CORRELATION BETWEEN NEEDLEPUNCH-REINFORCED GCL PEEL STRENGTH AND INTERNAL SHEAR STRENGTH

Landfill and mining applications often involve composite liner systems consisting of a geomembrane underlain by a GCL. Because of the low shear strength of hydrated bentonite, GCLs are manufactured using needlepunching, where nonwoven fibers from one geotextile are punched through the bentonite and the opposite geotextile, to provide internal reinforcement. The industry uses an index test, GCL peel strength (ASTM D6496), to assess the quality and strength of the needlepunched bond. Although design engineers commonly specify higher peel strengths for projects with stringent shear strength requirements, the published information on this subject presents conflicting results. To address this data gap, a correlation study between peel and internal shear strength was performed, involving 40 shear strength tests on hydrated GCL samples with varying peel strengths. Shear tests were performed at normal stresses of 240, 479, and 718 kPa (5000, 10000, and 15000 psf). To limit variability, one type of needlepunch-reinforced GCL was tested, with all shear samples subjected to the same hydration and consolidation. The following conclusions and recommendations are supported by the laboratory test results:

- For a given normal stress and set of hydration/consolidation conditions, a reinforced GCL's hydrated peak internal shear strength is a function of the GCL's peel strength. The relationship between peel strength, P_s, and peak internal shear strength, τ_p, appears to follow a power law relationship, $\tau_p = A(P_s)^B$, where A and B are constants.

- A comparison of interface shear data from the literature to the internal shear strength values measured in this study shows that the peak internal shear strength of needle-punch reinforced GCL-A will exceed interface shear strengths at low normal stresses (less than approximately 450 kPa, or 9400 psf).

- Design engineers should consider specifying a higher GCL peel strength for projects with high expected normal stresses, to ensure that the GCL bentonite layer will not be the critical slip plane.

- However, for a given set of testing conditions, once the GCL's peel strength reaches the level required to resist internal failure during interface testing, further increases in peel strength are not expected to result in any further improvement in shear performance.

- The industry should reconsider the current quality control practice of performing internal shear testing of needlepunch-reinforced GCLs at a 10 kPa (200 psf) normal stress, with a peak shear strength requirement of 24 kPa (500 psf). These values represent a very

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high friction angle of 68 degrees, indicating that a reinforced GCL will not be the critical slip plane at this normal stress.

- GCL manufacturers should continue performing periodic MQC internal shear tests to demonstrate product consistency. However, testing should be performed at higher normal stresses. A more appropriate normal stress may be 479 kPa (10000 psf), as this appears to be closer to the range of normal stresses at which the failure mode might transition from interface to internal.

- Instead of specifying frequent internal shear tests, design engineers should specify project-specific interface shear tests using representative site materials. Interface tests simulate the liner cross-section in the field, and therefore allow the weakest interface to be determined (including GCL internal failure).

- Peel strength tests, which can be performed much more quickly and cost-effectively, should be used as a surrogate in place of frequent internal shear tests.

- The observations in this study are based on testing performed on one type of reinforced GCL, GCL-A, and may not be applicable to other needlepunch-reinforced GCLs.

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Correlation Between Needlepunch-Reinforced Geosynthetic Clay Liner Peel Strength and Internal Shear Strength

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ABSTRACT

Landfill and mining applications often involve composite liner systems consisting of a geomembrane underlain by a geosynthetic clay liner (GCL). Because of the low shear strength of hydrated bentonite, GCLs are manufactured using needlepunching, where nonwoven fibers from one geotextile are punched through the bentonite and the opposite geotextile, to provide internal reinforcement. The industry uses an index test, GCL peel strength (ASTM D6496), to assess the quality and strength of the needlepunched bond. Although design engineers commonly specify higher peel strengths for projects with stringent shear strength requirements, the published information on this subject presents conflicting results. To address this data gap, a correlation study between peel and internal shear strength was performed, involving 40 shear strength tests on hydrated GCL samples with varying peel strengths. To limit variability, one type of needlepunch-reinforced GCL was tested, with all shear samples subjected to the same hydration and consolidation. The test results indicate that, for a given set of testing conditions, a GCL's peak internal shear strength is a function of its peel strength. The results of this study will be useful to design engineers in understanding appropriate GCL peel strength values for site-specific conditions.

