McCartney, J.S., Zornberg, J.G., and Swan, R.H. (2004). "Effect of Specimen Conditioning on Geosynthetic Clay Liner Shear Strength."
Proceedings of the *GeoAsia 2004 Conference*, Third Asian regional conference on Geosynthetics, Seoul, Korea, June 21-24, pp. 635-643.

Effect of Specimen Conditioning on Geosynthetic Clay Liner Shear Strength

J.S. McCartney & J.G. Zornberg
Department of Civil Engineering – GEO, The University of Texas at Austin, Austin, TX, USA
zornberg@mail.utexas.edu

R.H. Swan
SGI Testing Services, 4405 International Boulevard, Suite-B117, Norcross, Georgia 30093
testing@interactionspecialists.com

ABSTRACT: Specifications for laboratory shear strength testing of geosynthetic clay liners (GCLs) must replicate field conditions while still accounting for time and cost considerations. A database of 414 GCL internal and 534 GCL-geomembrane (GM) interface shear strength results has been assembled. Specifically, the results of large-scale direct shear tests conducted by a single independent laboratory are evaluated to develop guidelines on specimen conditioning. It was found that both the GCL internal and interface peak shear strengths decreased with increasing time of hydration (t_h). However, the GCL internal shear strength did not change for t_h beyond 48 hs and the GCL-GM interface shear strength did not change for t_h beyond 24 hs. The normal stress used during hydration affected significantly the peak shear strength due to bentonite swelling. Hydration under low normal stress followed by consolidation led to similar GCL internal peak shear strength as hydration under high normal stress. However, due to bentonite extrusion, hydration under high normal stress led to consistently lower GCL-GM interface peak shear strength than hydration under low normal stress followed by consolidation. Overall, GCL internal and interface large-displacement shear strengths were found to be relatively insensitive to conditioning.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are prefabricated geocomposite materials used in hydraulic barriers as an alternative to compacted clay liners. They consist of sodium bentonite clay bonded to one or two layers of geosynthetic backing materials (carrier geosynthetics). Moisture conditioning of the sodium bentonite component in the GCL plays an important role in the shear strength of GCLs in the laboratory and the field. The initial gravimetric water content of GCLs tested in the laboratory and installed in the field is relatively low (approximately 10%). At this low water content, the pore water pressures within the sodium bentonite are negative, and the clay particles have a flocculated structure, conditions that may contribute to the high strength of unhydrated sodium bentonite. Moisture conditioning involves hydration of the sodium bentonite as it comes into contact with water, and its subsequent consolidation under final normal stresses. The normal stress used during these two conditioning phases of the GCL affects significantly the change in shear strength. Hydration of the sodium bentonite leads to reduction of the negative pore water pressures and an increase in volume (swelling), depending on the level of normal stress. Swelling may lead to a change in structure of the clay particles. The combined effect of a reduction of negative pore pressures in the sodium bentonite and a change in soil structure leads to a drop in the contribution of the shear strength of sodium bentonite to the overall shear strength of GCLs. The effect of sodium bentonite conditioning also affects the geosynthetic component of GCLs. GCLs allowed to swell freely during hydration have been reported to experience pullout of reinforcing needle-punched fibers from the carrier geosynthetics. Zornberg et al. (2004) reported bilinear shear strength envelope for GCLs, with a break at a normal stress of approximately 100 to 200 kPa. This normal stress is consistent with the swelling pressure of the GCL (i.e., the level of normal stress at which no swelling occurs during hydration).

