Interface Shear Damage to a HDPE Geomembrane. I: Gravelly Compacted Clay Liner

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Abstract: An experimental program of large-scale direct shear tests has indicated that shear displacement of a high-density polyethylene (HDPE) geomembrane (GM) over a gravelly compacted clay liner (CCL) under moderate to high normal stress conditions can cause much greater damage to the geomembrane than static pressure alone. Essentially, no damage was observed at low normal stress. The greatest geomembrane damage occurred at high normal stress (1,658 kPa) and yielded an average of 169 holes/m^2, with a maximum hole size of 23 mm. Size, angularity, and hardness of the gravel particles are also important factors with regard to potential damage. Geomembrane damage was greatly reduced when a needle-punched geosynthetic clay liner (GCL) was placed between the geomembrane and gravelly CCL, including one test conducted at very high normal stress (4,145 kPa). The findings suggest that gravelly soils should be viewed with caution for the construction of GM/CCL composite liners for landfill bottom liner systems and other moderate- to high-stress applications. If there is a reasonable expectation for GM/CCL interface shear displacement, project-specific direct shear tests should be conducted to determine the potential for shear-induced geomembrane damage. Recommendations are provided for the performance of such tests and for design options when damage mitigation is necessary. **DOI:** **10.1061/(ASCE)GT.1943-5606.0001132.**

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Introduction

Geomembranes (GMs) are used as liquid and vapor barriers in a wide variety of engineered facilities, including dams, reservoirs, heap leach pads, and landfills. For a geomembrane to provide an effective barrier, physical damage in the form of tears and punctures must be minimized. The greatest risk of damage is associated with stress concentrations from direct contact with coarse soil particles (e.g., gravel or stones), which can occur from an underlying soil subgrade or an overlying granular soil layer (Nosko and Touze-Foltz 2000; Giroud and Touze-Foltz 2003). In such cases, protection layers are needed to guard against puncture and limit tensile strains that may lead to stress cracking and the development of holes in a geomembrane over time (Giroud 1973, 1982; Rowe et al. 2004; Peggs et al. 2005).

Extensive research has been conducted on the use of protection layers to mitigate geomembrane damage. Although some studies have investigated damage due to construction operations (Heerten 1994; Reddy et al. 1996a), most of this work has focused on damage that occurs due to static overburden pressure (Motan et al. 1993; Brummermann et al. 1994; Heerten 1994; Wilson-Fahmy et al. 1996; Narejo et al. 1996; Koerner et al. 1996; Zanzinger 1999; Tognon et al. 2000; Dickinson and Brachman 2008; Stark et al. 2008; Brachman and Sabir 2013). This research has included theoretical and numerical analyses (Wong and Wijewickreme 1993; Giroud et al. 1995), long-term creep puncture tests (Koerner et al. 2010), measurements of geomembrane strains from gravel contacts (Brachman and Gudina 2008a, b), and investigations of the protection provided by a geosynthetic clay liner (GCL) when placed between a rough subgrade and an overlying geomembrane (Narejo et al. 2002, 2007; Athanassopoulos et al. 2009; Allen and Narejo 2010; Brachman and Sabir 2010). On the other hand, the potential for geomembrane damage due to interface shear has not received comparable attention.

After installation, geomembranes are commonly subjected to shear stress from a variety of sources, including construction operations, waste settlement, seismic loading, and nearby slopes. Small displacements will occur on a geomembrane interface if the mobilized shear resistance is less than the peak shear strength, whereas larger displacements will occur if the peak strength is exceeded. In landfills, for example, compression and decomposition of municipal solid waste can produce large settlements (Edil et al. 1990; Park et al. 2002). In addition to causing potential problems with the grade and integrity of a cover system, these settlements create downdrag forces on the side slopes of a bottom liner system, which can cause local shear displacements even if the fill is globally stable (Stark and Poeppel 1994; Reddy et al. 1996b; Filz et al. 2001; Jones and Dixon 2005). Numerical simulations have indicated that depending on the conditions, these displacements can exceed 1 m on the side slopes of a bottom liner (Dixon et al. 2012; Sia and Dixon 2012). Global failures involving geomembrane/clay liner interfaces have been reported for landfills (Mitchell et al. 1990; Seed et al. 1990; Koerner and Soong 2000; Bonaparte et al. 2002; Benson 2002; Giroud 2005; Amaya et al. 2006); however, local shear failures are difficult to detect and will generally go unnoticed unless there is a specific incentive for investigation, e.g., an earthquake (Augello et al. 1995). Assessment of geomembrane integrity for interface shear conditions

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is therefore warranted, especially considering that local movements are buried within a landfill and any resulting damage is unlikely to be detected and repaired.

Some studies have investigated mechanisms of interface shear resistance, postpeak strength reduction, and material damage for geomembranes against other geosynthetics (Gilbert and Byrne 1996; Jones and Dixon 1998; Frost and Lee 2001; Triplett and Fox 2001; Li and Gilbert 2006) and against soils, including sands, sand-silt and sand-clay mixtures, and pure clays (Vaid and Rinne 1995; Dove and Frost 1999; Ling et al. 2001; DeJong and Westgate 2005; Fleming et al. 2006). However, only one study has investigated geomembrane damage due to interface shear against soils containing gravel (Fox et al. 2011). Fox et al. (2011) conducted large-scale direct shear tests of high-density polyethylene (HDPE) and linear low-density polyethylene (LLDPE) geomembranes over compacted gravelly sand at a single normal stress (958 kPa) to evaluate geomembrane integrity under specific operational conditions for a mineral reclamation facility. The results indicated that interface shear can produce greater geomembrane damage than static pressure alone. Although no corresponding studies have been conducted for gravelly clay, geomembranes are often placed over compacted clay liners (CCLs) that have appreciable gravel content. A study of 67 natural soil CCLs from North American landfills conducted by Benson et al. (1994) indicated that 46 CCLs (69%) contained gravel, 13 CCLs had gravel contents between 5 and 10%, and one CCL had a gravel content of 22%. Likewise, another database of 89 natural soil CCLs presented by Bonaparte et al. (2002) indicated that 28 CCLs (31%) contained gravel, 10 CCLs had gravel contents between 5 and 10%, and three CCLs had a gravel content of 10%. Heap leach pads represent another application in which geomembranes are often placed in contact with soils containing gravel and under high normal stress (Thiel and Smith 2003; Christie and Smith 2013).

CCLs are permitted to contain gravel because controlled laboratory tests have indicated that specimens with gravel contents as high as 60% by dry weight can yield the requisite low hydraulic conductivity, provided that the fine-grained matrix fills the voids between the large particles (Shelley and Daniel 1993). Some gravel within a CCL can even be beneficial with regard to shear strength, compaction stability, and bearing capacity (Daniel and Koerner 2007). As a result, gravel contents approaching 50% may be permissible for CCLs in some jurisdictions as long as the hydraulic conductivity requirement is achieved (Rowe et al. 2004). One problem, however, is that high gravel content may cause particle segregation in the field and produce a CCL that has high hydraulic conductivity zones and is susceptible to internal erosion (Daniel and Koerner 2007). Thus, as a practical matter, gravel content should be limited to approximately 20% to minimize these effects (C. H. Benson, personal communication, 2009), which is consistent with the maximum value reported for a large number of CCLs constructed in the field (Benson et al. 1994; Bonaparte et al. 2002). The maximum allowable particle size for a gravelly CCL is typically 25–50 mm, and, provided the surface is rolled smooth and free of protruding stones, geomembranes are commonly placed over such materials.