INTRODUCTION

Landfill and mining applications often involve composite liner systems consisting of a geomembrane underlain by a geosynthetic clay liner (GCL). Because of the inherently low shear strength of hydrated sodium bentonite, GCLs are manufactured using aggressive needlepunching, where barbed needles pull nonwoven fibers from one geotextile and punch them through the bentonite core and opposite geotextile, to provide internal reinforcement. The industry uses an index test, GCL peel strength (ASTM D6496), to assess the quality and strength of the needlepunched bond. Although design engineers commonly specify higher GCL peel strengths for projects with more stringent shear strength requirements, the information in the literature on this subject presents conflicting results, as discussed further below.

LITERATURE REVIEW

Past studies which have looked at the relationship between peak internal shear strength and peel strength include: Berard (1997), Richardson (1997), Fox et al. (1998), Eid et al. (1999), Olsta and Crosson (1999), von Maubeuge and Lucas (2002), and Zornberg et al. (2005). Fox et al. (1998) tested GCL samples with two different peel strengths, and found that higher peak shear strengths were associated with the higher peel strength samples. Zornberg et al (2005), evaluated a much larger database of test results which all involved the same GCL, the same conditioning procedures, and the same displacement rate. However, as shown in Figure 1, their test results showed no clear trends between peel and internal shear strengths, with the possible exception of tests at the highest normal stress (310 kPa), which showed a slight positive correlation. Based on these results, the authors concluded that internal shear strength is not very sensitive to peel strength, and added that the lack of correlation is likely explained by the fact that the two tests mobilize tension in the needlepunched fibers in different ways.

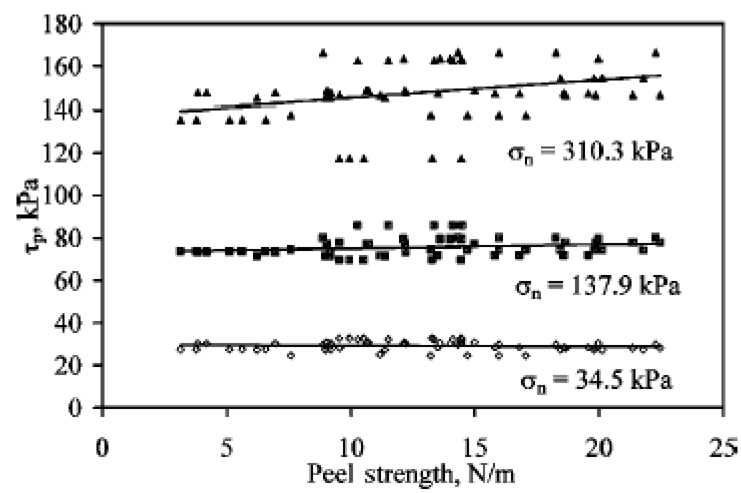

Figure 1. Relationship Between Peel Strength and Peak Internal Shear Strength (from Zornberg et al, 2005)

MATERIALS

To limit variability associated with different carrier geotextiles and different manufacturing processes, only one type of needlepunch-reinforced GCL was evaluated in this study: Bentomat ST (GCL A), manufactured by CETCO in Cartersville, Georgia. The GCL consists of a minimum of 3.6 kg/m^2 of sodium bentonite clay, between a 200 g/m^2 nonwoven geotextile and a 105 g/m^2 woven geotextile. GCL A is certified to have a minimum peel strength, P_s, of 610 N/m, by ASTM D6496. As part of this study, GCL samples with P_s values ranging from 740 to 2666 N/m were tested. Additionally, to provide comparative information with an unreinforced GCL ($P_s \approx$ zero), selected tests were also performed on a sample of Claymax 200R (GCL B), manufactured by the CETCO Cartersville, Georgia facility.

TEST PROCEDURES

The laboratory study described here involved 40 internal shear strength tests on reinforced GCL samples with varying peel strengths. Large-scale (300-mm x 300-mm) direct shear testing was performed by SGI Testing Services, in Norcross, Georgia. Prior to testing, each GCL sample was hydrated under a low normal stress of 10 kPa for 24 hours, and then consolidated under the test normal stress for an additional 24 hours. This sample preparation procedure was intended to conservatively simulate field conditions (hydration under low normal stress immediately after installation, followed by consolidation under the added weight of soil or waste). After hydration and consolidation, internal shear tests were performed in accordance with ASTM D6243, at normal stresses of 240, 479, and 718 kPa (5,000, 10,000, and 15,000 psf). The normal stresses were selected to fall within the range commonly encountered in landfill base liners. Samples were sheared at a displacement rate of 1 mm/min, with both peak and large displacement (75 mm) shear strength values reported.