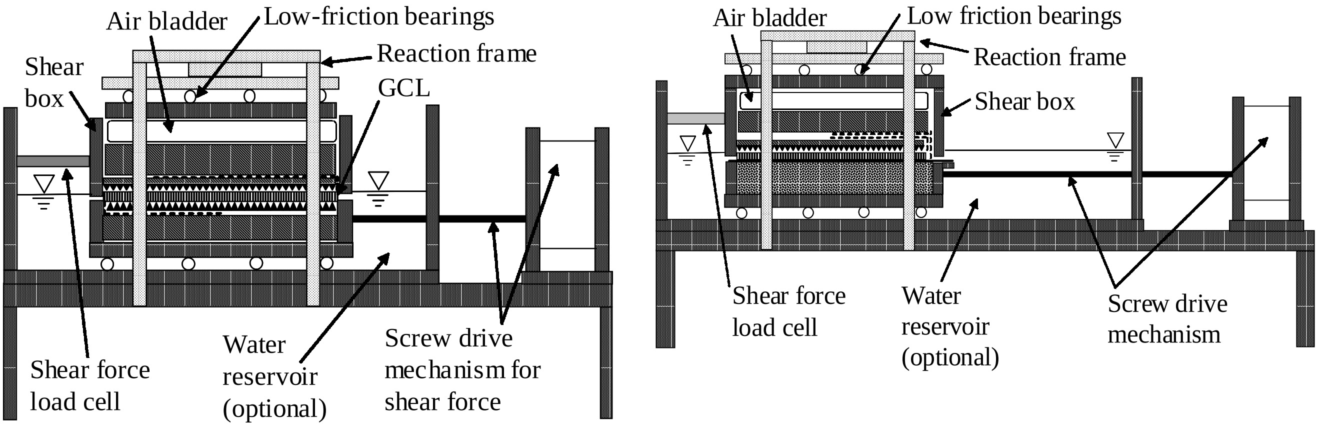
A large database referred herein as the GCLSS database was assembled using 414 GCL internal and 534 GCL-GM interface large-scale (305 mm by 305 mm) direct shear tests (McCartney et al. 2002). The tests were conducted by the Soil-Geosynthetic Interaction laboratory of GeoSyntec Consultants, currently operated by SGI Testing Services (SGI). SGI is an accredited testing facility with significant consistency in its testing procedures. It should be noted that procedures used for GCL direct shear tests conducted by SGI over the period 1992 to 2003 are consistent with *ASTM D6243*, even though this standard was only approved in 1998. Information from the GCLSS database is analyzed herein to evaluate the effect of GCL conditioning (*i.e.* hydration and subsequent consolidation) on GCL internal and GCL-GM interface shear strength. Specifically, the effect of conditioning on direct shear tests conducted under a wide range of σ_n on 5 GCLs and 6 geomembranes is investigated. Table 1 provides the designation of the GCLs and geomembranes investigated in this study, the product name, and a description of the GCL reinforcement characteristics and carrier geotextiles.

Table 1. GCL and Geomembrane Designation

GCL label	Product name	Description	GM label	Manufacturer name	Description
A	Bentomat® ST	GCL, needle-punched W-NW	**s**	GSE®	Geomembrane, Textured HDPE
B	Claymax® 500SP	GCL, stitch-bonded W-W	**t**	NSC®	Geomembrane, Textured HDPE
C	Bentofix® NS	GCL, thermally-locked, needle-punched W-NW	**u**	Polyflex®	Geomembrane, Textured HDPE
H	Bentomat® DN	GCL, needle-punched NW-NW	**v**	Serrot®	Geomembrane, Textured HDPE

2 METHODOLOGY

Figure 1(a) shows the configuration of the direct shear equipment used for GCL internal shear strength testing, and Figure 1(b) shows the configuration used for GCL-GM interface shear strength testing. The typical hydration process used in this study is a two-stage procedure similar to that reported by Fox *et al.* (1998) and Triplett and Fox (2001). GCL specimens were placed under a specified hydration normal stress (σ_h) outside the direct shear device and soaked in tap water during the specified hydration time (t_h). Current testing standards (*ASTM D6243*) do not require measurement of changes in pore pressures or vertical swell during GCL hydration and consolidation. Nonetheless, hydration of the sodium bentonite may be evaluated by the hydration time (Gilbert *et al.* 1997). Although times as high as 250 hs may be required to reach full hydration, hydration times beyond 72 hs have been reported not to significantly increase the GCL water content, especially under high normal stress (Stark and Eid 1996). The hydration normal stress, σ_h was often specified to equal the shearing normal stress (σ_n). In this case, shearing is conducted immediately after hydration at a constant shear displacement rate (SDR). The peak shear strength (τ_p) and large displacement shear strength (τ_{ld}) are recorded. However, if σ_h was less than σ_n (*e.g.* to simulate field conditions representative of bottom liners), pore pressures were allowed to dissipate during a consolidation period (t_c) before shearing. Gilbert *et al.* (1997) reported that t_c, estimated by one-dimensional consolidation theory, may range from several days to weeks. Additional details on the testing procedures are presented by Zornberg et al. (2004) and McCartney et al. (2002).



(a) (b)

Fig. 1. Direct shear device: (a) GCL internal testing configuration; (a) GCL-GM interface testing configuration

3 EFFECT OF CONDITIONING ON GCL INTERNAL SHEAR STRENGTH

Table 2 summarizes sets of several failure envelopes that were selected from the results of GCL internal shear strength tests with different conditioning procedures. Sets 1 and 2 compare the effect of t_h, Sets 3 and 4 compare the effect of σ_h when the GCL is not subsequently consolidated, and Sets 5 and 6 compare the effect of σ_h when the GCL is subsequently consolidated. As direct comparison between failure envelopes defined by a friction angle and cohesion intercept is difficult, a graphical comparison was selected for this evaluation.