This paper is the first of a companion pair of papers that present the findings of an experimental investigation of damage to HDPE geomembranes when placed against coarse (i.e., gravelly) soils and subjected to static pressure and large displacement interface shear. The focus of this paper is GM damage that results from interface shear with an underlying gravelly CCL. Athanassopoulos et al. (2012) and Fox et al. (2012) discussed some of the preliminary findings. Large-scale direct shear tests were conducted on GM/CCL composite liner specimens over a wide range of normal stress. Replicate shear tests were also conducted with a nonwoven/nonwoven (NW/NW) needle-punched (NP) GCL placed between the geomembrane and CCL to evaluate protection provided by the GCL. In each case, geomembrane integrity was assessed after sustained static pressure (i.e., prior to shear) and after shear to large displacement. Additional tests were conducted to determine the progression of geomembrane damage during shear and assess the effects of CCL gravel content and CCL water content on damage results. Implications of the findings with regard to engineering practice are discussed, and future research needs are identified for applications in which geomembranes are placed over CCLs containing gravel. The companion paper (Fox and Thielmann 2014) presents a corresponding investigation of shear-induced damage to a HDPE geomembrane under a gravel drainage layer, with and without a protection nonwoven geotextile at the interface.

Experimental Program

Materials

The experimental program was conducted using two common geosynthetic products. The HDPE geomembrane was manufactured by GSE Lining Technology (Houston, Texas). Geomembrane specimens had a thickness of 1.5 mm, coextruded texturing on one side, and the material properties given in Table 1. The GCL was Bentomat DN, a NW/NW NP product with no thermal bonding, manufactured by CETCO (Hoffman Estates, Illinois). GCL specimens contained granular bentonite (minimum dry $\text{mass}/\text{area} = 4.9\ \text{kg}/\text{m}^2$) held between two NW NP polypropylene geotextiles ($200\ \text{g}/\text{m}^2$). The average GCL peel strength, as obtained from five wide-width tests, was $2{,}231\ \text{N}/\text{m}$ and the coefficient of variation (SD/mean) was 8.5%.

Clay soil for the CCL specimens was obtained from a borrow source for CCL construction at a currently operating municipal solid waste landfill in southern California. This material had a liquid limit of 56 and a plastic limit of 29, and was processed to yield three different soils with the particle size distributions shown in Fig. 1. Soil #l represents the raw borrow clay with 7% subangular gravel and a maximum particle size of 10 mm. The natural gravel particles in Soil #1 consisted of soft shale. Soil #2 was passed through a 4.75-mm sieve and represents the clay with no gravel. Soil #3 was used for most of the tests and represents the clay with 20% gravel. To prepare Soil #3, the clay was passed through a 4.75-mm sieve and then mixed with angular crushed rock having a maximum particle size of 19 mm. The Unified Soil Classification for Soils #1 and #2 is CH, Sandy fat clay, and the Unified Soil Classification for Soil #3 is CH, Sandy fat clay with gravel. Fig. 2 shows the standard and modified Proctor compaction curves for Soils #1 and #3. The addition of gravel to the clay yielded an increase in dry unit weight and a decrease in optimum moisture content (OMC) for both compaction methods. The zero-air-voids (ZAV) curve corresponding to a specific gravity of 2.8 is also shown.

Table 1. Material Properties for HDPE Geomembrane

Properties	Value
Average/minimum thickness	1.47/1.42 mm
Density	0.945 g/cc
MD strength at yield/break	28.0/35.6 kN/m
TD strength at yield/break	27.1/30.1 kN/m
MD elongation at yield/break	16/586%
TD elongation at yield/break	17/475%
MD/TD tear resistance	227/218 N
Puncture resistance	654 N
Asperity height on textured side	0.508 mm

Note: MD = machine direction; TD = transverse direction.

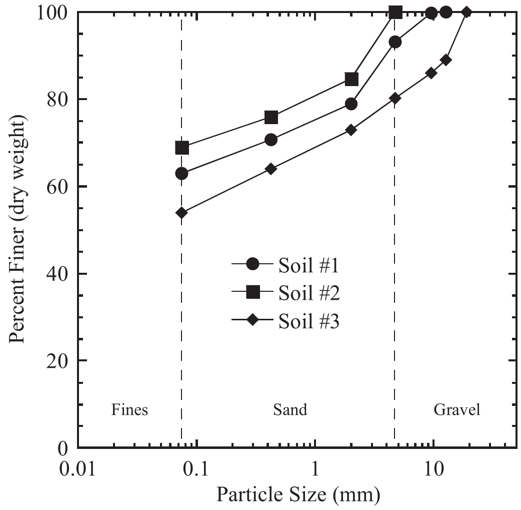


Fig. 1. Particle size distribution curves for three CCL soils

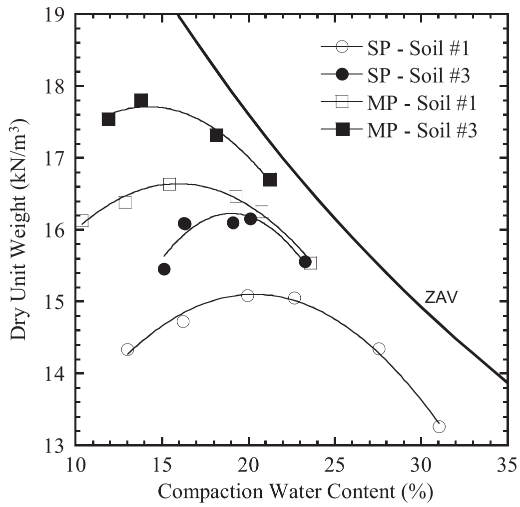


Fig. 2. Standard Proctor and modified Proctor compaction curves for Soils #1 and #3

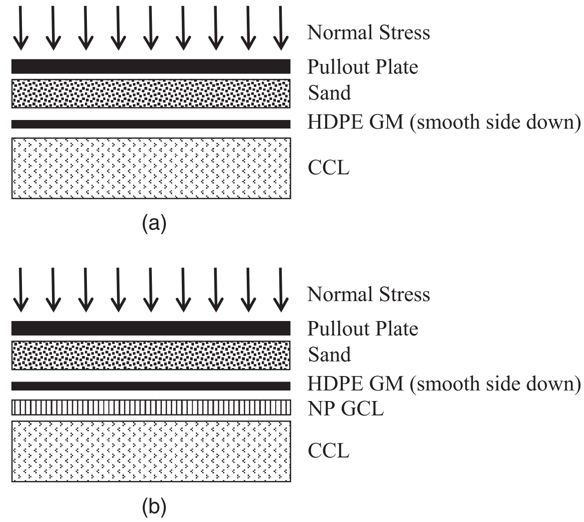


Fig. 3. Specimen configurations for (a) GM/CCL tests and (b) GM/GCL/CCL tests

Fig. 4. Surface of gravelly CCL after compaction for Test 5H1

Procedures

Geomembrane damage effects were evaluated for multiinterface specimens using the large dynamic direct shear machine described by Fox et al. (2006). The test chamber measures 305 × 1,067 mm in plan and provides a shearing surface area of 0.325 m^2. Specimens were sheared between a rigid pullout plate and the floor of the test chamber, each of which was covered with a rough gripping surface. The pullout plate was connected to a hydraulic actuator with a capacity of 245 kN and a maximum stroke of 254 mm. For normal stress $\sigma_n \leq 1{,}658$ kPa, the specimen shearing area was equal to that of the test chamber (305 × 1,067 mm). For $\sigma_n > 1{,}658$ kPa, a new pullout plate was manufactured with a narrower shearing surface on the underside, thus concentrating the applied force over a smaller area. Using this plate, test specimens measuring 152 × 1,067 mm were sheared for normal stress levels of up to 4,145 kPa.

