal stresses less than or equal to 360 kPa, the GM-A/GCL/GM-A, Hydrated interface exhibits the lowest peak strength and is the critical interface. However, the GM-A/CSL, Pre-wetted interface is critical for normal stresses greater than or equal to 360 kPa. Therefore, the peak combination strength envelope corresponds to the GM-A/CSL, Pre-wetted interface for normal stresses greater than about 360 kPa and is illustrated by the thin solid line in Figure 6. The normal stress at which the critical interface switches between the two interfaces may be approximately interpolated at 360 kPa (as shown) but could be found more precisely by additional tests at normal stresses in the range of 170 to 690 kPa. The peak combination strength envelope characterizes the peak strength of this liner system with GM-A for design purposes over the range of normal stresses tested. This combination strength envelope represents the lowest peak shear strength at each normal stress for all of the interfaces considered for proposed Liner System No. 1 and GM-A. As a result, this peak combination strength envelope is used to develop the corresponding LD combination strength envelope for GM-A instead of simply selecting the lowest LD strength envelope (Stark and Choi, 2004).

Figure 6 also presents the peak combination strength envelope for the textured GM-B geomembrane interfaces. The data in Figure 5 shows for normal stresses less than or equal to 690 kPa, the GM-B/GCL/GM-B, hydrated interface exhibits the lowest peak strength and is the critical interface for this geomembrane for these normal stresses. However, the GM-B/CSL, pre-wetted interface is critical for normal stresses greater than or equal to 1380 kPa. The normal stress at which the critical interface switches between the two has been approximately interpolated to be about 870 kPa (see Figure 6). This point can also be found with better precision by additional tests at normal stresses in the range of 690 to 1380 kPa. Accordingly, the peak combination strength envelope developed for Proposed Liner System No. 1 with GM-B is presented by a thick solid line in Figure 6 and combines portions of the peak failure envelope for both interfaces.

A comparison of the peak combination strength envelopes for GM-A and GM-B interfaces in Proposed Liner System No. 1 in Figure 6 shows that the peak combination strength envelope for the GM-B geomembrane is the same or slightly lower than the GM-A geomembrane for the range of normal stresses considered. Thus, the GM-B geomembrane is the critical geomembrane, but only slightly. This was considered when selecting only GM-B for the multi-interface tests, which was assumed to be conservative for this project.

4.2 Large Displacement Combination Strength Envelopes

For the interfaces involved in Proposed Liner System No. 2, only the GM-B geomembrane and subgrade material were tested in single interface tests. Figure 5 shows that the GM-B/GCL/GM-B, hydrated interface tests yielded the lowest peak strengths for the entire range of normal stresses, i.e., greater than the GM-B/Subgrade, Pre-wetted interface. Thus, the peak combination strength envelope for Liner System No. 2 is defined by the GM-B/GCL/GM-B, hydrated interface only.

The peak combination strength envelope for one or more interface(s) determines the LD combination strength envelope for that interface (Stark and Choi, 2004). Figure 7 shows the individual LD strength envelopes for all of the single interfaces in Test Series 1 through 9. Based on the peak combination strength envelope, Figure 8 shows the LD combination strength envelope (thick solid line) for the proposed Liner System No. 1, involving GM-A geomembrane. The LD combination strength envelope corresponds to the peak combination strength envelope because it is the critical interface(s) for the peak combination envelope for GM-A geomembrane. Therefore, movement will correspond to the peak critical interface(s) so the LD strengths for only these interfaces need to be considered. This LD combination strength envelope does not correspond to the lowest LD shear strength at each normal stress, but the LD strengths that correspond to the critical peak strength interfaces. In other words, the lowest LD strength will not be mobilized if the peak strength of that interface is not exceeded. For example, Figure 8 shows that the GM-A/GCL/GM-A, hydrated interface exhibits the lowest LD shear strength mainly because of the low strength of hydrated bentonite. However, this LD strength envelope should not be used for design for effective normal stresses greater than or equal to 360 kPa because the peak strength of the GM-A/GCL/GM-A, hydrated interface will not be exceeded beyond this normal stress (Figure 6). An effective normal stress of 360 kPa has been proposed via interpolation between the data points from the peak strength tests and could be determined precisely with additional tests at normal stresses between 170 and 690 kPa. Thus a LD shear condition will not be mobilized along the GM-A/GCL/GM-A, hydrated interface in the field. This confusion is easily resolved with multi-interface tests because this interface will not be critical and thus will not undergo large displacement as discussed below.

A similar LD combination strength envelope was developed for Proposed Liner System No. 1, with GM-B and is shown in Figure 9. Figure 9 shows the GM-B/GCL/GM-B, hydrated interface exhibits the lowest LD shear strength for the entire range of normal stresses tested. However, the LD strength envelope for this interface is critical only for normal stresses ranging from 0 to about 870 kPa. At normal stresses greater than 870 kPa the GM-B/CSL, pre-wetted interface is critical for LD strengths. At normal stresses greater than 870 kPa, the GM-B/CSL, Prewetted interface is critical, which results in the LD combination envelope changing interfaces, i.e., envelopes. This results in the LD combination strength envelope exhibiting a jump in the envelope (see Figure 9) at an effective normal stress of 870 kPa. Again, the value of 870 kPa, suggested here, has been proposed via interpolation between the data points from the peak strength tests, which may be found with accuracy by additional tests at normal stresses in that range.

Figure 10 shows that the critical LD strength envelopes for the Proposed Liner System No. 1 using GM-B and GM-A geomembranes. The GM-B geomembrane yields a lower LD strength envelope than the GM-A geomembrane for the entire range of normal stresses even with the jump in the LD combination strength envelope at an effective normal stress of 870 kPa.

The single interface test results for Proposed Liner System No. 2 with only a GM-B geomembrane and the native subgrade material (Figure 7) were considered to determine the appropriate LD strength envelope. Because the peak combination strength envelope defines the LD combination envelope, the GM-B/GCL/GM-B hydrated interface strength envelope should be the LD combination strength envelope. Interestingly, Figure 7 shows that out of the interfaces considered for Liner System No. 2, the GM-B/GCL/GM-B, hydrated interface yields the lowest LD strengths for the entire range of normal stresses. Thus, the GM-B/GCL/GM-B, hydrated interface also yields the LD combination strength envelope for Liner System No. 2. This is not always the case, i.e., the critical peak strength envelopes corresponds to the lowest LD failure envelope, as exhibited by the test results for Proposed Liner System No. 1.

5 MULTI-INTERFACE TEST RESULTS

To reduce the number of multi-interface tests and ensure a conservative result, only geomembrane GM-B was used for the multi-interface tests. In other words, if the stability analyses were acceptable using GM-B they would be acceptable using GM-A because GM-A yielded higher interface strengths.

The White/Black colored GM-B geomembrane exhibited a mean asperity height of 0.30 and 0.32 mm for the white and black sides of the geomembrane, respectively, while the Black/Black colored GM-B geomembrane exhibited mean asperity heights of 0.30 and 0.38 mm for the two sides of the geomembrane. The standard deviation for these mean asperity heights is about 0.038 mm. The slightly higher asperity heights for the Black/Black GM-B geomembrane help explain the Black/Black colored GM-B geomembrane yielding slightly higher values of peak interface strength than the White/Black colored GM-B geomembrane for the range of normal stresses considered. Asperity heights were not measured for GM-A because it was not used for all of the shear testing and it yielded high interface strengths.

The peak and LD strength envelopes for the five series of multi-interface tests are presented in Figures 11 and 12, respectively. Thus, each series of multi-interface tests provides its respective design strength envelope and allows the weakest geosynthetic interface(s)/material in the respective liner system for the full range of normal stresses to be identified by 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 only 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 displacement.

The composite liner system tested in multi-interface Test Series No. 10 contains all of the interfaces/materials of the single-interface tests series which were considered to determine the peak and LD combination envelopes for Liner System No 1. Hence, the results of this series allow a direct comparison between the single and multi interface tests results for this liner system under hydrated conditions. Similarly, the composite liner systems tested in multi-interface Test Series No. 12 and 14 contain all of the interfaces/materials tested in the single-interface tests that were considered to determine combination envelopes for Liner System No 2. Hence, the results of these two series also allow a direct comparison between the single and multi interface tests for Liner System No. 2. These comparisons are discussed in the next section. Multi-interface Test Series No. 11 and 13 utilized a GM-B black/white textured geomembrane, which was not used in the single interface tests so no direct comparison between single- and multi-interface tests can be made for these test series. Table 4 presents a summary of critical interfaces for the five multi-interface test series for the range of normal stresses considered. In all of the single and multi-interface tests, the geosynthetics were oriented in the machine direction to simulate field conditions because the machine direction is usually placed parallel to the slope.

The peak strength envelope representing Liner System No. 1, shown in Figure 11 was obtained from multi interface Test Series No. 10, i.e., Cushion Geotextile/GM-B/GCL/GM-B/CSL-Hydrated interfaces). The strength envelope corresponds to the lowest peak strength values of all of the multi-interface tests, for normal stresses greater than 170 kPa (also see Table 5). Table 4 shows that the critical interface shifts from the GM-B geomembrane/GCL, hydrated interface to the GM-B geomembrane/CSL, pre-wetted interface for normal stresses greater than 170 kPa for Liner System No. 1. This result suggests that the CSL is the cause of Liner System No. 1 exhibiting the lowest peak strengths of all the multi-interface tests because the CSL component is not used in Liner System No. 2. The low peak strength measured for the CSL was probably caused by: (1) the wet of optimum moisture content compaction water content, (2) pre wetting of the CSL surface before placement of the geomembrane and shearing, and (3) the range of texturing of the GM-B geomembranes. Conversely, Figure 12 shows that for the entire range of normal stresses, LD strengths for the hydrated multi-interface tests on Liner System No. 1 are higher than the LD strengths for the two hydrated multi-interface test series on Liner

System No. 2 and near the un-hydrated LD strength for Liner System No. 2. Thus, the LD strength envelopes must be selected based on the peak envelope (see open squares in Figure 12) and not simply the lowest LD envelope from all of the multi-interface tests.

Figures 11 and 12 show the results of Test Series 11 through 14 for Liner System No. 2. These test series utilized two types of GM-B geomembranes, i.e., geomembranes from the same manufacturer. The Black/White colored GM-B geomembrane yielded lower values of peak and LD strengths than the Black/Black colored GM-B geomembrane for the range of normal stresses considered. The white coloring on the surface of the geomembrane is used to reduce wrinkles after geomembrane placement. Thus, the peak and LD strengths are a function of the geomembrane type produced even by the same manufacturer. The Black/White colored GM-B geomembrane exhibited a mean and standard deviation asperity height of 0.30 and 0.043 mm for the white side and 0.32 and 0.033 mm for the black side, respectively. The Black/Black colored GM-B geomembrane exhibited a mean and standard deviation asperity height of 0.30 to 0.38 and 0.038 mm, respectively, which helps explains the Black/White colored GM-B geomembrane yielding lower values of peak strengths than the Black/Black colored GM-B geomembrane for the range of normal stresses considered.

Table 4 shows that the un-hydrated critical interface may possibly be stress dependent while the hydrated may not. Thus, the critical un-hydrated interface for Liner System No. 2 may change from one interface to another with increasing normal stresses. Table 4 also shows that in Test Series No. 11 with the Black/White colored geomembrane and un-hydrated GCL, the 410 g/m^2 Geotextile Cushion/Geomembrane interface is critical for the range of normal stresses considered. In Test Series No. 12 with the only difference from Test Series No. 11 being the use of the Black/Black colored geomembrane, the critical interface switches to the geomembrane/un-hydrated GCL interface for normal stresses of 2,070 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. 11, 12, 13, and 14 in Table 4 shows that upon hydration of the GCL, the critical interface shifts to one of the GCL/Geomembrane interfaces. Thus, if the GCL hydrates in an encapsulated design, a GCL interface will become critical depending on the normal stress.

As expected, the peak and LD strength envelopes obtained from multi-interface Tests Series No. 11 through 14 represent various configurations of Liner System No. 2. 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 Figures 11 and 12).

6 ANALYSIS AND COMPARISON OF TEST RESULTS

The fourteen series of single- and multi-interface tests on the two proposed liner systems provide a unique opportunity to compare the resulting peak and LD strength envelopes and the critical interfaces for each normal stress which is presented below.

Peak and LD combination envelopes obtained from the results of single-interface Test Series No. 3, 5, and 7 are compared with the results of multi-interface Test Series No. 10 for proposed Liner System No. 1. Similarly, for proposed Liner System No. 2, peak and LD combination envelopes obtained from the results of single-interface Test Series No. 3, 7, and 9 are compared with those obtained from multi-interface Test Series No. 14. These comparisons are appropriate because the combinations mentioned above involve all of the interfaces/materials tested in the two multi-interface tests for the respective liner systems. These comparisons are presented in Figure 13 through 16.

