LABORATORY MEASUREMENT OF GCL SHEAR STRENGTH

This paper discusses the laboratory measurement of internal and interface shear strengths of geosynthetic clay liners (GCLs). ASTM D6243, Standard Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liners (GCLs) by the Direct Shear Method, has several 'grey' areas as to how to run the testing. The authors are the three most recognized authorities on the shear testing of GCLs. Thus, this paper is a consensus on addressing these various issues related to GCL shear testing. The major conclusions are:

- The 300 x 300 mm direct shear box is the standard apparatus for testing GCLs. Ring shear and large scale shear boxes are primarily for research purposes only.
- One of the most important features of a good direct shear box is an aggressively textured and well draining gripping surface covering the plates. Truss plates (with teeth machined to 1-2 mm height) and a series of wood rasps have been used successfully by the authors.
- GCL specimens should be hydrated for at least 48 hours under low (0.5 psi) normal load outside the box to reach relatively full hydration and then consolidated under incremental loading until field conditions are reached.
- Incremental loading is generally applied using daily or half-daily increments with the normal stress doubling each time.
- A shear rate of 0.04 in./min. (1 mm/min) is sufficient for geomembrane/GCL interface shear strength testing.
- With currently available information, a shear rate of 0.004 in./min. (0.1 mm/min) is recommended for GCL internal shear strength testing.
- Shear-displacement curves should be included as part of any GCL testing report.
- A failed specimen is inspected and mode of failure (geotextile tear, needlepunch fiber pullout, etc.) is recorded.

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Laboratory Measurement of GCL Shear Strength

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Abstract: This paper discusses the laboratory measurement of internal and interface shear strengths of geosynthetic clay liners (GCLs). All relevant issues are addressed, including test apparatus, gripping/clamping, hydration, consolidation, shearing rate, and post-test measurements. The standard 300 × 300 mm direct shear box is expected to remain the apparatus of choice for GCL strength testing, although ring shear and large-scale direct shear devices have been used for research purposes. One of the most important features of a shear device is the specimen gripping/clamping system. A poor gripping/clamping system may cause progressive failure of a GCL specimen, resulting in erroneous peak and large displacement shear strengths. GCL specimens should be hydrated to equilibrium and, if necessary, subjected to consolidation stresses that match expected field loading conditions. The appropriate shearing rate is an issue of continuing debate. Available information indicates that internal strengths of dry GCLs and geomembrane/GCL interface shear strengths are essentially constant for shearing rates of 1 mm/min. or less. Peak internal shear strengths of hydrated GCLs generally increase with increasing shearing rate. Residual internal shear strengths of hydrated GCLs may increase or remain constant with increasing shearing rate. A maximum displacement rate of 0.1 mm/min. is recommended for hydrated GCL internal shear tests until this issue is resolved. Once a test is completed, the mode of failure should be recorded and GCL water contents should be measured. Shear stress-displacement relationships should be included as part of any GCL testing report.

Keywords: geosynthetic clay liner, bentonite, shear strength, direct shear, ring shear, laboratory testing

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Geosynthetic clay liners (GCLs) are now widely used as hydraulic barriers in waste containment facilities, ponds, canals, and other related engineering works. For facilities involving slopes, GCL shear strength is often the primary factor governing design. A stability analysis must consider the internal shear strength of the GCL and interface shear strengths between the GCL and adjacent materials. Due to the variability of GCL products and adjacent materials, each of these strength values must be obtained from project- and product-specific tests under conditions that closely approximate those expected in the field. New data on the variability of GCL shear test results is presented by Chiu and Fox (2003).

The focus of this paper is the laboratory testing procedure used to measure the shear strengths of GCLs and GCL interfaces. This paper is preceded by many published works on this topic, in particular Daniel *et al.* (1993), Frobel (1996), Gilbert *et al.* (1996), Stark and Eid (1996), Eid and Stark (1997), Fox *et al.* (1997), Gilbert *et al.* (1997), Fox *et al.* (1998), Koerner (1998), Eid *et al.* (1999), Marr (2001), Olsta and Swan (2001), Triplett and Fox (2001), and Fox and Stark (2003). Discussions in the current paper have benefited greatly from the insight provided in these past works and summarize some of the latest thinking on the measurement of GCL internal and interface shear strengths.

ASTM Standard Test Procedure

ASTM D 6243, the current standard test method for GCL internal and interface shear strength, requires that GCLs be tested in direct shear with a minimum specimen dimension of 300 mm (square or rectangular specimens are recommended). The gripping/clamping system should securely hold the test specimen and not interfere with the measured shear strength. Shearing surfaces should be rigid and permit free water flow into and out of the specimen (if applicable). Rough textured shearing surfaces are required for internal strength tests. End clamping of geosynthetics is permitted to facilitate shearing at the desired location. Specimen conditioning procedures are specified by the user, including test configuration, soil compaction criteria (if applicable), hydration/consolidation procedures, normal stress level(s), and method of shearing. Specimens should be sheared to a minimum displacement (Δ) of 50 mm using displacement-controlled (*i.e.*, constant rate of displacement) or stress-controlled methods, the latter of which includes constant stress rate, incremental stress, and constant stress creep. Displacement control is needed to measure post-peak response and test data must be corrected for any machine friction that is included in the measured shear force. For displacement-controlled tests, ASTM D 6243 recommends the following maximum displacement rate R,

$$R = \frac{\Delta_f}{50 t_{50} \eta} \tag{1}$$

where:

Δ_f = estimated displacement at peak or large displacement shear strength as requested by the user,

t_{50} = time required for the specimen to reach 50 percent consolidation (double-drained conditions), and

η = 1 for internal GCL shear with drainage at both boundaries
= 4 for shear of the interface between GCL and an impermeable material
= 0.002 for shear of the interface between a GCL and a pervious material

If excess pore pressures are not expected to develop on the failure surface for a GCL interface shear test, ASTM D 6243 allows a shearing rate of 1 mm/min. At the end of the test, the failed specimen is inspected and the mode of failure is recorded. Discussions in the following sections are presented within the context of ASTM D 6243.

