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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, shear displacement 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 torsional ring shear and large-scale direct shear devices have been used for research. 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 and consolidated to match expected field hydration and loading conditions. Consolidation stresses should be applied in small increments to minimize bentonite extrusion. The appropriate displacement rate during shear is an issue of continuing debate. Available data indicates that internal strengths of dry GCLs and geomembrane/GCL interface shear strengths are essentially constant for displacement rates of 1 mm/min. or less. Peak internal shear strengths of hydrated GCLs generally increase with increasing displacement rate. Residual internal shear strengths of hydrated GCLs may increase or remain constant with increasing displacement 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 vs. displacement relationships should be included as part of all GCL testing reports.

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

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Introduction

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-specific 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 (2004).

The focus of this paper is the laboratory testing procedure used to measure 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 (2004). Discussions in the current paper have benefited greatly from insights provided in these publications and summarize some of the latest thinking on the measurement of GCL internal and interface shear strengths.

ASTM Standard Test Procedure

The current standard test procedure, ASTM Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method (D 6243), requires that GCLs be tested in direct shear with a minimum specimen dimension of 300 mm. The test specimen is sheared between two shearing blocks, each of which is covered with a gripping system (i.e., rough surface) that transfers shear stress to the specimen. End clamping of geosynthetics at the edges of the shearing blocks is permitted to facilitate shearing at the desired location within the specimen. The gripping/clamping system should securely hold the test specimen to the shearing blocks and not interfere with the measured shear strength. The gripping system should also be rigid and permit free water flow into and out of the specimen (if necessary). 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. 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 shear 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) under similar normal stress conditions, and

η = 1 for internal GCL shear with drainage at both boundaries
= 4 for shear of the interface between a 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 maximum displacement 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 primarily using direct shear and torsional ring shear devices. The direct shear device has several advantages, including shear that occurs in one direction, the capability to test relatively large specimens with minimal edge effects, and shear displacement that 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 100 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 device 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 device is that the area of the failure surface decreases during shear, which may increase the shearing normal stress ($\sigma_{n,s}$) and require an area correction for data reduction. To avoid this problem, many GCL direct shear devices have a top shearing block that moves across a longer bottom shearing block. However, this results in the movement of previously unconsolidated and unsheared material into the failure surface, which can also potentially alter the measured shear stress-displacement (τ-Δ) response.

The torsional ring shear device has the advantage that unlimited shear displacement is possible, making it ideal for the measurement of residual shear strength. Also, the failure surface area is constant during shear. 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 different parts of the specimen to fail at different times during the test (i.e., progressive failure). In the ring shear device, progressive failure theoretically proceeds from the outer edge of the test specimen 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. Values of τ_p measured from ring shear tests are usually in agreement with those measured from direct shear tests if the ratio of inside specimen diameter to outside specimen diameter exceeds 0.7 (Stark and Poeppel 1995). Comparative tests on dry bentonite/GMX and hydrated needle-punched (NP) GCL/GMX interfaces using ring shear and direct shear devices yielded τ_p values, but not τ-Δ relationships, that were in close agreement (Stark and Eid 1996, Eid and Stark 1997). The modified Bromhead ring shear device used in these studies had an inside diameter to outside diameter ratio equal to 0.4. 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 shear strengths are measured in one direction with nominally uniform shear displacement.

Specimen Gripping/Clamping System

One of the most important aspects of a GCL shearing device is the gripping/clamping system that secures the test specimen to the shearing blocks. The gripping system should provide high friction against the specimen and may contain short sharp pins or teeth that "bite" into the geosynthetics, producing even higher resistance to slippage. The clamping system usually consists of a wrap-around mechanism or mechanical compression clamps that securely fasten the ends of the geosynthetics to the edges of the shearing blocks. Ideally, to obtain 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 blocks. If slippage occurs, tensile forces will be generated in the geosynthetics and progressive failure of the test specimen may result. Because many gripping systems used for GCL testing are not sufficiently aggressive to shear strong materials (e.g., reinforced GCLs) without assistance, clamping systems are used to facilitate shearing of GCL test specimens in nearly all testing laboratories. In addition to preventing slippage, a gripping system 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 systems 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 blocks (Trauger et al. 1997, Olsta and Swan 2001). Fox et al. (1997) used modified metal connector plates (i.e., joint connector plates for wood truss construction), which have the advantage of providing a well drained surface in addition to a large number of sharp teeth that uniformly grip a GCL specimen. These plates provided a sufficiently aggressive gripping system that even very strong NP GCLs could be sheared internally without the use of end clamps (Fox et al. 1998). Triplett and Fox (2001) glued single-sided GMX specimens to the top shearing block for GMX/NP GCL interface strength tests. This method prevented slippage of the GMX but was limited to lower normal stresses by the shear strength of the glue ($\sigma_{n,s}$ < approx. 280 kPa). 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 to materials near the failure surface.