Sample peel strengths were measured in accordance with ASTM D6496, using 200-mm long x 100-mm wide specimens, with results reported in terms of average strength per sample width (N/m).

RESULTS AND DISCUSSION

A summary of the GCL peel strength data, together with the measured peak and large displacement internal shear strengths, is presented in Table 1. These data were used to generate Figure 1, a plot of peak shear strength, τ_p, as a function of peel strength, P_s. Three sets of data are shown, corresponding to the three different normal stresses tested (σ_n = 240, 479, and 718 kPa). Figure 1 shows that, for a given normal stress, the reinforced GCL's hydrated peak internal shear strength is a function of the GCL's peel strength. Power law regressions for each normal stress result in the following equations (valid for $44 < P_s < 2666$ N/m):

$$\tau_P\ (kPa) = 9.73 \cdot (P_s)^{0.4101} \qquad (\text{for } \sigma_n = 240\ kPa)$$

$$\tau_P\ (kPa) = 24.55 \cdot (P_s)^{0.3463} \qquad (\text{for } \sigma_n = 479\ kPa)$$

$$\tau_P\ (kPa) = 33.16 \cdot (P_s)^{0.3364} \qquad (\text{for } \sigma_n = 718\ kPa)$$

Zornberg et al. (2006) pointed out that positive correlations presented in some earlier studies may have been dominated by a few data points with zero peel strength. In this study, even if the unreinforced data points ($P_s \approx 44$ N/m) are excluded, there still appears to be clear positive correlation between the peel and shear strength data sets for the P_s values ranging from 740 to 2666 N/m.

Table 1. Summary of GCL Peel Strength (ASTM D6496) and Internal Shear Strength (ASTM D6243) Data

GCL Type	**Roll No.**	**Peel - 6496** Ave (N/m)	**Normal Stress** (kPa)	**Peak Shear Strength** (kPa)	**LD (75-mm) Shear Strength** (kPa)
B	78	43.8	239.5	45.1	20.8
A	2991	665.5	239.5	124.0	30.0
A	2900	963.2	239.5	144.8	31.8
A	2949	1068.3	239.5	190.4	36.4
A	2802	735.5	239.5	143.4	29.3
A	2851	1295.9	239.5	214.8	37.2
A	2707	665.5	239.5	159.2	29.7
A	2754	612.9	239.5	116.3	28.6
A	9361	858.1	239.5	182.4	34.9
A	11959	1943.9	239.5	246.1	55.8
A	12001	1348.5	239.5	177.0	34.5
A	346	739.9	239.5	144.0	26.0
A	1696	1085.8	239.5	163.6	34.5
A	203	1598.0	239.5	209.7	31.4
A	271	1908.9	239.5	208.9	40.9
A	460	2412.4	239.5	184.2	46.5
A	145	2666.3	239.5	252.4	25.2
A	3284	770.6	239.5	159.8	28.2
B	78	43.8	478.9	91.9	44.0
A	346	739.9	478.9	236.3	47.9
A	346	739.9	478.9	245.4	50.7
A	1696	1085.8	478.9	256.0	64.6
A	203	1598.0	478.9	320.0	56.0
A	203	1598.0	478.9	322.5	49.0
A	203	1598.0	478.9	310.4	47.7
A	271	1908.9	478.9	348.5	61.7
A	460	2412.4	478.9	354.2	62.5
A	145	2666.3	478.9	373.3	53.9
A	145	2666.3	478.9	382.1	59.9
A	145	2666.3	478.9	389.0	63.2
A	3284	770.6	478.9	248.1	50.6
B	78	43.8	718.4	121.0	60.0
A	346	739.9	718.4	281.8	65.5
A	346	739.9	718.4	289.6	68.8
A	1696	1085.8	718.4	317.1	85.9
A	203	1598.0	718.4	392.8	77.8
A	271	1908.9	718.4	436.1	84.1
A	460	2412.4	718.4	457.0	84.2
A	145	2666.3	718.4	495.9	75.6
A	3284	770.6	718.4	353.0	73.5