Shearing Devices

Shear strengths of GCLs and GCL interfaces have been measured using direct shear and ring shear devices. The direct shear device has several advantages such as shear occurs in one direction, relatively large specimens can be tested, and shear displacement is nominally uniform across the width of the specimen. The primary disadvantage of the standard 300 × 300 mm direct shear test device is that the maximum shear displacement (typically 50 to 75 mm) is not sufficient to measure the residual shear strength (τ_r) of most GCLs and GCL interfaces. Fox *et al.* (1997) developed a direct shear machine capable of shearing large GCL specimens (406 × 1067 mm). The maximum displacement of that device (203 mm) was sufficient to achieve residual internal shear conditions for GCLs (Fox *et al.* 1998) but was insufficient to achieve residual shear conditions for textured geomembrane (GMX)/GCL interfaces (Triplett and Fox 2001). Another disadvantage of the direct shear test is that the area of the failure plane decreases during shear, which may increase the normal stress (σ_n) and require an area correction for data reduction. To avoid this problem, many GCL direct shear devices have a top shearing surface that moves across a longer bottom shearing surface. However, this results in the movement of previously unsheared material into the failure plane, which can also potentially alter the measured shear stress-displacement (τ-Δ) response.

The torsional ring shear test has the advantage that unlimited shear displacement is possible, making it ideal for the measurement of residual shear strength. The disadvantages of ring shear are that shear displacement does not occur in one direction (which may be important for geosynthetics that display in-plane anisotropy), relatively small specimens are tested, and shear displacement is not uniform across the width of the specimen. Non-uniform shear displacement can cause progressive failure of a test specimen (theoretically proceeding from the outer edge to the inner edge) and thus affects the measured value of peak shear strength (τ_p). The measurement of τ_r is not affected by non-uniform displacement across the specimen. Stark and Poeppel (1995) showed that the error for τ_p is minimal if the ratio of inside specimen diameter to outside specimen diameter exceeds 0.7. Comparative tests between large-scale direct shear and torsional ring shear have also exhibited close agreement (Stark and Eid 1996, Eid and Stark 1997). Currently, ASTM D 6243 does not allow for the substitution of torsional ring shear testing for direct shear testing. Direct shear is likely to remain the preferred test method for GCLs because large specimens can be tested and peak strengths are measured in one direction with nominally uniform shear displacement.

Specimen Gripping/Clamping

One of the most important aspects of a GCL shearing device is the gripping/clamping system that secures the test specimen to the shearing surfaces. The gripping system refers to a rough (textured) plate or series of plates that cover the shearing surfaces and provide high friction against the surface of the specimen. A gripping surface may also contain sharp teeth that "bite" into a geosynthetic, producing even higher resistance to slippage. The clamping system refers to mechanical compression clamps that securely fasten the ends of the geosynthetics to the edges of the shearing surfaces.

Ideally, to ensure accurate stress-displacement behavior, a gripping/clamping system should enforce uniform shearing of the test specimen over the entire failure surface at all levels of displacement. To achieve such a condition, the gripping system must prevent any slippage between the test specimen and the shearing surfaces. If slippage occurs, tensile forces will be generated in the geosynthetics and progressive failure of the test specimen may result. Because most gripping surfaces used for GCL testing are not sufficiently aggressive to shear strong materials (e.g., reinforced GCLs) without assistance, mechanical compression clamps are used to facilitate shearing of GCL test specimens in nearly all testing laboratories. In addition to preventing slippage, a gripping surface should not interfere with the measured shear strength over a wide range of normal stress and should provide excellent drainage for hydrated GCL tests.

A few studies have reported the development of effective gripping surfaces for the shear of GCLs and GCL interfaces. The third author has had good success using a "textured steel grip" that consists of a parallel arrangement of wood working rasps attached to the shearing surfaces (Trauger *et al.* 1997, Olsta and Swan 2001). Fox *et al.* (1997) used modified metal connector plates, which have the advantage of providing a well drained surface in addition to a large number of 2 mm sharp teeth that uniformly grip a GCL specimen. These plates provided a sufficiently aggressive gripping surface that even very strong needle-punched GCLs could be sheared internally without the use of mechanical end clamps (Fox *et al.* 1998). Triplett and Fox (2001) glued single-sided GMX specimens to one of the shearing surfaces for GMX/needle-punched (NP) GCL interface strength tests. This method prevents slippage of the GMX but is limited to lower normal stresses by the shear strength of the glue (σ_n < approx. 280 kPa in the Triplett and Fox study). Gluing is not recommended for GCL specimens because of possible interference with the failure mechanism (e.g., pullout of fibers, rupture of stitches). Gluing has been used for NP GCLs tested in ring shear (Eid *et al.* 1999), however careful steps were followed to ensure that the glue was not applied above and below the failure surface material.