The type of gripping system can have a large impact on the quality of shear test results. Figure 1 presents τ vs. Δ relationships for internal shear of hydrated NP GCLs obtained using three different gripping/clamping systems. Figures 1(a) and 1(b) present data for a woven (W)/nonwoven (NW) NP GCL product and Figure 1(c) presents data for a NW/NW NP GCL product. The figures correspond to different GCL lots, rolls, and products and are thus probably not suitable for direct quantitative comparison. Instead, the shapes and similarity of the curves are important for the current discussion. Figure 1(a) shows the results of four shear tests conducted using the modified metal connector plate gripping system without end clamps. Inspection of the failed specimens indicated no discernable slippage between the gripping surfaces and the carrier geotextiles during these tests. The relationships display similar smooth shapes and sharp narrow peaks at low displacements. The τ-Δ relationships in Figure 1(a) are probably an accurate representation of actual material shear behavior. Figure 1(b) shows relationships obtained using the textured steel gripping system with end clamps. These curves display slightly wider peaks with small stress undulations but still have good overall similarity. Figure 1(c) shows relationships that suggest problems occurred during shear. These relationships display double peaks, unusually wide peaks, poor similarity, an absence of post-peak strength reduction ($\sigma_{n,s}$ = 96 kPa), and undulations that are non-physical. The erroneous relationships in Figure 1(c) were probably caused by slippage due to a poor specimen gripping system. The resulting progressive failure effects will produce an inaccurate (likely conservative) peak failure envelope and an inaccurate (likely unconservative) large displacement failure envelope. 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 peak and large displacement shear strengths, 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 occurs within an encapsulated GCL over the design life of a waste disposal facility. Thiel et al. (2001) and

