CHARACTERIZATION OF GCL SHEAR STRENGTH VARIABILITY

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McCartney, J.S., and Zornberg, J.G. (2003). "Characterization of GCL Shear Strength Variability." Proceedings of the 2003 North American Conference on Geosynthetics, Winnipeg, Canada, September 28 - October 1 (CD-ROM).

ABSTRACT: Variability in geosynthetic clay liner (GCL) internal and GCL-geomembrane (GM) interface shear strength measured using large-scale direct shear tests is evaluated in this study. Several sources of GCL peak shear strength uncertainty are identified, including laboratory equipment and procedures, GCL and GM material variability, and conditioning/test procedures. Uncertainty related to GCL and GM material variability is found to arise in GCL and GM specimens taken from different manufacturing lots, with specimens from the same lot having similar behavior. The contributions to the material variability of the GCL fiber reinforcements, the GM textured asperities, and the bentonite are addressed separately. GCL peel strength results do not to correlate well with GCL internal and GCL-GM shear strength results, indicating that this test is not appropriate for characterizing the material variability in the GCL internal reinforcements or the GCL-GM interlocking capabilities. Comparison of the shear strength variability obtained for reinforced and unreinforced GCLs indicates that the contribution of the bentonite to the reinforced GCL internal shear strength variability is relevant, though lower in magnitude than the contribution of the reinforcement. Material variability in the bentonite water content at the completion of the test is not a major source of internal or interface shear strength variability.

RÉSUMÉ: La variabilité dans le GCL interne et résistance au cisaillement d'interface de GCL-GM a mesuré employer les essais directs à grande échelle de cisaillement est évaluée dans cette étude. Plusieurs sources d'incertitude maximale de résistance au cisaillement de GCL ont été identifiées, y compris l'équipement et les procédures de laboratoire, la variabilité matérielle de GCL et de GM, et les conditions d'essai. L'incertitude liée à la variabilité matérielle de GCL et de GM s'est avérée pour surgir dans des spécimens de GCL et de GM pris de différents sorts de fabrication, avec des spécimens du même sort ayant le comportement semblable. Les contributions à la variabilité matérielle des renforts de fiber de GCL, des aspérités texturisées une consistance rugueuse par GM, et du bentonite ont été adressées séparément. Des résultats de résistance à peau de GCL se sont avérés pour ne pas se corréler bien avec le GCL interne et des résultats de résistance au cisaillement de GCL GM, indiquant que cet essai n'était pas approprié pour caractériser la variabilité matérielle dans les renforts internes de GCL ou les possibilités enclenchantes de GCL GM. La comparaison de la variabilité de résistance au cisaillement obtenue pour GCLs renforcé et non renforcé indique que la contribution du bentonite à la résistance au cisaillement interne renforcée de GCL est également appropriée à la contribution du renfort. La variabilité matérielle dans la teneur en eau de bentonite à l'accomplissement de l'essai s'est avérée pour ne pas être une source importante de variabilité interne ou d'interface de résistance au cisaillement.

1. INTRODUCTION

Variability in GCL internal and GCL-geomembrane (GM) interface shear strength is an important topic for both designers and manufacturers. Designers must consider possible deviations from the model being used to quantify the safety of a project, while manufacturers must evaluate quality control and material consistency. Past studies have investigated GCL shear strength (Gilbert et al. 1996; Fox et al. 1998; Triplett and Fox 2001), but little insight has been gained so far on variability in shear strength values. This is most likely due to the high costs and lengthy times required to run the multiple large-scale direct shear tests necessary to address GCL shear strength variability.

This study benefits from a large database, referred herein as the GCLSS database, which includes 375 GCL internal and 388 GCL-GM interface large-scale (305 mm by 305 mm) direct shear tests. The GCLSS database is useful to address the sources of GCL internal and GCL-GM interface shear strength variability. The tests were conducted between 1992 and 2002 by Soil-Geosynthetic Interaction laboratory of GeoSyntec Consultants, currently operated by SGI Testing Services (SGI). SGI is an accredited testing facility, and used test procedures that were consistent with ASTM D6243 (ASTM 1998), even before the standard was instituted. Test conditions reported for each series in the GCLSS database include specimen preparation and conditioning procedures, hydration time (t_h), consolidation time (t_c), normal stress during hydration (σ_h), normal stress during shearing (σ_n), and shear displacement rate (SDR). Also, the water content at the end of shearing (*w*) and the GCL peel strength were reported for selected tests. The specific effects of each of these variables on the GCL internal and GCL-GM interface shear strength have been addressed elsewhere (McCartney et al. 2002). The specific focus of this paper is on the influence of these variables on the shear strength variability.

This study includes the results of three analyses: (1) identification of the different sources of shear strength uncertainty, (2) statistical characterization of the overall GCL internal and GCL-GM interface material variability, and (3) investigation of different properties that have been correlated to GCL shear strength, such as peel strength and the bentonite water content. These analyses focus on the peak shear strength results from direct shear tests involving four GCL types and two GM types. These will be referred to as GCL A (needle-punched), GCL B (stitch-bonded), GCL C (needle-punched and thermally-locked) and GCL F (unreinforced bentonite sandwiched between woven carrier geotextiles) as well as GM s and GM v (textured HDPE, 80-mil, different manufacturers).

2. SOURCES OF SHEAR STRENGTH UNCERTAINTY

Figures 1(a) and 1(b) show the GCL internal and GCL-GM interface shear strength results for all GCLs in the GCLSS database under different conditioning/test procedures for normal stresses less than 100 kPa.