The effectiveness of a gripping surface can have a large effect on the quality of shear test results. Figure 1 presents τ vs. Δ relationships for internal shear of hydrated NP GCLs that were obtained using three different gripping/clamping systems. Figures 1(a) and 1(b) present data for W/NW NP GCLs (from different production lots and rolls) and Figure 1(c) presents data for a NW/NW NP GCL. Figure 1(a) shows the results of four shear tests that were conducted using the metal connector plate gripping system without end clamps. Inspection of the failed specimens indicated no slippage between the shearing surfaces and the carrier geotextiles during these tests. The relationships display similar smooth shapes and sharp narrow peaks at low displacements (Δ_p). Figure 1(b) shows relationships obtained using the textured steel gripping surface with end clamps. Peak shear strengths are smaller at similar σ_n values and the curves display slightly wider peaks with small stress undulations. In contrast, Figure 1(c) shows relationships that suggest problems occurred during shear. These relationships display double peaks, unusually wide peaks, greatly different shapes and values of Δ_p as σ_n increases, an absence of post-peak strength reduction, and undulations that are non-physical. The erroneous relationships in Figure 1(c) probably resulted from poor specimen gripping/clamping procedures and will produce inaccurate (likely conservative)

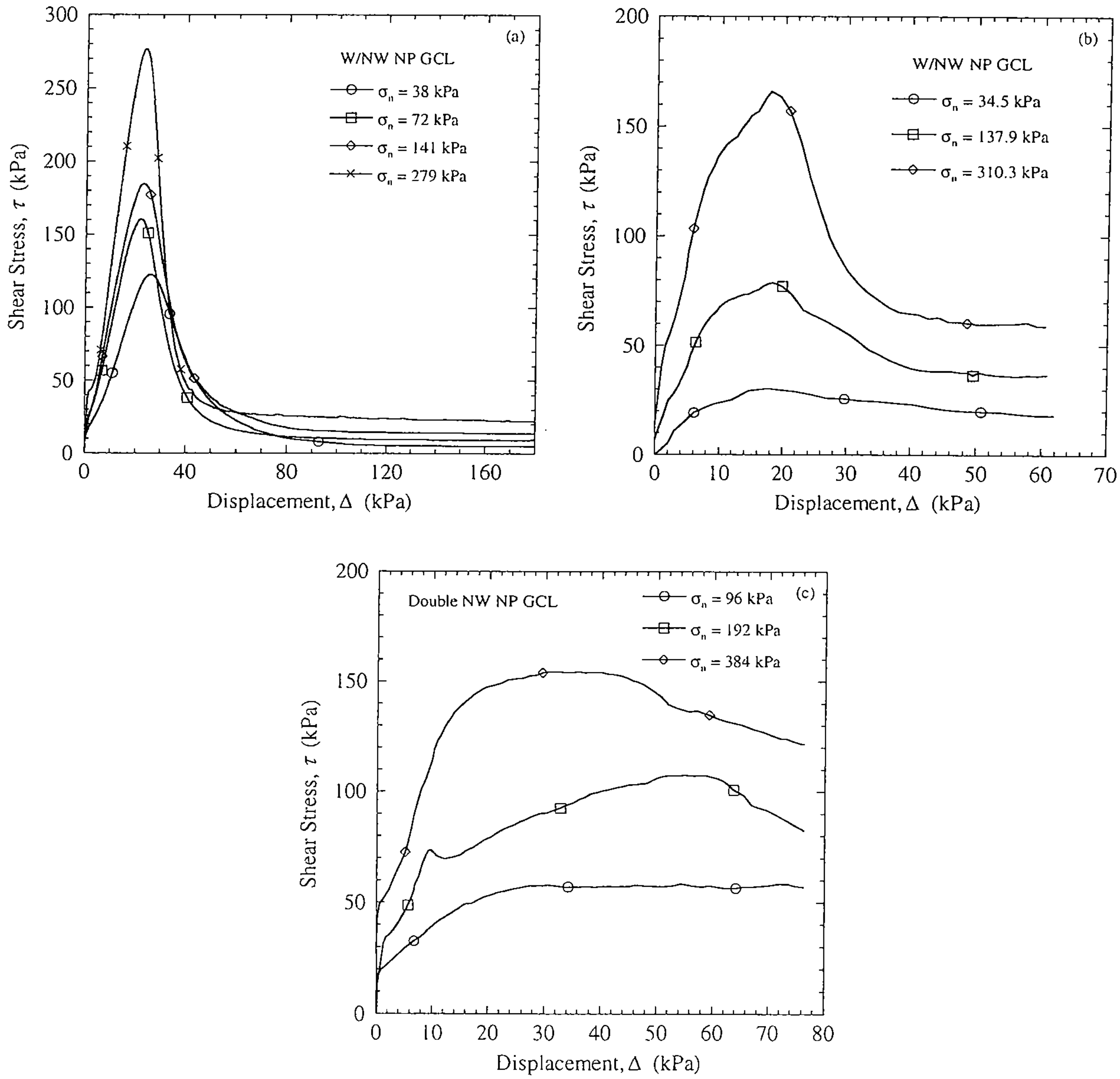

Figure 1. Examples of stress-displacement relationships for internal shear of NP GCLs: (a) curves obtained using modified metal connector plates without end clamps (Fox *et al.* 1998), (b) curves obtained using a textured steel grip with end clamps, and (c) curves that suggest problems occurred during shear.

peak failure envelopes and inaccurate (likely unconservative) large displacement failure envelopes. Machine friction problems are another possible cause of erroneous shear stress-displacement relationships and can result in unconservative peak and large displacement failure envelopes.