Figure 13 shows that the peak combination strength envelope from the single-interface tests is in agreement with the peak strength envelope from multi-interface test series No. 10. However, the table in Figure 13 shows that the critical interface for some of the normal stresses differs between the single- and multi-interface tests. The critical interface in the multi-interface tests switches to the geomembrane/GCL hydrated interface at a normal stress of 690 kPa instead of 1380 kPa as observed in the single-interface tests. Figure 13 also shows that the same two interfaces are critical for the single- and multi-interface tests, which is a good indication of the reproducibility of these two test types.

Figure 14 compares the peak combination strength envelope from the single-interface tests with the corresponding peak strength envelope from multi-interface Test Series No. 14 for Liner System No. 2. For this liner system comparison, the critical interface is the same for both methods of testing, i.e., GM-B/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. However, Figure 14 also shows that 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 solely influenced by the applied normal stresses. Conversely, the components of a composite liner system may behave more as a single entity in a multi-interface test which results in the higher strengths.

Comparisons of LD strength envelopes from the single- and multi-interface tests for Liner Systems No. 1 and 2 are presented in Figures 15 and 16, respectively. These figures show a larger difference in the LD envelopes than the peak envelopes for the single- and multi-interface test results. In both cases the multi-interface tests yield higher LD envelopes than the single-interface tests. The higher strengths in the multi-interface tests are probably caused by some of the test details, such as clamping of the geosynthetics in the single interface tests.

7 EFFECTS OF GCL HYDRATION

Table 6 presents a summary of the effect of hydration on peak and LD shear strengths of interfaces tested in single-interface Test Series No. 1 through 4 and multi-interface Test Series No. 11 through 14. The following observations can be made from Table 6:

- The magnitude of peak and LD strength loss due to hydration is proportional to the normal stress at shearing. In general, a peak strength loss of 2% to 30% occurred because of GCL hydration. A larger strength loss occurred due to hydration for the LD strength which decreased by 5% to 50%. This strength loss is caused by the large displacement damaging some of the needle-punched reinforcement and hydrated bentonite being much weaker than un-hydrated bentonite.
- Typically, minimal strength loss was observed for lower normal stresses (70 kPa and 170 kPa) and much greater strength loss occurred for normal stresses higher than 170 kPa. This is probably due to hydration occurring at 70 kPa for 24 hours which is similar to the low normal stresses for shearing of 70 and 170 kPa versus the higher normal stresses which allowed full hydration of the bentonite before consolidation at the desired normal stress.

- The magnitude of strength loss is more pronounced for single-interface tests than multi-interface tests for the range of normal stresses considered. Assuming multi-interface tests are more representative of field conditions than single-interface tests, it may be inferred that single inter-face tests yield conservative estimates of the peak and LD strength envelopes with a hydrated GCL by focusing on one interface.

8 DESIGN STRENGTH ENVELOPE

The main field mechanism that could hydrate the bentonite of the GCL for the two proposed liner systems is moisture entering through defects in the upper and/or lower geomembranes that encapsulate the GCL. Erickson and Thiel (2002) recommend that the shear strength along a slip plane within the bentonite of an encapsulated GCL can be represented by the average of the hydrated and un-hydrated shear strengths. Thus, it is conservatively assumed that 50% of the bentonite will be completely hydrated even though the GCL is encapsulated by two geomembranes.

Hydration of the GCL was accomplished prior to the laboratory shear testing described herein by drilling five small holes per specimen to simulate the worst case scenario for defects in a geomembrane during installation. Because the GCL was hydrated (see Table 7), the peak design strength envelope can be obtained using the arithmetic average of the hydrated and un-hydrated strengths (see Table 6). The average between the hydrated and un-hydrated strengths for Liner System No. 2 are used to develop the allowable or design strength envelope (solid line) shown in Figure 17. Figure 17 can be used for the specification of geosynthetic interface strength by denoting the acceptable and non-acceptable zones. Static and seismic stability should be performed to confirm that adequate factors of safety and earthquake induced permanent deformations are achieved using the design strength envelope. If the necessary stability analyses reveal that a lower or higher strength envelope yields acceptable factors of safety and permanent deformations, the design strength envelope shown in Figure 17 can be revised. If the stability analyses show a lower strength envelope is required to achieve the design factors of safety and permanent deformations, all of the geosynthetics and materials tested herein are suitable because the design strength envelope plots above the back-calculated strength envelope for the design factors of safety and permanent deformations. If the stability analyses show a higher strength envelope is required to achieve the design factors of safety and permanent deformations, different geosynthetics and/or liner system configurations may be required. For example, a geosynthetic manufacturer must demonstrate that their geosynthetics exhibit material and interface strengths greater than the design strength envelope shown in Figure 17, i.e., in the acceptable zone. If the measured strengths plot on or below the design strength envelope, the geosynthetics do not meet the specified envelope and should be rejected. This comparison should occur prior to shipment of the geosynthetics to the project site to prevent having to ship the geosynthetics back to the supplier or manufacturer.

The corresponding LD strength envelope for Liner System No. 2 is also obtained by averaging the hydrated and un-hydrated strengths, see Figure 18, and can be used to accept or reject geosynthetics based on the results of stability analyses. The LD strength envelope is applicable to side slopes (Stark and Choi 2004) and situations where earthquake induced permanent deformations exceed three to four inches.

9 CONCLUSIONS

Based on the results obtained from the testing program described herein, the following conclusions 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. Multi-interface tests on composite liner system yield similar peak strengths as those from single-interface tests, however, there may or may not be agreement on the critical interface at each effective normal stress.
- Irrespective of geomembrane type and manufacturer, hydration of the GCL lowers the peak and LD strengths of an encapsulated GCL, but the GCL may or may not become the critical interface or material.
- The magnitude of GCL strength loss is related to the effective normal stresses at which GCL hydration occurs with the lower hydration stresses yielding lower strengths because of additional swelling.

- 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 is probably caused by the rigid clamping of the geosynthetics which results in some tensile strains in the geosynthetics. Thus, single interface tests appear to yield a conservative estimate of the LD strength.

ABBREVIATIONS

CSL: Compacted Soil Liner
GCL: Geosynthetic Clay Liner
GM: Geomembrane
HDPE: High Density Polyethylene
LCRS: Liquid Collection and Recovery System
LD: Large Displacement
MSW: Municipal Solid Waste
t_{100} = Theoretical time for 100% primary consolidation

REFERENCES

ASTM D421-85 (2002). *Standard Practice for Dry Preparation of Soil Samples for Particle-Size Analysis and Determination of Soil Constants,* West Conshohocken, Pa. USA.

ASTM D422-63 (1998). *Standard Test Method for Particle-Size Analysis of Soils,* West Conshohocken, Pa. USA.

ASTM D1557-02 (2007). *Standard Test Methods for Laboratory Compaction Characteristics of Soil Using Modified Effort (56,000 ft-lbf/ft^3(2,700 kN-m/m^3)),* West Conshohocken, Pa. USA.

ASTM D4318-00 (2005). *Standard Test Methods for Liquid Limit, Plastic Limit, and Plasticity Index of Soils,* West Conshohocken, Pa. USA.

ASTM D4632-91 (2003). *Standard Test Method for Grab Breaking Load and Elongation of Geotextiles,* West Conshohocken, Pa. USA.

ASTM D5084-03 (2003). *Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter*, West Conshohocken, PA.

ASTM D5321-02 (2002). *Standard Test Method for Determining the Coefficient of Soil and Geosynthetic or Geosynthetic and Geosynthetic Friction by the Direct Shear Method,* West Conshohocken, Pa. USA.ASTM D6243-98 (2006). *Standard Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method,* West Conshohocken, Pa. USA.

Bove, J. A. (1990). Direct Shear Friction Testing for Geosynthetics in Waste Containment, *Proceedings of ASTM Symposium on Geosynthetic Testing for Waste Containment Applications*, Special Technical Publication 1081, pp. 241-256.

Byrne, R. J., Kendall, J. and Brown, S. (1992). Cause and Mechanism of Failure, Kettleman Hills Landfill B-19, Unit IA, *Proc. of ASCE Specialty Conference on Performance and Stability of Slopes and Embankments-II*, ASCE, New York, New York, USA, pp. 1188-1215.

Daniel, D. E. and Shan, H. Y. (1992). Effects of Partial Wetting of Gundseal on Strength and Hydrocarbon Permeability, *Research Report Prepared for Gundle Lining System, Inc.*, University of Texas at Austin, Austin, Texas, USA, 13p.

Dove, J. E. and Frost, J. D. (1999). Peak Friction Behavior of Smooth Geomembrane-Particle Interfaces, *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, Vol. 125, No. 7, pp. 544-555.

Eid, H. T. & Stark, T. D. (1997). Shear Behavior of an Unreinforced Geosynthetic Clay Liner. *Geosynthetics International*, 4, No. 6, pp. 645– 659.

Erickson, R. B., and Theil, R. (2002). Design and Application of the Geomembrane Supported GCL in One-Product and Encapsulated Composite Liner Systems. *Proc. of International Symposium on Clay Geosynthetic Barrier*, Nuremberg, Germany, April 16-17, pp. 31 – 40.

Fox P. J., and Stark, T. D. (2004). State-of-the-art report: GCL Shear Strength and its Measurement, *Geosynthics International*, Vol. 11, No. 3, pp. 141 - 175.

Fox, P.J. and Kim, R.H. (2008). “Effect of progressive failure on measured shear strength of Geomembrane/GCL interface.” *J. of Geotechnical and Geoenvironmental Engineering* ASCE, Vol. 134, No. 4, pp. 459-469.

Jones, D.R.V. and Dixon, N. (1998). “Shear strength properties of geomembrane/geotextile interfaces.” *Geotextiles and Geomembranes*, Vol. 16, No 1, pp. 45-71.

Karademir, T. and Frost, J.D. (2011). “Elevated Temperature Effects on Geotextile-Geomembrane Interface Strength". *Proceedings of Specialty Conf. GEO-FRONTIERS 2011*, ASCE, Dallas, TX, March, 2011, pp. 1023-1033.

Koerner, R. M., Martin, J. P. and Koerner, G. R. (1986). Shear Strength Parameters Between Geomembranes and Cohesive Soils, *Geotextiles and Geomembranes*, 4(1), pp. 21-30.

Li, M. H. and Gilbert, R.B. (2006). “Mechanism of post-peak strength reduction for textured geomembrane-nonwoven geotextile interface.” *Geosynthetic International*, Vol. 13, No. 5, pp. 206 - 209.

Martin, J. P., Koerner, R. M. and Whitty, J. E. (1984). Experimental Friction Evaluation of Slippage Between Geomembranes, Geotextiles, and Soils, *Proceedings of International Conference on Geomembranes*, Denver, Colorado, USA, pp. 191-196.

Mitchell, J. K., Seed, R. B. and Seed, H. B. (1990). Kettleman Hills Waste Landfill Slope Failure I: Liner-System Properties, *J. of Geotechnical Engineering*, ASCE, 116(4), pp. 647-668.

Negussey, D., Wijewickreme, W. K. D. and Vaid, Y. P. (1989). Geomembrane Interface Friction, *Canadian Geotechnical Journal*, Vol. 26, No. 1, pp. 165-169.

O’Rourke, T. D., Druschel, S. J. and Netravali, A. N. (1990). Shear Strength Characteristics of Sand-Polymer Interfaces, *J. of Geotechnical Engineering*, ASCE, 116(3), pp. 451-469.

Seed, R. B. and Boulanger, R. W. (1991). Smooth HDPE-Clay Liner Interface Shear Strengths: Compaction Effects, *J. of Geotechnical Engineering,* ASCE, Vol. 117, No. 4, pp. 686-693.

Seed, R. B., Mitchell, J. K. and Seed, H. B. (1990). Kettleman Hills Waste Landfill Slope Failure II: Stability Analysis, *J. of Geotechnical Engineering*, ASCE, Vol. 116, No. 4, pp. 669-689.

Saxena, S. K., and Wong, Y. T. (1984). Friction Characteristics of a Geomembrane, *Proceedings of International Conference on Geomembranes*, Denver, Colorado, USA, pp. 187-190.

Stark, T.D., D. Arellano, D. Evans, V. Wilson, and J. Gonda. (1998). Unreinforced Geosynthetic Clay Liner Case History, *Geosynthetics International Journal*, Industrial Fabrics Association International (IFAI), Vol. 5, No. 5, December, 1998, pp. 521-544.

Stark, T. D. (1999). Stability of Waste Containment Facilities, *Proceedings of Waste Tech '99*, National Solid Wastes Mgmt. Association, New Orleans, LA, USA, February, pp. 1-24.

Stark, T. D. and Choi, H. (2004). Peak vs. Residual Interface Strengths for Landfill Liner and Cover Design, *Geosynthetics International Journal*, Vol. 2, No. 6, pp. 1-7.

Stark, T. D. and Poeppel, A. R. (1994). Landfill Liner Interface Strengths from Torsional Ring Shear Tests, *J. of Geotechnical Engineering*, ASCE, Vol. 120, No. 3, March, pp. 597-615.

Stark, T. D., Williamson, T. A., and Eid, H. T. (1996). HDPE Geomembrane/Geotextile Interface Shear Strength, *Journal of Geotechnical Engineering*, ASCE, Vol. 122, No. 3, March, pp. 197-203.

