Dynamic shear testing of a geomembrane/geosynthetic clay liner interface

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ABSTRACT: A series of large-scale direct shear tests were performed to measure the interface shear strength between a textured geomembrane (GMX) and a needle-punched geosynthetic clay liner (NP GCL) for large ranges of normal stress ($\sigma_{n,s}$ = 13 to 2071 kPa) and shear displacement rate (R = 0.1 to 29,000 mm/min.). The experimental data indicate that failure mode of a GMX/GCL specimen depends on both $\sigma_{n,s}$ and R. Tests conducted at low to moderate normal stress levels ($\sigma_{n,s} \leq 692$ kPa) produced interface failures for all displacement rates. At higher normal stress levels, partial or complete internal GCL failures occurred for low displacement rates ($R \leq 100$ mm/min.) and interface failures occurred for high displacement rates ($R \geq 10{,}000$ mm/min.). Peak shear strengths were largely unaffected by displacement rate except at very low (13 kPa) and very high (2071 kPa) normal stress levels. Displacement rate had a significant effect on large-displacement shear strengths at higher normal stresses ($\sigma_{n,s} \geq 692$ kPa), partly due to the effect of R on specimen failure mode.

1 INTRODUCTION

Geosynthetic liner systems are used in waste containment facilities throughout the world and are sometimes subjected to earthquakes or other dynamic loads (e.g., during construction and operations). As such, characterization of dynamic shear behavior can be important in the assessment of long-term performance. Although considerable research has been conducted on the interface shear strength between geomembranes (GMs) and geosynthetic clay liners (GCLs) (Byrne 1994, Gilbert et al. 1996, Triplett and Fox 2001, McCartney et al. 2009), only very limited work has been published on dynamic shear behavior (LoGrasso et al. 2002, Kim et al. 2005). These studies were limited to low normal stress conditions and relatively small shear displacements.

A laboratory research program has been completed at The Ohio State University to investigate the dynamic shear strength of the interface between a textured geomembrane (GMX) and a needle-punched (NP) GCL (Ross 2009). Direct shear tests were conducted for a large range of normal stresses using a dynamic shear machine capable of achieving large displacements and high displacement rates. Using this machine, Nye and Fox (2007) presented the results of an extensive program of monotonic (i.e., single direction) and cyclic (i.e., back-and-forth) internal shear tests for a needle-punched (NP) GCL at a single normal stress. Additional monotonic test data has been presented by Fox et al. (2008) and Fox et al. (2009) for multiple normal stress levels. This paper presents similar monotonic test results for a GMX/NP GCL interface.

2 PROCEDURES

A series of direct shear tests were conducted using the dynamic shear machine described by Fox et al. (2006) and shown in Figure 1. The main features of this device include large specimen size (305 × 1067 mm), large range of normal stress (1 to 2071 kPa), large maximum shear displacement (254 mm), large range of displacement rate (0.01 to 60,000 mm/min for zero load) and the capability to measure specimen volume change. Using this machine, GMX/GCL specimens were sheared between the floor of the test chamber and a horizontal pullout plate. The floor is covered with an aggressive gripping surface (modified truss plates) that has sharp 1-2 mm teeth which firmly hold a GCL without end-clamping and a large number of holes and channels that permit free access to water. The GMX specimen was glued to the underside of the pullout plate. Both shearing surfaces prevent specimen slippage and related progressive failure effects (Fox and Kim 2008). Each GMX/GCL specimen was free to fail at the interface or within the GCL. Specimen volume change

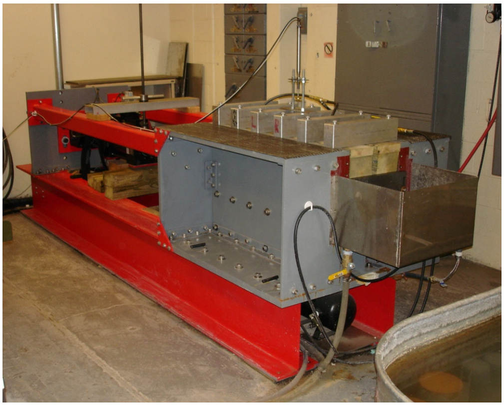

Figure 1. Dynamic direct shear machine.

was monitored throughout hydration and shear using an LVDT.

The experimental program was performed using two geosynthetic products: Bentomat® DN, a NW/NW NP GCL with no thermal bonding manufactured by CETCO (Hoffman Estates, Illinois, USA), and 60 mil Micro Spike®/Smooth, a HDPE GMX with single-sided structured texturing manufactured by Agru America (Georgetown, South Carolina, USA). Twenty-five GCL peel tests (ASTM D 6496) yielded an average peel strength of 2170 N/m. Each GCL specimen was hydrated under the shearing normal stress using the two-stage accelerated hydration procedure of Fox et al. (1998) and further described by Fox and Stark (2004). Twenty-nine displacement-controlled monotonic GMX/GCL interface shear tests were conducted at five levels of shearing normal stress ($\sigma_{n,s}$ = 13, 348, 692, 1382 and 2071 kPa) and shear displacement rates R ranging from 0.1 to 29,000 mm/min. The normal stress range was sufficiently large to include conditions typical of cover systems and bottom liner systems of very deep (150 m) landfills.