The multiinterface specimens had two configurations, GM/CCL and GM/GCL/CCL, as shown in Fig. 3. From top to bottom, the GM/CCL specimens consisted of sand, geomembrane, and CCL. Each CCL subgrade was composed of Soil #1, #2, or #3 and was compacted in two lifts using a large hand tamper to a final thickness of approximately 75 mm. New subgrade soil was used for each test, and the target water content for compaction was 22% in most cases. Fig. 4 shows a typical view of a CCL specimen after compaction in the test chamber using Soil #3. The top surface of the CCL was smooth, and the gravel particles (lighter in color) did not protrude outward. After compaction, the CCL was sprayed with 100 mL of water to wet the shearing surface. The geomembrane was then placed on the CCL with the smooth side down to facilitate the observation of damage features and ensure that failure occurred at the GM/CCL interface. The edges of the geomembrane were not fixed or clamped to the shearing surfaces to avoid possible progressive failure effects (Fox and Kim 2008). A 25-mm-thick layer of clean medium sand was placed on the geomembrane and lightly tamped, the pullout plate was placed on the sand, and normal stress was applied to the specimen. No additional water was provided after the application of normal stress. Specimens for the GM/GCL/CCL tests were prepared identically to those for the GM/CCL tests, except that a hydrated NW/NW NP GCL was placed between the geomembrane and CCL. The GCL specimens were prehydrated outside of the shear machine using a controlled hydration procedure in which the appropriate amount of water was added to bring the specimen to the expected final water content after shearing (Fox et al. 1998; Fox and Stark 2004).

A total of 20 tests were conducted for the experimental program, each consisting of a static pressure stage and a shearing stage. For the static pressure stage, the normal stress was released after 24 h, the position of the geomembrane on top of the CCL or GCL was marked, and the geomembrane was removed and assessed for damage. For the shearing stage, the geomembrane was repositioned to its original location on top of the CCL or GCL, the specimen was reassembled, and the same normal stress was applied for an additional 24 h. The multiinterface specimen was then sheared to a final displacement of 150 mm at a constant displacement rate of 1.0 mm/min. After shearing was completed, the geomembrane was removed and again assessed for damage. Two full-depth samples of each CCL were taken to obtain average values for final water content and final dry unit weight. The gravel content of the CCLs precluded the use of sampling tubes, and unit weights were measured using a wax coating/water immersion method. Three shallow samples of each CCL were also taken to obtain the average final water content near the shearing surface. Three samples of each GCL were taken for the GM/GCL/CCL tests to obtain the average final GCL water content.

Damage assessments for the geomembrane specimens included visual inspection, a bright light test, and measurement of the number and size of holes. Visual inspections and photographs focused on damage features, such as indentations, scratches, gouges, wrinkles, and holes. For the bright light test, the geomembrane was held against a bright halogen lamp in a dark room. The holes were counted and the longest and perpendicular (to longest) dimensions of each were measured using a caliper. Hole size was taken as the average of these two measurements. The CCL and GCL specimens were also inspected and photographed after each stage of testing.

Table 2 summarizes the experimental program for the GM/CCL tests. Tests 1A–5A were conducted to investigate the effect of normal stress on GM damage ($\sigma_n = 72{-}1{,}658$ kPa). Test 5P was conducted to investigate the progression of geomembrane damage during shear. For this test, the shearing stage was stopped intermittently and the geomembrane was removed, assessed for damage, and then carefully repositioned to continue shearing under the same normal stress. Several additional GM/CCL tests were conducted to investigate the effects of CCL water content (5L1, 5L2, 5H1, and 5H2) and CCL gravel content (3C, 3D, 5C, and 5D) on geomembrane damage. Table 3 summarizes the experimental program for the GM/GCL/CCL tests. Tests 2B–7B were conducted over a broader normal stress range ($\sigma_n = 348{-}4{,}145$ kPa) to investigate protection provided to the geomembrane by placing a hydrated NW/NW NP GCL at the GM/CCL interface.

Results

Final Water Content and Dry Unit Weight

Tables 2 and 3 provide key results from the experimental program. Fig. 5 presents the final dry unit weight versus final water content (after shearing) for the CCL specimens. The compaction curves from Fig. 2 are also included for comparison. Final CCL conditions, as a whole, lie to the wet side of optimum. Excluding the 5L and 5H tests, which were compacted at different water contents, final CCL water contents for the GM/CCL tests fall in a narrow range from 19.4 to 21.6%. These data also show a general trend of increasing dry unit weight with increasing normal stress level. The 5L and 5H tests yielded lower and higher water contents, respectively, and corresponding higher and lower dry unit weights. The lowest final water content for the experimental program, measured for Test 5L1, falls on the line of optimums for Soil #3. Final CCL water contents for the GM/GCL/CCL tests were consistently higher than for the GM/CCL

Table 2. Summary of Experimental Program and Results for GM/CCL Tests

		CCL								
Test	Normal stress σ_n (kPa)	Soil type [gravel content (%)]	Target water content (%)	Final water content (%)	Final surface water content (%)	Final dry unit weight (kN/m^3)	Peak shear strength τ_p (kPa)	Large displacement shear strength τ_{150} (kPa)	GM hole count n	GM maximum hole size s (mm)
1A	72	Soil #3 (20)	22	—	16.9	—	31.4	31.1	0	—
2A	348	Soil #3 (20)	22	21.0	17.7	16.1	123	107	0	—
3A	693	Soil #3 (20)	22	21.5	17.6	15.6	271	271	13	16.8
3C	693	Soil #1 (7)	22	21.6	22.1	15.4	199	111	0	—
3D	693	Soil #2 (0)	22	21.3	21.9	15.7	219	128	0	—
4A	1,176	Soil #3 (20)	22	20.2	19.1	16.0	372	318	13	20.6
5A	1,658	Soil #3 (20)	22	19.4	17.2	16.7	722	627	55	23.4
5C	1,658	Soil #1 (7)	22	20.9	20.9	15.9	437	218	0	—
5D	1,658	Soil #2 (0)	22	21.1	21.1	16.0	454	234	0	—
5P	1,658	Soil #3 (20)	22	20.4	—	16.8	610	578	32	17.0
5L1	1,658	Soil #3 (20)	18	17.4	20.5	16.8	480	350	12	7.1
5L2	1,658	Soil #3 (20)	18	19.4	20.2	16.6	477	305	1	14.2
5H1	1,658	Soil #3 (20)	26	25.0	22.8	15.7	379	331	12	14.0
5H2	1,658	Soil #3 (20)	26	23.5	18.6	15.9	472	314	6	6.1

Table 3. Summary of Experimental Program and Results for GM/GCL/CCL Tests

Test	Normal stress σ_n (kPa)	Soil type [gravel content (%)]	CCL: Target water content (%)	CCL: Final water content (%)	CCL: Final surface water content (%)	CCL: Final dry unit weight (kN/m^3)	GCL: Final water content (%)	Peak shear strength τ_p (kPa)	Large displacement shear strength τ_{150} (kPa)	GM hole count n
2B	348	Soil #3 (20)	22	24.6	21.1	15.9	80.30	80	69	0
3B	693	Soil #3 (20)	22	24.4	—	15.5	57.60	157	109	0
4B	1,176	Soil #3 (20)	22	23.7	22.0	16.3	47.00	271	208	0
5B	1,658	Soil #3 (20)	22	23.1	19.3	16.6	41.60	367	259	0
6B	2,146	Soil #3 (20)	22	21.9	19.6	16.7	38.70	430	295	0
7B	4,145	Soil #3 (20)	22	21.8	21.2	16.8	36.50	643	487	0

tests, which is presumably due to additional water being available from the hydrated GCL specimens. These data also show a clear trend of decreasing water content and increasing dry unit weight with increasing normal stress.