Takasumi, D. L., Green, K. R. and Holtz, R. D. (1991). Soil-Geosynthetic Interface Strength Characteristics: A Review of State-of-the-Art Testing Procedures, *Proceedings of Geosynthetics '91 Conference*, Atlanta, Georgia, USA, Vol. 1, pp. 87-100.

Taylor, D. W. (1948). *Fundamentals of Soil Mechanics.* Wiley, New York.

Williams, N. D., and Houlihan, M. F. (1987). Evaluation of Interface Friction Properties Between Geosynthetics and Soils, *Proc. of Geosynthetics '87 Conference*, New Orleans, LA, USA, Vol. 2, pp. 616-627.

Yegian, M. K., and Lahlaf, A. M. (1992). Discussion of Kettleman Hills Waste Landfill Slope Failure I: Liner-System Properties, *Journal of Geotechnical Engineering*, ASCE, Vol. 118, No. 4, pp. 643-645.

COMPARISON OF SINGLE AND MULTI GEOSYNTHETIC AND SOIL INTERFACE TESTS

Timothy D. Stark, Fawad S. Niazi, and Timothy C. Keuscher

Table Captions:

Table 1. Single-Interface Test Details

Test Series	Interface Test Configuration	Specimen Size (m)	GCL Soaking		Minimum Consolidation Time (hr) [a]	Normal Stress during Consolidation and Shearing (kPa) [b]
			Normal Stress during Soaking (kPa)	Soaking Time (hr)		
1 (GM-B) & 2 (GM-A)	1.5-mm HDPE/GCL/ 1.5-mm HDPE- Unhydrated	0.3 x 0.3	N/A	N/A	24	70
		0.3 x 0.3	N/A	N/A	24	170
		0.3 x 0.3	N/A	N/A	24	690
		0.3 x 0.3	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	2070
3 (GM-B) & 4 (GM-A)	1.5-mm HDPE/GCL/ 1.5-mm HDPE- Hydrated	0.3 x 0.3	70	48	72	70
		0.3 x 0.3	70	48	72	170
		0.3 x 0.3	70	48	72	690
		0.3 x 0.3	70	48	72	1380
		0.15 x 0.15	70	48	72	1380
		0.15 x 0.15	70	48	72	2070
5 (GM-B) & 6 (GM-A)	1.5-mm Textured HDPE geomembrane/ CSL- Pre-wetted	0.3 x 0.3	N/A	N/A	24	70
		0.3 x 0.3	N/A	N/A	24	170
		0.3 x 0.3	N/A	N/A	24	690
		0.3 x 0.3	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	2070
7 (GM-B) & 8 (GM-A)	410 g/m^2 Cushion Geotextile/ 1.5-mm Textured HDPE- Pre-wetted	0.3 x 0.3	N/A	N/A	1	70
		0.3 x 0.3	N/A	N/A	1	170
		0.3 x 0.3	N/A	N/A	1	690
		0.3 x 0.3	N/A	N/A	1	1380
		0.15 x 0.15	N/A	N/A	1	1380
		0.15 x 0.15	N/A	N/A	1	2070
9 (GM-B)	1.5-mm Textured HDPE geomembrane/ Subgrade- Pre-wetted	0.3 x 0.3	N/A	N/A	24	70
		0.3 x 0.3	N/A	N/A	24	170
		0.3 x 0.3	N/A	N/A	24	690
		0.3 x 0.3	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	1380
		0.15 x 0.15	N/A	N/A	24	2070

a. A consolidation time of one (1) hour is used instead of 24 or 72 hours for the 1.5 mm Textured HDPE/410 g/m^2 Cushion Geotextile interface because no soils had to undergo consolidation. The use of one hour is to allow sufficient time for the geotextile and geomembrane to engage prior to shearing.

b. Shearing displacement rate of 1.01 mm/minute (0.04 inch/minute) was used for all the tests in accordance with ASTM D5321 and D 6243.

Table 2. Multi-Interface Test Details

Test Series	Interface Test Configuration	Specimen Size (m)	GCL Soaking		Minimum Consolidation Time (hr)	Normal Stress during Consolidation and Shearing (kPa) [a]
			Normal Stress during Soaking (kPa)	Soaking Time (hr)		
10 (GM-B Black/ White)	410 g/m^2 Cushion Geotextile/1.5-mm HDPE/GCL/1.5-mm HDPE/CSL-Hydrated	0.3 x 0.3	70	48	72	70
		0.3 x 0.3	70	48	72	170
		0.3 x 0.3	70	48	72	690
		0.3 x 0.3	70	48	72	1380
		0.15 x 0.15	70	48	72	1380
		0.15 x 0.15	70	48	72	2070
11 (GM-B Black/ White) & 12 (GM-B Black/ Black)	410g/m^2 Cushion Geotextile/1.5-mm HDPE/GCL/ 1.5-mm HDPE/ Subgrade Soil (#4 Sieve minus)-Un-hydrated	0.3 x 0.3	N/A	N/A	72	70
		0.3 x 0.3	N/A	N/A	72	170
		0.3 x 0.3	N/A	N/A	72	690
		0.3 x 0.3	N/A	N/A	72	1380
		0.15 x 0.15	N/A	N/A	72	1380
		0.15 x 0.15	N/A	N/A	72	2070
13 (GM-B Black/ White) & 14 (GM-B Black/ Black)	410g/m^2 Cushion Geotextile/1.5-mm HDPE/GCL/ 1.5-mm HDPE/ Subgrade Soil (#4 Sieve minus)-Hydrated	0.3 x 0.3	70	48	72	70
		0.3 x 0.3	70	48	72	170
		0.3 x 0.3	70	48	72	690
		0.3 x 0.3	70	48	72	1380
		0.15 x 0.15	70	48	72	1380
		0.15 x 0.15	70	48	72	2070

a. Shearing displacement rate of 1.01 mm/minute (0.04 inch/minute) was used for all the tests in accordance with ASTM D5321 and D 6243.

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 and Black/White Colored HDPE Geomembranes	a. Polyflex, Inc. (GM A) b. GSE Lining Technology, Inc. (GM B)	a. Both companies use similar manufacturing process (nitrogen injection) b. 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. c. Mean asperity heights: GM-A = not measured; GM-B White/Black = 0.30 and 0.32 mm, respectively; and GM-B White/Black = 0.30 and 0.32 mm; Black/Black = 0.30 and 0.38 mm
GCL	CETCO – Bentomat DN	a. Needle-punched b. High peel strength (7 kN/m according to ASTM D4632-91) c. Initial moisture content to be representative of manufactured moisture content of GCL
410 g/m^2 Non-woven Geotextile	GSE Lining Technology, Inc.	Non-woven geotextiles
Compacted Soil Liner (CSL) (k ≤ 1.0 x 10^{-6} cm/sec)	Relative Compaction of 90 % based on Laboratory Modified Proctor Compaction Test and a moisture content of 2 % wet of optimum (14 %) and dry unit weight (17.34 to 17.45 kN/m^3) to achieve the desired hydraulic conductivity of 1 x 10^{-6}	Maximum Dry Unit Weight and Optimum Moisture Content (ASTM D1557-02)
		Gradation with Hydrometer (ASTM D422-63)
		Atterberg Limits (ASTM D4318-00)
		Hydraulic Conductivity (ASTM D5084-03) conducted at a confining pressure of 138 kPa
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 to 16.68 kN/m^3)to achieve the desired sub-grade behavior	a. Maximum Dry Unit Weight and Optimum Moisture Content (ASTM D1557) b. Gradation Analysis (ASTM D421-85)

Table 4. Summary of Critical Interfaces at Different Normal Stresses from Multi-Interface Tests

Effective Normal Stresses (kPa)	Test Series				
	Liner No. 1	Liner No. 2			
	10 GM-B-Black/White-CSL-Hydrated	11 GM-B-Black/White-Subgrade Soil-Unhydrated	12 GM-B-Black/Black-Subgrade Soil-Unhydrated	13 GM-B Black/White-Subgrade Soil-Hydrated	14 GM-B-Black/Black-Subgrade Soil-Hydrated
70	GM-B/GCL Hydrated	Cushion Geotextile/ GM-B - Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	GM-B/GCL Hydrated	GM-B/GCL Hydrated
170	GM-B/GCL Hydrated	Cushion Geotextile/ GM-B - Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	GM-B/GCL Hydrated	GM-B/GCL Hydrated
690	GM-B/CSL Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	GM-B/GCL Hydrated	GM-B/GCL Hydrated
1380	GM-B/CSL Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	GM-B/GCL Hydrated	GM-B/GCL Hydrated
2070	GM-B/CSL Pre-wetted	Cushion Geotextile/ GM-B - Pre-wetted	GM-B/GCL Unhydrated	GM-B/GCL Hydrated	GM-B/GCL Hydrated

Table 5. Summary of Peak and Large Displacement Shear Strengths from Multi-Interface Tests

Test Series	Effective Normal Stress (kPa)	Peak Shear Strength (kPa)	Ratio of Peak Shear Strength to Effective Normal Stress	Large Displacement Shear Strength (kPa)	Ratio of Large Displacement Shear Strength to Effective Normal Stress
10 GM-B-Black/White-CSL-Hydrated	70	38	0.54	25	0.36
	170	81	0.48	40	0.24
	690	260	0.38	197	0.29
	1380	408	0.30	296	0.21
	2070	523	0.25	338	0.16
11 GM-B-Black/White-Subgrade Soil-Unhydrated	70	34	0.49	24	0.34
	170	79	0.46	49	0.29
	690	288	0.42	149	0.22
	1380	538	0.39	270	0.20
	2070	854	0.41	415	0.20
12 GM-B-Black/Black-Subgrade Soil-Unhydrated	70	36	0.51	25	0.36
	170	83	0.49	55	0.32
	690	289	0.42	177	0.26
	1380	600	0.43	329	0.24
	2070	878	0.42	499	0.24
13 GM-B Black/White-Subgrade Soil-Hydrated	70	34	0.49	26	0.37
	170	77	0.45	42	0.25
	690	274	0.40	103	0.15
	1380	457	0.33	172	0.12
	2070	685	0.33	236	0.11
14 GM-B-Black/Black-Subgrade Soil-Hydrated	70	35	0.50	26	0.37
	170	81	0.48	54	0.32
	690	279	0.40	153	0.22
	1380	512	0.37	236	0.17
	2070	743	0.36	264	0.13

Table 6. Summary of the Effects of Hydration on Peak and Large Displacement Shear Strengths

Test Series	Effective Normal Stress (kPa)	Peak Shear Strength (kPa)				Large Displacement Shear Strength (kPa)			
		Un-hydrated	Hydrated	% Strength Loss	Average Peak Strength	Un-hydrated	Hydrated	% Strength Loss	Average LD Strength
2 & 4 GM-A/ GCL/ GM-A	70	41.9	40.8	2.5	41.4	32.8	29.6	9.8	31.2
	170	91.3	87.9	3.7	89.6	61.0	56.5	7.4	58.7
	690	345.7	279.9	19.1	312.8	207.8	121.1	41.7	164.4
	1380	684.7	500.3	26.9	592.5	354.6	191.0	46.1	272.8
	2070	1057.1	719.3	32.0	888.2	531.0	226.3	57.4	378.6
1 & 3 GM-B/ GCL/ GM-B	70	34.4	31.4	8.6	32.9	23.7	26.0	-9.3	24.8
	170	81.1	74.5	8.1	77.8	49.9	46.8	6.2	48.3
	690	285.4	243.7	14.6	264.5	160.1	99.1	38.1	129.6
	1380	584.1	481.2	17.6	532.7	333.5	196.9	41.0	265.2
	2070	898.0	623.7	30.5	760.9	433.3	222.8	48.6	328.0
11 & 13 GM-B-Black/ White-Subgrade Soil-Multi	70	34.0	34.0	0.0	34.0	24.0	26.0	-8.3	25.0
	170	79.0	77.0	2.5	78.0	49.0	42.0	14.3	45.5
	690	288.0	274.0	4.9	281.0	149.0	103.0	30.9	126.0
	1380	538.0	457.0	15.1	497.5	270.0	172.0	36.3	221.0
	2070	854.0	685.0	19.8	769.5	415.0	236.0	43.1	325.5
12 & 14 GM-B-Black/ Black-Subgrade Soil-Multi	70	36.0	35.0	2.8	35.5	25.0	26.0	-4.0	25.5
	170	83.0	81.0	2.4	82.0	55.0	54.0	1.8	54.5
	690	289.0	279.0	3.5	284.0	177.0	153.0	13.6	165.0
	1380	600.0	512.0	14.7	556.0	329.0	236.0	28.3	282.5
	2070	878.0	743.0	15.4	810.5	499.0	264.0	47.1	381.5

Table 7. GCL Water Contents (Percent) – Before and After Hydration

Test Series	Effective Normal Stress (kPa)	Initial Water Content w_i (%)	Final Water Content w_f (%)
11 GM-B- Black/White- Subgrade Soil- Unhydrated	70	16.7	18.5
	170	16.7	19.0
	690	16.7	18.6
	1380	16.7	18.3
	2070	16.7	17.9
13 GM-B Black/White- Subgrade Soil- Hydrated	70	16.9	86.6
	170	16.9	81.6
	690	16.9	48.8
	1380	16.9	45.1
	2070	16.9	41.3
12 GM-B- Black/Black- Subgrade Soil- Unhydrated	70	19.2	20.2
	170	19.2	19.8
	690	19.2	20.9
	1380	19.2	21.2
	2070	19.2	21.6
14 GM-B- Black/Black- Subgrade Soil- Hydrated	70	18.4	80.2
	170	18.4	67.0
	690	18.4	49.8
	1380	18.4	45.8
	2070	18.4	42.3

COMPARISON OF SINGLE AND MULTI GEOSYNTHETIC AND SOIL INTERFACE TESTS

Timothy D. Stark, Fawad S. Niazi, and Timothy C. Keuscher

Figure Captions:

Figure 1. General Description of Proposed Composite Bottom Liner Systems for Waste Containment Facilities: (a) Liner System No. 1, (b) Liner System No. 2

Figure 2. Schematic diagram of Laboratory Direct Shear Test

Figure 3. Typical Shear Stress vs. Displacement relationship for Single-Iinterface Test between Nonwoven Cushion Geotextile against GM-A Textured HDPE Geomembrane under Hydrated and Consolidated Conditions, which is Test Series No. 7 in Table 1.