Examination of shear stress-displacement relationships is an easy way to make a preliminary assessment of the quality of GCL shear test results. Currently, some production testing laboratories provide shear stress-displacement relationships along with failure envelopes and shear strength parameters, while other laboratories do not. It is recommended that shear stress-displacement relationships be routinely included as part of the test results package for a GCL shear testing program.

Hydration Stage

GCLs and GCL interfaces should be sheared under hydrated conditions when hydration is expected in the field. Full hydration should always be expected in the field unless the bentonite is encapsulated between two geomembranes (GMs). Encapsulated GCLs are constructed by placing a second GM over an unreinforced GM-supported GCL. Reinforced GCLs have also been placed between two textured geomembranes in some applications. It is currently unknown how much bentonite hydration can be expected for an encapsulated GCL. Giroud *et al.* (2002) presented theoretical analyses of bentonite hydration through GM defects. Test data on this issue is not available.

Tap water is almost always used for the hydration of GCL test specimens. A notable exception is the shear tests reported by Koerner (1998) in which four different GCL products were sheared after hydration with distilled water, tap water, mild leachate, harsh leachate, and diesel fuel. GCL specimens should be initially hydrated under the normal stress expected in the field at the time of hydration. This hydration normal stress (σ_h) and will often be a low value. Ideally, a GCL specimen should be hydrated to equilibrium (i.e., until vertical displacement ceases), a procedure that may require a hydration time (t_h) as long as several weeks. As a practical alternative, a GCL can be considered as fully hydrated when the change in thickness is less than 5 percent over a 12 hr. period (Gilbert *et al.* 1997). However, using this criterion will still require t_h = 10 to 20 days. Most production testing facilities currently hydrate GCLs for 1 to 2 days.

Full hydration to equilibrium may not be practical for production testing in which GCL specimens are hydrated in the shearing device. There are two possibilities to circumvent this problem. First, some direct shear devices have separate shearing frame and shear box assemblies so that multiple GCL specimens can be hydrated simultaneously outside of the shearing frame. In this case, shear tests are not delayed by the lengthy time required to hydrate each specimen. Second, an accelerated hydration procedure can be used (Fox *et al.* 1998). A GCL specimen is hydrated for 2 days under a very low normal stress by adding just enough water to reach the expected final water content after shearing is completed (estimated from previous tests). The specimen is then placed in the shearing device and hydrated with free access to water for another 2 days under the desired σ_h. Most GCL specimens attain equilibrium in less than 24 hr. using this procedure (Fox *et al.* 1998, Triplett and Fox 2001). Fig. 2 illustrates the performance of the accelerated hydration procedure for two specimens of a W/NW NP GCL product. One specimen was placed dry in the shearing device and hydrated with free access to water under a σ_h = 38 kPa. A second specimen was hydrated using the accelerated procedure. In this case, the specimen was brought to a water content of 185 percent and cured for 2 days under a 1 kPa normal stress. The specimen was then placed in the shearing device and hydrated with free access to water under σ_h = 38 kPa for an additional 2 days. Measurements of internal pore pressure and vertical displacement during hydration indicate that the GCL specimen hydrated using the accelerated procedure reached equilibrium in 10 hr.

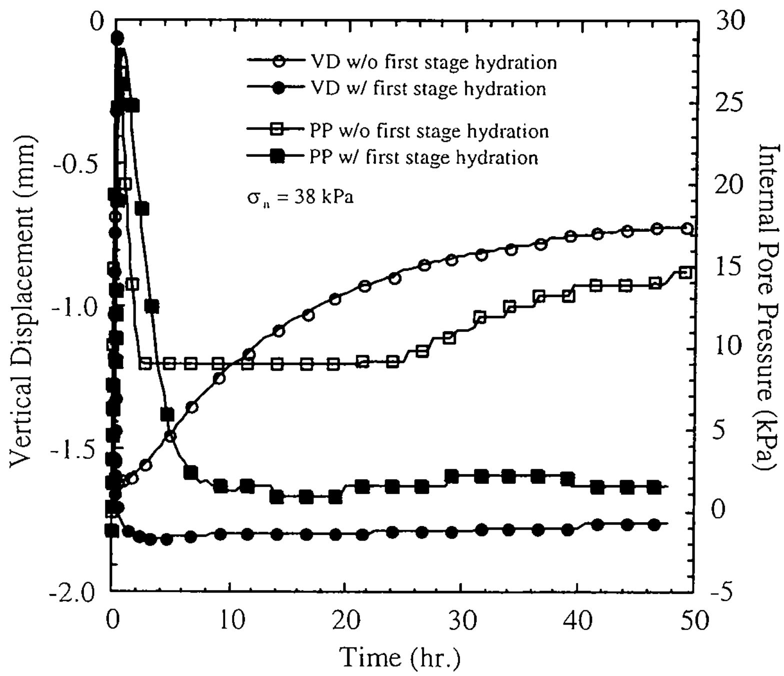

Figure 2. Effect of accelerated hydration procedure for NP GCL (Fox *et al.* 1998).