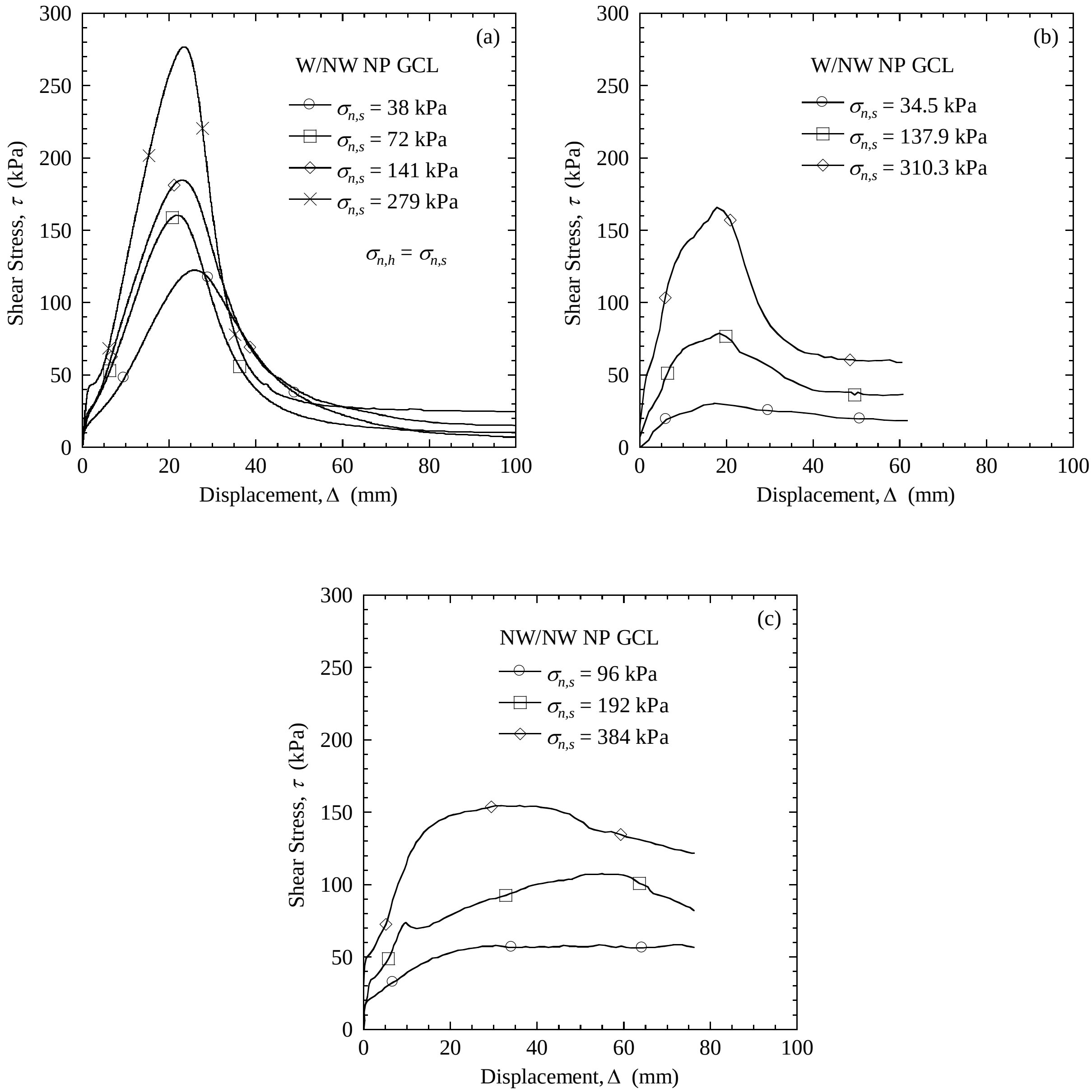

FIG. 1—*Examples of stress-displacement relationships for internal shear of NP GCLs: (a) curves obtained using modified metal connector plates without end clamps (Fox et al. 1998), (b) curves obtained using a textured steel grip with end clamps, and (c) curves that suggest problems occurred during shear.*

Giroud et al. (2002) presented theoretical analyses of long-term bentonite hydration due to water migration through overlaps and defective seams for GM-supported GCLs. However, test data on this issue is unavailable.

Tap water is almost always used for the hydration of GCL test specimens. GCL specimens should be initially hydrated under the normal stress expected in the field at the time of hydration. This hydration normal stress ($\sigma_{n,h}$) will often be a low value. Ideally, a GCL specimen should be hydrated to equilibrium (i.e., until volume change ceases), a procedure that may require a hydration time (t_h) as long as several weeks. As a practical alternative, Gilbert et al. (1997) suggested that a GCL can be considered fully hydrated when the change in thickness is less than 5 percent over a 12 h period. However, using this criterion will typically still require t_h = 10 to 20 days. Most production testing facilities currently hydrate GCLs for 1 to 2 days.

Hydration to equilibrium may not be practical for production testing in which GCL specimens are hydrated in the shearing device. There are two ways 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. As a result, shear tests are not delayed by the lengthy time required to hydrate each specimen. Second, an accelerated hydration procedure can be used to reduce the in-device hydration time (Fox et al. 1998). According to this method, a GCL specimen is hydrated outside of the shearing device for two days under a very low normal stress by adding just enough water to reach the expected final hydration water content (estimated from previous tests). The specimen is then placed in the shearing device and hydrated with free access to water for two additional days under the desired $\sigma_{n,h}$. Most GCL specimens attain equilibrium in less than 24 h using this procedure (Fox et al. 1998, Triplett and Fox 2001). Figure 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 $\sigma_{n,h}$ = 38 kPa. A second specimen was hydrated using the accelerated procedure. In this case, the GCL specimen was placed in a shallow pan, brought to a water content of 185 percent, and cured for two days under a 1 kPa normal stress (applied using dead weights). The GCL specimen was then placed in the shearing device and hydrated with free access to water under $\sigma_{n,h}$ = 38 kPa for an additional two days. Measurements of internal pore pressure and vertical displacement (i.e., volume change) during hydration indicate that the GCL specimen hydrated using the accelerated procedure reached equilibrium within 10 h.