Figure 4. Typical Shear Stress vs. Displacement relationship for Multi-interface Test on Cushion Geotextile above Black/White GM-B Textured HDPE Geomembrane underlain by GCL and GCL underlain by another Black/White GM-B Textured HDPE Geomembrane underlain by Subgrade Soil minus No. 4 sieve, which is Test Series No. 11 in Table 2.

Figure 5. Peak Strength Envelopes from Single Interface Tests on Proposed Liner Systems No. 1 and 2

Figure 6. Peak Combination Strength Envelopes from Single Interface Tests for Liner System No. 1 with GM-A and GM-B Geomembranes

Figure 7. LD Strength Envelopes from Single Interface Tests on Proposed Liner Systems No. 1 and 2

Figure 8. LD Combination Strength Envelope from Single Interface Tests for Liner System No. 1 with GM-A Geomembrane

Figure 9. LD Combination Strength Envelope from Single Interface Tests for Liner System No. 1 with GM-B Geomembrane

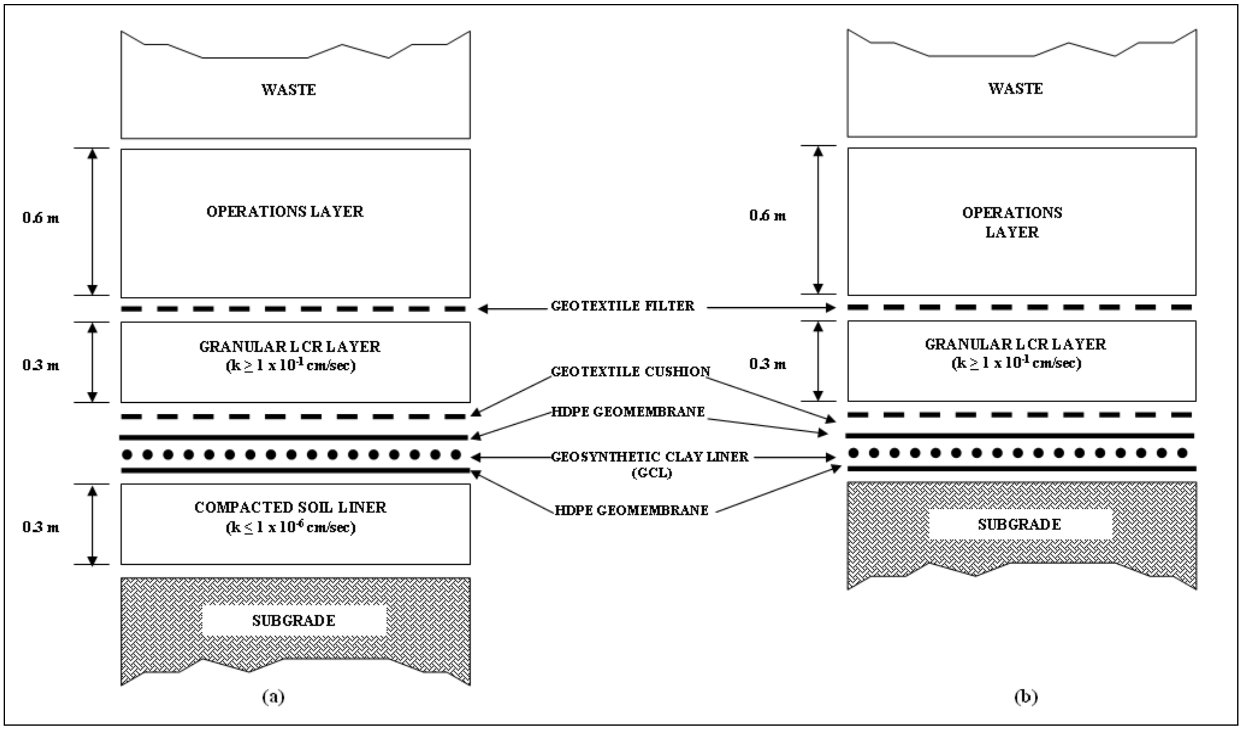


Figure 1. General Description of Proposed Composite Bottom Liner Systems for Waste Containment Facilities: (a) Liner System No. 1, (b) Liner System No. 2

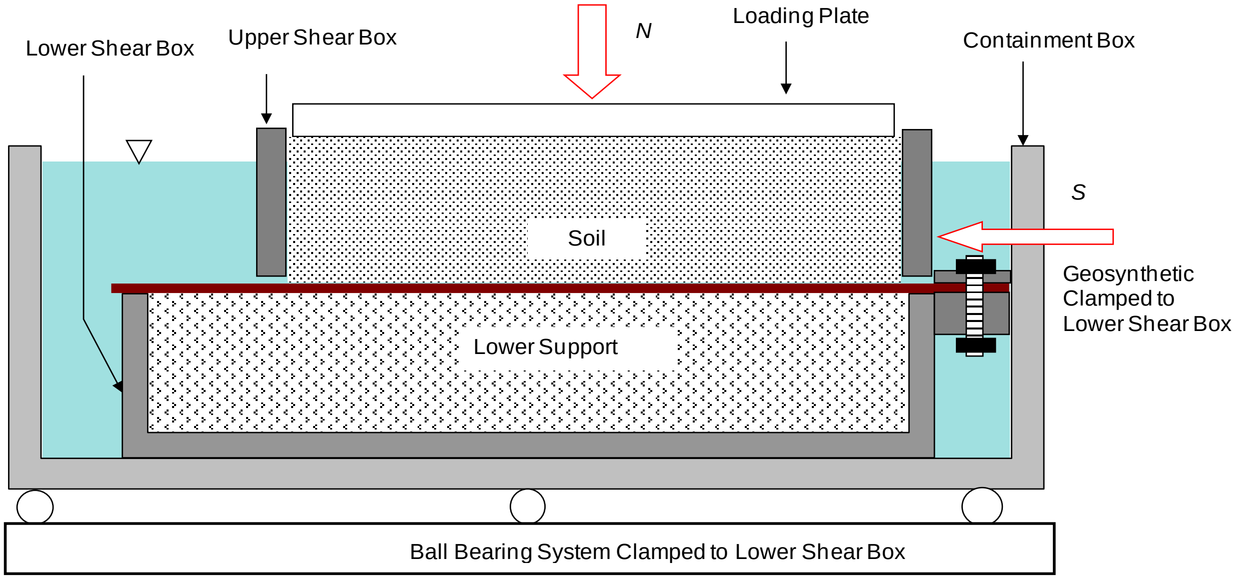


Figure 2. Schematic diagram of the laboratory direct shear test configuration

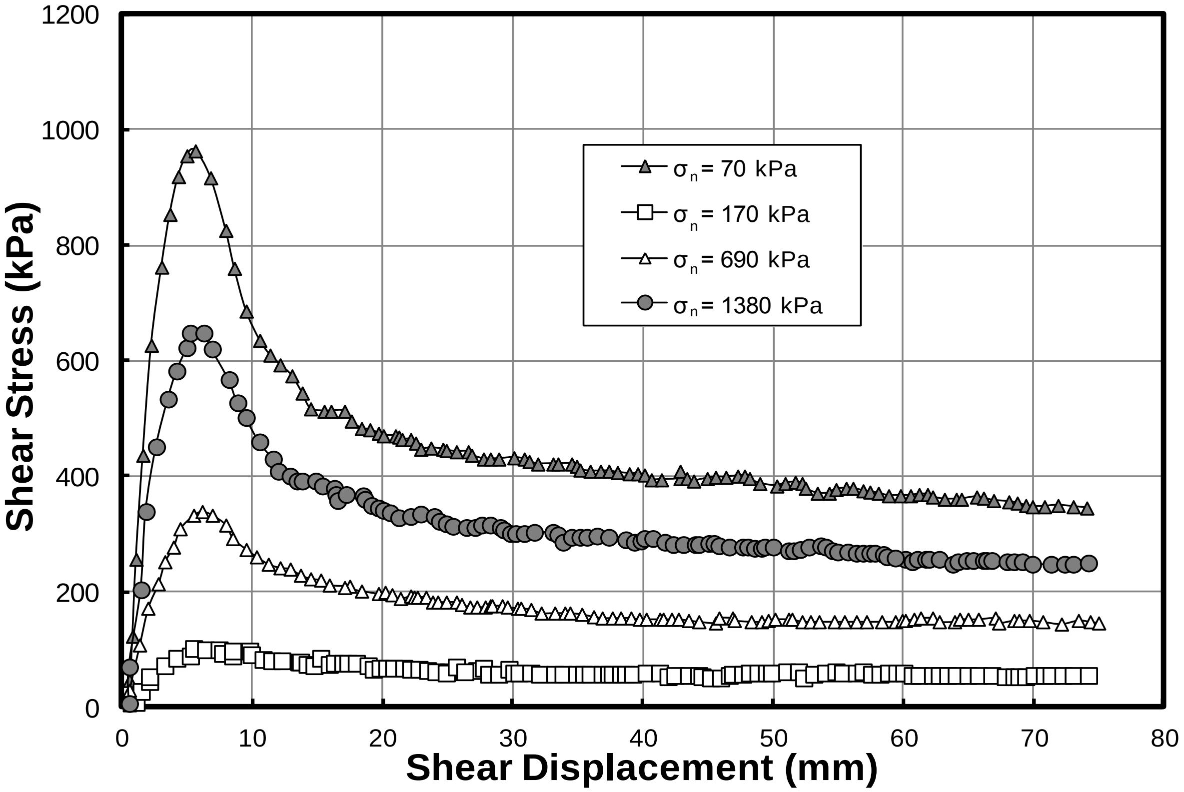


Figure 3. Typical Shear Stress vs. Displacement relationship for Single-Interface Test between Nonwoven Cushion Geotextile against GM-A Textured HDPE Geomembrane under Hydrated and Consolidated Conditions, which is Test Series No. 7 in Table 1.

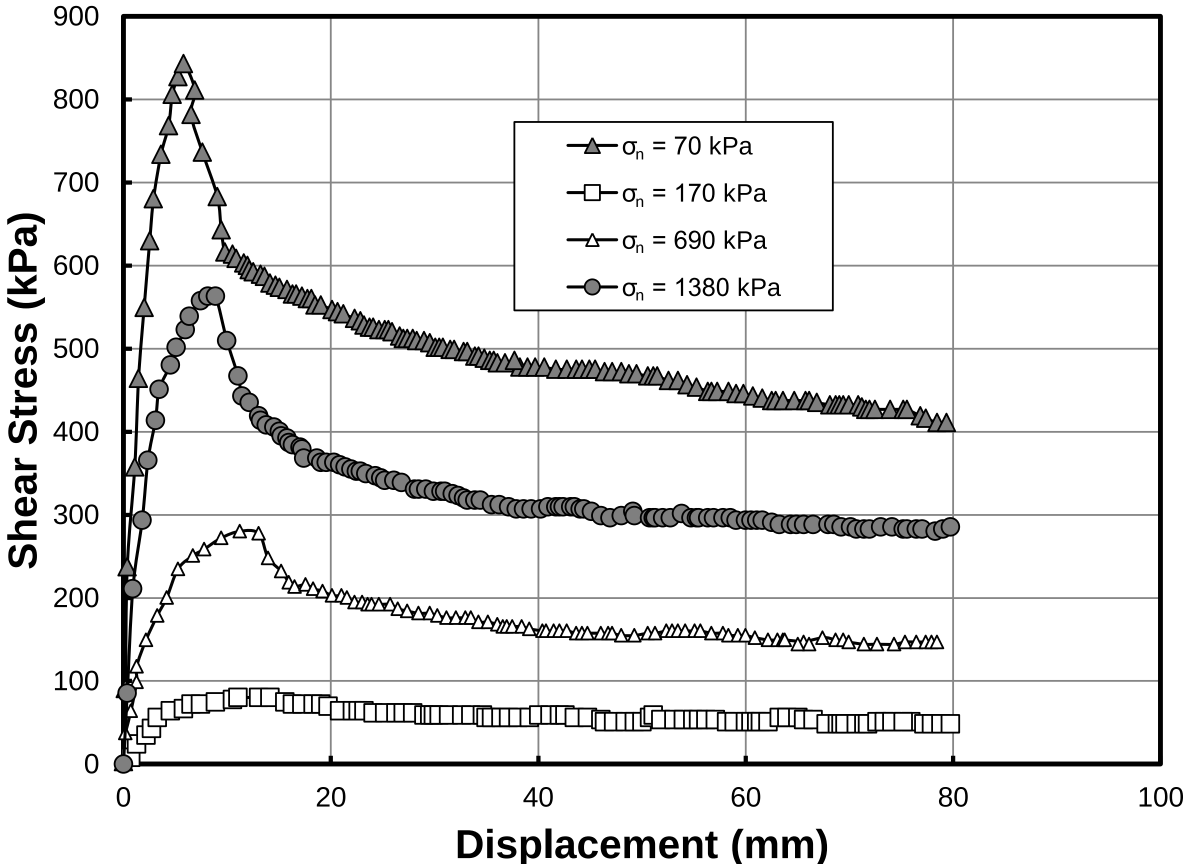


Figure 4. Typical Shear Stress vs. Displacement relationship for Multi-interface Test on Cushion Geotextile above Black/White GM-B Textured HDPE Geomembrane underlain by GCL and GCL underlain by another Black/White GM-B Textured HDPE Geomembrane underlain by Subgrade Soil minus No. 4 sieve, which is Test Series No. 11 in Table 2.