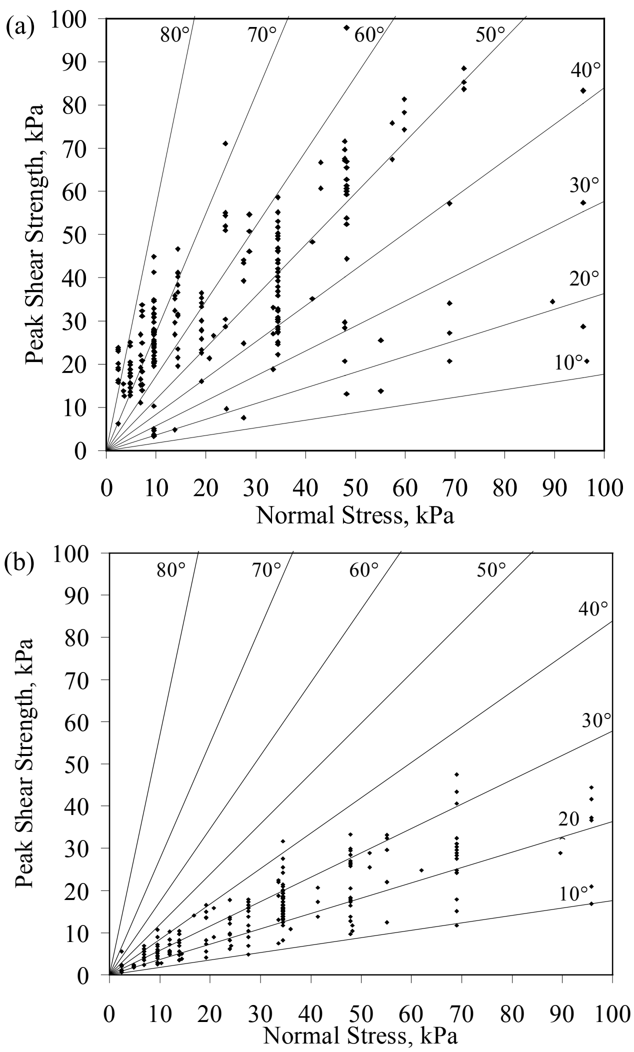


Figure 1: Shear strength of all GCLs for σ_n < 100 kPa: (a) GCL Internal, (b) GCL-GM interface

This wide range of shear strength values emphasizes the need to distinguish between the effect of physical variables (e.g., normal stress, conditioning/test procedures) on the shear strength, and inherent material variability (e.g., variability in the fiber reinforcement density, water absorption by the bentonite in a given period of time). This may be done through identifying different sources of uncertainty.

In this study, a source of uncertainty is defined as an aspect of equipment, material properties, or conditioning/testing procedures that lead to uncertainty in GCL shear strength. Figure 2 summarizes the different sources of uncertainty relevant for evaluation of the GCL internal and GCL-GM interface shear strength.

GCL internal and GCL-GM interface shear strength uncertainty
- (*1*) Uncertainty due to differences in laboratory equipment and procedures
- (*2*) Uncertainty due to materials
- (*3*) Uncertainty due to specimen conditioning and shear displacement rate

Figure 2: Sources of uncertainty

Source of uncertainty (*1*) is expected to arise due to differences in measurement devices, specimen gripping mechanisms, and conditioning/testing procedures used by different laboratories. Source (*1*) is not evaluated in this study, as the shear strength information in the GCLSS database was obtained from a single laboratory using consistent testing procedures. Source of uncertainty (*2*) is expected to arise from using different GCL or GM types or manufacturers as well as from inherent material variability of a single GCL or GM type. Source of uncertainty (*3*) may arise due to differences in conditioning (e.g., hydration, consolidation) or test (e.g., normal stress or rate of shearing) conditions, which have been related directly to GCL shear strength and indirectly to differences in shear-induced pore water pressures (McCartney et al. 2002). This study is mainly concerned with source of uncertainty (*2*), but the combined effect of sources of uncertainty (*2*) and (*3*) will also be addressed.

3. UNCERTAINTY DUE TO MATERIALS AND CONDITIONING/TEST PROCEDURES

Uncertainty due to materials is a very broad category whose analysis is aided by separating the GCLs/GMs into three different categories: (*i*) GCLs/GMs from the same manufacturing lot (where material differences are minimal), (*ii*) GCLs/GMs of the same type but from different manufacturing lots, and (*iii*) GCLs/GMs of different types (where material differences are maximal). In addition, shear strength variability of GCLs of the same type but from different lots is expected to arise from GCL reinforcement or GM texturing asperity variability, as well as from bentonite variability. The classification of shear strength uncertainty due to materials is shown in Figure 3.

Uncertainty due to GCL and GM materials
- (*2-i*) Repeatability of a single GCL-GM type (single lot)
- (*2-ii*) Overall material variability of a single GCL-GM type (different lots)
  - (*2-ii-a*) Reinforcement and asperity variability
  - (*2-ii-b*) Bentonite variability
- (*2-iii*) Different GCL-GM types or manufacturers

Figure 3: Uncertainty due to materials

Source of uncertainty (*2-i*) should be accounted for when the actual manufacturing lot of the GCL to be used during construction has been identified, and this project-specific information is available (e.g., from a project-specific testing program). It should be noted that a GCL manufacturing lot is not strictly standardized, but is typically defined as a set of rolls produced in a shift, day or even week, with materials manufactured together or from the same source. As will be shown in section 4, GCLs and GMs taken from the same manufacturing lot have comparatively low shear strength variability, for which reason source of uncertainty (*2-i*) is referred to in this study as the repeatability.