Consolidation Stage

If the shear strength of a GCL or GCL interface is desired at the hydration normal stress, then shearing can begin once the GCL is fully hydrated. However, normal stress often increases on a GCL after hydration in the field and shear strength values are needed at higher normal stress levels. The best test procedure to obtain these strengths is to consolidate GCL test specimens from $\sigma_{n,h}$ to various shearing normal stresses. It is important to follow the same normal stress sequence for hydration/consolidation in the

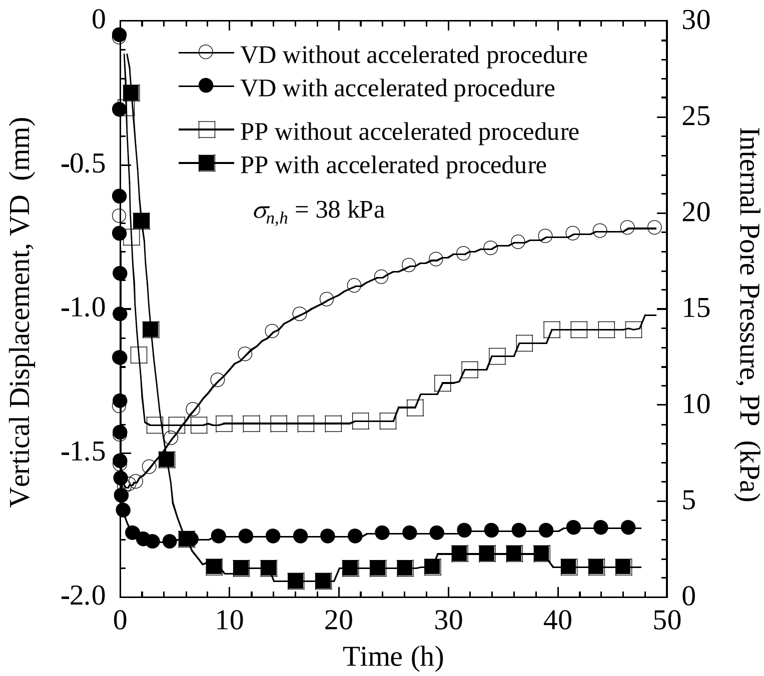

FIG. 2—*Effect of accelerated hydration procedure for a W/NW NP GCL (Fox et al. 1998).*

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 shear tests conducted on a hydrated GMX/GM-supported GCL (i.e., bentonite) interface. Specimens hydrated at $\sigma_{n,h}$ = 17 kPa and then consolidated to $\sigma_{n,s}$ (Figure 4) showed 25 to 30 percent lower shear strengths than corresponding specimens that were hydrated under the shearing normal stress, i.e., $\sigma_{n,h} = \sigma_{n,s}$ (Figure 3). Hydration at low normal stress results in more water being adsorbed into the double-layers of the bentonite particles, apparently not all of which is expelled during subsequent consolidation. Hydration stress history has also been shown to affect the peak and large displacement 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. A single rapid normal stress change from $\sigma_{n,h}$ to $\sigma_{n,s}$ is not appropriate for a hydrated GCL specimen unless the change is small (e.g., $\sigma_{n,s} - \sigma_{n,h} \leq \sigma_{n,h}$). Instead, consolidation loads should be applied in small increments to avoid extrusion of bentonite from the specimen. Continuous-loading (i.e., ramp-loading) and incremental-loading procedures have been used with success. The maximum rate of stress increase for a continuous-loading procedure will depend on GCL type, $\sigma_{n,h}$, and experience. Incremental consolidation loads are generally applied using daily or half-day increments with a maximum load-increment-ratio (LIR) of 1 (i.e., normal stress doubled each time). If bentonite extrusion is observed with LIR = 1, tests should be repeated with a smaller LIR (e.g., 0.5). Vertical displacement measurements are sometimes used to establish the duration of each load increment. The next load increment can be applied even if consolidation is not completed for the previous increment. However, the GCL should 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).