Fig. 6 presents the final CCL and GCL water contents for GM/CCL Tests 1A–5A and GM/GCL/CCL Tests 2B–7B. The CCL water contents fall in a generally narrow range, with surface water contents lower than corresponding average water contents for both the GM/CCL and GM/GCL/CCL tests. This difference likely resulted from extreme shear strains that occurred at the top surface of each CCL and produced a thin hard layer at the shearing interface. Final GCL water contents decrease nonlinearly from 80.3% at $\sigma_n = 348$ kPa to 36.5% at $\sigma_n = 4{,}145$ kPa and are slightly lower than similar measurements from previous studies (Fox and Ross 2011), which likely results from the lack of free water available during these tests.

Static Pressure Stage

Inspection of geomembrane specimens following the initial 24-h static pressure stage indicated relatively little damage and, in some cases, no damage. For the GM/CCL tests, no damage was observed at the lowest normal stress level for Geomembrane 1A ($\sigma_n = 72$ kPa). Damage then increased with increasing normal stress for Geomembranes 2A–5A. Similar to the findings of Brachman and Sabir (2010), application of higher normal stress to the CCL specimens caused greater compaction of the clay matrix around the gravel particles, which in turn caused these particles to protrude outward from the CCL surface and the geomembrane to experience more significant local indentations (dimples). Fig. 7 presents Geomembranes 4A and 5A after the static pressure stage and shows minor to moderate indentations. These tests were conducted at high normal stress using Soil #3 (20% hard angular gravel; particle size $\leq$19 mm) and produced the most significant geomembrane damage due to static pressure alone. Much less damage was observed for GM/CCL tests using Soil #1 (7% soft subangular gravel; particle size $\leq$10 mm), and no damage was observed for GM/CCL tests using Soil #2 (no gravel). Geomembranes for the GM/GCL/CCL tests, all of which were conducted using Soil #3, displayed a few shallow indentations at high normal stress but overall experienced essentially no damage as a result of the protection provided by the GCL. Bright light tests indicated that no holes were created in the geomembranes for any of the static pressure tests.

Shearing Stage

Stress-Displacement Relationships

Fig. 8 presents the shear stress, τ, versus shear displacement, Δ, relationships measured during the shearing stage for GM/CCL Tests 1A–5A and GM/GCL/CCL Tests 2B–7B. Tables 2 and 3 list the peak τ_p and large displacement τ_{150} shear strengths, and Fig. 9 presents the postpeak strength ratios, τ_{150}/τ_p. Failure occurred at the GM/CCL interface for the GM/CCL tests and at the GM/GCL interface for the GM/GCL/CCL tests. Internal GCL failures might have occurred for the GM/GCL/CCL tests at the higher normal stress levels if the geomembrane specimens had been textured on both sides (Fox and Ross 2011). The stress-displacement relationships generally show a similar response consisting of a rapid rise to peak strength at $\Delta = 3{-}12$ mm followed by a gradual postpeak strength reduction. Most tests, including all of the GM/GCL/CCL tests, did not reach a residual shear condition at $\Delta = 150$ mm. Shear stress for Tests 1A and 3A gradually increased throughout the shearing process and yielded $\tau_p \approx \tau_{150}$. Postpeak strength ratios for the GM/GCL/CCL tests were lower than for the GM/CCL tests and those

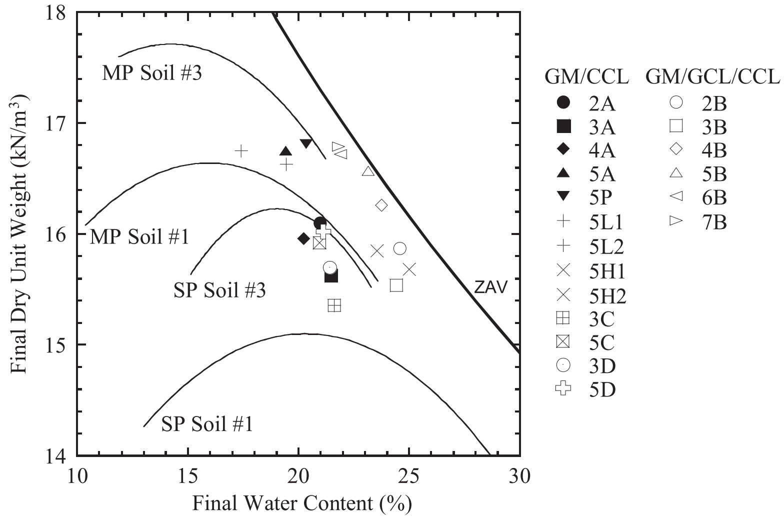


Fig. 5. Final dry unit weight versus final water content for CCL specimens

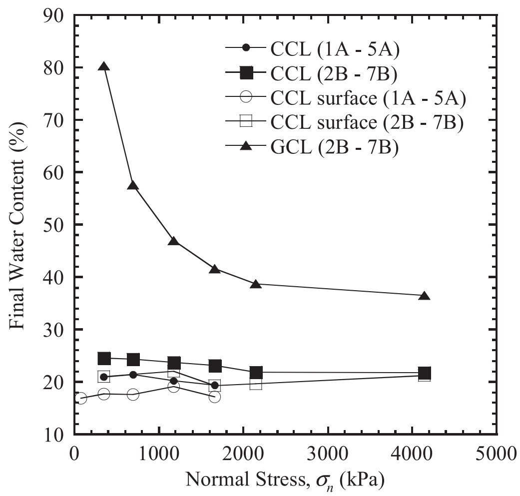


Fig. 6. Final water contents for CCL and GCL specimens

reported by Triplett and Fox (2001) for similar interfaces sheared at $\sigma_n = 7-486$ kPa.

Shear Strength

Fig. 10 shows peak and large displacement failure envelopes for the same GM/CCL and GM/GCL/CCL tests. Shear strengths for the GM/CCL interface were substantially higher and more irregular than for the GM/GCL interface. In particular, Test 5A ($\sigma_n = 1{,}658$ kPa) produced a sharp increase in peak and large displacement strengths. Failure envelopes for both test series are nonlinear; however, the GM/GCL/CCL envelopes indicate a friction angle that decreases with increasing normal stress, whereas the GM/CCL envelopes generally indicate the reverse. The irregularity and reverse trend of the GM/CCL envelopes is attributed to varying degrees of shear resistance between gravel particles in the CCL and the overlying geomembrane and sand layer. As the normal stress increased, greater frictional resistance and mechanical interlocking between the CCL and geomembrane yielded higher shear strength for the GM/CCL interface. Other investigations have also reported higher strengths for smooth geomembranes sheared against a geonet (Stark et al. 1998)

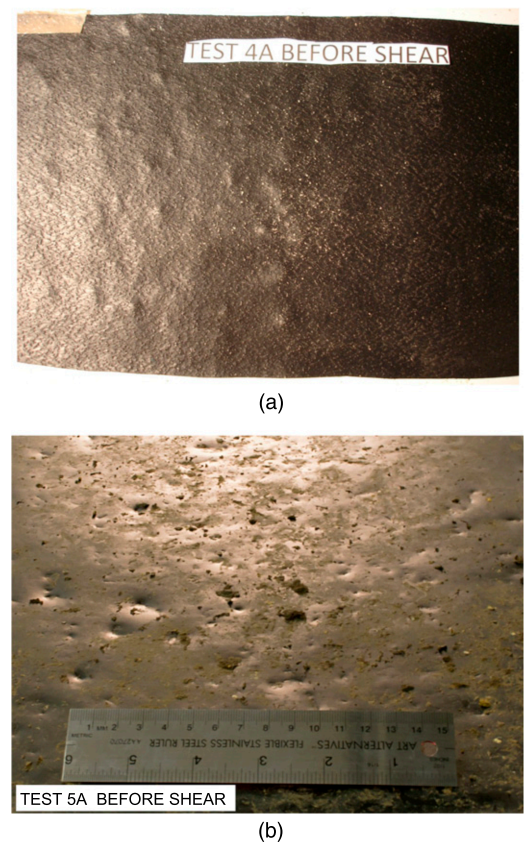


Fig. 7. Geomembranes after static pressure stage for GM/CCL tests: (a) 4A, textured side; (b) 5A, smooth side (scale length = 152.4 mm)

and granular soils (Breitenbach and Swan 1999; Fleming et al. 2006; Dove and Frost 1999) as a result of local geomembrane deformation effects, including upward curvature of failure envelopes. In addition, the development of holes in the geomembrane at higher stress levels (see "Geomembrane Damage" section) allowed some of the protruding gravel particles to shear directly against the overlying sand layer, which further increased the measured shear strength for these tests.