Source of uncertainty (*2-ii*) should be accounted for when the actual type of GCL to be used during construction has been selected, but the actual manufacturing lot has not been identified (i.e. if project-specific information is not available, but product-specific data is) or there are several manufacturing lots used for a single project. Further evaluation of source of uncertainty (*2-ii*) indicates that the overall variability of a single GCL from different manufacturing lots arises from: (*2-ii-a*) variability in internal GCL fiber reinforcement (or in GCL-GM interlocking connections) and (*2-ii-b*) variability in bentonite composition (or in the amount of bentonite extruded from the GCL into the GM interface). It is likely that variability in the fiber reinforcements and the bentonite composition are also present in source (*2-i*) as well, but their effects on the repeatability are significantly lower than those of source of uncertainty (*2-ii*).

Source (*2-iii*) should be accounted for when the type of GCL and GM to be used during construction has not been selected. It should be noted that different GCL types (needle-punched, stitch-bonded, thermally-locked, unreinforced) have different internal reinforcement types and carrier geotextile surface treatments while different GMs may have different polymer type and surface texturing. Figure 5 shows the variability in shear strength due to source of uncertainty (*2-iii*) while maintaining the conditioning/test conditions constant (with exception of the unreinforced GCL F). This figure indicates that the particular internal reinforcements, and the means by which the reinforcements are secured to the carrier geotextiles of the GCL (e.g., thermally-locking), will significantly impact the shear strength of the GCL.

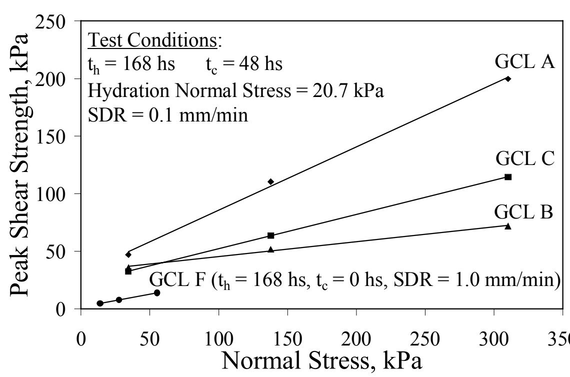


Figure 5: Shear strength variability due to source of uncertainty (*2-iii*)

Source of uncertainty (*2-ii*) is examined in detail in section 5 of this paper, but at this point it is interesting to view the combined effect of source of uncertainty (*2-ii*) and (*3*). Figure 4 shows a set of internal peak shear strength envelopes for GCL A with four hydration scenarios. In all of the tests, the specimens were hydrated for a time t_h under a normal stress equal to that used during shearing. The water content at the end of shearing increased significantly from t_h = 0 hs to t_h = 24 hs but only slightly for t_h values beyond 24 hs. This figure shows a significant variability for each of the failure envelopes, but a clear decreasing peak shear strength with increasing t_h. This indicates that conditioning/test conditions should be held constant when examining material variability.

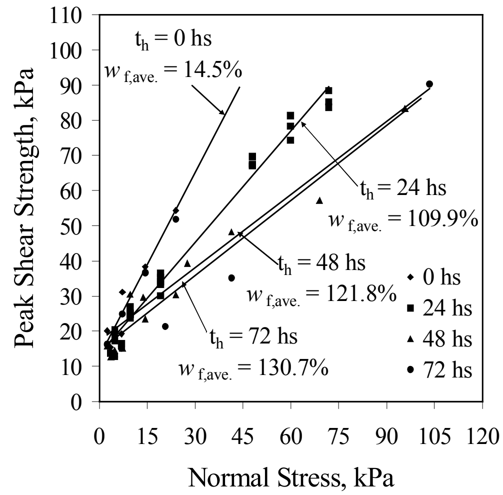


Figure 4: Shear strength variability due to sources of uncertainty (*2-ii*) and (*3*)

4. REPEATABILITY

Repeatability should be evaluated in an engineering test conducted using the same materials. With GCLs, a small amount of variability is expected in a direct shear test on the same GCL product due to variations in the fiber reinforcement and bentonite composition. Also, as a direct shear test on reinforced GCL destroys the reinforcing structure of the GCL, multiple tests on an identical specimen are not possible. Consequently, the source of variability (*2-i*) can be assessed by comparing the results of tests conducted by a single laboratory using specimens collected from a single manufacturing lot. Figure 6 shows shear stress-displacement curves for GCL A specimens obtained from rolls of the same lot and tested by the same laboratory using the same levels of σ_n. All of these specimens had approximately the same gravimetric water contents at the end of shearing (about 90%). These results illustrate that a very good repeatability can be achieved in the stress-strain-strength response when tests are conducted in the same laboratory using same-lot specimens. As there are only three peak shear strength values to compare at each normal stress, the percent relative difference is a better quantification of the repeatability than the standard deviation. The relative difference, RD, is defined as:

$$\text{RD} = \frac{\tau_{HIGH} - \tau_{LOW}}{\tau_{LOW}} \times 100 \qquad (1)$$

Among the tests shown in Figure 6, the maximum relative difference in peak shear strength values is less than 6%.

Figure 7 shows shear stress-displacement curves for GCL A specimens and THDPE GM specimens. The tests were conducted using GCL and GM specimens from rolls of the same lot and tested by the same laboratory using the levels of same σ_n. All of the GCLs in these tests showed similar gravimetric water contents at the end of shearing (71 to 74%). Among these tests, the maximum relative difference in peak shear strength values is less than 10%. Although the absolute difference between peak shear strength values increases with normal stress, the relative difference remains approximately constant.