Table 2. Sets of GCL Internal Failure Envelopes

Set number	Analysis type	GCL label	Number of tests	Test conditions				σ_n range (kPa)	Peak			Large-displacement		
				SDR (mm/min)	σ_h (kPa)	t_h (hs)	t_c (hs)		ϕ (°)	c (kPa)	R^2	ϕ (°)	c (kPa)	R^2
1	Effect of t_h	A	7	1.0	0.0	0	0	2.4 - 35	60.1	12.9	0.921	N/A	N/A	N/A
		A	27	1.0	σ_n	24	0	3.4 - 72	46.6	13.5	0.987	8.6	2.1	0.842
		A	31	1.0	σ_n	48	0	2.4 - 97	35.4	14.4	0.948	N/A	N/A	N/A
		A	8	1.0	σ_n	72	0	2.4 - 103	34.7	17.4	0.840	8.5	2.8	0.943
2	Effect of t_h	B	7	1.0	σ_n	24	0	24 - 690	7.3	53.4	0.818	4.6	12.7	0.962
		B	25	1.0	4.8	48	0	2.4 - 982	4.4	24.3	0.949	N/A	N/A	N/A
		B	10	1.0	7.2	96	0	10 - 1000	4.6	24.1	0.976	N/A	N/A	N/A
3	Effect of σ_h	A	27	1.0	σ_n	24	0	3.4 - 72	46.6	13.5	0.987	8.6	2.1	0.842
		A	2	1.0	4.8	24	0	14 - 24	37.1	10.7	1.000	4.0	3.3	1.000
4	Effect of σ_h	A	31	1.0	σ_n	48	0	2.4 - 97	35.4	14.4	0.948	N/A	N/A	N/A
		A	5	1.0	4.8	48	0	14 - 276	29.9	35.9	0.991	4.4	2.0	0.996
6	Effect of σ_h and t_c	H	6	1.0	σ_n	24	0	4.8 - 483	33.8	19.7	0.997	5.3	23.8	0.997
		H	6	1.0	3.4	24	24	6.9 - 690	32.1	33.0	0.988	8.5	29.9	0.996
5	Effect of σ_h and t_c	A	27	1.0	σ_n	24	0	3.4 - 72	46.6	13.5	0.987	8.6	2.1	0.842
		A	3	1.0	6.9	60	24	4.8 - 29	50.1	12.4	0.991	N/A	N/A	N/A

Note: N/A is not available

Figure 2 shows the effect of t_h on τ_p and τ_{ld} for GCL *A* (needle-punched) tested using σ_n ranging from 2.4 to 100 kPa (Set 1). The specimens were conditioned using the same normal stress during hydration and shearing (*i.e.* $\sigma_h = \sigma_n$). The results show a decreasing τ_p with increasing t_h. However, no further changes in τ_p are observed for t_h beyond 48 hs. Significant scatter can be observed in the peak data, especially at very low σ_n (below 10 kPa). Some test results for specimens hydrated with t_h = 72 hs show even higher τ_p than unhydrated specimens. The scatter decreases at higher σ_n. Unlike the τ_p data, the results show that t_h does not affect τ_{ld}.