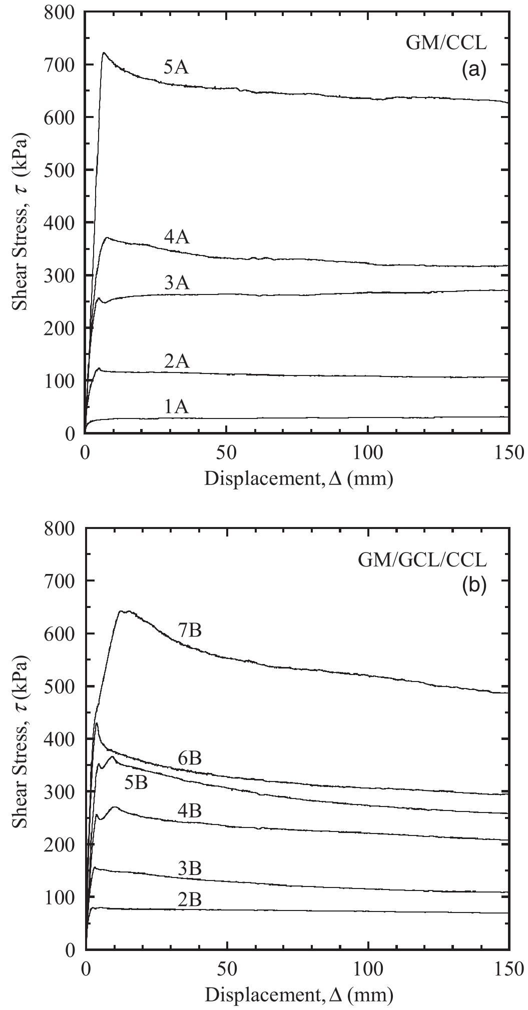


Fig. 8. Shear stress-displacement relationships for (a) GM/CCL tests and (b) GM/GCL/CCL tests

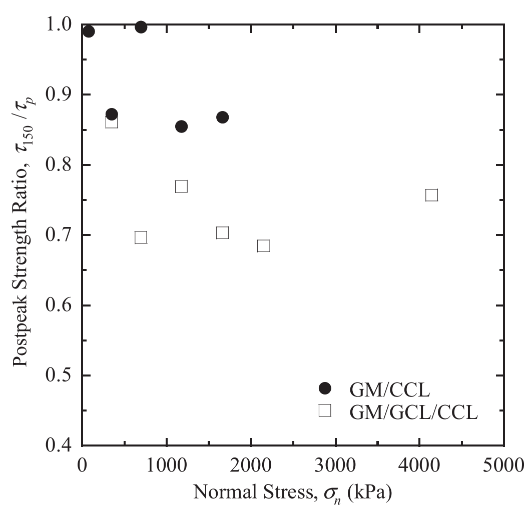


Fig. 9. Postpeak strength ratios

Minimum values of the secant friction angle for the GM/CCL interface are 17.5° for peak strength and 15.1° for large displacement strength (Test 4A). Corresponding minimum values for the GM/GCL interface are 8.8 and 6.7° (Test 7B). For a similar smooth GM/NP GCL (NW side) interface sheared at $\sigma_n = 7-486$ kPa, the data of Triplett and Fox (2001) give slightly higher minimum secant friction angles of 9.5° for peak and 7.6° for large displacement (200 mm) conditions. The minimum large displacement secant friction angle measured for the GM/GCL interface (6.7°) is higher than the range of 4.6–4.9° expected for residual internal shear of a hydrated GCL (Fox et al. 1998; Fox and Ross 2011).

Geomembrane Damage

Effect of Normal Stress Level. Although beneficial in terms of shear strength, greater contact and interlocking between gravel particles in a CCL and an overlying geomembrane during interface shear can be highly detrimental to the integrity of the geomembrane. The GM/CCL tests are first considered. Visual inspections of the geomembranes after shearing revealed minimal to moderate damage (e.g., scratches and gouges) for low normal stress conditions ($\sigma_n \le 348$ kPa) and severe damage (e.g., gouges, wrinkles, and holes) for higher normal stress conditions ($\sigma_n \ge 693$ kPa). Geomembrane 1A experienced minimal damage in the form of light scratches in the direction of shear. Photographs of Geomembranes 2A–5A are shown in Fig. 11 and indicate progressively increasing damage. Geomembrane 2A contains significant longitudinal scratches and gouges; however, no holes were created at this normal stress. Geomembranes 3A and 4A show greater damage, including deep wrinkles and gouges, and contained 13 holes each. Geomembrane 5A experienced the highest level of damage for the experimental program. In addition to extensive scratching, gouging, and wrinkling, this specimen contained 55 holes with a maximum hole size of 23.4 mm. The hole count for Geomembrane 5A translates to an average of 169 holes/m^2. Fig. 12 shows the final CCL shearing surface for Test 5A, including many protruding gravel particles that were responsible for the observed damage. Some gravel particles indicate local displacement relative to the surrounding clay matrix. Geomembrane damage measurements for Tests 1A–5A are presented in Fig. 13 and indicate that both hole count n and maximum hole size s increased with increasing normal stress. Interestingly, the hole count correlates roughly with the irregular trend of GM/CCL failure envelopes in Fig. 10. This suggests that as normal stress increased, greater amounts of gravel contact, puncture, and interlocking with the geomembrane and overlying sand layer contributed to higher measured interface strength.

Relative to their GM/CCL counterparts, geomembrane specimens from GM/GCL/CCL Tests 2B–5B experienced much less damage due to interface shear. Essentially, no damage was observed for low and moderate normal stress conditions and only minor damage was observed for high normal stress. As an example, Geomembrane 5B is shown in Fig. 14(a) and displays several shallow longitudinal indentations. Based on these positive results, GM/GCL/CCL Tests 6B and 7B were conducted at higher normal stress levels of 2,146 and 4,145 kPa. The most significant damage occurred for Geomembrane 7B, which is shown in Figs. 14(b and c). One section of Geomembrane 7B displayed longitudinal indentations with some gouging; however, no holes were discovered and the overall condition was good. Fig. 15 shows that the final condition of the GCL for Test 7B was also good, with no evidence of wrinkles or holes. If geomembrane holes were to develop in a GM/GCL/CCL liner system, the GCL would be expected to seal around the protruding gravel particles and provide additional protection (Shan and Daniel 1991; Fox et al. 2000).