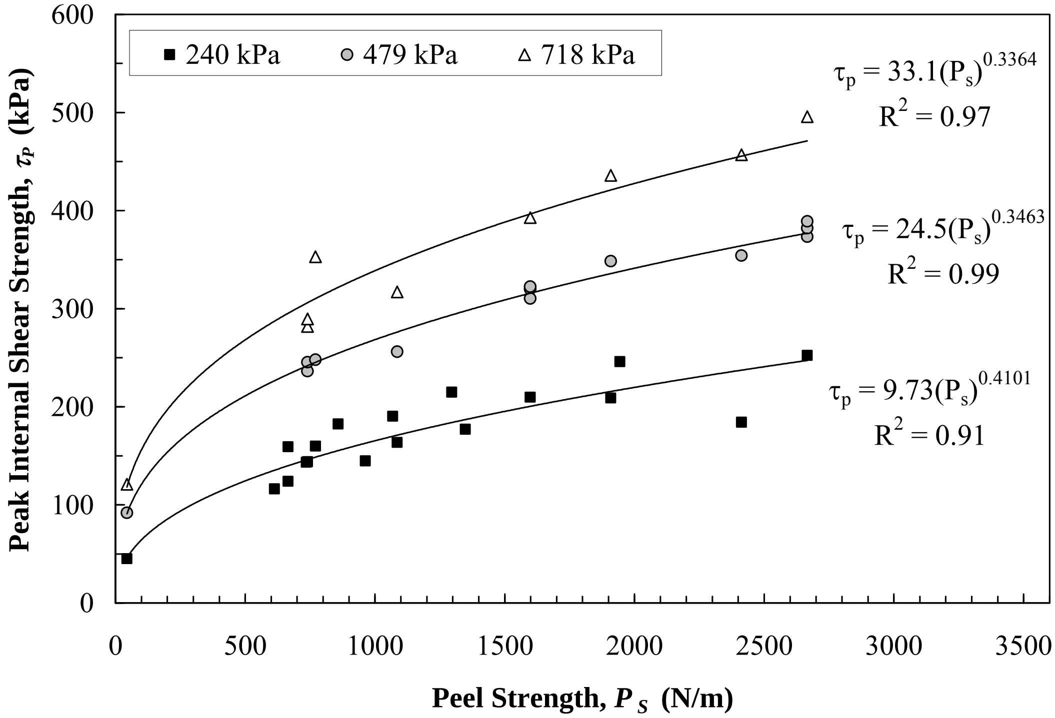

Figure 2. Peak Hydrated Internal Shear Strength (ASTM D6243) as a Function of Sample Peel Strength (ASTM D6496)

A review of the large-displacement (75-mm) shear strengths in Table 1 suggests that there is little or no correlation between peel strength and large-displacement shear strength. This is not surprising, considering that in a properly run internal shear strength test, the needlepunch fibers that provide internal reinforcement are significantly damaged at 75-mm of displacement, either by pullout or tensile failure.

The peak shear strength data in Table 1 can also be plotted as a function of normal stress, as shown in Figure 3. Performing a linear regression on each data set yields the following equations, in the form of the familiar Mohr-Coulomb failure envelope (valid for 240 < σ_n < 718 kPa):

$$\tau_P\ (kPa) = 10 + \sigma_n \tan 9^\circ \qquad \text{(for } P_s = 44\ N/m\text{)}$$

$$\tau_P\ (kPa) = 92 + \sigma_n \tan 16^\circ \qquad \text{(for } P_s = 740\ N/m\text{)}$$

$$\tau_P\ (kPa) = 92 + \sigma_n \tan 18^\circ \qquad \text{(for } P_s = 1086\ N/m\text{)}$$

$$\tau_P\ (kPa) = 128 + \sigma_n \tan 21^\circ \qquad \text{(for } P_s = 1598\ N/m\text{)}$$

$$\tau_P\ (kPa) = 104 + \sigma_n \tan 25^\circ \qquad \text{(for } P_s = 1909\ N/m\text{)}$$

$$\tau_P\ (kPa) = 135 + \sigma_n \tan 27^\circ \qquad \text{(for } P_s = 2666\ N/m\text{)}$$

