State-of-the-Art Report: GCL Shear Strength and Its Measurement – Summary of Ten-Year Update

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ABSTRACT

In 2004, the *Geosynthetics International* (GI) published a special issue on GCLs that was well received (*Geosynthetic Clay Liners I*). In the 2004 special issue, a state-of-the-art report titled: GCL Shear Strength and Its Measurement was published by the authors. In particular, the 2004 state-of-the-art report discusses testing techniques, variables, displacement rates, post-shear investigations, shear stress-displacement behavior, shear strength interpretation, recommendations for GCL shear strength for slope stability analyses, and future research needs. This paper presents a summary of the major changes to the 2004 state-of-the-art report that appear in the second special issue of GI on GCLs (*Geosynthetic Clay Liners II*) in 2015. The three areas significantly augmented since the 2004 state-of-the-art report in 2015 *Geosynthetic Clay Liners II* are: dynamic shear strength, creep shear testing, and design strength envelopes for encapsulated GCLs, which are briefly summarized herein.

1. INTRODUCTION

1.1 Background

Internal and interface shear strengths of geosynthetic clay liners (GCLs) are needed for static and seismic stability analyses in the design of waste containment facilities, heap leach pads, and other facilities that incorporate these materials as hydraulic barriers. Particular attention is often given to these strengths because bentonite, the essential component of a GCL, is a weak material after hydration and thus can provide a potential surface for slope movement and possibly failure. Reported values of GCL internal and interface shear strengths show significant variability due to variability in component materials and manufacturing processes (Fox and Stark 2004), differences in testing equipment and procedures (Eid et al. 1999), and changes in the design, manufacture, and application of GCLs over time (Eid and Stark 1997). As a result, it has long been recognized that design shear strength parameters for GCLs and other geosynthetics must be obtained using project-specific materials tested under conditions simulating those expected in the field (Koerner *et al.* 1986, Bove 1990, Eith *et al.* 1991, Koerner and Daniel 1993, Gilbert *et al.* 1997, Stark et al. 1998). Shear strengths of GCLs and GCL interfaces are routinely measured using laboratory shear tests and are dependent on many factors. Understanding of the effect and importance of these factors has evolved over recent years and new information on several issues (*e.g.,* dynamic shear strength and long-term performance) have become available since 2004. In 2004, a state-of-the-art report titled: GCL Shear Strength and Its Measurement was published by the authors in a special issue of *Geosynthetics International* (GI) called *Geosynthetic Clay Liners I*. The ten year update to this paper will appear in a special issue of GI termed *Geosynthetic Clay Liners II* in 2015 and is described below.

Fox and Stark (2015) present a 10-year update to the 2004 state-of-the-art report on the shear strength and shear strength testing of GCLs that is published in *GCL Special Issue II*. Essential concepts of GCL laboratory shear testing, shear stress–displacement behavior, and shear strength interpretation are presented along with new information on dynamic shear strength, long-term performance or creep, and design strength envelopes for slope design involving encapsulated GCLs is added to Fox and Stark (2015). The full paper in *GCL Special Issue II* also addresses assessment of shear test quality, specimen size, shearing devices, specimen gripping/clamping system, specimen selection and trimming, gap setting and multi-interface tests, normal stress selection and number of tests, hydration stage, consolidation stage, shearing stage, and final specimen inspection and water contents. Finally, recommendations regarding GCL shear strength behavior and current GCL strength testing practice, improvements for GCL strength testing and reporting are suggested, and future research needs are identified. Fox and Stark (2015) also contains some changes in notion that the authors consider preferable to notation presented in the original SOA report, e.g., using c_i and ϕ_i for interface shear strength parameters instead of a (adhesion) and δ (friction angle). In the 2015 version δ is used for shear displacement in shear stress-displacement relationships and not friction angle.

This paper presents a summary of three areas significantly augmented in the 2015 state-of-the-art report in *Geosynthetic Clay Liners II*, which are: dynamic shear strength, creep shear testing, and design strength envelopes for encapsulated GCLs.