3 RESULTS

Figure 2 shows relationships for shear stress τ versus shear displacement Δ that were obtained for GMX/GCL interface tests conducted at the highest normal stress ($\sigma_{n,s}$ = 2071 kPa). In each case, shear stress quickly rises to a peak strength τ_p and then decreases to a substantially lower large-displacement (200 mm) shear strength τ_{200}. Interestingly, the failure mode changes with displacement rate for these tests. Failure occurred internal to the GCL for R = 0.1 and 1 mm/min., partially internal to the GCL and partially at the GMX/GCL interface for R = 100 mm/min., and at the GMX/GCL interface for R = 10,000 and 16,000 mm/min. Specimens with complete internal GCL failures reached a residual shear condition, whereas shear strength for the specimens

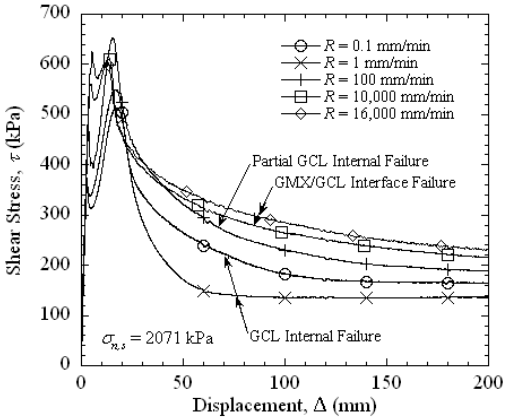

Figure 2. Shear stress versus displacement relationships for $\sigma_{n,s}$ = 2071 kPa and varying displacement rates.

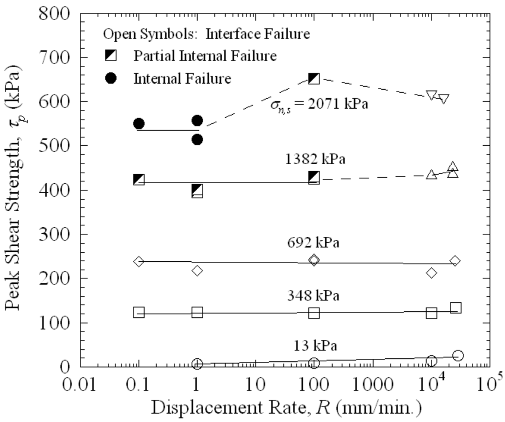

Figure 3. Effect of displacement rate on peak shear strength for GMX/GCL interface.

with partial internal and interface failures was still decreasing at Δ = 200 mm.

Figure 3 shows a plot of τ_p versus R for the GMX/GCL shear tests at all normal stress levels. Tests conducted at $\sigma_{n,s}$ = 13, 348, and 692 kPa produced interface failures for all displacement rates. At $\sigma_{n,s}$ = 1382 kPa, partial GCL internal failures occurred for R = 0.1, 1, and 100 mm/min., with slower rates yielding larger internal failure percentages, and interface failures occurred for R = 10,000 and 25,000 mm/min. The failures at $\sigma_{n,s}$ = 2071 kPa were discussed previously. The data clearly indicate that, above a certain threshold normal stress, failure mode depends on both normal stress and displacement rate. Internal failures occurred at high normal stress and low displacement rates. As normal stress decreased or displacement rate increased, the failure mode transitioned to interface failure. Thus, shear displacement rate had a major influence on failure mode for these materials at high normal stress and may be generally more significant in this regard than previously considered.

Peak shear strength increased substantially with increasing displacement rate for $\sigma_{n,s}$ = 13 kPa (τ_p = 7.75 kPa at 1 mm/min., τ_p = 26.5 kPa at 29,000 mm/min.) and was essentially independent of R for $\sigma_{n,s}$ = 348, 692 and 1382 kPa. Values of τ_p also increased with increasing rate for $\sigma_{n,s}$ = 2071 kPa, which is related to the transition in failure mode. Nye and Fox (2007) and Fox et al. (2009) found that internal shear strength of NP GCLs generally increases with increasing displacement rate, which could explain the failure mode transition observed at the higher normal stress levels in Figure 3.