Effect of Gravel Content. Much less geomembrane damage was observed for GM/CCL tests conducted using the CCLs with lower gravel contents. Fig. 16 shows two geomembranes tested at high normal stress ($\sigma_n = 1{,}658$ kPa). Geomembrane 5C was sheared

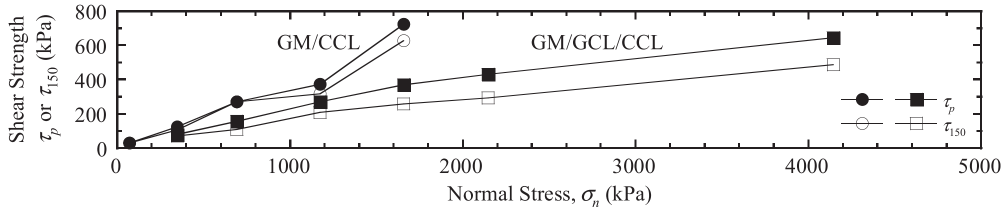
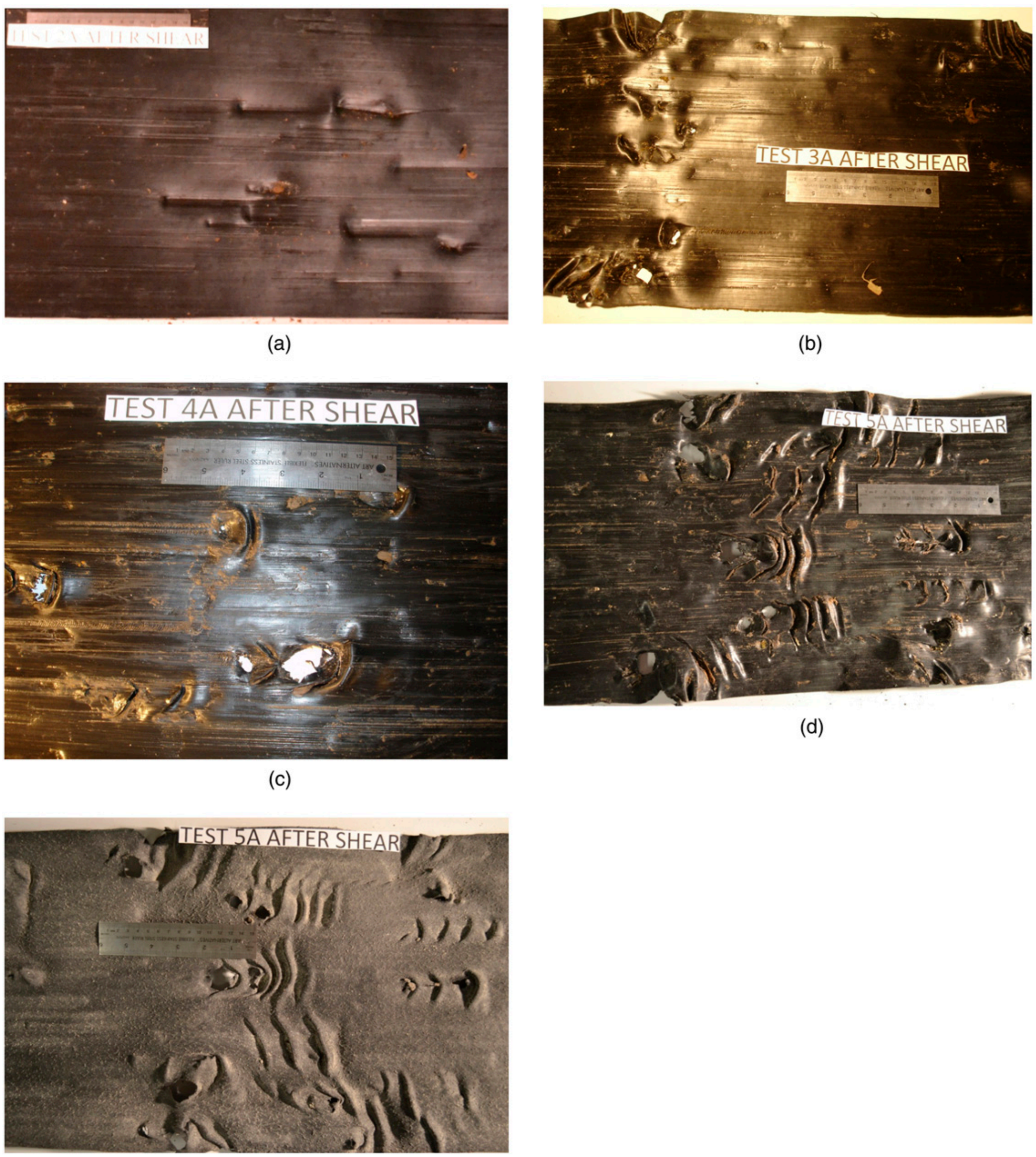


Fig. 10. Peak and large displacement failure envelopes



(a) (b) (c) (d) (e)

Fig. 11. Geomembranes after shearing stage for GM/CCL tests: (a) 2A, smooth side; (b) 3A, smooth side; (c) 4A, smooth side; (d) 5A, smooth side; (e) 5A, textured side

over a CCL compacted using Soil #1 and displays deep scratches and gouges. Geomembrane 5C experienced much less damage than Geomembrane 5A due to the lower percentage and less aggressive gravel in Soil #1 as compared with Soil #3. All else being equal, geomembrane damage would be expected to scale with the percentage of gravel. However, Soil #1 also had smaller, softer, and less angular gravel particles that were observed to break down during the shearing process. Smaller gravel particles will experience less outward protrusion from the CCL surface, and less angular or softer gravel particles will be less likely to indent and interlock with the

Fig. 12. CCL surface after shearing stage for GM/CCL Test 5A (shear direction is to the right)

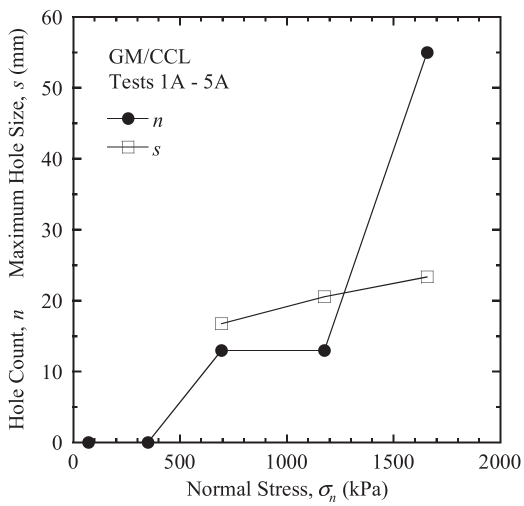


Fig. 13. Geomembrane damage after shearing stage for GM/CCL tests

geomembrane during shear. Based on these observations, the size, angularity, and hardness of gravel particles are considered to be important factors with regard to potential geomembrane damage. Geomembrane 5D was sheared over a CCL compacted using Soil #2 (no gravel) and displays minor scratches. The final condition of the CCL surface for Test 5D was smooth, and, unlike Fig. 12, showed no evidence of stress concentrations or local displacement effects. Geomembranes 3C and 3D experienced lower levels of damage with the same general trends as Geomembranes 5C and 5D.