1.2 GCL Special Issue II

This paper present only a small portion of the complete 2015 State-of-the-Art Report that is published in *GCL Special Issue II* in *GI* so readers are encouraged to review the entire special issue. Table 1 lists the eight GCL related papers and their authors that are included in *GCL Special Issue II*. These two issues of *Geosynthetics International* occupy the first two 2015 issues of the GI. *GCL Special Issue II* presents the latest research on GCLs and updates some of the papers published in *GCL Special I*, e.g., Fox and Stark (2004).

Table 1. Papers and authors published in *GCL Special II* in *GI*

Paper Title	Authors
Interface Transmissivity Measurements in Multicomponent GCLs	Bannour and Touze-Foltz
Anionic Polymer Treatment of Bentonite Clay for Chemical-Resistant GCLs	di Emidio, Mazzieri, Flores, Van Impe, and Bezuijen
State-of-the-Art Report: GCL Shear Strength and Its Measurement	Fox and Stark
Temperature and Moisture Effects on Textured Geomembrane and GCL Interface Shear Strength	Hanson, Chrysovergis, Yesiller, and Manheim
Characteristics and Hydraulic Properties of Dense Prehydrated GCLs	Mazzieri, and di Emidio
Hydraulic Conductivity and Interface Transmissivity of GCL Below Poured Concrete	Rowe and Hosney
Observations of solar-driven downslope moisture migration at the GMB-GCL interface of an exposed composite landfill liner	Take, Brachman, and Rowe
Thermal Exposure Conditions Observed in a Black HDPE Geomembrane Composite Liner Exposed to Solar Radiation	Take, Rowe, Brachman, and Arnepalli

2. DYNAMIC SHEAR STRENGTH

Dynamic shear strength is important because waste disposal and other facilities with geosynthetic liner systems are commonly constructed in seismic regions because over fifty percent of the United States classifies as a Seismic Impact Zone according to Subtitle D of the Resource Conservation and Recovery Act (USEPA 1995).. Design and long-term performance assessment for such facilities requires information on shear strength behavior under dynamic loading conditions. Dynamic shear tests are typically conducted using monotonic (i.e., single direction) or cyclic loading. In comparison to static shear tests, a larger number of variables must be considered for dynamic shear tests, including displacement rate for monotonic tests and waveform, amplitude, frequency, and number of cycles for cyclic tests. Post-cyclic static shear strength is another important measurement for cyclic tests. Shear displacement information and degradation of strength parameters with stress reversals takes on greater significance for dynamic shear tests because such data is needed for permanent displacement-based stability analyses (e.g., Matasovic *et al.* 1998). Although experimental studies on dynamic shear strength have been conducted for a variety of geosynthetic interfaces, including GT/GN, GM/GN, GT/GM, and GM/GM (Kavazanjian *et al.* 1991; Yegian and Lahlaf 1992; De and Zimmie 1998; Kim *et al.* 2005), data is limited for GCLs and GCL interfaces. The development of a better understanding of dynamic shear strength, including new constitutive models (Arab *et al.* 2012; Arab *et al.* 2013), is a current research need for GCLs.