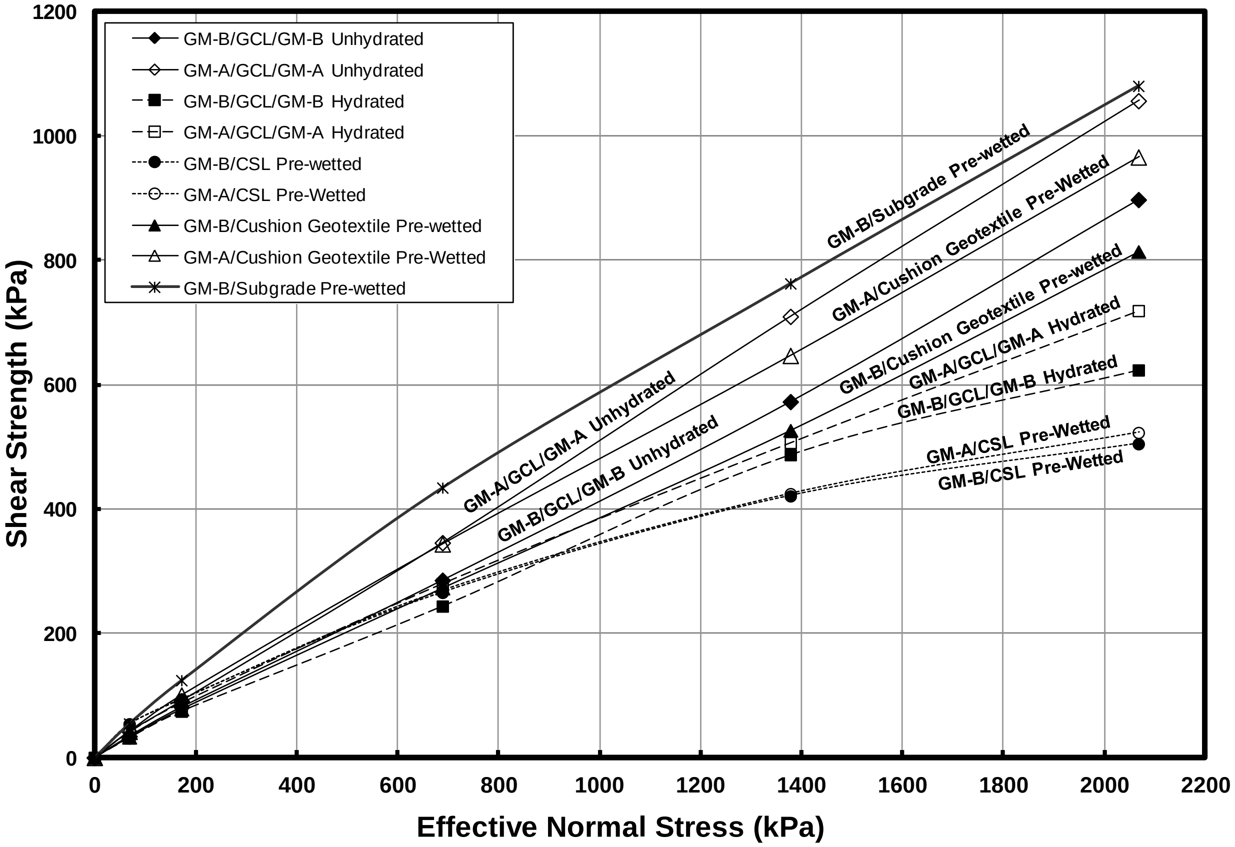


Figure 5. Peak Strength Envelopes from Single Interface Tests on Proposed Liner Systems No. 1 and 2

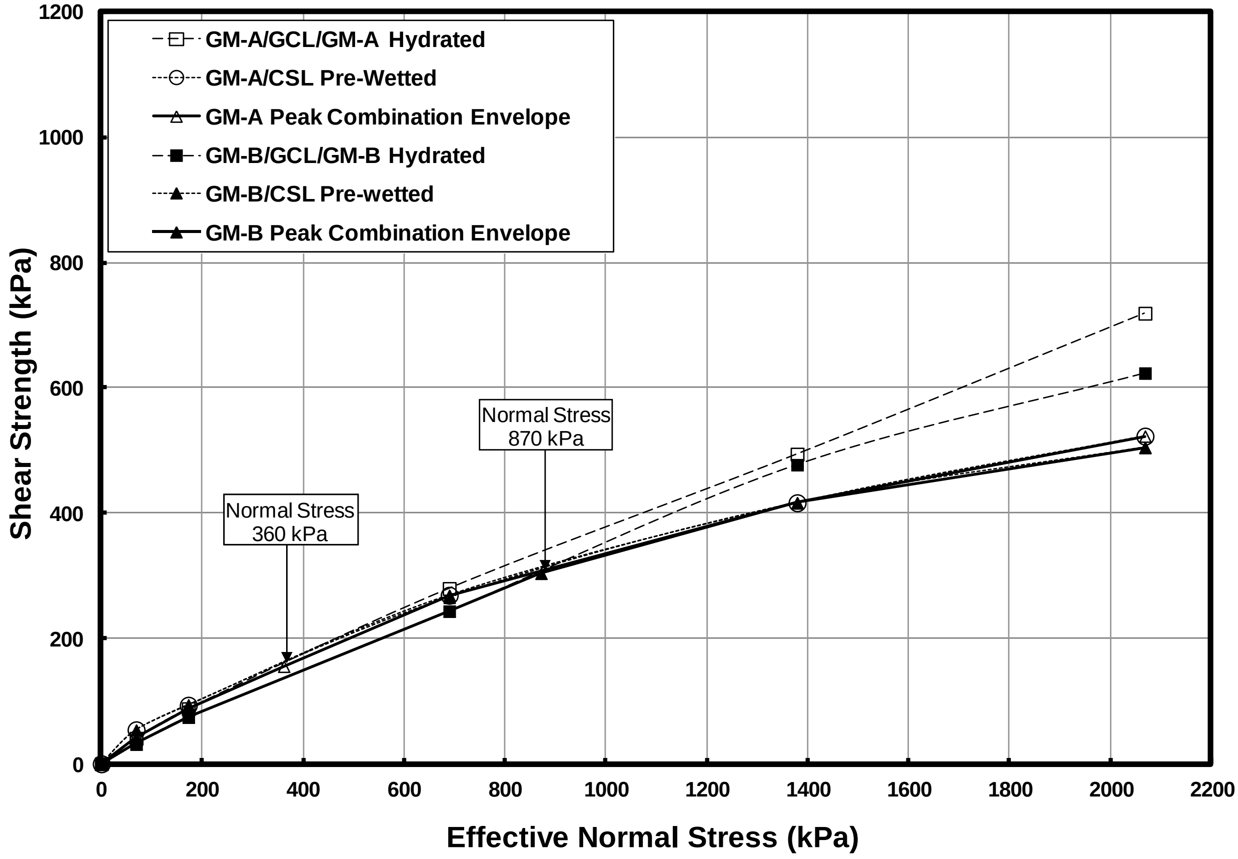


Figure 6. Peak Combination Strength Envelopes from Single Interface Tests for Liner System No. 1 with GM-A and GM-B Geomembranes

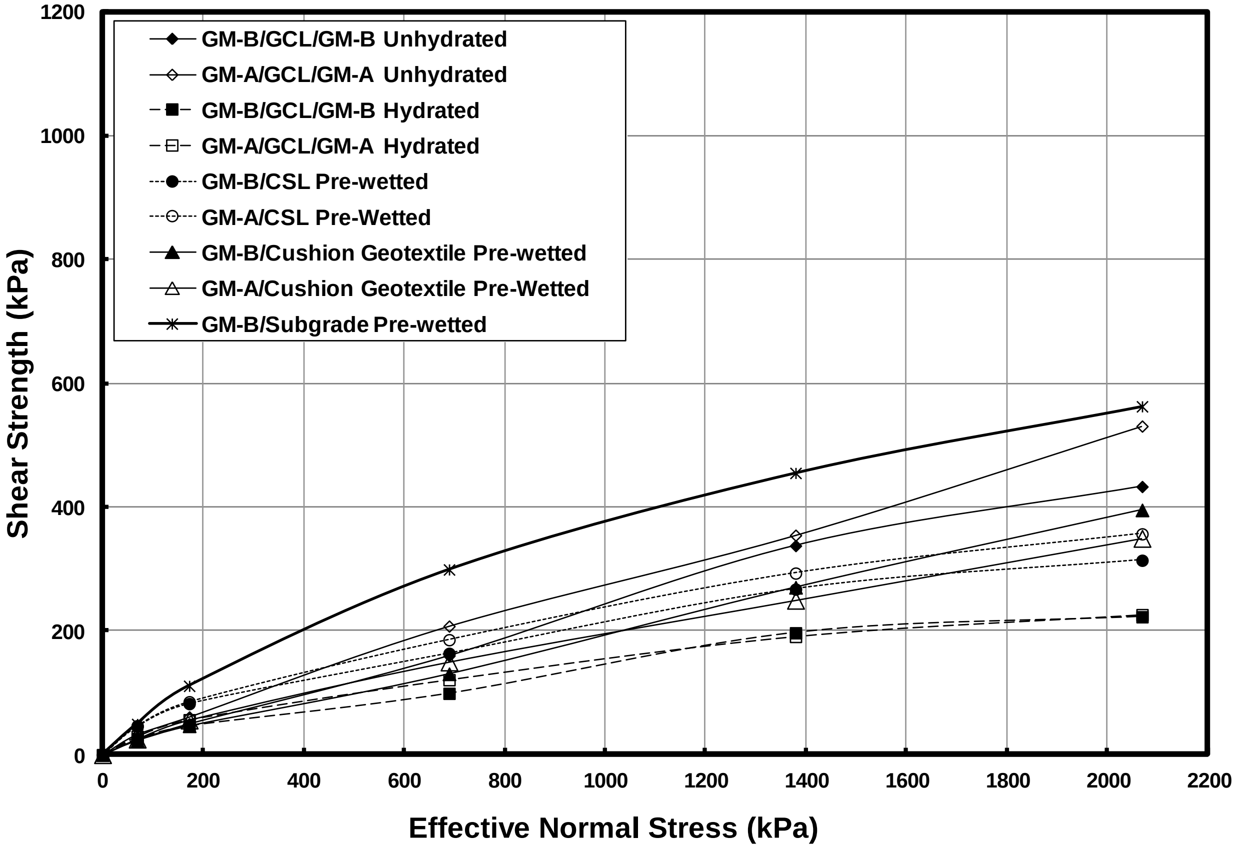


Figure 7. LD Strength Envelopes from Single Interface Tests on Proposed Liner Systems No. 1 and 2