Effect of CCL Water Content. Four additional GM/CCL tests were conducted at high normal stress ($\sigma_n = 1{,}658$ kPa) to investigate the effect of CCL water content on geomembrane damage. Fig. 17 presents the damage measurements from Geomembranes 5L1, 5L2, 5A, 5P, 5H1, and 5H2. Although the data display significant scatter, the general trend indicates less geomembrane damage for CCLs compacted near OMC and well to the wet side of OMC than for CCLs compacted slightly to the wet side of OMC. Visual inspection of the geomembranes also supports this conclusion. Variation of CCL consistency with changing water content provides a reasonable explanation. At lower water contents, the CCL matrix has higher stiffness and experiences less compaction under the applied normal stress. This reduces outward protrusion of the gravel particles and damage to the geomembrane. Fox et al. (2011) also reported relatively low levels of geomembrane damage, which is partly attributed to high stiffness of the gravelly sand subgrade in that study. At higher water contents, the CCL matrix is softer and

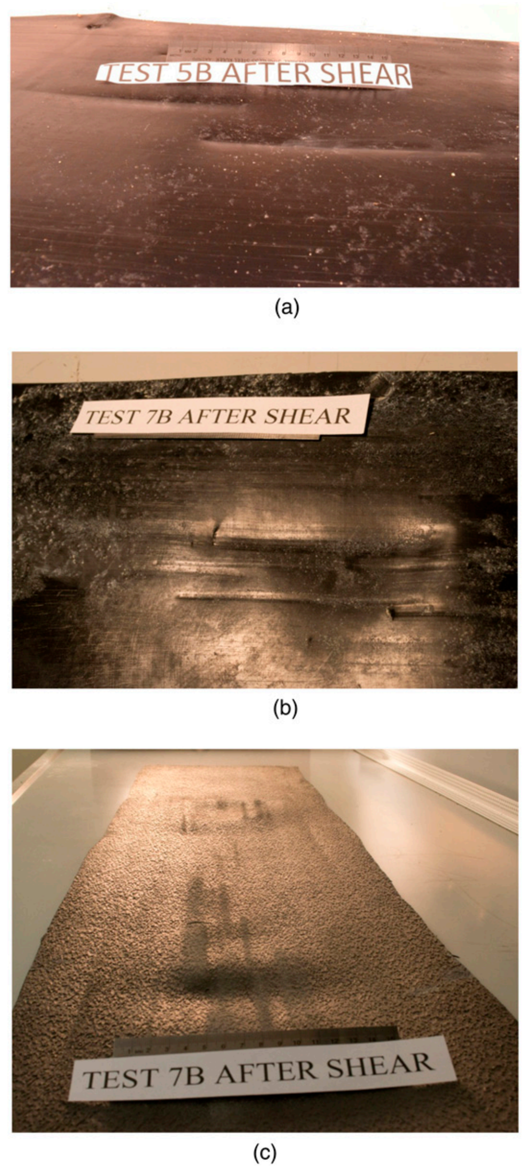


Fig. 14. Geomembranes after shearing stage for GM/GCL/CCL tests: (a) 5B, smooth side; (b) 7B, smooth side; (c) 7B, textured side

gravel particles provide less shear resistance, which also reduces geomembrane damage. This is consistent with the lower measured shear strengths for Tests 5H1 and 5H2, as compared with Tests 5A and 5P, in Table 2. Although lower CCL water content yielded less geomembrane damage in this study, the effect of compaction water content on CCL hydraulic conductivity must also be considered for design.

Effect of Shear Displacement. Shear displacement was stopped intermittently for Test 5P to assess the progress of geomembrane damage. Fig. 18 presents the stress-displacement relationship and damage measurements. Although the intermittent shearing procedure likely altered results for this test, shear strength and final damage measurements are in reasonable agreement with those for Test 5A. The hole count was zero leading up to peak strength and, at peak, one small hole was measured. Thereafter, the hole count and maximum hole size increased almost linearly to final values of 32 and 17.0 mm at $\Delta = 150$ mm. Although nearly all of the holes were created during postpeak shear, damage at the peak strength condition was significant. Fig. 19 shows Geomembrane 5P at peak strength

Fig. 15. GCL after shearing stage for GM/GCL/CCL Test 7B: (a) top surface; (b) bottom surface

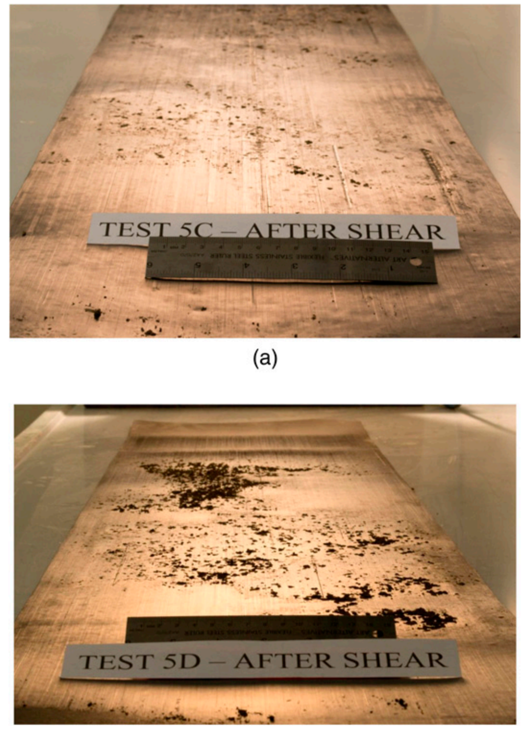


Fig. 16. Geomembranes after shearing stage for GM/CCL tests: (a) 5C, smooth side; (b) 5D, smooth side

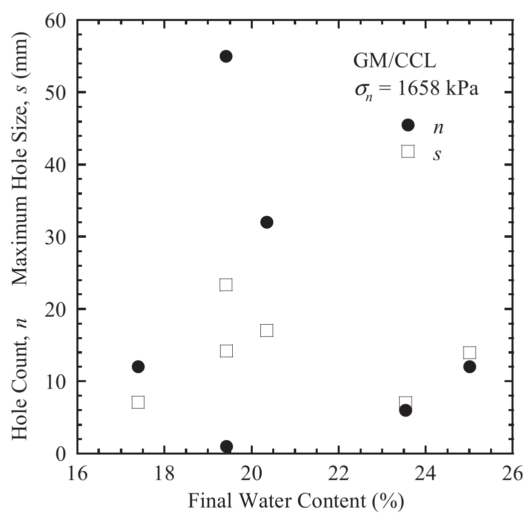


Fig. 17. Geomembrane damage after shearing stage for GM/CCL tests with varying CCL water content

and at the end of shearing. In addition to the development of one hole, considerable indentation and gouging damage was observed at peak strength. The final condition indicates severe damage similar to Geomembrane 5A and yields an average of 98 holes/m^2

Implications for Practice and Research

Engineering Design

Results from the preceding experimental investigation of shear-induced damage to a HDPE geomembrane over a gravelly CCL have potentially important implications for the design of facilities that use these materials for bottom liner systems. Large-scale direct shear tests have indicated that shear displacement over a gravelly CCL can cause much greater damage to a geomembrane than static pressure alone. Depending on conditions, severe damage is possible, such as the measured average of 169 holes/m^2 for Geomembrane 5A. The damage for Geomembrane 5A was obtained using high normal stress and a CCL with 20% crushed rock, and is thus more likely to be representative of a worst case. However, even if given field conditions produce 100 times fewer holes (i.e., 2 holes/m^2), this level of damage is several orders of magnitude beyond values generally expected for landfill liner systems (Giroud and Touze-Foltz 2003). The findings are especially significant considering that according to current standards of practice, the geomembranes in this study would not require protection from the underlying, smoothly compacted CCLs. Moreover, geomembranes in bottom liner systems are often subjected to significant shear stress from waste settlement, seismic loading, and buttressing of waste fills. Although shear displacement below a geomembrane is never desirable because it can put the geomembrane into tension, case studies of global failures indicate