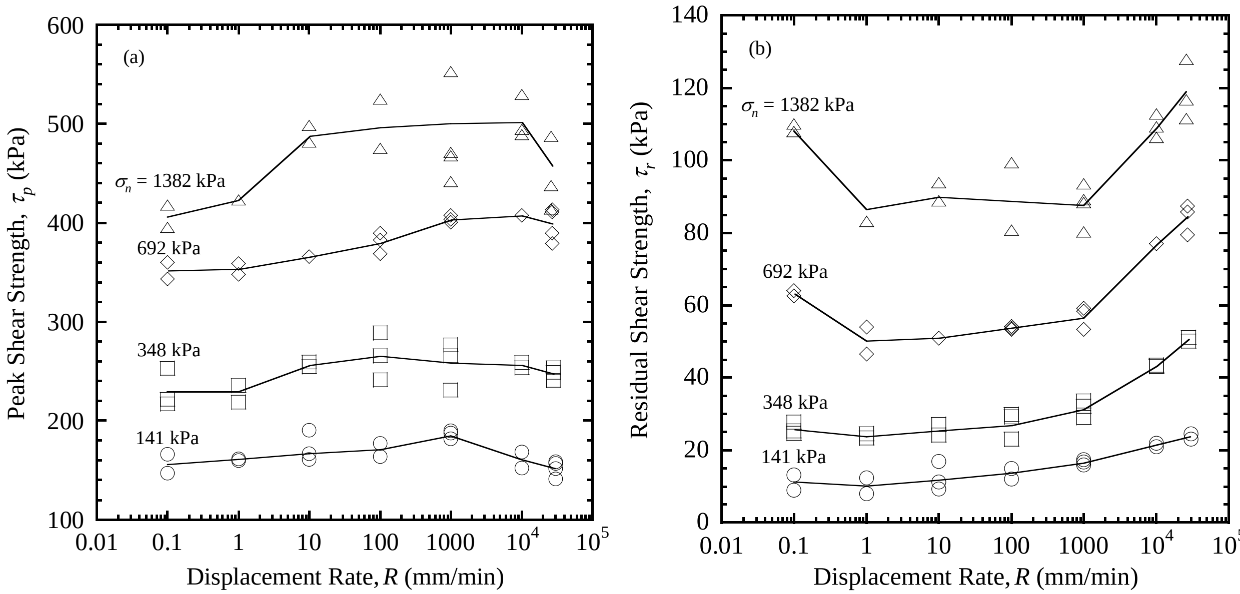
2.1 Unreinforced GCLs

In the first study of GCL dynamic internal shear strength, Lai *et al.* (1998) performed stress-controlled cyclic simple shear tests on an unreinforced geomembrane-supported GCL. Dry and hydrated specimens (dia. = 80 mm) were subjected to normal stress levels ranging from 39 to 67 kPa and sinusoidal excitations at a frequency of 0.09 Hz. For the dry GCL specimens, GCL internal shear strength did not degrade during 200 loading cycles for cyclic stress ratios (shear stress amplitude/static peak shear strength) less than one and post-cyclic static strength increased slightly due to bentonite densification. Conversely, shear strength of the hydrated GCL specimens decreased under cyclic loading. Similar to natural clays, the number of cycles required to cause failure decreased with increasing cyclic stress ratio

2.2 Reinforced GCLs

2.2.1 Monotonic Shear

Nye and Fox (2007) and Fox and Sura (2014) present experimental data from monotonic internal shear tests of a hydrated needle-punched (NP) GCL with a woven (W) and nonwoven (NW) geotextile (W/NW NP GCL) for four normal stress levels (σ_n = 141, 348, 692, and 1382 kPa) and seven displacement rates (R = 0.1, 1, 10, 100, 1000, 10,000 mm/min, and 30,000 mm/min). Peak shear strengths are presented in Fig. 1(a) and for each normal stress, increase and then decrease with increasing shear displacement rate. Maximum values of peak strength were measured for R = 100 to 10,000 mm/min and represent increases of approximately 20% above the corresponding static strength values (R = 0.1 mm/min). Beyond these maximum values, peak strengths decrease at the highest displacement rates. Corresponding residual shear strengths are presented in Fig. 1(b). For each normal stress, values decrease and then increase with increasing displacement rate, with a minimum at approximately R = 1 mm/min. This decreasing-increasing trend becomes more prominent with increasing normal stress. The decrease of residual strength between R = 0.1 and 1 mm/min is attributed to generation of positive shear-induced excess pore pressures. Beyond R = 1 mm/min, the gradual increase and then sharp increase in residual strength is attributed to rate-dependent undrained shear strength of the hydrated bentonite. Fig. 1(b) indicates that the standard displacement rate for static shear tests of hydrated GCLs (R = 0.1 mm/min) yields unconservative values of residual shear strength, especially for higher normal stress levels. Additional results on reinforced GCLs are presented in Fox and Stark (2015).