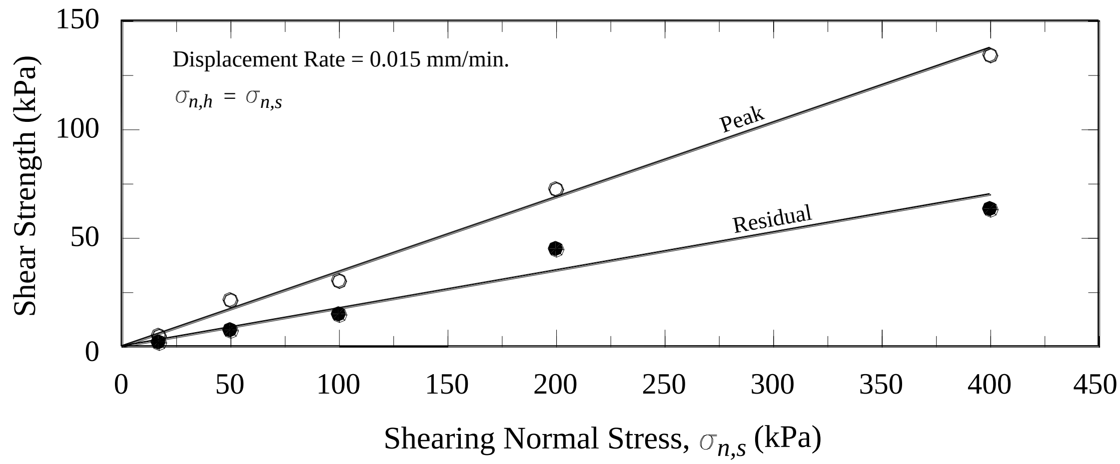

FIG. 3—*Peak and residual failure envelopes for a GMX/bentonite interface hydrated at the shearing normal stress (Eid and Stark 1997).*

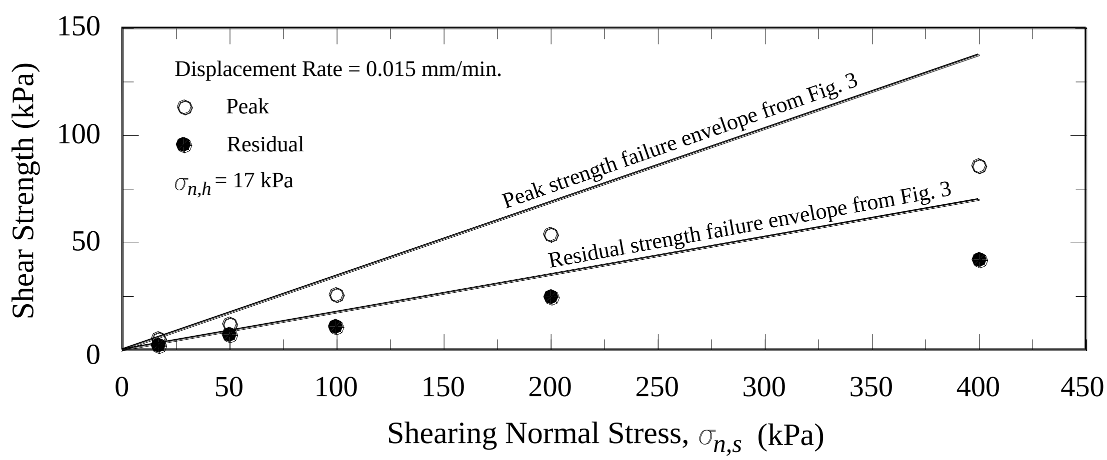

FIG. 4—*Peak and residual failure envelopes for a GMX/bentonite interface hydrated at* $\sigma_{n,h}$ *= 17 kPa and then consolidated to the shearing normal stress (Eid and Stark 1997).*

The unavoidable drawback for 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 simultaneously 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 shear displacement rate (i.e., shearing rate). The maximum allowable displacement rate is important because it 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. Conversely, the shear strength of dry unreinforced GCLs should show minimal displacement rate effects. Eid and Stark (1997) demonstrated that, indeed, the shear strength of dry unreinforced encapsulated GCLs is essentially constant for displacement rates less than 1 mm/min. Therefore, the industry default displacement rate of 1 mm/min. is recommended for such tests. The rest of this section is concerned with the appropriate displacement rate for hydrated GCLs.

Maximum displacement rates given by Equation 1 are based on dissipation of shear-induced excess pore pressures generated within the hydrated bentonite. Using consolidation data for four GCL products, Shan (1993) estimated that maximum displacement rates for internal shear tests would range from 0.001 to 0.0001 mm/min. Shear tests conducted to Δ = 50 mm using these rates will require 34.7 and 347 days, respectively. Such test durations are clearly prohibitive for production testing. Furthermore, many data sets indicate that internal shear failures of hydrated reinforced GCLs occur at a bentonite-geotextile interface (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 (or nearly-drained) shear strengths should be obtained. Thus, the practicality and applicability of Equation 1 for shear testing of hydrated GCLs is questioned.