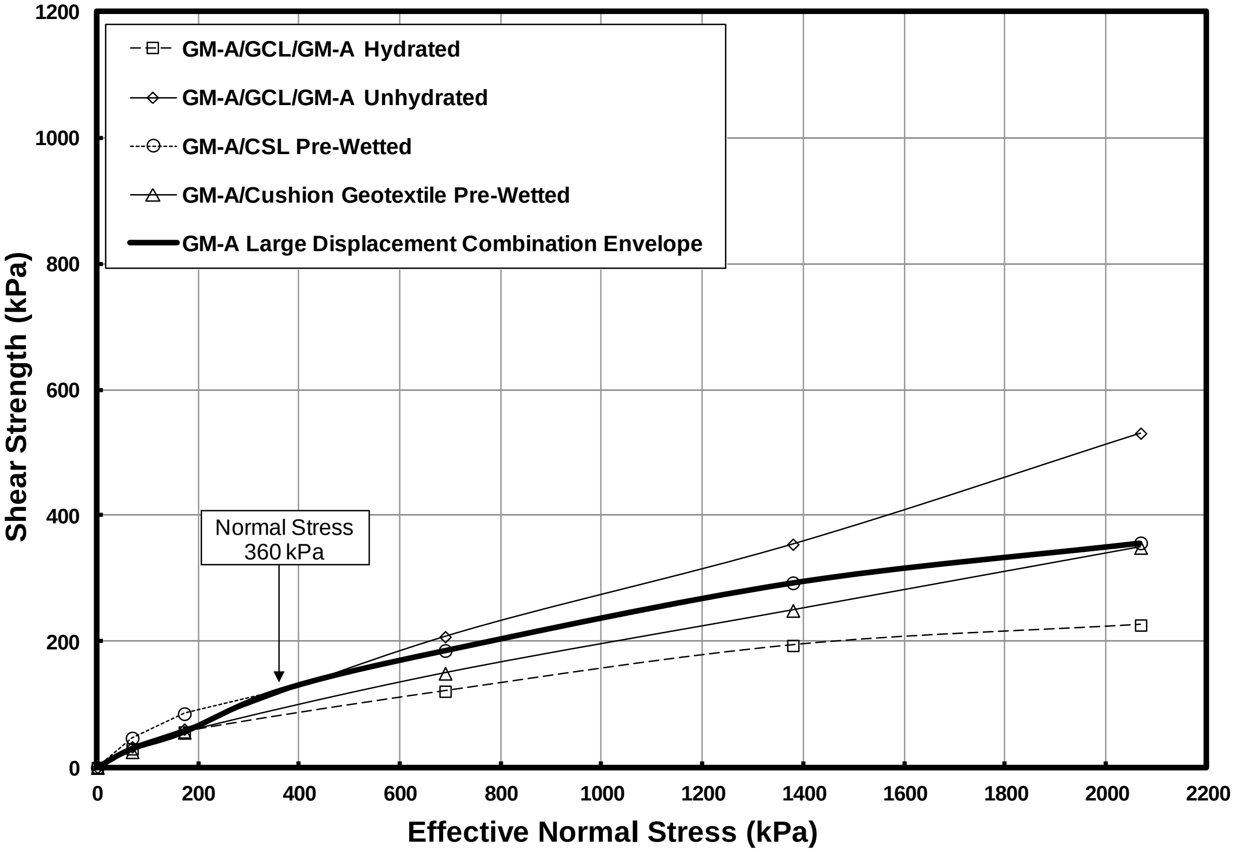


Figure 8. LD Combination Strength Envelope from Single Interface Tests for Liner System No. 1 with GM-A Geomembrane

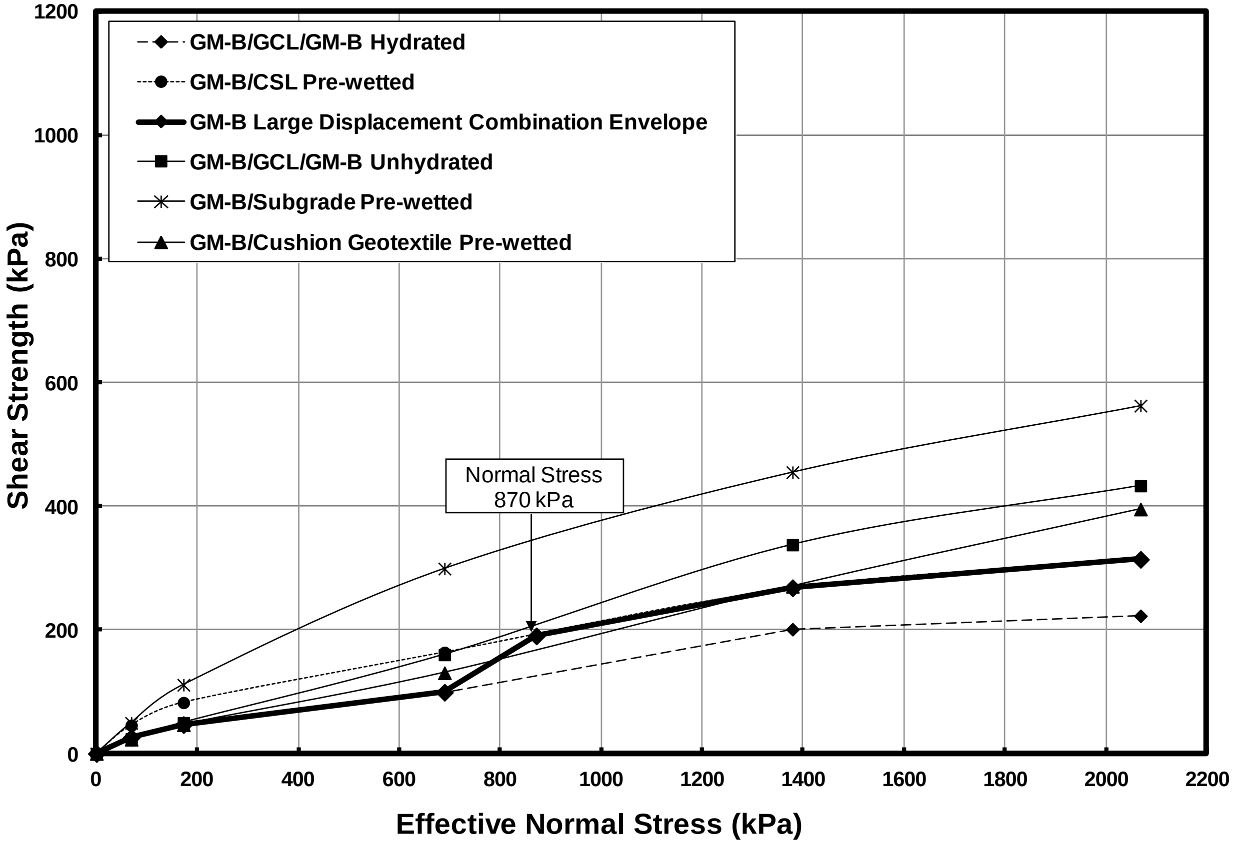


Figure 9. LD Combination Strength Envelope from Single Interface Tests for Liner System No. 1 with GM-B Geomembrane

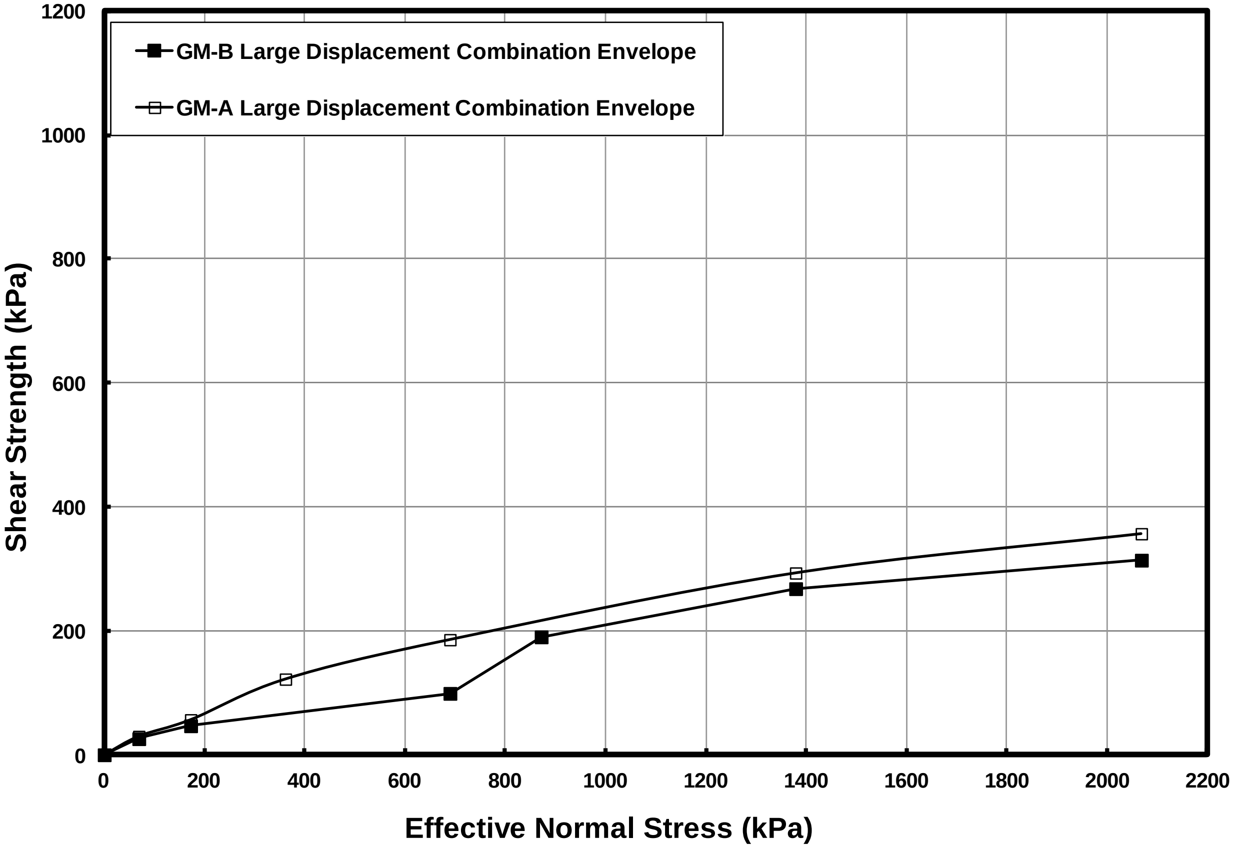


Figure 10. Comparison of LD Combination Strength Envelopes from Single Interface Tests for Liner System No. 1 (GM-A vs. GM-B)