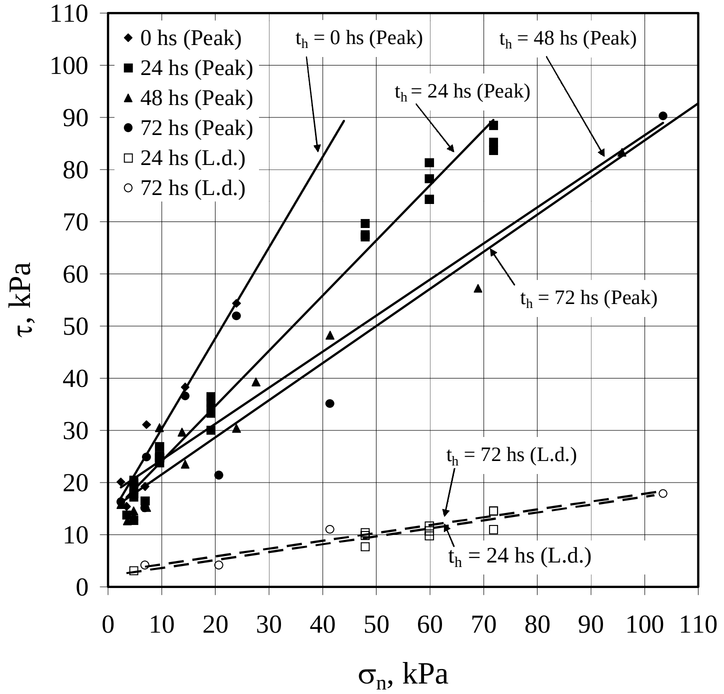


Fig. 2. Effect of t_h on peak and large-displacement shear strength of GCL A (Set 1 in Table 2)

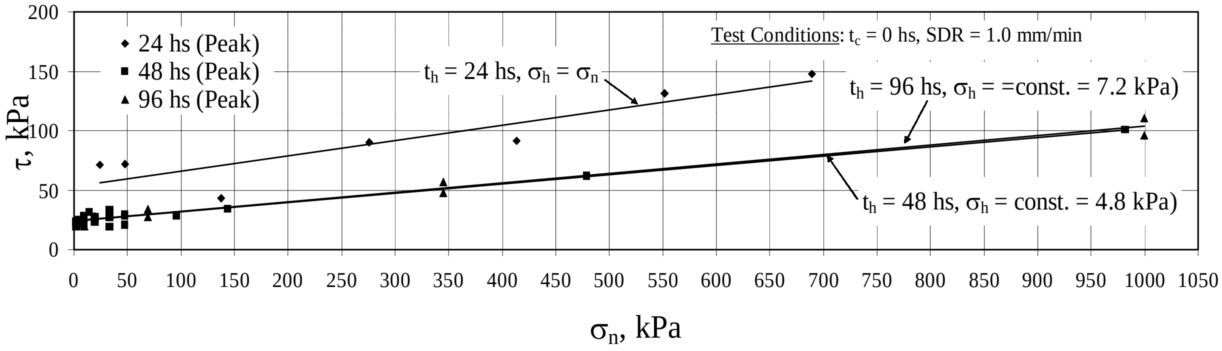


Fig. 3. Effect of t_h on peak and large-displacement shear strength of GCL B (Set 2 in Table 2)

Figure 3 shows the effect of t_h on τ_p for GCL *B* (Stitch-bonded) tested using σ_n ranging from 4.8 to 1000 kPa (Set 2). It should be noted that the GCLs with t_h = 24 hs were hydrated under $\sigma_h = \sigma_n$, while the other GCLs used a constant, relatively low σ_h. Despite this difference, GCL *B* envelopes also show a decrease in τ_p with increasing t_h. However, consistent with the GCL *A* results, no further changes are observed for t_h beyond 48 hours. Scatter is observed in Figure 3 for tests conducted under low σ_n, but little scatter is observed for σ_n above approximately 100 kPa.

Figure 4 shows the effect of σ_h on τ_p and τ_{ld} for GCL *A* specimens hydrated during 24 hs (Set 3). The normal stress used for first failure envelope during hydration was $\sigma_h = \sigma_n$, while a constant, relatively low σ_h (4.8 kPa) was used in the other failure envelope. The normal stress in the latter failure envelope was increased from σ_h to σ_n without allowing consolidation of the bentonite before shearing (t_c = 0 hs). Despite some scatter in the data points, the τ_p obtained when $\sigma_h = \sigma_n$ is consistently higher than that obtained when hydration is conducted using a relatively low σ_h. Unlike the differences in τ_p results, the τ_{ld} results are insensitive to σ_h. Although not shown in Figure 4, the results of Set 4 showed a similar trend as those reported for Set 3.

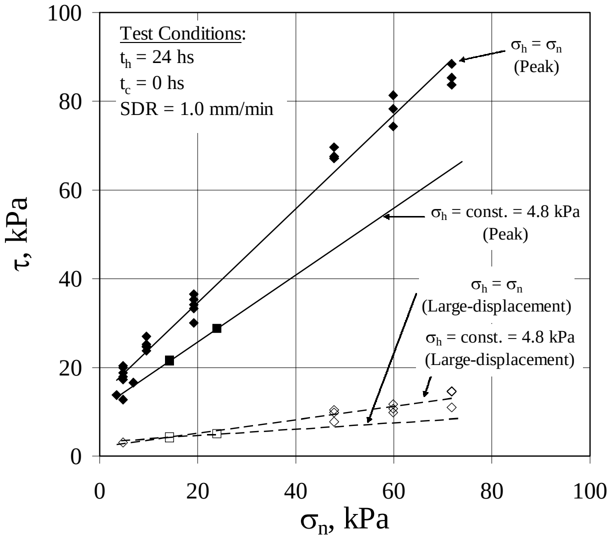


Fig. 4. Effect of σ_h on GCL A shear strength with $t_c = 0$ (Set 3 in Table 2)