(a) (b)

Figure 1. Monotonic shear tests on hydrated W/NW NP GCL: (a) peak shear strengths; (b) residual shear strengths (figures from Fox and Sura 2014).

2.2.2 Cyclic Shear

Cyclic loading can reduce the subsequent static shear strength of a NP GCL. Fox *et al.* (2006) and Nye and Fox (2007) present results of displacement-controlled cyclic internal shear tests on the same hydrated W/NW NP GCL for σ_n = 141 kPa and various combinations of displacement amplitude Δ_a , and frequency f . After cyclic loading, each specimen was subjected to monotonic shear with R = 0.1 mm/min. Peak and residual static shear strengths are shown in Fig. 2 along with the corresponding data from a static shear test with no prior cycling (Δ_a = 0). Higher cyclic displacement amplitude yields progressively lower post-cyclic static peak strengths, which is due to greater levels of damage to the needle-punched reinforcement. The reinforcement was almost completely ruptured for Δ_a = 25 mm, leaving the specimen with little more than residual shear strength afterward. Post-cyclic residual shear strengths were unaffected by previous cyclic loading and yield a static secant residual friction angle of 4.9°.

2.3 GMX/GCL Composite Liners

2.3.1 Monotonic Shear

Ross and Fox (2014) present experimental data from monotonic shear tests of a composite liner consisting of a textured HDPE geomembrane (GMX) over a hydrated NW/NW NP GCL for five normal stress levels (σ_n = 13, 348, 692, 1382, and 2071 kPa) and five displacement rates (R = 0.1, 1, 100, 10,000, and 30,000 mm/min). This data indicates peak shear strengths and failure modes of the GMX/GCL composite liners are dependent not only on normal stress as previously reported (e.g., Eid 2011; Fox and Ross 2011), but also on shear displacement rate. GCL internal failures occurred at high normal stress and low shear displacement rate. As normal stress decreased or displacement rate increased, the failure mode transitioned to GMX/GCL interface. These data also indicate the standard displacement rate for static shear tests of GMX/GCL composite liners (R = 1 mm/min) yield a conservative (i.e., lowest) value of peak shear strength for each normal stress. Peak and residual strength envelopes for the GMX/GCL Composite Liner tested are presented in Fig. 3 and are drawn for a static displacement rate (R = 1 mm/min) and the maximum displacement rate (30,000 mm/min). Peak strength envelopes are slightly stress dependent and show dependence on displacement rate at higher normal stress. Large-displacement strength envelopes show greater dependence on displacement rate at higher normal stress due to the effect of changing failure mode, and in particular decreases slightly between σ_n = 692 and 1382 kPa as the failure mode changes from interface to internal shear.