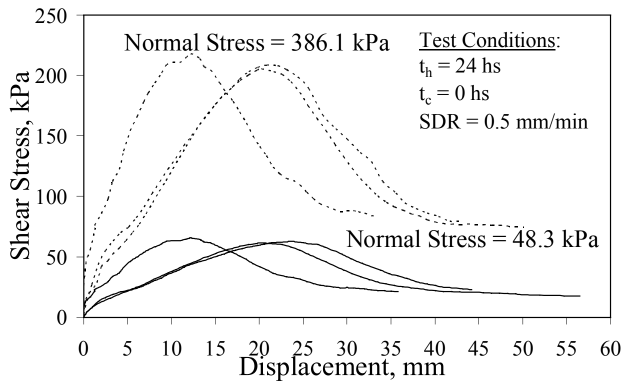


Figure 6: Repeatability of test results on GCL A same-lot specimens

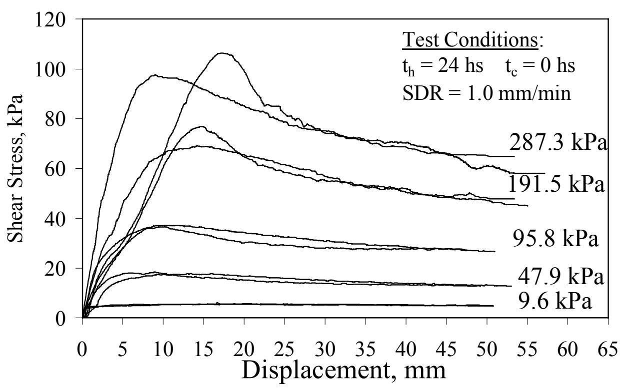


Figure 7: Repeatability of GCL A-GM interface shear strength for same-lot specimens

GCL-GM interface shear strength repeatability may change if the GCL or GM is obtained from different lots while the other is not. Figure 8 shows the interface shear strength results obtained using GCL specimens from the same lot, but GMs from different lots (solid lines). Also, Figure 8 shows the interface shear strength results obtained using GCL specimens from different lots and GM specimens from the same lots (dashed lines). The relative difference between the pairs of shear strength values is less than 20% for both situations. The variability in shear strength induced by using either GCL or GM specimens from different manufacturing lots is greater than the variability in interface shear strength using GCLs and GMs from the same manufacturing lot (Figure 7). However, these results suggest that GCLs and GMs taken from different lots contribute similarly to the GCL-GM interface shear strength variability.

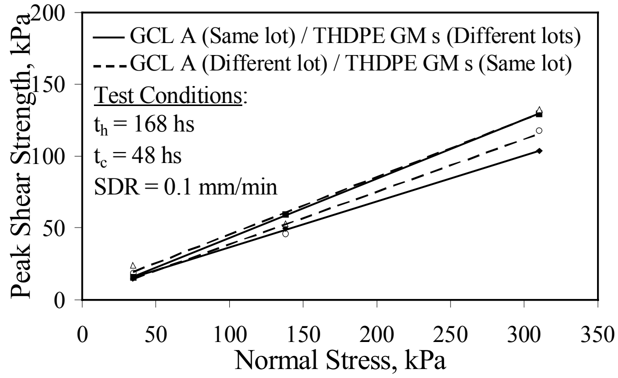


Figure 8: Effect of GCL and GM on the shear strength repeatability

5. MATERIAL VARIABILITY

5.1 Overall Material Variability

The source of variability (*2-iii*) may be assessed by evaluating thirteen sets of multiple GCL internal and GCL-GM interface tests summarized in Table 1. Each set of tests was conducted using the same GCL type, same σ_n, and same conditioning/test conditions. The GCL and GM specimens in these sets were obtained from different manufacturing lots. For each set, the table indicates the mean τ_p [$E(\tau_p)$], standard deviation [$s(\tau_p)$], c.o.v. [$s(\tau)/E(\tau)$], and maximum relative difference (RD) values for each set of peak shear strength data. It should be noted that the maximum percent relative difference values for the thirteen sets of different-lot data are significantly higher (23 to 58%) than those observed for the sets of same-lot data shown in Section 4 (6 to 10%). This indicates that the effects of variability in fiber reinforcement and bentonite composition are more significant for GCLs and GMs from different lots.

Sets 1, 2 and 3 include data from 102 internal shear strength tests on GCL A, and Sets 9, 10 and 11 include data from 123 GCL A – GM s interface shear strength tests. These tests were conducted using the same conditioning/test conditions (t_h = 168 hs, t_c = 48 hs, SDR = 0.1 mm/min) and three different normal stresses (σ_n = 34.5, 137.9, 310.3 kPa). These particular GCL A and GM s specimens were obtained from different manufacturing lots and tested between January 1998 and April 2002. Evaluation of statistical information on the τ_p results for these six sets in Table 1 shows an increasing $E(\tau_p)$ and $s(\tau_p)$, but decreasing c.o.v. and maximum RD with increasing σ_n. As a constant c.o.v. indicates a linear increase in variability with normal stress, the slight decrease in c.o.v. with normal stress indicates that the magnitude of the variability increases nonlinearly with normal stress for GCL internal shear strength in Sets 1 to 3 as well as for GCL-GM interface shear strength in Sets

Table 1: Statistical Analysis of Selected GCL Internal and GCL-GM Interface Shear Strength Sets