A comparison of these equations shows that the peak Mohr-Coulomb friction angle increases with increasing peel strength. The largest increase (9 to 16 degrees) occurs between the unreinforced sample and the lowest-peel strength reinforced sample. For reinforced samples, doubling the peel strength results in approximately a 5- to 7-degree improvement in peak friction angle. These equations also show an general increase in cohesion with increasing peel strength. The largest increase in cohesion (10 to 92 kPa) occurs between the unreinforced samples and the lowest-peel strength reinforced sample. These relationships may have a physical significance, as it has been suggested by Fox et al. (1998) and Gilbert et al. (1996) that entanglement of the needlepunched fibers in the anchoring geotextile is a frictional mechanism. However, these observations are only preliminary; further research is needed to better understand the exact mechanisms by which needlepunching improves GCL shear strength.

Plotting the peak internal shear strength test results as Mohr-Coulomb failure envelopes also allows for a direct comparison with the failure envelopes of other interfaces. Chiu and Fox (2004) evaluated a large database of GCL internal and interface shear test results from the literature, manufacturers, and their own tests. Their aggregate data for the interface between a textured geomembrane and a hydrated needlepunch-reinforced GCL (nonwoven geotextile side) yielded the following regression equation (Chiu and Fox, 2004):

$$\tau_P\ (kPa) = 4.54 + 0.775 \cdot (\sigma_n)^{0.92} \qquad \text{(for } 2 < \sigma_n < 1034\ kPa\text{)}$$

This expression is plotted on Figure 3, alongside the internal shear failure envelopes. Interestingly, a comparison of the textured geomembrane/GCL interface “best fit” failure envelope from Chiu and Fox to the internal shear strength failure envelopes developed in this study shows that for normal loads less than approximately 450 kPa, all of the reinforced GCL internal shear values exceed the interface shear values. In other words, the data suggests that for normal stresses up to 450 kPa, the GCL bentonite layer will not be the critical slip plane. At normal stresses greater than 450 kPa, the interface shear envelope exceeds the peak internal shear envelope of the reinforced GCL with the lowest peel strength (740 N/m). At normal stresses greater than approximately 600 kPa, the interface shear envelope exceeds the peak internal shear strength of the GCL with the next lowest peel strength (1086 N/m). This exercise provides some insight into how peel strength can influence the “critical” normal stress, where the failure mode changes from interface shear to internal shear. It also supports the current practice of specifying a higher GCL peel strength for projects with high expected normal stresses.

It is also interesting to note that, for a given set of testing conditions, once the GCL's peel strength reaches the level required to resist internal failure during interface testing, further increases in peel strength are not expected to result in any improvement in interface shear performance.