Consolidation Stage

If the shear strength of a GCL or GCL interface is desired at the hydration normal stress (σ_h), then shearing can begin at once the GCL is fully hydrated. However, normal stress often increases on a GCL after hydration in the field and shear strength is needed at a higher normal stress level. The best test procedure to obtain this shear strength is to consolidate a GCL test specimen from σ_h to the shearing normal stress (σ_n). It is important to follow the same normal stress sequence for hydration/consolidation in the laboratory as expected in the field because this sequence affects the shear strength of hydrated bentonite (Eid and Stark 1997). Figures 3 and 4 show this effect for internal shear of a hydrated GM-supported GCL. Specimens hydrated at σ_h = 17 kPa and then consolidated to σ_n showed 25 to 30 percent lower shear strength than corresponding specimens that were hydrated under the shearing normal stress (i.e., $\sigma_h = \sigma_n$). Hydration at low normal stress apparently results in more water being adsorbed into the double-layer of the bentonite particles, not all of which is expelled during subsequent consolidation. Hydration stress history has also been shown to affect the peak and large displacement

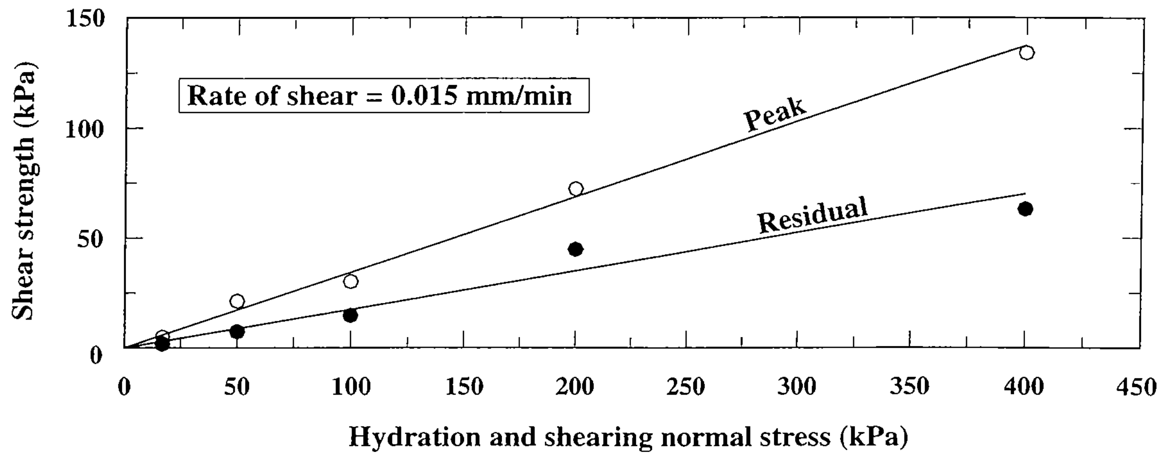

Figure 3. Peak and residual failure envelopes for a GMX/GM-supported GCL interface hydrated at the shearing normal stress (Eid and Stark 1997).

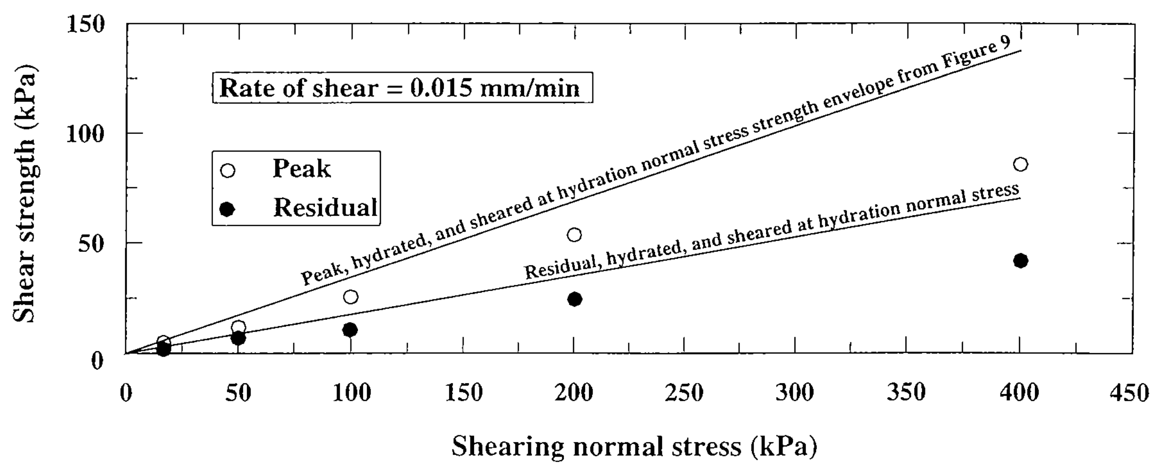

Figure 4. Peak and residual failure envelopes for a GMX/GM-supported GCL interface hydrated at σ_n = 17 kPa and then consolidated to the shearing normal stress (Eid and Stark 1997).

shear strengths of GMX interfaces with needle-punched and stitch-bonded GCLs (Hewitt *et al.* 1997).