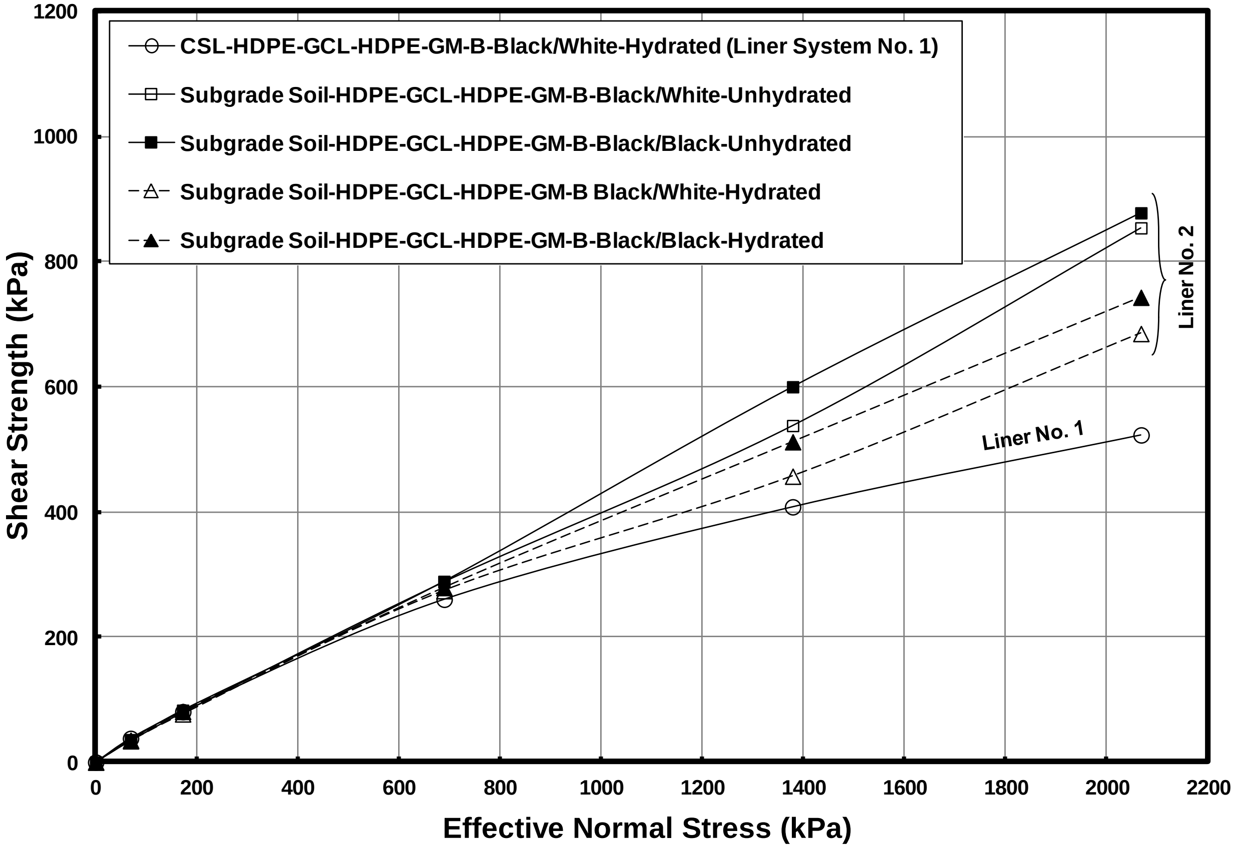


Figure 11. Peak Strength Envelopes from Multi-Interface Tests

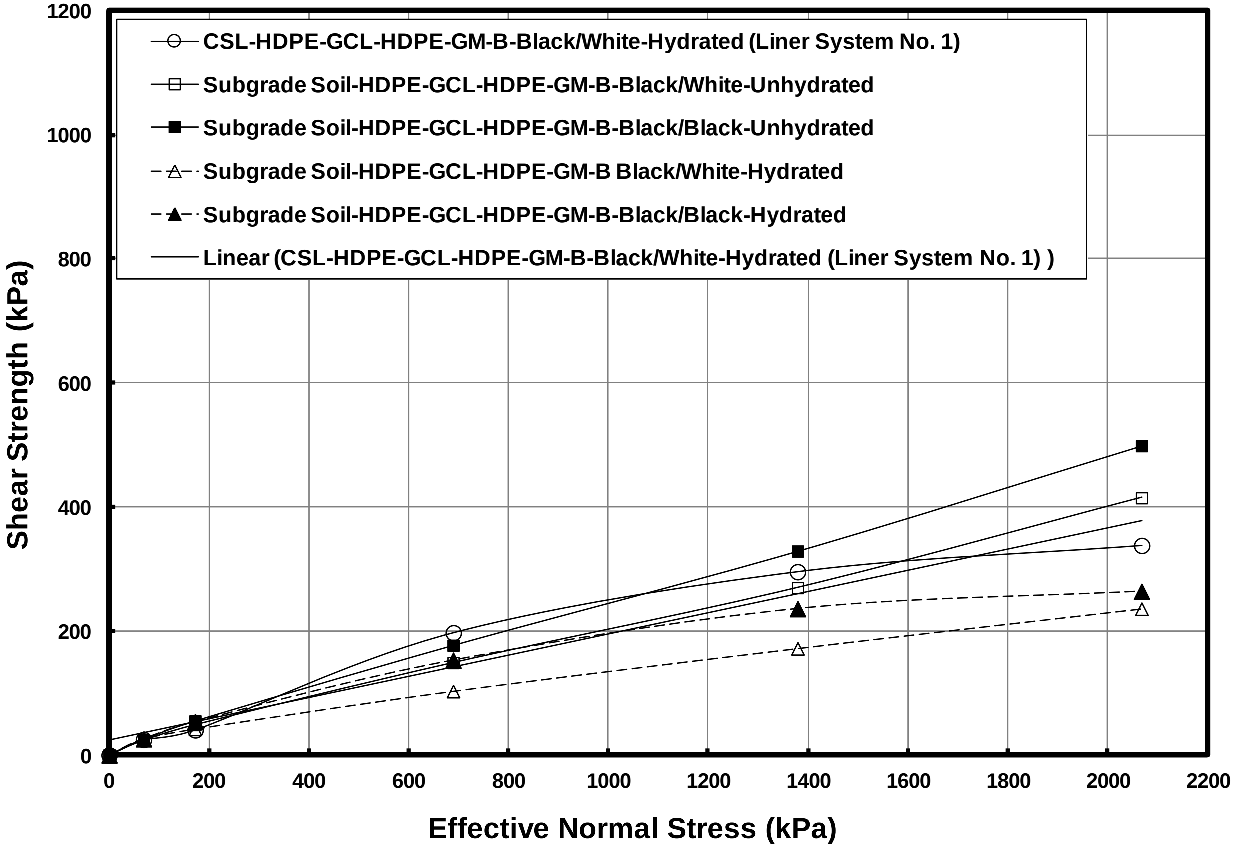
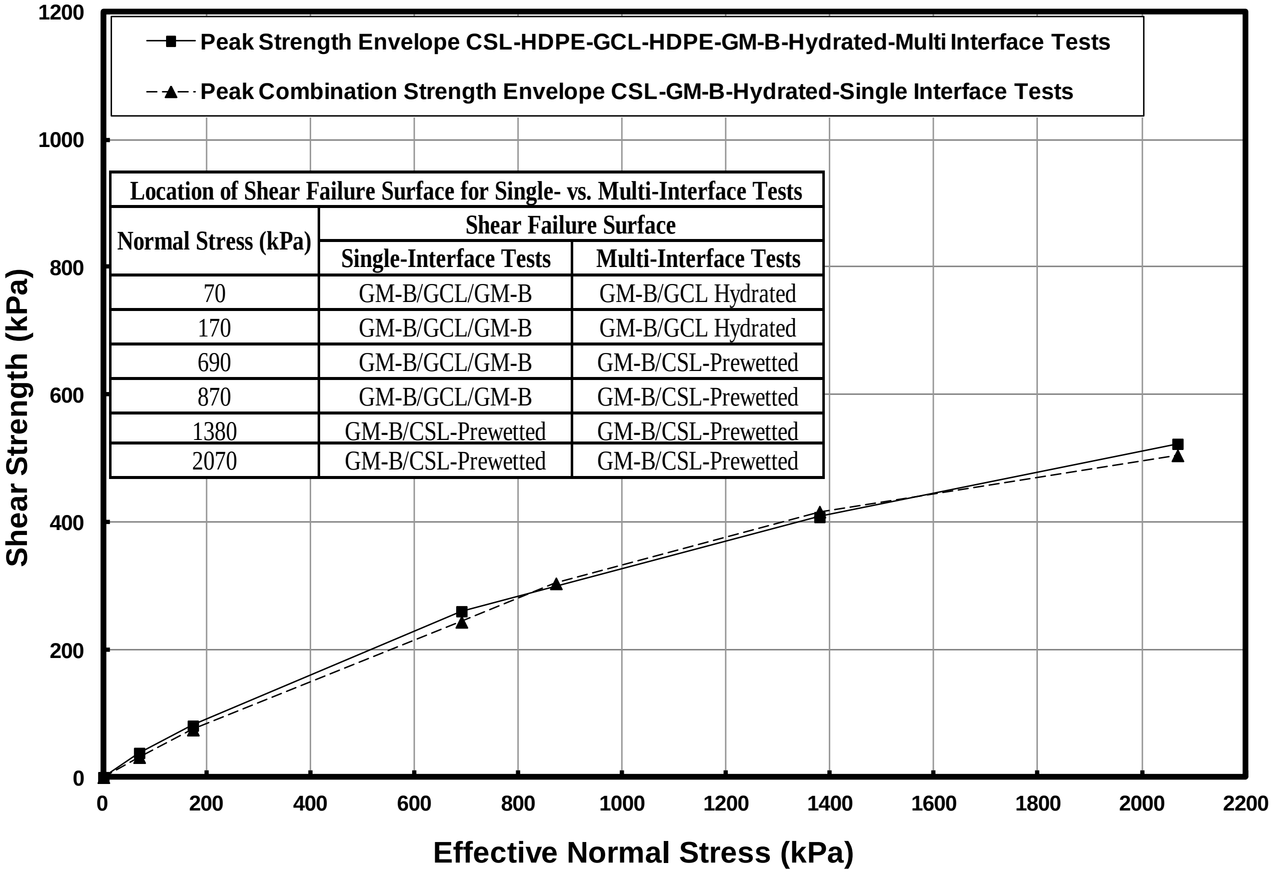


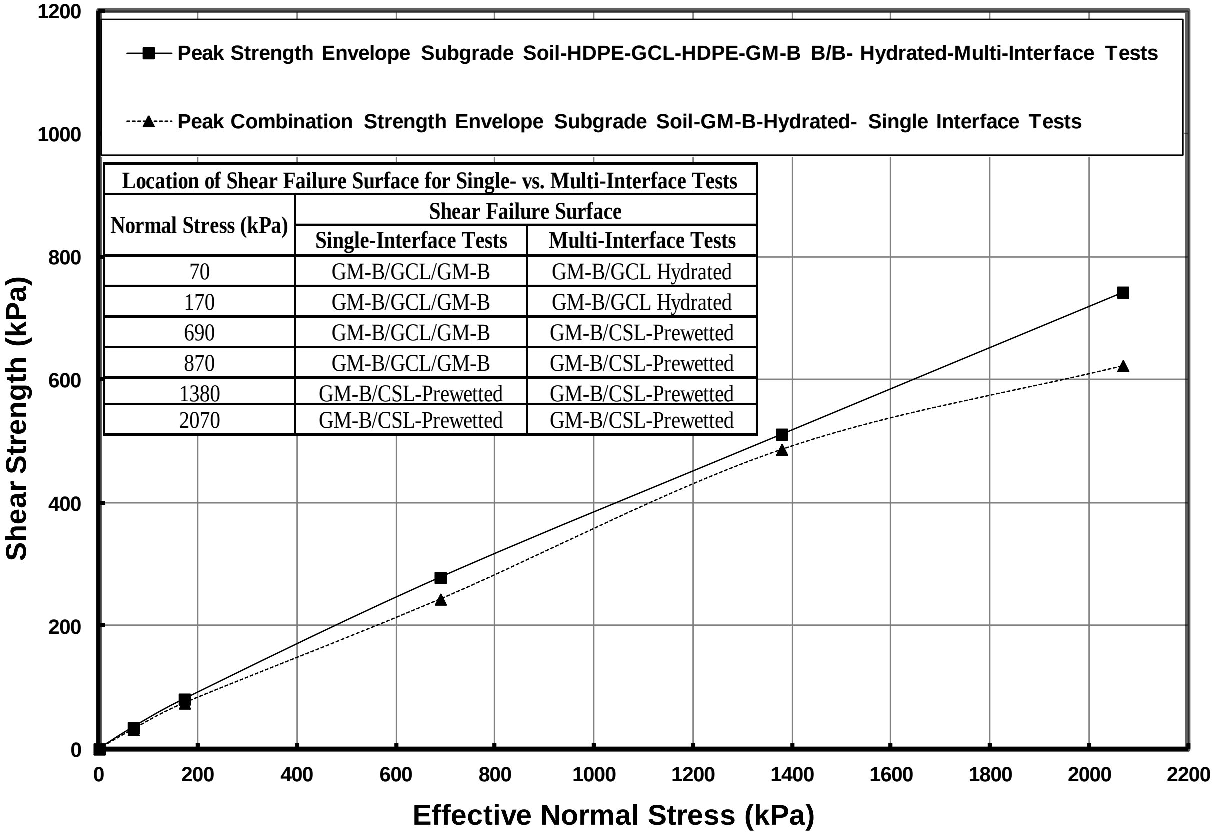
Figure 12. LD Strength Envelopes from Multi-Interface Tests



Location of Shear Failure Surface for Single- vs. Multi-Interface Tests

Normal Stress (kPa)	Shear Failure Surface	
	Single-Interface Tests	Multi-Interface Tests
70	GM-B/GCL/GM-B	GM-B/GCL Hydrated
170	GM-B/GCL/GM-B	GM-B/GCL Hydrated
690	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
870	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
1380	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted
2070	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted

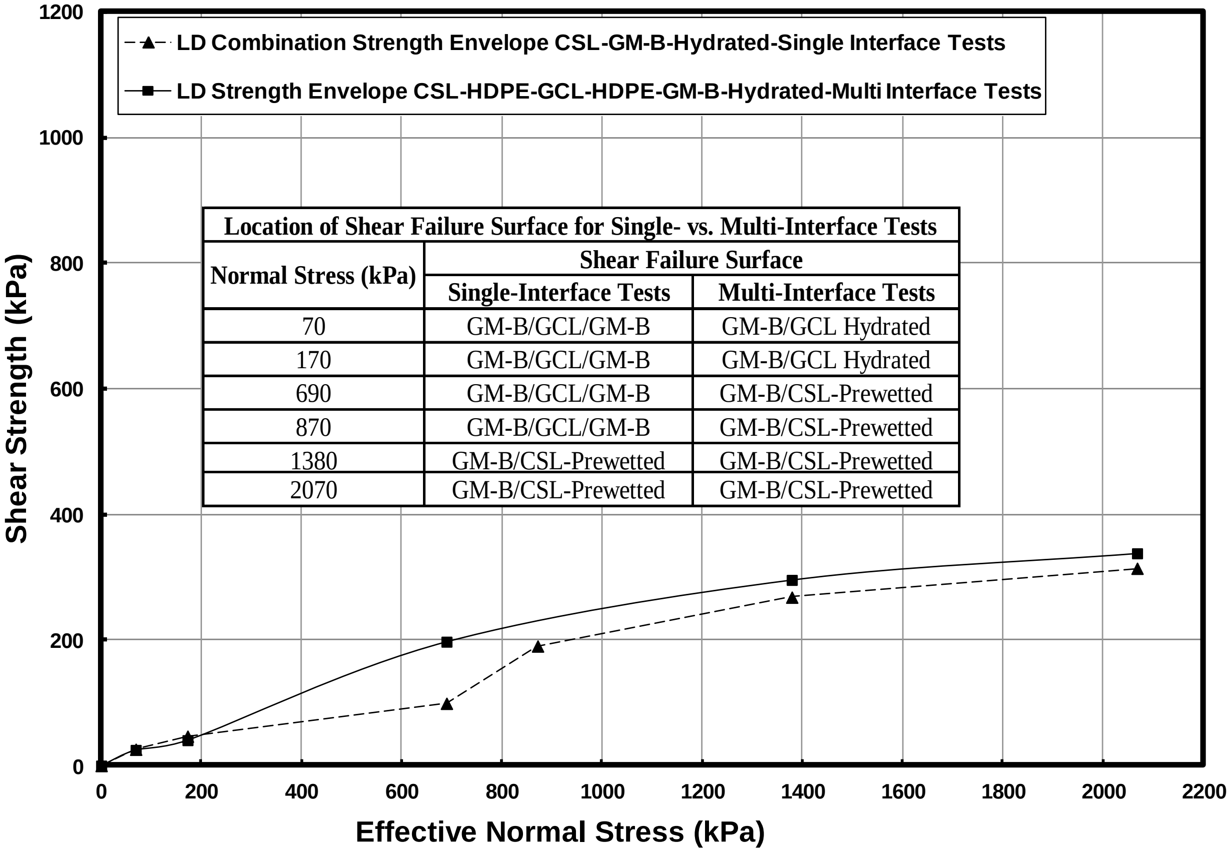
Figure 13. Comparison of Peak Strength Envelopes from Single- and Multi-Interface Tests (Liner System No. 1)