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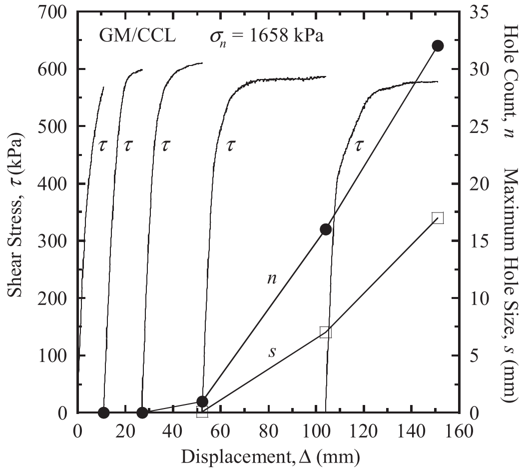

Fig. 18. Intermittent shear stress-displacement relationship and progressive geomembrane damage for GM/CCL Test 5P

(a)

(b)

Fig. 19. Geomembrane for GM/CCL Test 5P: (a) at peak strength; (b) after shearing stage completed; labels P3 and P5 indicate the third and fifth shearing increments

that such displacements can occur if the GM/CCL interface is relatively weak (Mitchell et al. 1990; Koerner and Soong 2000; Benson 2002). The extensive body of past research on geomembrane protection has not accounted for possible additional damage caused by static pressure combined with interface shear. Thus, currently accepted standards of practice for placement of geomembranes over gravelly CCLs in bottom liner systems may lead to unanticipated vulnerability for these geomembranes. In general, the test results suggest that additional measures, such as requiring the top lift of a CCL to be free of gravel or placing a NP GCL at the GM/CCL interface, may be needed to protect geomembranes from an underlying gravelly CCL when interface shear is expected under moderate to high normal stress conditions.

Direct Shear Testing

The experimental results also have important implications for direct shear testing practice. Although GM/CCL interface shear tests have been performed in production and research laboratories for decades, shear-induced geomembrane damage from gravelly CCLs has not been previously reported to the authors' knowledge. In light of the current study, there are several possible explanations: (1) conventional shear boxes are smaller and have closer boundaries that provide more lateral support to a geomembrane, especially if the geomembrane is clamped around all edges; (2) the normal stress range is typically lower; (3) geomembranes are often placed against a hard backing plate, which will essentially maintain a flat CCL surface and reduce the potential for gravel particles to indent and interlock with the geomembrane; and (4) the gravel fraction of a CCL soil is sometimes removed prior to shear testing because of equipment size limitations or sieving requirements for other tests (e.g., Proctor tests).

Based on these considerations, several changes are recommended for interface shear tests involving gravelly CCLs and geomembranes. Direct shear tests should be conducted using multiinterface specimens and project-specific conditions. Thus, the geomembrane should be placed between actual field materials and not clamped to a hard backing plate. The gravel fraction should not be removed from a CCL soil for damage results to be meaningful. Finally, the appropriate normal stress range for deep landfills and heap leach pads may require the use of specialized high-capacity equipment. Development or revision of standard test procedures may be necessary to account for multiinterface specimens and assessment of geomembrane damage due to interface shear.

Future Research Needs

Limitations of the current study highlight the need for future research. With regard to CCLs, additional investigations are needed to better understand the effects of gravel content, gravel particle characteristics (e.g., size, angularity, and hardness), compaction water content, and magnitude of shear displacement on shear-induced geomembrane damage. In particular, the risk posed by borderline materials, such as CCLs containing smaller, less angular gravel than Soil #3, requires investigation. Detailed quantitative studies of geomembrane deformation would be useful for borderline cases. Research is also needed with regard to CCL soil type and geomembrane polymer type, thickness, texturing condition, and temperature. More broadly, the current study suggests that shear-induced damage may be an important consideration for geomembranes that interface with other coarse soils, such as an overlying gravel drainage layer (Fox and Thielmann 2014). Finally, the general applicability of the static pressure performance test for assessment of geomembrane damage may need to be reevaluated for field conditions that involve possible interface shear displacement. Development of new standard test procedures may be warranted and reconsideration of geomembrane protection guidelines may be necessary in light of new data that include the effects of such displacement.

Conclusions and Recommendations

The following conclusions are based on the foregoing experimental investigation of shear-induced damage to a HDPE GM over a gravelly CCL, with and without a needle-punched GCL at the interface:

1. Geomembrane specimens placed over CCLs with 20% angular gravel and subjected to 24 h of static pressure (i.e., no shear) displayed relatively little damage and, in some cases, no damage. Damage was not observed at the lowest normal stress level ($\sigma_n = 72$ kPa) and then increased with increasing normal stress. The greatest damage occurred for GM/CCL tests at the highest normal stress level ($\sigma_n = 1{,}658$ kPa) and consisted of minor to moderate indentations associated with protruding gravel particles in the underlying CCL. No holes were created in the geomembranes for any of the static pressure tests.
2. Measured shear strengths for the GM/CCL interface were substantially higher and more irregular than for the GM/GCL interface, which is partly attributed to varying degrees of contact and interlocking between gravel particles in the CCL and the overlying geomembrane and sand layer. Although beneficial in terms of shear strength, such interlocking can be highly detrimental to the integrity of the geomembrane.
3. Interface shear for the GM/CCL specimens caused minimal to moderate geomembrane damage (e.g., scratches and gouges) at low normal stress ($\sigma_n \leq 348$ kPa) and severe geomembrane damage (e.g., gouges, wrinkles, and holes) at moderate to high normal stress ($\sigma_n \geq 693$ kPa). The greatest damage occurred at the highest normal stress level ($\sigma_n = 1{,}658$ kPa) and yielded an average of 169 holes/m^2 and a maximum hole size of 23.4 mm.
4. Geomembrane damage due to interface shear was greatly reduced by placement of a hydrated needle-punched GCL at the GM/CCL interface. Essentially, no damage was observed for low and moderate normal stress conditions and only minor damage was observed for high normal stress conditions, including one test conducted at a very high normal stress ($\sigma_n = 4{,}145$ kPa).
5. Much less damage was observed for geomembranes sheared over CCLs containing less aggressive gravel particles. Size, angularity, and hardness of gravel particles are important factors with regard to potential geomembrane damage. Geomembranes sheared against CCLs with no gravel displayed only minor scratches.
6. Geomembrane damage varied with water content of the gravelly CCL. Tests conducted with CCLs compacted near OMC and well to the wet side of OMC yielded less geomembrane damage than tests with CCLs compacted slightly to the wet side of OMC.
7. One GM/CCL test was conducted with progressive damage assessments and indicated that geomembrane damage increased during shear displacement, with nearly all holes created after peak shear strength. Considerable indentation and gouging damage was observed at the peak strength condition for this specimen.
8. The experimental results illustrate the general importance of conducting project-specific shear tests, including multiinterface tests, to assess possible geomembrane damage and determine shear strengths for the design of liner systems.

Subject to further assessment and verification, the following provisional recommendations can be made at this time. Gravelly clay soils can be considered for the construction of GM/CCL composite liners for landfill cover systems and other low stress applications but should be viewed with caution for landfill bottom liner systems and other moderate- to high-stress applications. If a gravelly CCL is considered for a bottom liner and there is a reasonable expectation for GM/CCL interface shear displacement, project-specific direct shear tests should be conducted to determine the potential for shear-induced geomembrane damage. Recommendations are provided for the performance of such tests. If these tests indicate significant damage, a designer has several options: (1) require the top lift of the CCL to be free of gravel; (2) place a NP GCL at the GM/CCL interface; or (3) include an intentional slip interface above the liner to limit shear displacement at the GM/CCL interface. Options 1 and 2 are preferred because Option 3 can be difficult to implement and will not protect a GM from static pressure damage. In general, a nonwoven geotextile should not be used to provide geomembrane protection from an underlying gravelly CCL because this may increase lateral flow at the interface and compromise the composite function of the liner.

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