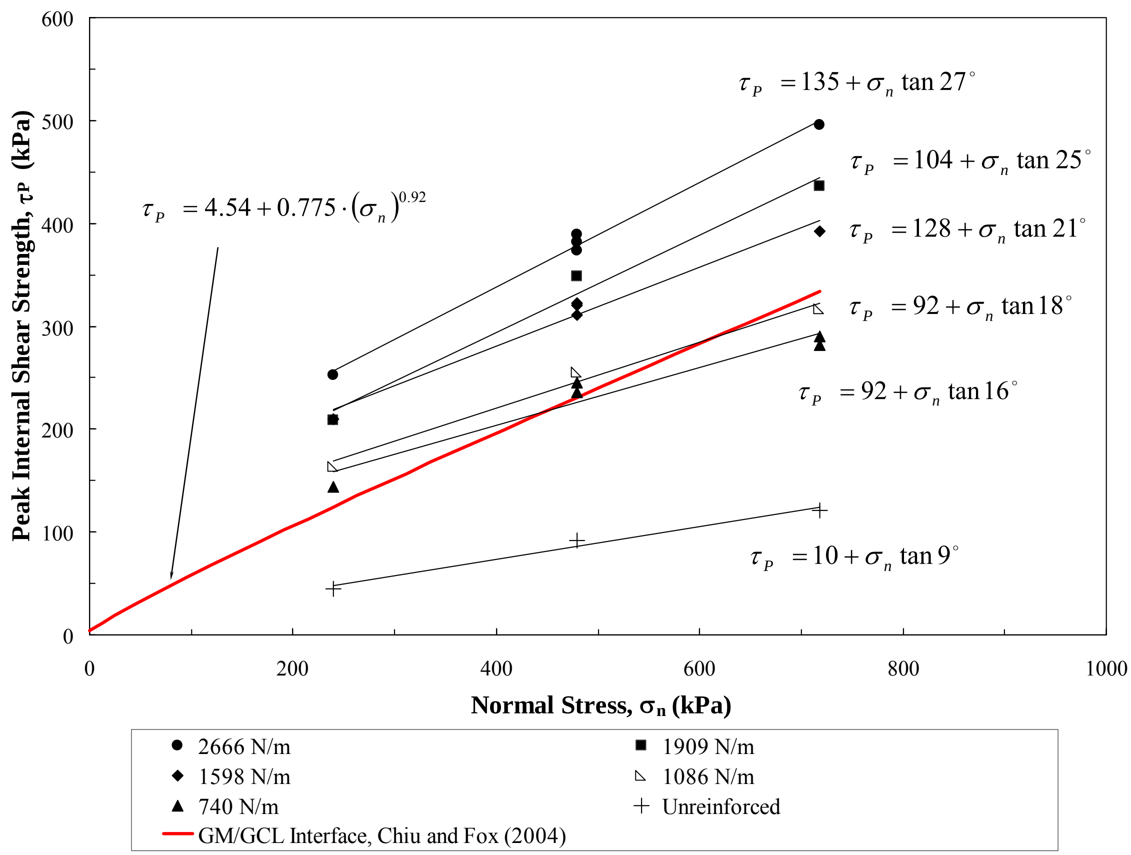

Figure 3. Mohr-Coulomb Failure Envelopes

Please note that the critical normal stresses discussed above are only examples for this particular data set, and should not be applied to project-specific situations. As discussed in previous studies (Chiu and Fox, 2004), the transition between failure modes and the normal stress at which such a transition might occur are dependent on the specific materials and testing conditions. Our study focuses on GCL peel strength, only one of the many variables involved. Several other variables (including GCL bentonite moisture content, hydration/consolidation steps, shear displacement rate, geomembrane texturing, soil properties, etc.), will also determine the critical normal stress at which the failure mode might transition from interface to internal. Accordingly, project-specific interface shear testing with representative site materials is always recommended.

CONCLUSIONS AND RECOMMENDATIONS

A correlation study between peel strength and internal shear strength was performed on hydrated GCL samples with varying peel strengths. Shear tests were performed at normal stresses of 240, 479, and 718 kPa. The following conclusions and recommendations are supported by the laboratory test results:

- For a given normal stress and set of hydration/consolidation conditions, a reinforced GCL's hydrated peak internal shear strength is a function of the GCL's peel strength. The relationship between peel strength, P_s, and peak internal shear strength, τ_p, appears to follow a power law relationship, $\tau_p = A(P_s)^B$, where A and B are constants.

- A comparison of interface shear data from the literature to the internal shear strength values measured in this study shows that the peak internal shear strength of needle-punch reinforced GCL-A will exceed interface shear strengths at low normal stresses (less than approximately 450 kPa).

- Design engineers should consider specifying a higher GCL peel strength for projects with high expected normal stresses, to ensure that the GCL bentonite layer will not be the critical slip plane.

- However, for a given set of testing conditions, once the GCL's peel strength reaches the level required to resist internal failure during interface testing, further increases in peel strength are not expected to result in any further improvement in shear performance.

- The industry should reconsider the current quality control practice of performing internal shear testing of needlepunch-reinforced GCLs at a 10 kPa normal stress, with a peak shear strength requirement of 24 kPa. These values represent a very high friction angle of 68 degrees, indicating that a reinforced GCL will not be the critical slip plane at this normal stress.

- GCL manufacturers should continue performing periodic MQC internal shear tests to demonstrate product consistency. However, testing should be performed at higher normal stresses. A more appropriate normal stress may be 479 kPa, as this appears to be closer to the range of normal stresses at which the failure mode might transition from interface to internal.

- Instead of specifying frequent internal shear tests, design engineers should specify project-specific interface shear tests using representative site materials. Interface tests simulate the liner cross-section in the field, and therefore allow the weakest interface to be determined (including GCL internal failure).

- Peel strength tests, which can be performed much more quickly and cost-effectively, should be used as a surrogate in place of frequent internal shear tests.

- The observations in this study are based on testing performed on one type of reinforced GCL, GCL-A, and may not be applicable to other needlepunch-reinforced GCLs.

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