Figure 4 shows a corresponding plot of displacements at peak shear strength Δ_p for the GMX/GCL tests. At the lowest normal stress (13 kPa), values of Δ_p were relatively constant and ranged from 2 to 4 mm. The other tests at higher normal stress display

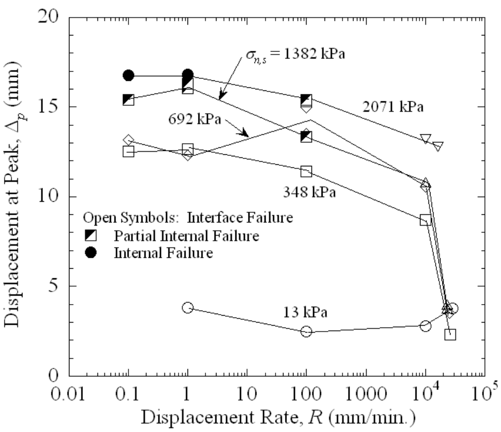

Figure 4. Effect of displacement rate on displacement at peak shear strength for GMX/GCL interface.

very different behavior. In general, Δ_p decreased with increasing displacement rate and, for R ≤ 10,000 mm/min., ranged from 9 to 17 mm. At the fastest displacement rate, however, Δ_p decreased sharply to 2-4 mm, except at $\sigma_{n,s}$ = 2071 kPa. Figure 4 also shows that Δ_p generally increased with increasing normal stress at each displacement rate. This trend is opposite to that observed for GCL internal shear strength tests (Fox et al. 2009).

Figure 5 presents τ_{200} versus R for the GMX/GCL shear tests. Displacement rate had little effect on large-displacement strengths for $\sigma_{n,s}$ = 13 and 348 kPa. However, a decreasing and then increasing trend is observed for $\sigma_{n,s}$ = 692, 1382 and 2071 kPa. The trend for $\sigma_{n,s}$ = 692 kPa is not related to failure mode and may be due to pore pressure conditions on the failure surface. The trends at $\sigma_{n,s}$ = 1382 and

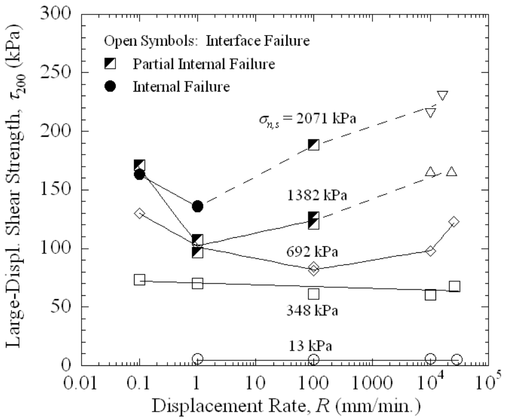

Figure 5. Effect of displacement rate on large-displacement shear strength for GMX/GCL interface.

2071 kPa are likely a combination of pore pressure effects and differing failure modes. A GCL internal failure will generally have smaller large-displacement shear strength than a GMX/GCL interface failure (Triplett and Fox 2001, Chiu and Fox 2004, Fox and Ross 2010). Thus, the partial or complete GCL internal failures produced relatively low values of τ_{200} at high normal stress.

The above data has potential ramifications for the recommended displacement rate for GMX/GCL static shear tests at high normal stress. Recommended displacement rates for internal and interface static shear tests of GCLs are 0.1 and 1 mm/min, respectively (Fox and Stark 2004). A slower rate was recommended for internal shear tests to allow more time for dissipation of possible shear-induced excess pore pressures from the failure surface. On the other hand, the GMX/GCL interface tests of Triplett and Fox (2001) did not show a clear displacement rate effect and 1 mm/min. was considered reasonable. Figure 3 and 5 clearly indicate that displacement rate effects are more complex than previously considered and, as such, recommended values for static shear tests of GMX/GCL interfaces may need to be reevaluated.

4 CONCLUSIONS

This paper presents measured dynamic shear strengths of the interface between a HDPE textured geomembrane (GMX) and a hydrated needle-punched geosynthetic clay liner (NP GCL). A series of displacement-controlled monotonic (i.e. single-direction) shear tests were performed for large ranges of normal stress ($\sigma_{n,s}$ = 13 to 2071 kPa) and shear displacement rate (R = 0.1 to 29,000 mm/min.). The experimental data indicate that failure mode of a GMX/GCL specimen depends on both normal stress and displacement rate. Tests conducted at low to moderate normal stress levels ($\sigma_{n,s} \leq 692$ kPa) produced interface failures for all displacement rates. At higher normal stress levels, partial or complete internal GCL failures occurred for low displacement rates ($R \leq 100$ mm/min.) and interface failures occurred for high displacement rates ($R \geq$ 10,000 mm/min.). Peak shear strengths were largely unaffected by displacement rate except at very low (13 kPa) and very high (2071 kPa) normal stress. Displacement at peak strength generally increased with increasing normal stress and decreased with increasing displacement rate. Displacement rate had a significant effect on large-displacement shear strengths at higher normal stresses ($\sigma_{n,s} \geq 692$ kPa), partly due to its effect on specimen failure mode.

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