When GCLs are hydrated under a $\sigma_h < \sigma_n$, testing procedures often specify that the GCL is subsequently consolidated under the normal stress to be used during shearing. Figure 5 shows the effect of σ_h on τ_p and τ_{ld} for needle-punched GCL *H* specimens hydrated during 24 hs (Set 5). The hydration normal stress used in tests on the unconsolidated GCLs was $\sigma_h = \sigma_n$, while a constant, relatively low σ_h (3.4 kPa) was used in tests on the consolidated GCL. However, differently than the second failure envelope in Set 3 hydrated using σ_h = 4.8 kPa (Figure 4), the normal stress in the consolidated GCL tests was increased from σ_h to σ_n and then allowed to consolidate during 24 hs before shearing. In this case, the τ_p envelope obtained using $\sigma_h = \sigma_n$ is essentially the same as that obtained when the specimen is consolidated after hydration conducted using a relatively low σ_h. Although not shown in Figure 5, the results of Set 6 showed a similar trend as those reported for Set 5.

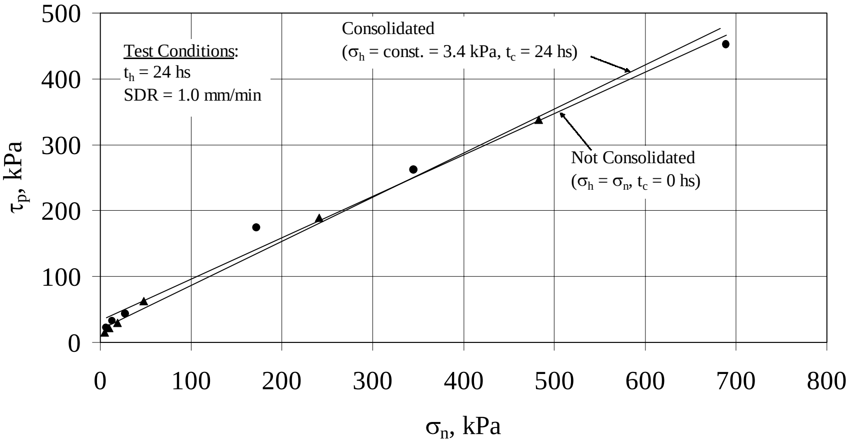


Fig. 5. Effect of σ_h on GCL H shear strength with t_c = 24 hs (Set 5 in Table 2)

In summary, hydration using $\sigma_h = \sigma_n$ with increasing t_h leads to decreasing GCL internal shear strengths (Sets 1 and 2). However, the results show that beyond a certain hydration time, the shear strength does not decrease with further hydration. Specifically, the GCL internal shear strength was found to not decrease significantly beyond hydration times of 48 hs. GCL internal specimens hydrated under a constant $\sigma_h < \sigma_n$ and sheared at σ_n without allowing subsequent consolidation were found to have lower τ_p than specimens hydrated at $\sigma_h = \sigma_n$ (Sets 3 and 4). The lower τ_p may be explained because these tests are undrained, in which positive pore water pressures present because of the increase in normal stress without allowing time for drainage decrease the effective stress in the GCL. This would occur in the field if the GCL were allowed to hydrate, then a large normal stress would be placed on the GCL in a short period of time. GCL internal specimens hydrated under a constant $\sigma_h < \sigma_n$ and subsequently consolidated for at least 24 hs were found to have a similar τ_p to specimens hydrated at $\sigma_h = \sigma_n$ (Sets 5 and 6). Specifying two conditioning phases (hydration using a $\sigma_h < \sigma_n$ followed by consolidation at σ_n and finally shearing at σ_n) is recommended if such stages are representative of field conditions. However, specifying two conditioning phases appears unnecessary since similar results are obtained by specifying a single conditioning phase (hydration at $\sigma_h = \sigma_n$ followed by shearing under σ_n). This finding may indicate that hydration has a greater effect on the dissipation of suction within the GCL than on pullout of the reinforcing fibers from the carrier geotextile during swelling. If pullout were to occur, the peak shear strength of the reinforced GCL should be similar to an unreinforced GCL, which is significantly lower than that of a reinforced GCL (Zornberg et al. 2004). Accordingly, for the particular values of σ_h and t_h in this study, hydration at $\sigma_h < \sigma_n$ was insufficient to cause of reinforcing fiber pullout from the carrier geotextile.