Many studies have been conducted on the effect of displacement rate on measured internal shear strength of hydrated GCLs. GCL shear strength has been found to increase with increasing displacement rate in most cases, although some key studies have produced contradictory results. 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 $\sigma_{n,s}$ = 72 kPa and displacement rates ranging from 0.01 to 10 mm/min. (Fox et al. 1998). Both values increased 3 to 5 percent for each log cycle of displacement rate. Contrary to Figure 5(b), Stark and Eid (1996) found that τ_r of a W/NW NP GCL at $\sigma_{n,s}$ = 17 kPa was independent of displacement rate. Figures 6 and 7 present peak shear strengths for W/NW NP GCLs 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 values above and below the swell

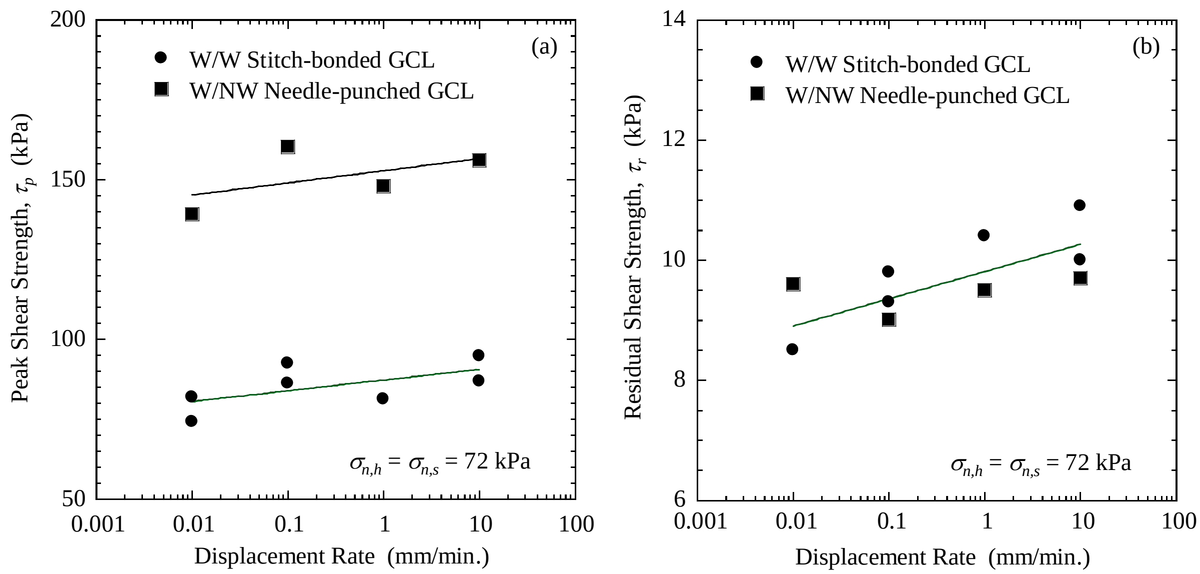

FIG. 5—*Effect of displacement rate on: (a) peak internal shear strength, and (b) residual internal shear strength of reinforced GCLs at* $\sigma_{n,s}$ *= 72 kPa (Fox et al. 1998).*