Little data is currently available on the optimal consolidation procedure for GCL specimens in the laboratory. An instantaneous stress increase from σ_h to σ_n is not appropriate for a hydrated GCL specimen unless the difference is small (e.g., $\sigma_n - \sigma_h \leq \sigma_h$). Instead, consolidation loads should be applied in small increments to avoid extrusion of bentonite laterally or vertically out of the specimen. Continuous-loading (i.e., ramp-loading) and incremental-loading procedures have been used with success. The maximum rate of stress increase for the continuous-loading procedure will depend primarily on GCL type, σ_h, and experience. Incremental-loading consolidation is generally applied using daily or half-day increments with a load-increment-ratio of one (i.e., normal stress doubled each time). Sometimes vertical displacement measurements are used to establish the duration of each load increment. Load increments can be applied even if consolidation is not completed for the previous increment. However, the GCL must be fully consolidated under the final load increment so that no excess pore pressures exist within the specimen at the start of shearing. Full consolidation can be estimated using vertical displacement data in a similar manner as that for standard oedometer tests (e.g., $\sqrt{t}$ or log t graphical construction procedures).

The unavoidable drawback to the consolidation stage is the time required. There is no accelerated procedure available to rapidly consolidate hydrated GCLs. The only way to avoid the impact of long consolidation times on a testing program is to hydrate/consolidate multiple GCL specimens in separate shear boxes outside of the shearing frame (see previous section).

Shearing Stage

With the exception of stress-controlled creep shear tests, GCL shear tests should be displacement-controlled so that post-peak behavior can be measured. The only issue for the shearing stage that remains unresolved is the displacement rate (i.e., shearing rate). The maximum allowable displacement rate greatly affects the time required to perform GCL shear tests. It might be expected that the shear strength of hydrated GCLs is rate-dependent because shear-induced excess pore pressures may be generated in the bentonite and because both hydrated bentonite and geosynthetics display creep and strain rate effects. Correspondingly, the shear strength of dry unreinforced GCLs should show minimal shearing rate effects. Eid and Stark (1997) demonstrated that, indeed, the shear strength of dry encapsulated GCLs is essentially constant for shearing rates less than 1 mm/min. Therefore, the default (industry accepted) shearing rate of 1 mm/min. is recommended for such tests. The rest of this section is concerned with the appropriate shearing rate for hydrated GCLs.

The maximum displacement rate for hydrated GCLs and GCL interfaces as given by Equation 1 is based on dissipation of shear-induced pore pressures in hydrated bentonite. Based on GCL consolidation test data, Shan (1993) estimated required shearing rates that allow for pore pressure dissipation would range from 0.001 to 0.0001 mm/min. For example, if Δ_f = 50 mm and t_{50} = 0.5 day, then Equation 1 gives R = 0.0014 mm/min.

for an internal shear test (double-drained) and $R = 0.00035$ for an interface shear test against a GM. Shear tests conducted to $\Delta = 50$ mm using these rates will require 25 and 99 days, respectively. These times are prohibitive for production testing and might even be too long for academicians! Furthermore, many data sets indicate that internal shear failures of hydrated NP GCLs occur at one of the bentonite-geotextile interfaces (Gilbert *et al.* 1996, Fox *et al.* 1998, Eid *et al.* 1999). Assuming this interface is essentially drained since it is at the boundary of the GCL, shear-induced pore pressures should be small and drained shear strengths should be obtained. Thus, the practicality and applicability of Equation 1 to GCL shear testing is questioned.

Several studies have been conducted on the effect of displacement rate on measured internal shear strength of hydrated GCLs. In most cases, GCL shear strength has been found to increase with increasing displacement rate. However, some contradictory results have also been obtained. A sampling of such results is presented in Figures 5 – 7. Figure 5 shows τ_p and τ_r values for stitch-bonded and needle-punched GCLs obtained for displacement rates of 0.01 to 10 mm/min and $\sigma_n = 72$ kPa (Fox *et al.* 1998). Both values increased 3 to 5 percent for each cycle of displacement rate. In contrast to Fig. 5(b), the data of Stark and Eid (1996) indicate that τ_r of a W/NW NP GCL at $\sigma_n = 17$ kPa is independent of displacement rate. Figures 6 and 7 present peak shear strengths for a W/NW NP GCL obtained over several log cycles of displacement rate by Eid *et al.* (1999) and McCartney *et al.* (2001), respectively. Both studies performed tests over a similar normal stress range that included normal stress levels above and below the swell pressure of bentonite (approx. 130 kPa, Stark 1997). The results are, however, quite different. Eid *et al.* (1999) found that, for high σ_n, τ_p was constant at low shearing rates and increased at higher rates. The trend in the data was not consistent at lower normal stresses. McCartney *et al.* (2002) showed that τ_p decreased with increasing displacement rate for high σ_n and increased with increasing displacement rate for low σ_n. Other studies have found that τ_p increased with increasing displacement rate (Daniel *et al.* 1993, Berard 1997, Gilbert *et al.* 1997, Zelic *et al.* 2002). Considering the above data, the appropriate displacement rate for internal shear of hydrated GCLs remains unclear. Until this issue is resolved, a maximum displacement rate of 0.1 mm/min. is recommended for hydrated GCL internal shear tests.

Two studies have investigated the effect of displacement rate on hydrated GM/GCL interface shear strengths. Using a ring shear device, Eid and Stark (1997) tested interface strengths of an unreinforced GCL placed against a GMX under hydrated conditions. The normal stress was 17 kPa and shearing rates ranged from 0.015 to 18.5 mm/min. Residual interface strengths were independent of shearing rate. The peak internal strength increased approximately 13 percent per log cycle of shear rate. All failures occurred between the hydrated bentonite and the GMX. Triplett and Fox (2001) found that shearing rate had no effect, on average, on interface shear strengths between the woven side of a needle-punched GCL and various HDPE GMs at $\sigma_n = 72$ kPa. These results suggest that a shearing rate of 1 mm/min. is acceptable for hydrated GM/NP GCL interfaces, but may be too fast for hydrated encapsulated GCLs.