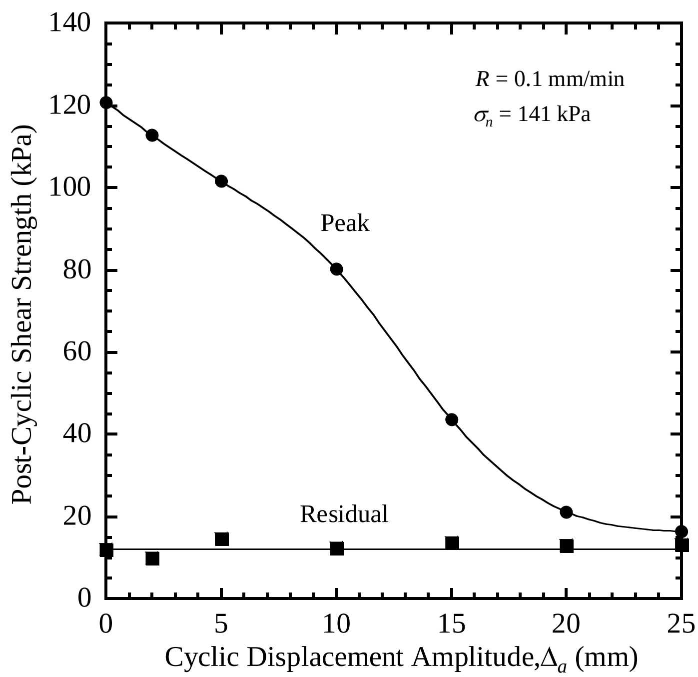
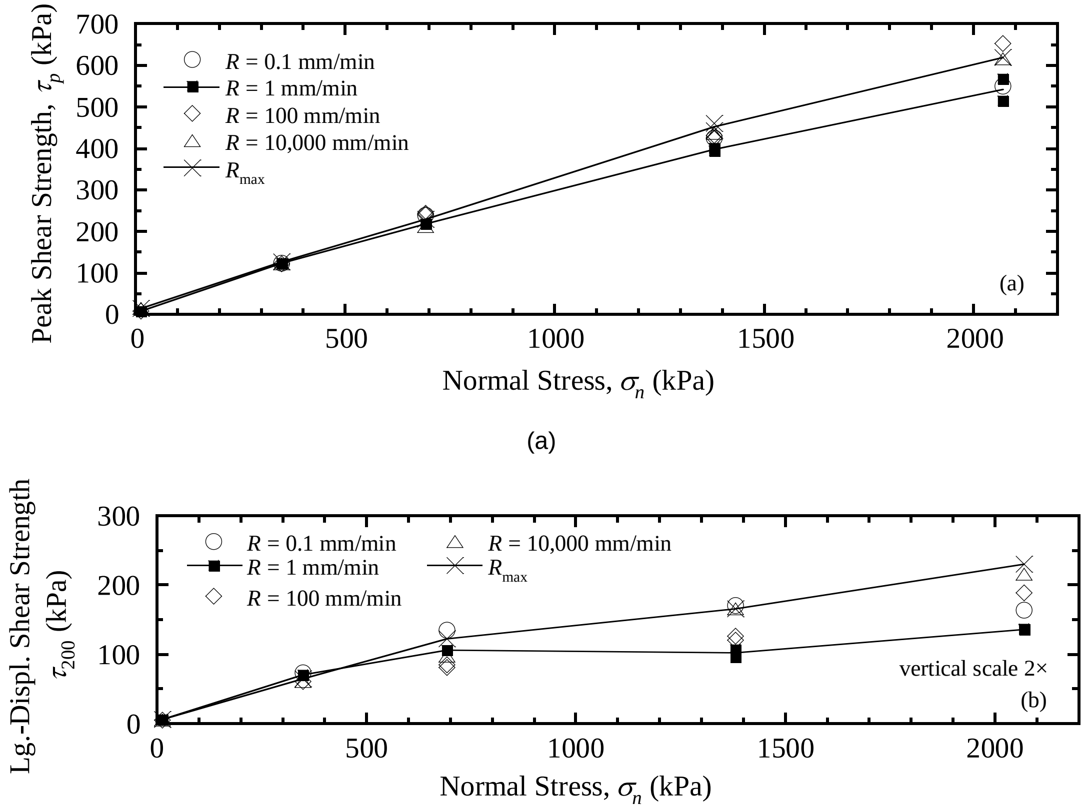


Figure 2. Post-cyclic peak and residual static shear strengths for hydrated W/NW NP GCL (figure from Nye and Fox 2007).