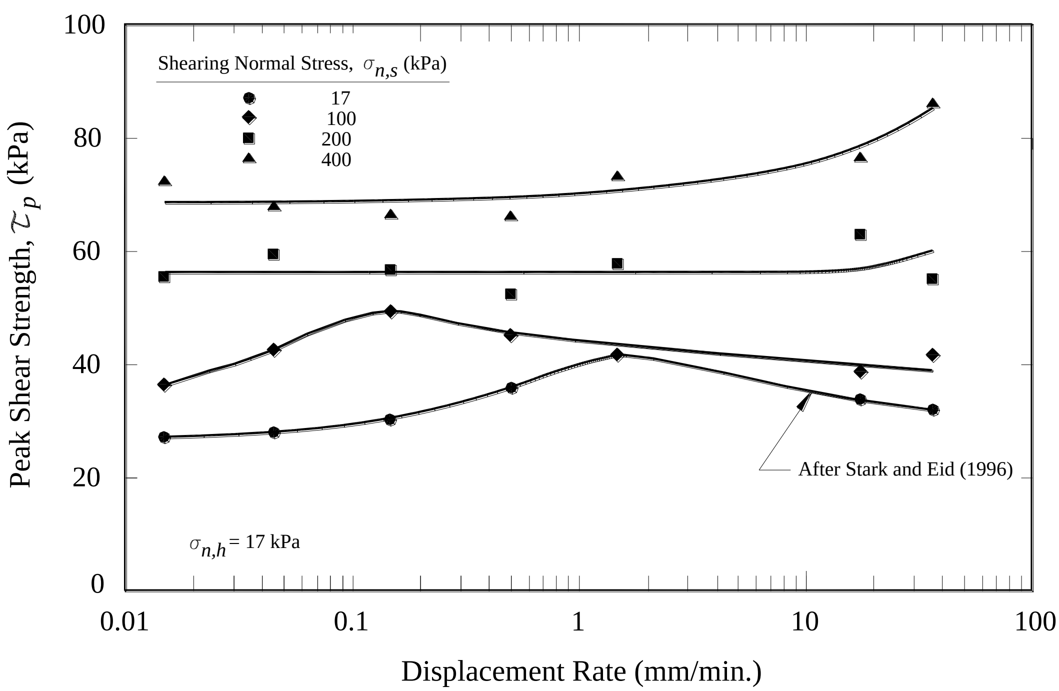

FIG. 6—*Effect of displacement rate on peak internal shear strength of a W/NW NP GCL at four normal stress levels (Eid et al. 1999).*

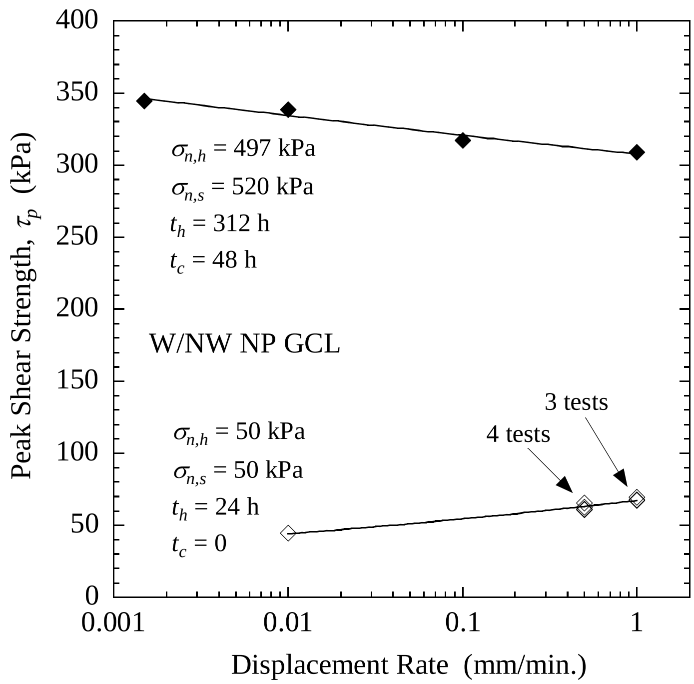

FIG. 7—*Effect of displacement rate on peak internal shear strength of a W/NW NP GCL at two normal stress levels. Variable t_c = consolidation time (McCartney et al. 2002).*

pressure of bentonite (approx. 130 kPa, Shan and Daniel 1991, Stark 1997). The results are, however, quite different. Eid et al. (1999) found that, for high $\sigma_{n,s}$, τ_p was constant at low displacement rates and increased at higher rates. At lower $\sigma_{n,s}$, the curves display peaks with lower shear strengths on either side. McCartney et al. (2002) showed that τ_p decreased with increasing displacement rate for high $\sigma_{n,s}$ and increased with increasing displacement rate for low $\sigma_{n,s}$. Several 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 these results, the appropriate displacement rate for internal shear of hydrated GCLs remains unclear. Since the current default displacement rate (1 mm/min.) generally produces less conservative shear strengths, a maximum displacement rate of 0.1 mm/min. is recommended for hydrated GCL internal shear tests until this issue is resolved. It should be noted that some data sets (e.g., Figure 6) suggest an even slower rate may be necessary. More research is needed on this issue.