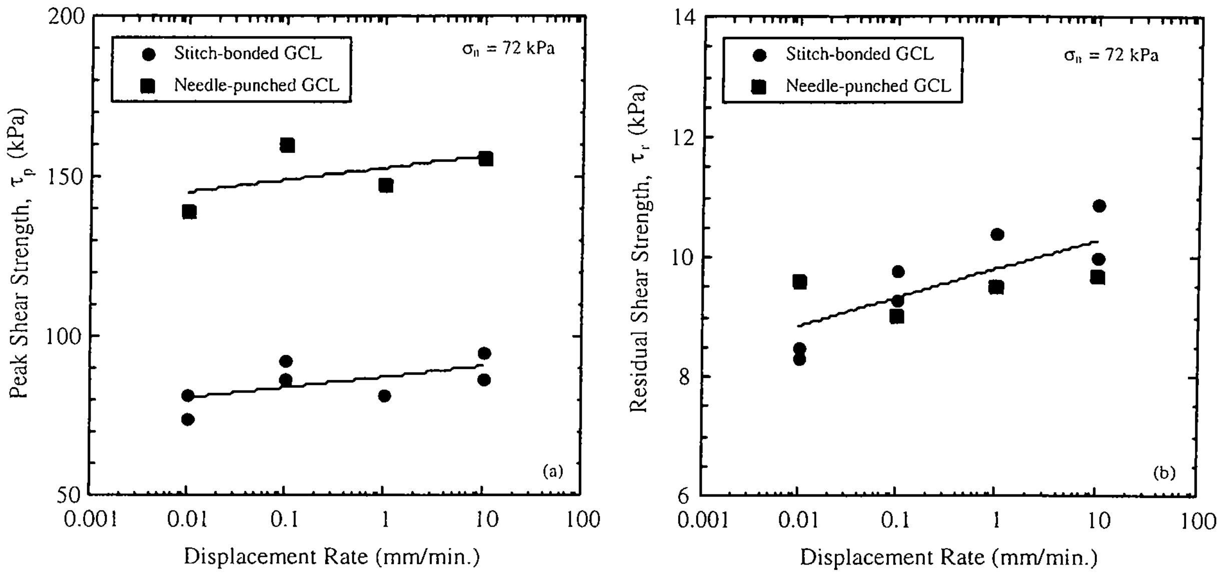

Figure 5. Effect of displacement rate on: (a) peak, and (b) residual internal shear strength of reinforced GCLs at σ_n = 72 kPa (Fox *et al.* 1998).

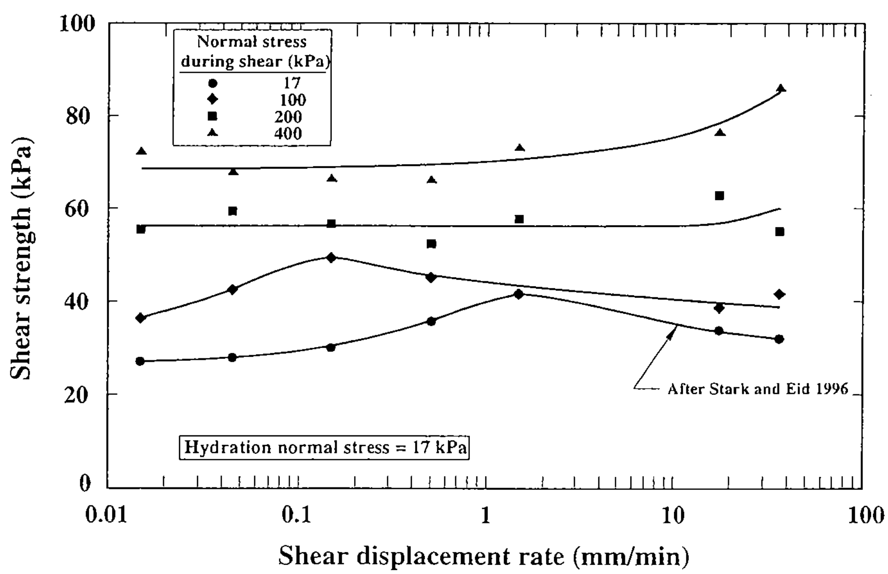

Figure 6. Effect of displacement rate on peak internal shear strength of a W/NW NP GCL at four normal stress levels (Eid *et al.* 1999).

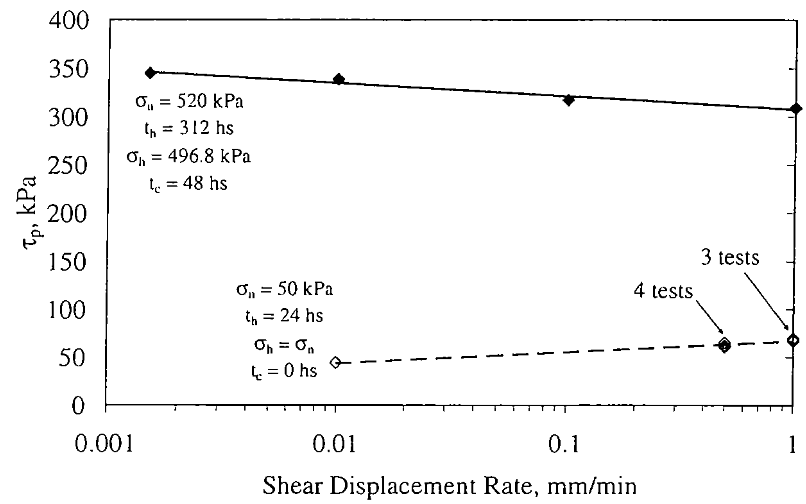

Figure 7. Effect of displacement rate on peak internal shear strength of a W/NW NP GCL at two normal stress levels (McCartney *et al.* 2002).