2.3.2 Cyclic Shear

Three studies have been conducted using shake tables to investigate the cyclic shear strength of smooth HDPE geomembrane (GMS)/GCL interfaces under low normal stress (Lo Grasso *et al.* 2002; Park *et al.* 2004; Kim *et al.* 2005). Lo Grasso *et al.* (2002) tested the interface between a GMS and W/W geotextile (GT)-supported GCL (σ_n = 3.2 kPa) and reported that increasing frequency produced larger dynamic friction angles, with values of 17° and 21° measured for 5 and 8 Hz, respectively. Park *et al.* (2004) report the opposite finding for a GMS sheared against an unreinforced GM-supported GCL and a W/NW NP GCL (σ_n = 1.6 to 6.8 kPa; f = 2 to 10 Hz); in those tests, normal stress and frequency did not affect dynamic friction angle. Kim *et al.* (2005) investigated the effects of displacement rate for a GMS sheared against dry and submerged (not fully hydrated) specimens of a NW/NW NP GCL (σ_n = 10.9 and 22.5 kPa). These shear tests used a cyclic triangular waveform with varying displacement rates (R = 1 to 10,000 mm/min) and amplitudes (Δ_a = 13 to 127 mm). To avoid the effects of progressive interface polishing for multiple tests on a single specimen, each specimen was "pre-sheared" prior to testing; thus, the reported data apply to large displacement shear conditions. Shear strengths for the dry specimens increased slightly with increasing displacement rate, whereas values for the submerged specimens were relatively insensitive to displacement rate.

Athanassopoulos et al. (2010) performed a displacement-controlled cyclic shear test of a sand/GCL/sand liner system (σ_n = 1.6 to 6.8 kPa, Δ_a = 13 to 127 mm, f = 2 to 10 Hz). The GCL was a W/NW NP product with a thin polyethylene GM laminated to the NW side. After 25 cycles, inspection of the failed specimen indicated that shearing occurred between the laminated geomembrane and the cover soil layer, and no visible damage to the GCL. The results of precyclic and post-cyclic tests of the GCL material indicate no significant changes in material properties and provide additional evidence that the GCL specimen did not sustain damage due to cyclic loading.



(a)

(b)

Figure 3. Monotonic shear tests for a GMX/NP GCL composite liner: (a) peak strength envelopes; (b) large-displacement strength envelopes (Ross and Fox 2014).

Ross *et al.* (2011) present results for a series of large-scale cyclic shear tests for a GMX/NW/NW NP GCL composite liner with σ_n = 13 to 2071 kPa and Δ_a = 2 to 30 mm. Similar to the corresponding monotonic shear tests the failure mode of the GMX/NP GCL specimens is dependent on both σ_n and Δ_a. All tests conducted at low to intermediate normal stress levels (σ_n ≤ 692 kPa) produced interface failures. Partial to complete internal failures were observed for some tests at low Δ_a and high σ_n**.** Interface failures occurred for the largest displacement amplitude (Δ_a = 30 mm) at all normal stress levels. In general, the testing program indicates a more complex relationship among normal stress, shear displacement rate, and failure mode than has been previously reported for these materials under cyclic hear conditions.

3. GCL CREEP

This section presents some of the new results on GCL creep and durability testing that have been presented since Fox and Stark (2004). GCL creep is continuing shear displacement under constant normal and shear stress conditions. Polypropylene and polyethylene based geotextiles are commonly used in GCLs and are subject to both creep and degradation due to stress cracking and oxidation. Creep is caused by the polymer molecules rearranging to resist externally applied loads which can reduce their thickness and facilitate additional creep. Polymer degradation can occur when fibers are exposed to oxygen which can accelerate creep by reducing fiber strength.

Müller et al. (2008) present results of inclined plane tests at 2.5H:1V (21.8^0) and show hydrating fluid has a significant impact of bentonite strength and thus long-term creep. Use of de-ionized water results in limited ion exchange in bentonite so use of tap water is preferred to simulate ion exchange that will likely occur in the field. Without ion exchange and mobilization of some bentonite shear strength, applied shear stress must be resisted by reinforcing fibers which can result in internal failure due to fiber disentanglement or fracture of the fibers at thermally fixed anchor points on the carrier geotextile.

In accordance with Thies et al. (2002), Müller et al. (2008) also conclude that short-term peel strengths are not indicative of times-to-failure observed in long-term shear strength tests because higher peel strengths resulted in shorter times-to-creep failure. For design purposes it is recommended that accelerated creep tests be performed using air oven drying (Müller et al., 2003) to assess fiber degradation and long-term shear strength testing to assess creep potential instead of applying factors of safety to short-term peel test results. If the GCL is encapsulated between two GMXs, this air oven accelerated testing may not be warranted due to limited oxygen in the field.