	GCL information		GM information				Test conditions				Peak shear strength			
Set number	Type	Manufacturer label	Type	Manufacturer label	Thickness	Number of tests	t_h (hs)	t_c (hs)	SDR (mm/min)	Normal Stress (kPa)	Mean $E(\tau_p)$ (kPa)	St.dev. $s(\tau_p)$ (kPa)	c.o.v.	Maximum RD (%)
1	Needle-punched	A		Internal		34	168	48	0.1	34.5	38.8	10.3	0.26	56
2	Needle-punched	A		Internal		34	168	48	0.1	137.9	94.5	22.0	0.23	54
3	Needle-punched	A		Internal		34	168	48	0.1	310.3	176.3	33.6	0.19	51
4	Needle-punched	A		Internal		5	0	0	1.0	517.1	404.4	41.4	0.10	23
5	Needle-punched	A		Internal		8	24	0	1.0	9.6	25.2	1.3	0.05	13
6	Needle-punched	A		Internal		18	48	0	1.0	9.6	31.1	5.8	0.19	55
7	Stitch-bonded	B		Internal		5	48	0	1.0	9.6	26.4	3.3	0.12	27
8	Unreinforced	F		Internal		6	24	0	1.0	9.6	3.9	0.7	0.19	35
9	Needle-punched	A	THPDE	s	80-mil	41	168	48	0.1	34.5	18.0	3.8	0.21	58
10	Needle-punched	A	THPDE	s	80-mil	41	168	48	0.1	137.9	60.8	9.6	0.16	50
11	Needle-punched	A	THPDE	s	80-mil	41	168	48	0.1	310.3	122.9	16.6	0.14	42
12	Needle-punched	A	THPDE	v	80-mil	7	24	0	1.0	172.4	73.5	8.1	0.11	27
13	Needle-punched	A	THPDE	v	80-mil	7	24	0	1.0	344.7	138.5	16.5	0.12	31
14	Needle-punched	A	THPDE	v	80-mil	7	24	0	1.0	689.5	264.6	31.8	0.12	34

9 to 11. Comparing the variability in internal and interface shear strength values, the maximum RD are similar, while the c.o.v. values of the interface data are slightly lower.

As the mean interface shear strength is lower than the mean internal shear strength, the lower c.o.v. values for the interface results indicates that the variability is lower for internal shear strength for the same conditioning/test procedures and normal stresses. This is most likely due to differences in internal and interface shear strength mobilization (e.g., bentonite shear strength, GCL internal reinforcements, or GM asperity-GCL connections).

Sets 4, 5 and 6 in Table 1 include variability data from additional direct shear tests conducted using the same GCL tested in Sets 1, 2 and 3 (GCL A, needle-punched), but using different conditioning/test conditions and normal stresses. Set 4 includes GCL A specimens that were sheared under unhydrated conditions at a high normal stress (517.1 kPa). A lower variability is observed in these shear strength values than in Sets 1 to 3, as quantified by the c.o.v. and the maximum RD. Sets 5 and 6 include GCL A specimens tested under two hydration conditions at a low normal stress (9.6 kPa). The shear strength variability in these two sets differs significantly, with Set 5 having the lowest variability and Set 6 having one of the highest. Although the normal stress and the conditioning/test conditions are not the main source of GCL shear strength variability, evaluation of Sets 4, 5 and 6 indicate that the magnitude of variability is affected by both. Tests with longer hydration times and lower normal stress show higher variability. Sets 7 and 8 include data from other GCLs: GCL B (stitch-bonded) and GCL F (unreinforced) tested under the same conditions and normal stress as Set 6. Although the mean shear strength values of Sets 6 and 7 are very different (they have different reinforcement), Set 6 still shows relatively high variability. This indicates that the GCL reinforcement type may affect the shear strength variability slightly, but the material variability within a single GCL type (from different lots) is more significant. Set 8 will be discussed in more detail in Section 5.3.

Sets 12 through 14 in Table 1 include variability data from a set of 21 direct shear tests conducted using the same GCL tested in Sets 9 to 11 (GCL A), but a different GM (GM v) and different conditioning/test conditions (t_h = 24 hs, t_c = 0 hs, SDR = 1.0 mm/min). Three different σ_n (172.4, 344.7, and 689.5 kPa) were used in this program. The different GM and conditioning/test conditions led to a relatively constant c.o.v. and maximum RD value, indicating that variability increases linearly with normal stress. This c.o.v. is smaller than that obtained for Sets 9, 10, and 11 using different conditioning/test conditions, suggesting that conditioning/testing procedures have some effect on the GCL-GM interface variability.

Figure 9 shows the actual probability density functions (PDFs) for τ_p at each σ_n (Sets 1, 2, 3, 9, 10 and 11 in Table 1). These PDFs quantify the statistical information on τ_p useful for reliability-based design or data forecasting. Also included in each figure are two parametric PDFs (normal and lognormal) and one nonparametric PDF for the data sets. The nonparametric PDF was developed using a normal kernel density function (Bowman and Azzalani 2000). The nonparametric PDFs were developed by creating locally-weighted PDFs at each value, and adding them to develop a global PDF. Nonparametric PDFs are capable of capturing the actual trends in the data, while parametric PDFs are restricted by their underlying mathematical model. This is apparent in Figure 10(a), 10(b), and 10(c), where bimodal trends in GCL internal peak shear strength is observed. The parametric densities could not capture the bimodality, while the nonparametric densities capture the shape of the data. This bimodality is most likely due changes in the properties of GCL A over the time period of this testing program. The parametric and nonparametric densities capture the behaviour of the GCL-GM interface shear strength data equally well. The interface shear strength values are slightly skewed to lower shear strength values. Although the normal density also appears to capture the overall trend in the data, negative values are possible by the underlying model.