Post-Test Measurements

A failed GCL or GCL interface test specimen should be inspected after shearing to assess the surface(s) on which failure occurred and the general nature of the failure. Unusual distortion or tearing of the specimen should be recorded and may indicate problems with the specimen gripping system. Also, the condition of the geosynthetics at specimen end clamps (if present) should be recorded. Evidence of high tensile forces at the clamps, such as tearing or necking of the geosynthetics, are indications that progressive failure may have occurred in the test. Final water contents (w_f) of the GCL specimen (minimum 5 specimens are recommended) should be taken after shearing can be used to assess the level and uniformity of hydration that was achieved. The shearing device must be disassembled and water content measurements taken fairly quickly for w_f values to have validity.

Specification of Testing Program and Delivery of Test Results

Shear tests of GCLs or GCL interfaces should be conducted according to the guidelines of ASTM D 6243. This section presents a list of additional considerations from Fox and Stark (2003) that deserve particular attention to ensure that quality test results are obtained.

When requesting a shear testing program for a GCL or GCL interface, a user should require the following:

1. Calibration of the shear testing device for accuracy of normal stress and shearing force at a minimum of once every 2 years,
2. A specimen gripping system that can impart uniform or nearly uniform shear displacement to the test specimen,

3. Full GCL hydration is achieved (if applicable) before consolidation of the GCL to the desired shearing normal stress (if applicable),
4. Consolidation of a GCL should occur in small increments so as to minimize bentonite extrusion,
5. Measurement of vertical displacement during hydration, consolidation, and shearing, and
6. Thorough inspection of failed specimens and measurements of final GCL water content.

When requesting a shear testing program for a GCL or GCL interface, a user should specify the following:

1. Specimen selection and trimming procedures,
2. Number of tests,
3. Specimen configuration (bottom to top),
4. Soil compaction criterion (if applicable),
5. Number of interfaces (single or multiple) to be tested at the same time,
6. Orientation of the GCL or GCL interface (machine or cross-machine direction),
7. Hydration normal stress and hydration time duration,
8. Consolidation procedure, including stress increments or load-increment-ratio and duration,
9. Shearing procedure, including shearing normal stress and displacement rate.

When receiving the results of a shear testing program for a GCL or GCL interface, a user should expect the following:

1. Description of all specimen sampling and trimming procedures,
2. Description of all testing equipment,
3. Description of specimen configuration and preparation conditions,
4. Description of all test conditions (hydration, consolidation, shearing),
5. Shear stress-displacement relationships,
6. Vertical displacement data during hydration, consolidation, and shearing,
7. Peak and large displacement shear strengths,
8. Peak and large displacement failure envelopes,
9. Location and condition of the failure plane(s) within the test specimens, and
10. Initial and final GCL water contents.

Conclusions

The foregoing discussion of the laboratory measurement of the shear strength of GCLs and GCL interfaces has led to the following conclusions:

1. Direct shear is expected to remain the preferred test method for GCLs because large specimens can be tested and peak strengths can be measured in one direction with nominally uniform shear displacement.

2. Perhaps the most important feature of a GCL shear device is the specimen gripping system. Ideally, the gripping surface should prevent slippage between the test specimen and the shearing blocks. Because many gripping surfaces do not provide sufficient resistance to slippage, mechanical compression clamps are often used to hold the ends of the geosynthetics during shear. These clamps may result in the development of tension in the geosynthetics and may cause progressive failure of the specimen. The effect of progressive failure is to reduce the peak shear strength and increase the large displacement (but not residual) shear strength.

3. All non-encapsulated GCLs should be hydrated to equilibrium under the normal stress expected in the field at the time of field hydration. Encapsulated GCLs are generally tested in the dry condition and the design shear strength is calculated using known values of hydrated bentonite shear strength and the average level of bentonite hydration expected over the life of the facility.

4. After hydration, a GCL should be consolidated to the final design normal stress for shearing. It is recommended that the consolidation load be applied using small increments to minimize bentonite extrusion from the specimen. The specimen should be fully consolidated under the final increment, which may take several days, so that excess pore pressures are zero prior to the start of shearing.

5. The most appropriate displacement rate for GCL internal and interface shear tests remains a point of continuing debate. Available data indicate that dry encapsulated GCLs and hydrated GM/GCL interfaces show essentially no rate effects and can be sheared at 1 mm/min. No information is available on displacement rate effects for other GCL interfaces (e.g., GCL/drainage geocomposite, GCL/soil). The appropriate displacement rate for internal shear tests remains unclear. Most studies indicate that internal shear strength increases with increasing displacement rate, although some key studies have produced contradictory results. Until this issue is resolved, a maximum displacement rate of 0.1 mm/min. is recommended for GCL internal shear tests. It should be noted that some data sets suggest an even slower rate is necessary.

6. Examination of shear stress-displacement relationships is an easy way to make a preliminary assessment of the quality of GCL shear test results. It is recommended that shear stress-displacement relationships be routinely included as part of the test results package for a GCL shear testing program.

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