Location of Shear Failure Surface for Single- vs. Multi-Interface Tests

Normal Stress (kPa)	**Shear Failure Surface**	
	Single-Interface Tests	**Multi-Interface Tests**
70	GM-B/GCL/GM-B	GM-B/GCL Hydrated
170	GM-B/GCL/GM-B	GM-B/GCL Hydrated
690	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
870	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
1380	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted
2070	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted

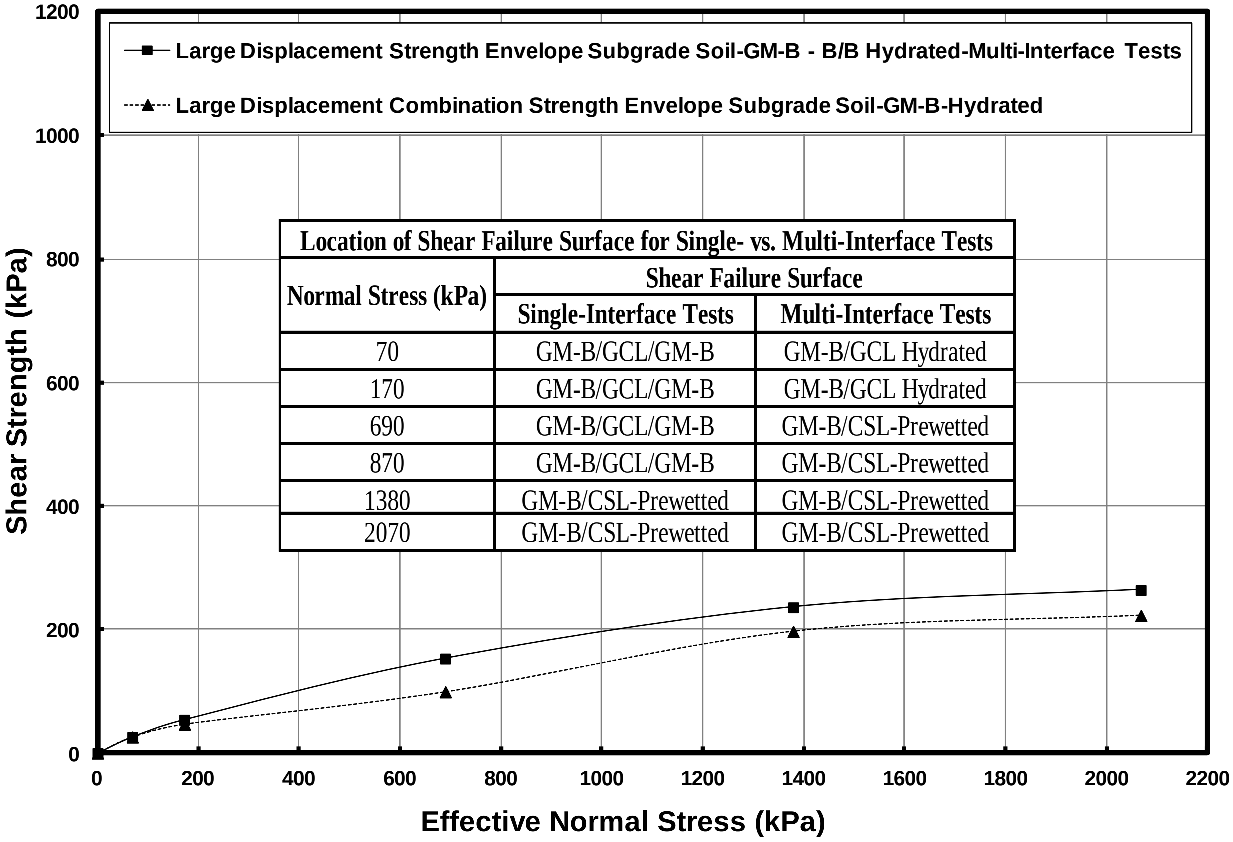
Figure 14. Comparison of Peak Strength Envelopes from Single- and Multi-Interface Tests (Liner System No. 2)



Location of Shear Failure Surface for Single- vs. Multi-Interface Tests

Normal Stress (kPa)	Shear Failure Surface	
	Single-Interface Tests	**Multi-Interface Tests**
70	GM-B/GCL/GM-B	GM-B/GCL Hydrated
170	GM-B/GCL/GM-B	GM-B/GCL Hydrated
690	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
870	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
1380	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted
2070	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted

Figure 15. Comparison of LD Strength Envelopes from Single- and Multi-Interface Tests (Liner System No. 1)



Location of Shear Failure Surface for Single- vs. Multi-Interface Tests

Normal Stress (kPa)	Shear Failure Surface	
	Single-Interface Tests	Multi-Interface Tests
70	GM-B/GCL/GM-B	GM-B/GCL Hydrated
170	GM-B/GCL/GM-B	GM-B/GCL Hydrated
690	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
870	GM-B/GCL/GM-B	GM-B/CSL-Prewetted
1380	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted
2070	GM-B/CSL-Prewetted	GM-B/CSL-Prewetted

Figure 16. Comparison of LD Strength Envelopes from Single- and Multi-Interface Tests (Liner System No. 2)

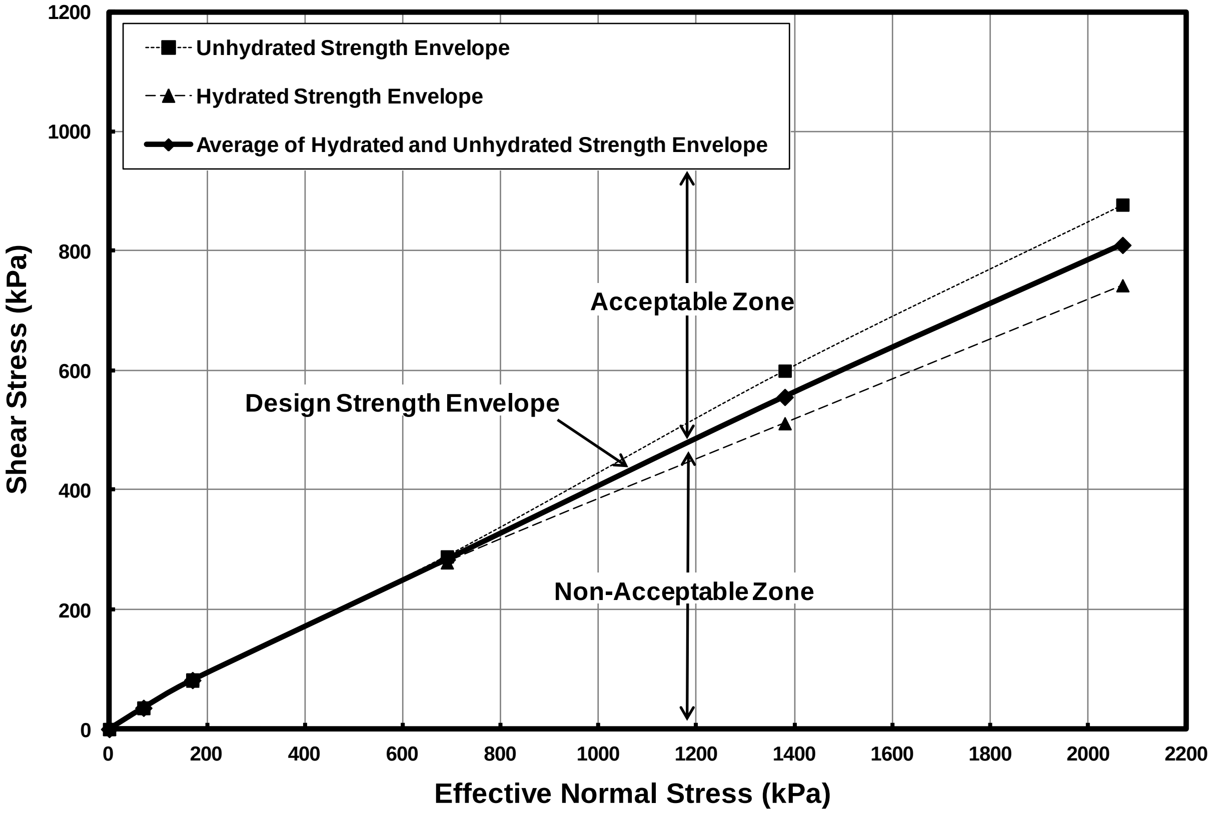


Figure 17. Design Peak Strength Envelope from Multi-Interface Tests for Liner System No. 2

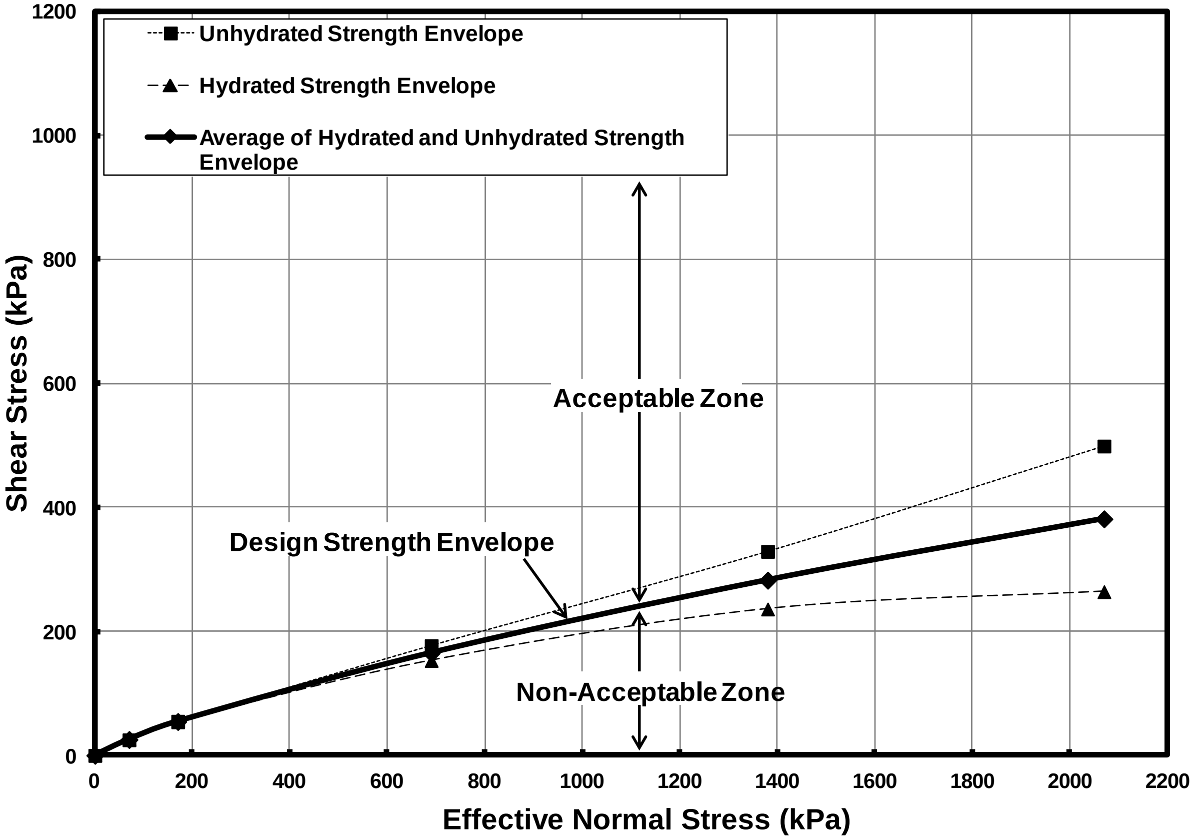


Figure 18. Design LD Strength Envelope from Multi-Interface Tests for Liner System No. 2