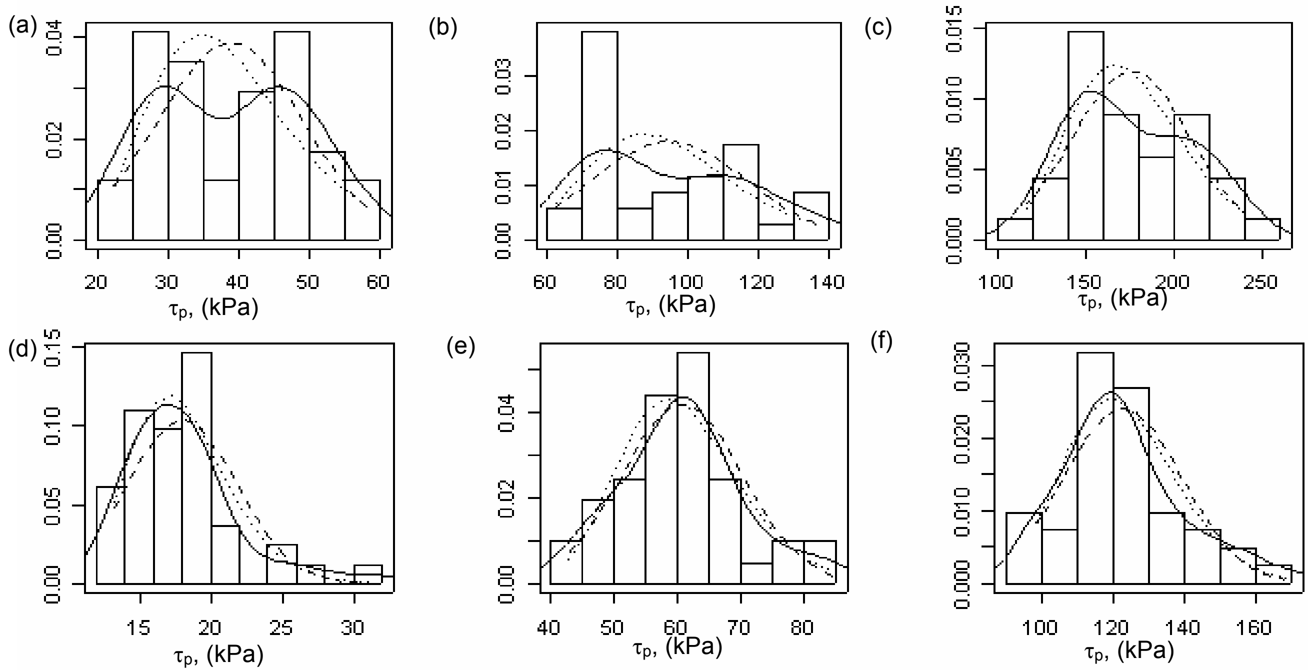


Figure 9: PDFs of the peak shear strength data: (a) Set 1; (b) Set 2; (c) Set 3; (d) Set 9; (e) Set 10; (f) Set 11; Note: Solid line = Nonparametric PDF, Dashed line = Normal PDF; Dotted line = Lognormal PDF

Because of the bimodal distribution noted in the internal GCL shear strength data, the statistics (e.g., mean, standard deviation) may be affected by the location of the two modes. Bootstrap sampling (Efron and Tibshirani 1993) constitutes an interesting analysis tool useful for providing nonparametric confidence intervals on the statistics, as well as allowing further comparison between the statistics for the different sets in Table 1. Bootstrapping involves randomly selecting values from a current sample (with replacement after selection) to form a new sample with the same size as the current sample. It is likely that the new sample will have different values than the current sample as well as different statistics. If this is repeated several times, a range of statistics may be found, which can be evaluated using a boxplot. The particular boxplot used in this study includes a box defined by the 25 and 75% quantiles of the data set, a center line defined by the median, whiskers defined by the 10 and 90% quantiles, as well as any outliers. Figure 10 shows the boxplots of the means, standard deviations and maximum relative differences from bootstrapped samples of Internal GCL Sets 1, 2, 3, and GCL-GM Interface Sets 9, 10 and 11. Plotted on top of the boxplots are arrows indicating the value of the statistic calculated for the original data sets, which correspond well with the center line of the boxplots. The boxplots for