Zanzinger and Alexiew (2000), Koerner *et al.* (2001), and Zanzinger and Saathoff (2012) present mathematical models for the extrapolation of GCL creep test results to long time periods, such as 100 years to address applicable regulations. The necessary extrapolation is typically an Arrhenius model and three or more orders of magnitude in time (*e.g.,* 1000 h creep test to 100 yr. GCL design life) and thus the predictions contain considerable uncertainty. However, these studies indicate the times to shear failure depend on the applied shear stress. The long-term internal shear stress for a NW/NW NP-GCL estimated through extrapolation of creep test data at a test temperature of 80°C is 42kPa, i.e., only 38% of the short term shear stress, under a normal stress of 50 kPa for a minimum of 100 years.

4. DESIGN STRENGTH ENVELOPES FOR ENCAPSULATED GCLS

It is becoming more common to encapsulate GCLs in bottom liner systems to increase environmental protection. Erickson and Thiel (2002) recommend the shear strength along a slip surface within the bentonite of a GCL 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.

This section discusses the testing and analysis for estimating the design strength envelope for an encapsulated GCL. The GCL must be tested at the manufactured moisture, which is straight forward, and with the bentonite hydrated between to geomembranes. Hydration of the GCL encapsulated between two GMXs can be facilitated prior to laboratory shear testing by drilling five small holes to simulate the worst case scenario for defects in a geomembrane during installation. Because the GCL is allowed to hydrate, the peak hydrated strength envelope can be obtained and plotted with the peak dry strength envelope to estimate the arithmetic mean of the hydrated and un-hydrated strengths. The average between the hydrated and un-hydrated strengths for a GMX/NW/NW NP-GCL/GMX encapsulated liner system are used to develop the design strength envelope (solid line) shown in Fig. 4. The peak and large displacement design envelopes can be used to specify peak and large displacement geosynthetic interface strengths by denoting the acceptable and non-acceptable zones.

Figure 4 shows the peak design strength envelope was obtained using the arithmetic average of the hydrated and un-hydrated peak strengths. The peak design strength envelope (solid line) shown in Figure 4 separates the zones of acceptable and non-acceptable internal and interface strengths for conformance testing prior to GCL shipment to the project site. Therefore, Figure 4 can be used for the specification of GCL and geosynthetic interface strength by denoting the acceptable and non-acceptable zones for manufacturers or distributors. 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 and Acceptable Zone. If the 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 4 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 used should exhibit a design strength envelope that 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 their geosynthetics exhibit material and interface strengths greater than the design strength envelope shown in Figure 4, 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 an encapsulated GCL in a bottom liner system is also obtained by averaging the hydrated and un-hydrated strengths, see Figure 5, 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.