4 EFFECT OF CONDITIONING ON GCL-GM INTERFACE SHEAR STRENGTH

Table 3. Sets of GCL-GM Interface Failure Envelopes

Set number	Analysis type	Interface characteristics			Number of tests	Test conditions				σ_n range (kPa)	Peak			Large-displacement		
		GCL	GM type	GM label		SDR (mm/min)	t_h (hs)	σ_h (kPa)	t_c (hs)		ϕ (°)	c (kPa)	R^2	ϕ (°)	c (kPa)	R^2
7	Effect of t_h	K	Textured HDPE	u	3	1.0	0	0.0	0	69-345	25.1	23.96	0.996	11.6	49.76	0.750
		K	Textured HDPE	u	4	1.0	48	σ_n	0	241-965	27.0	1.03	0.995	17.1	1.72	0.984
8	Effect of t_h	A	Textured HDPE	s	3	1.0	0	0.0	0	241-965	25.3	45.51	0.961	16.8	6.55	0.995
		A	Textured HDPE	s	19	1.0	24	σ_n	0	6.9-483	18.0	9.47	0.961	9.9	6.3	0.679
		A	Textured HDPE	s	6	1.0	48	σ_n	0	51-345	12.2	16.39	0.861	8.4	6.65	0.885
9	Effect of t_h	C	Textured HDPE	t	4	1.0	0	0.0	0	16-670	21.8	13.88	0.995	9.9	12.83	0.971
		C	Textured HDPE	t	3	1.0	1	σ_n	0	20-62	20.9	1.21	0.999	15.8	1.14	0.999
		C	Textured HDPE	t	3	1.0	24	13.8	0	34-138	23.3	0.00	1.000	16.2	1.03	0.996
10	Effect of t_h	B	Textured HDPE	t	5	1.0	0	0.0	0	2.4-48	31.2	1.29	0.995	22.5	1.73	0.985
		B	Textured HDPE	t	18	1.0	24	13.8	0	2.4-103	17.9	3.93	0.881	9.8	4.13	0.797
11	Effect of t_h	B	Textured VLDPE	u	3	1.0	0	0.0	0	12-48	32.7	2.51	1.000	27.4	1.80	1.000
		B	Textured VLDPE	u	3	1.0	48	250.0	0	12-48	18.6	4.67	0.996	11.3	5.51	0.971
12	Effect of σ_h and t_c	A	Textured HDPE	v	36	1.0	24	σ_n	0	6.9-689	20.7	5.83	0.971	11.0	6.7	0.997
		A	Textured HDPE	v	3	1.0	24	68.9	12	138-552	19.7	3.10	0.997	11.1	12.07	0.979
13	Effect of σ_h and t_c	A	Textured LLDPE	u	4	1.0	72	σ_n	0	6.9-55.2	28.8	2.19	0.999	23.5	1.17	0.995
		A	Textured LLDPE	t	4	1.0	72	σ_n	0	6.9-55.2	26.3	2.55	0.999	19.3	1.65	0.995
		A	Textured LLDPE	s	3	1.0	72	0.0	48	4.8-19.2	20.6	0.23	0.998	15.8	0.65	0.976

Table 3 shows several additional comparisons between failure envelopes that were defined from the results of GCL-GM shear strength tests with different conditioning procedures. Sets 7 through 10 show the effect of t_h, and Sets 11 and 12 show the effect of σ_h when the GCL is subsequently consolidated. Again, graphical comparison of these failure envelopes is presented.

Figure 6(a) shows that hydration time has a similar effect on τ_p of GCL-GM interfaces (needle-punched GCL *A* and a textured HDPE geomembrane *s*, Set 7) as on GCL internal τ_p. While the range of σ_n used for the different envelopes in Set 7 is different, the interfaces with no hydration show a significantly higher τ_p than the other interfaces. The interfaces with times of hydration of 24 and 48 hs show no significant difference in the τ_p envelopes. Figure 6(b) shows that hydration of the interface between GCL *C* (needle-punched and thermally-locked) and a textured HDPE geomembrane *t* with hydration times as low as 1 hour results in an insignificant decrease in τ_p (Set 8). The time of hydration of 1 hour resulted in an increase in water content from about 15% (average unhydrated water content) to 78.9%. The results in Figure 6 indicate that interfaces will continue to hydrate beyond t_h = 1 hs, but little further decrease in shear strength will occur. A time of hydration of at least 24 hs is still recommended to ensure even hydration of the GCL specimen. The results of Sets 9 and 10 are consistent with the trends shown in Figure 6 for internal GCL shear strength.