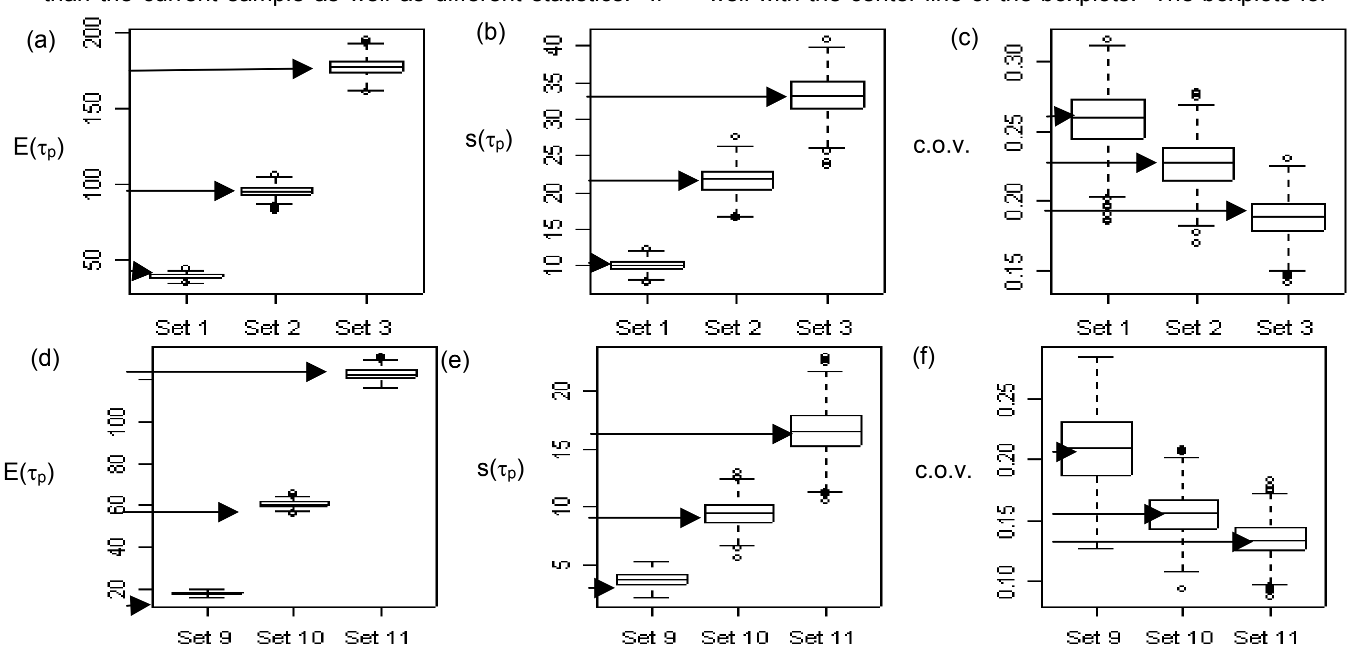


Figure 10: Boxplots of bootstrapped statistics of internal and interface shear strength sets in Table 1 (arrows = original values): (a) Means; (b) Standard deviations; (c) c.o.v. values; (d) Means; (e) Standard deviations; (f) c.o.v. values

the mean internal shear strength in Figure 10(a) are wider than those for the mean interface shear strength in Figure 10(d). For example, the mean of bootstrapped samples from Set 3 ranges from 155 kPa to 195 kPa, most likely because of bimodality: some of the samples were dominated by the mode at 150 kPa [Figure 10(c)] and others dominated by the mode at 205 kPa. Evaluation of the c.o.v. values in Table 1 for Sets 1 to 3 and Sets 9 to 11 indicates that the c.o.v. values are slightly different (~0.2), but the c.o.v. boxplots in Figures 10(c) and 10(f) show this is not the case, as the boxes do not overlap.

5.2 Inherent Variability of Fiber Reinforcements

As the shear strength of fiber reinforced soil can be obtained by accounting separately for the tensile contribution of fibers and the shear contribution of soil (Zornberg 2002), the contribution to the total internal or interface variability of the fiber reinforcement variability and bentonite variability can be evaluated separately. Peel strength results have been reported to provide an index of the density (and possibly the contribution) of fiber reinforcements in needle-punched GCLs (Eid et al. 1999). In addition, the peel strength may provide an indication of the interlocking connections between the entangled fibers on the GCL surface and the GM textured asperities. Consequently, an assessment is made herein of the peel strength variability as a potential measure of the variability of fiber contribution to GCL internal and GCL-GM interface shear strength [source of variability (*2-iii-a*)]. The peel strength test (ASTM D6496) involves clamping the carrier geotextiles of a 100 mm wide unhydrated GCL specimen, and applying a force normal to the GCL plane required to separate the geotextiles. It should be noted that the peel strength test mobilizes the fibers in a manner that may not be representative of the conditions in which the fibers are mobilized during shearing.

A total of 75 peel strength tests were conducted using GCL A specimens. Specifically, five tests were conducted using GCL A specimens from 15 rolls from different lots used for the testing program described for Sets 1 to 3 and 9, to 11 in Table 1. The peel strength specified by the GCL A manufacturer is 6.5 N/m. The peel strength results were found to vary significantly (mean of 12.51 and standard deviation of 5.51 N/m). The relationship between peel strength and peak shear strength obtained using GCL specimens collected from these 15 rolls is shown in Figure 11. Although a slight increasing trend of peel strength with increasing shear strength can be observed at high normal stress, the results suggest that the peel strength is not sensitive to GCL internal or GCL-GM interface shear strength. Consequently, no conclusion can be drawn regarding the effect of the variability of peel strength on the variability of the fiber contribution to GCL internal shear strength [source of variability (*2-ii-a*)]. Instead, these results suggest that the peel strength is not a good indication of the contribution of fibers to the peak shear strength. Evaluation of the effect of GCL fiber reinforcement type on internal shear strength variability can be made by comparing Set 7 for GCL B with Set 6 for GCL A. Only a slightly lower variability is observed for GCL B despite the significant difference in fiber type/density for stitch-bonded and needle-punched GCLs.