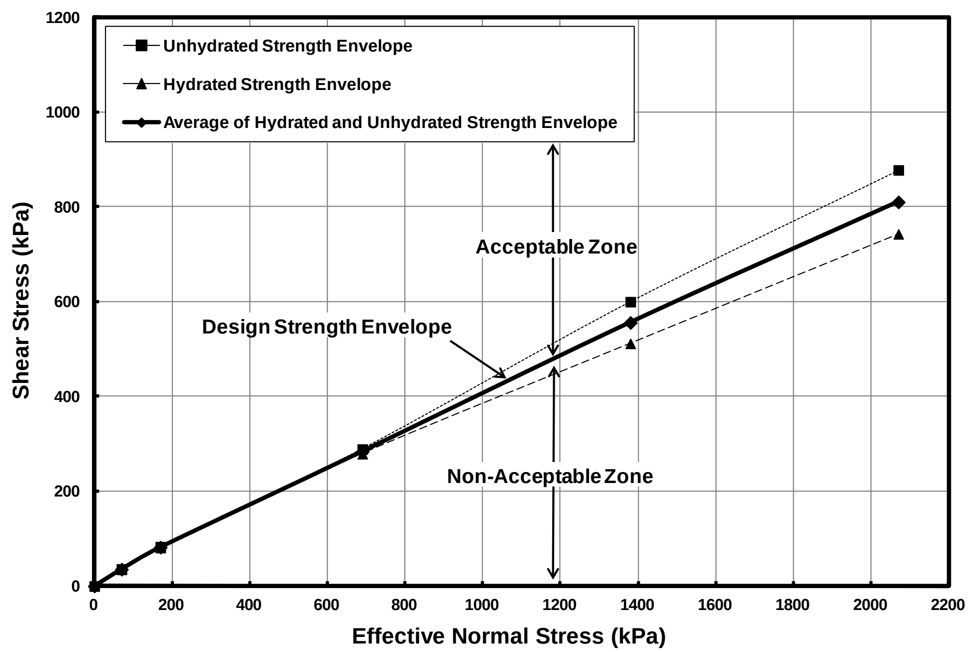


Figure 4. Design Peak Strength Envelope from Multi-Interface Direct Shear Tests for encapsulated GCL

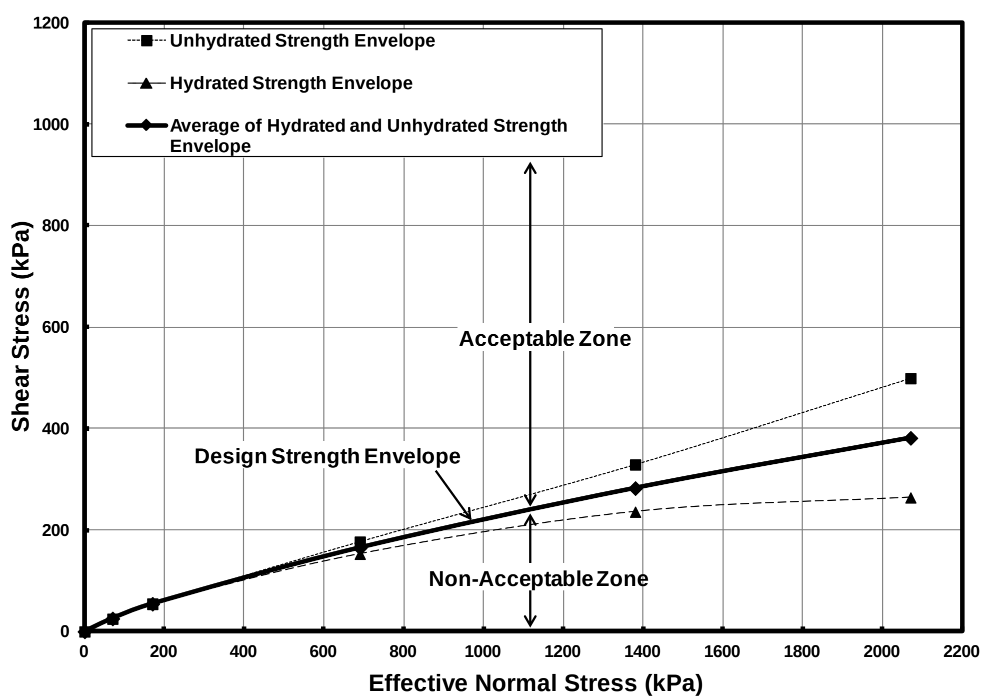


Figure 5. Design LD Strength Envelope from Multi-Interface Direct Shear Tests for encapsulated GCL

5. SUMMARY

Over the past 10 years since Fox and Stark (2004), significant advances in GCL shear strength testing have occurred, especially in the areas of dynamic shear strength, creep testing, and design strength envelopes for encapsulated GCLs. This paper briefly summarizes the recent developments in these three areas that are presented in Fox and Stark (2015). The accompanying state-of-the-art report titled: GCL Shear Strength and Its Measurement published by the authors presents the full investigations and advancements since 2004 and is published in the second special issue of *Geosynthetics International* (GI) on GCLs (*GCL Special Issue II*). Table 1 presents the other GCL related papers included in *GCL Special Issue II*, which will be published in the first two 2015 issues of GI.

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