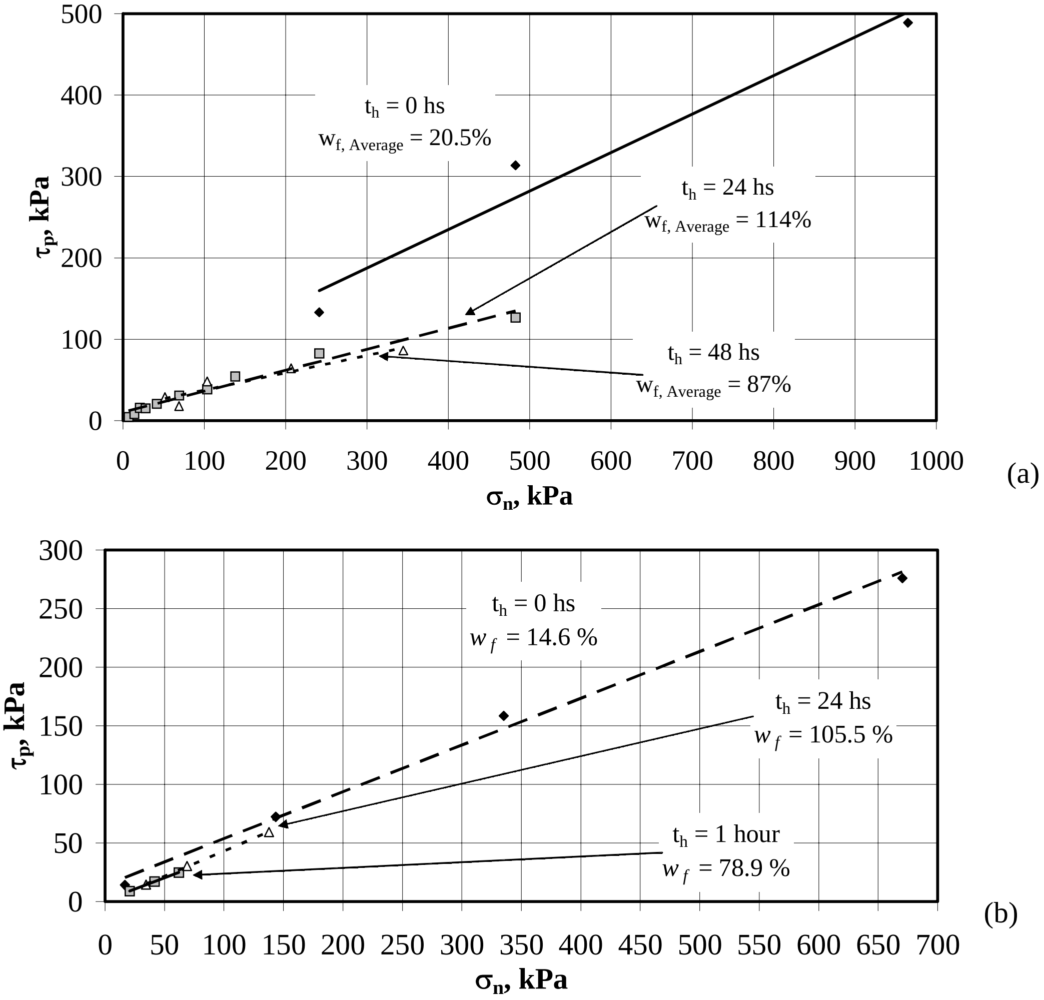


Fig. 6. Effect of t_h on τ_p of the interface between a textured GM and: (a) GCL A; (b) GCL C

Figure 7 shows the effect σ_h on τ_p and τ_{ld} for three tests on the interface between GCL *B* (stitch-bonded) and a textured HDPE geomembrane. This figure indicates that the interface shear strength decreases significantly after hydration (t_h = 24 hs) at $\sigma_h = \sigma_n$. A more significant shear strength decrease is obtained if the specimen is hydrated (t_h = 24 hs) using a smaller σ_h (of about tenth of the stress used during shearing and subsequent consolidation). This figure also shows that hydration at σ_h less than σ_n with subsequent consolidation has little effect on the large-displacement shear strength.