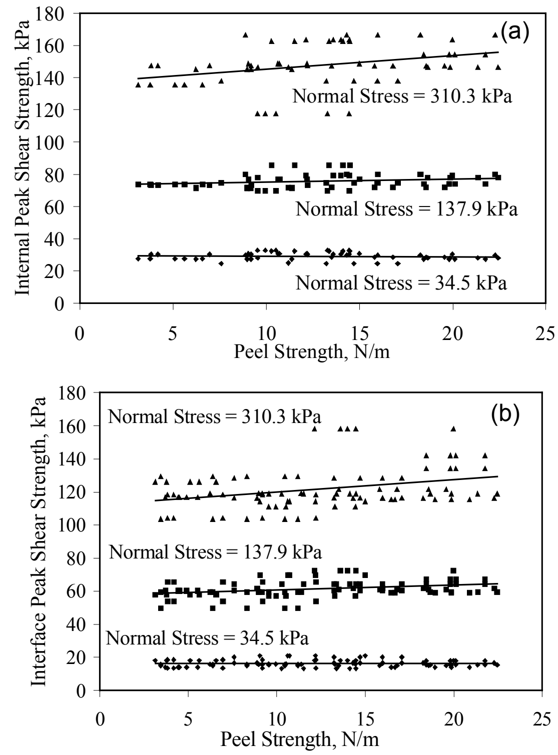
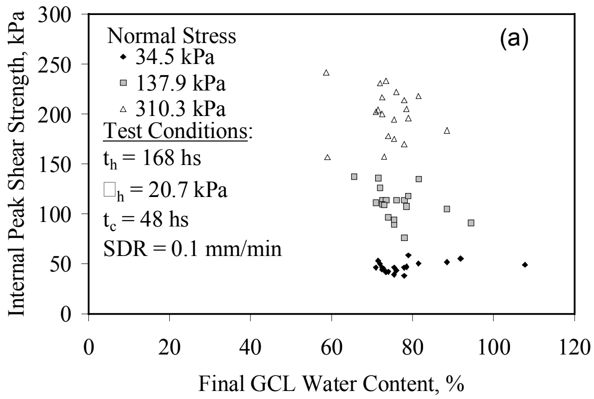


Figure 11: Relationship between peel strength and shear strength for (a) Sets 1, 2, 3; (b) Sets 9, 10 and 11

5.3 Inherent Variability of Sodium Bentonite

Source of variability (*2-ii-b*) may be assessed by comparing the internal shear strength variability of reinforced and unreinforced GCLs. Set 8 (Table 1) includes variability data from 6 direct shear tests conducted using an unreinforced GCL (GCL F). The tests were conducted using the same relatively low normal stress (9.6 kPa) and same conditioning/test procedures (t_h = 24 hs, t_c = 48 hs, SDR = 1.0 mm/min) as the reinforced GCLs (GCLs A and B) in Sets 6 and 7. The variability of direct shear test results for unreinforced GCLs allows assessment of the contribution bentonite shear strength variability to the total reinforced GCL shear strength variability. As mentioned above, the maximum percent relative difference and c.o.v. values for set 8 are similar to those obtained for reinforced GCLs (Sets 1-7), despite the significantly lower magnitude of the mean and standard deviation. Even though internal shear strength variability has often been attributed to the fibers, the similar c.o.v. values obtained for reinforced and unreinforced GCLs suggests that the variability of the bentonite [source of variability (*2-ii-b*)] is relevant and should be examined further. Also the variability in bentonite extrusion is expected to be a major source of GCL-GM interface shear strength variability. However, quantification of this variability is difficult, as the amount of bentonite extruded during hydration, consolidation and shearing would have to be quantified. However, stopping the test at these times to collect extruded bentonite by separating the GCL from the GM would change the properties of the interface. The amount of extrusion at the end of the test is likely to be similar for most GCL-GM tests, as McCartney et al. (2002) reported that GCL-GM interfaces have similar large-displacement shear strength.



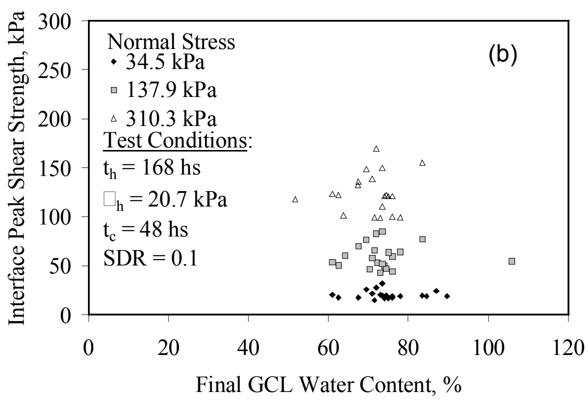


Figure 12: Relationship between GCL water content at the end of shearing and (a) GCL internal shear strength (Sets 1 to 3); (b) GCL-GM interface shear strength (Sets 9 to 11)

Another factor related to the contribution of bentonite to GCL shear strength variability is the water content of the GCL. It is expected that higher water contents will lead to lower GCL shear strength as the bentonite has a lower suction. If the bentonite component of different GCLs absorbs variable quantities of water in the same time period, then this variability may be related to the shear strength variability. However, Figure 12 shows that the water content measured at the end of the test for the GCLs in Sets 1 to 3 and Sets 9-11 does not correlate well with the peak GCL internal or GCL-GM interface shear strength. This indicates that the variability in the quantity of water absorbed during a fixed period of time does not affect the shear strength variability.

6. CONCLUSIONS

A database of 375 GCL internal and 388 GCL-GM interface shear strength tests was used to analyze the sources of GCL shear strength variability. The following conclusions may be drawn from this study:

- Good repeatability of results was obtained for tests conducted by the same laboratory using GCL/GM specimens from the same manufacturing lot. However, significant variability was obtained for tests conducted using different-lot GCL/GM specimens.
- Conditioning/test procedures, normal stress and internal reinforcements were found to have some effect on the variability.
- Peel strength was found not to correlate well with the GCL internal or GCL-GM interface peak shear strength. The peel strength variability cannot be used to infer the effect of fibers on the variability of GCL and GCL-GM shear strength.
- The unreinforced GCL shear strength variability was found to be high relative to the magnitude of the mean shear strength, suggesting that the bentonite shear strength variability may contribute to reinforced GCL shear strength variability.
- The bentonite water content at the end of shearing was found not to correlate well with GCL internal or GCL-GM interface shear strength, indicating that the variability in the quantity of water absorbed during a fixed period of time does not affect significantly the peak shear strength.

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