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) measured shear strengths of hydrated unreinforced GM-supported GCL/GMX interfaces ($\sigma_{n,h} = \sigma_{n,s}$ = 17 kPa) at displacement rates ranging from 0.015 to 18.5 mm/min. Peak internal strengths increased approximately 13 percent per log cycle of displacement rate and residual internal shear strengths were independent of displacement rate. All failures occurred at the hydrated bentonite/GMX interface. Triplett and Fox (2001) found that displacement rate had no effect, on average, on interface shear strengths between the woven side of a NP GCL and various HDPE GMs at $\sigma_{n,h}$ = $\sigma_{n,s}$ = 72 kPa. These results suggest that a displacement rate of 1 mm/min. is acceptable for hydrated GM/NP GCL interfaces, but may be too fast for hydrated unreinforced encapsulated GCLs.

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 gripping system. The condition of the geosynthetics at the end clamps (if present) should also be recorded. Evidence of high tensile forces at the clamps, such as tearing or necking of the geosynthetics, are indications that progressive failure probably occurred during the test. Depending on the extent of localized distress, such a test may be invalid and may need to be repeated using an improved gripping system. Final water contents (w_f) of the GCL specimen (minimum 5 specimens recommended) and subgrade soil (if applicable) should be taken after shearing 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 and GCL interfaces should be conducted in accordance with ASTM D 6243. This section presents a list of additional considerations from Fox and Stark (2004) that deserve particular attention to ensure that quality test results are obtained.

When contracting for GCL shear tests, a user should *require* the following:

1. Regular calibration of shear testing device for accuracy of normal stress and shearing force (minimum once per year recommended),
2. A specimen gripping system that can impart uniform shearing to the test specimen without slippage,
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 in small increments to minimize bentonite extrusion,
5. Measurement of specimen volume change during hydration, consolidation, and shearing,
6. Thorough inspection of failed specimen(s), and
7. Measurement of initial and final GCL water contents and subgrade soil water contents (if applicable).

When contracting for GCL shear tests, a user should *provide* the following:

1. GCL material(s) (from actual jobsite if possible),
2. Subgrade soil(s) (if applicable),

3. Geosynthetic interface material(s) (if applicable), and
4. Hydration liquid (if different from tap water).

When contracting for GCL shear tests, a user should *specify* the following:

1. Specimen selection, trimming, and archiving procedures,
2. Number and type 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 GCL or GCL interface (machine or cross-machine direction),
7. Hydration normal stress and hydration time duration (or termination criterion),
8. Consolidation procedure, including load increments (or load-increment-ratio) and load increment duration (or termination criterion), and
9. Shearing procedure, including shearing normal stress levels and shear displacement rate.

When receiving the results of GCL shear tests, a user should *expect* the following:

1. Description of specimen selection, trimming, and archiving procedures,
2. Description of testing equipment,
3. Description of specimen configuration and preparation conditions,
4. Description of test conditions (hydration, consolidation, shearing),
5. Shear stress-displacement relationships,
6. Specimen volume change data during hydration, consolidation, and shearing,
7. Peak and large displacement shear strengths,
8. Location and condition of failure surface(s) within test specimens, and
9. Initial and final GCL water contents and subgrade soil water contents (if applicable).

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 shear 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 (i.e., rough surfaces that cover the shearing blocks). Ideally, the gripping system should be rigid, provide good drainage, and prevent slippage between the test specimen and the shearing blocks. Because some gripping systems do not provide sufficient resistance to slippage, a wrap-round mechanism or mechanical compression clamps are often used to hold the ends of the geosynthetics during shear. These clamping procedures may result in the development of tension in the geosynthetics and may cause progressive failure of the test specimen. The effect of

progressive failure is to reduce the peak shear strength and increase the large displacement (but not residual) shear strength.

3. GCL specimens should be fully hydrated under the normal stress expected in the field at the time of hydration. Encapsulated GCLs (i.e., bentonite contained between two geomembranes) may be tested in the dry condition or at various levels of hydration, depending on the average hydration level expected in the field over the life of the facility.

4. After hydration, a GCL specimen should be consolidated to the shearing normal stress (if applicable) using small load increments to minimize bentonite extrusion. The specimen should be fully consolidated under the final increment, which may take several days, so that excess pore pressures are dissipated prior to the start of shearing.

5. The most appropriate shear displacement rate for GCL internal and interface shear tests remains a point of continuing debate. Available data indicate that dry encapsulated GCLs and hydrated geomembrane/GCL interfaces show essentially no displacement 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 GCL 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 indicate that an even slower displacement rate is necessary. More research is needed on this issue.

6. Examination of shear stress vs. 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 vs. displacement relationships be routinely included as part of the test results package for a GCL shear testing program.

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