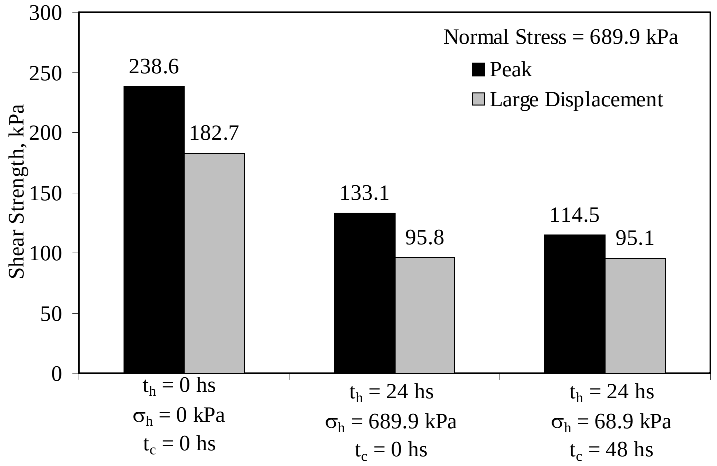


Fig. 7. Effect of consolidation on τ of the interface between GCL B and a textured HDPE geomembrane

Figure 8 shows the effect of σ_h on τ_p and τ_{ld} for the interface between GCL *A* and a textured HDPE geomembrane *v* for the cases in which specimens are hydrated under $\sigma_h = \sigma_n$ and not consolidated and when the interfaces are consolidated for 12 hs (Set 11). This figure shows similar results to Figure 7, although the difference in shear strength over a wide range of σ_n is not significant. Set 12 includes three different GCL *A* interfaces, two that were hydrated under $\sigma_h = \sigma_n$ and one that was hydrated under a σ_h = 0 kPa and subsequently consolidated for 48 hs. As the cohesion intercept in these failure envelopes is negligible, their shear strength may be compared by inspecting the friction angles reported in Table 3. Despite the different geomembranes, it is clear that the interface that was hydrated under σ_h = 0 kPa has significantly lower τ_p and τ_{ld} than when specimens were hydrated under $\sigma_h = \sigma_n$.

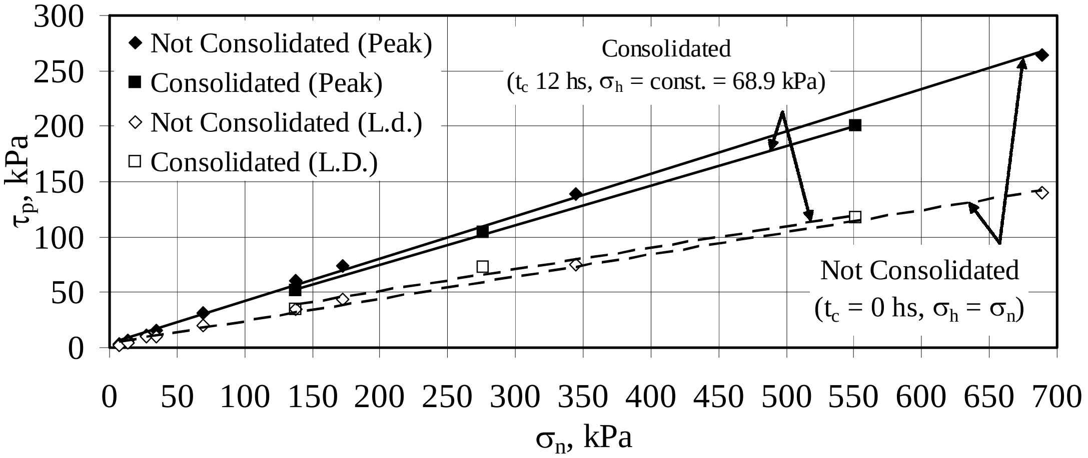


Fig. 8. Effect of consolidation on τ of the interface between GCL A and a textured HDPE geomembrane

Similar to GCL internal shear strength, hydration using $\sigma_h = \sigma_n$ with increasing t_h leads to decreasing GCL-GM interface shear strength (Sets 7 through 10). However, the results show that beyond a certain hydration time, the shear strength does not decrease with further hydration. Specifically, the GCL-GM shear strength does not decrease significantly after t_h = 1 hs, although t_h = 24 hs is still recommended for specifications to ensure uniform hydration. Contrary to the results of the internal shear strength tests, GCL-GM interfaces hydration using $\sigma_h < \sigma_n$ then subsequently consolidated, had similar or lower τ_p than interfaces hydrated under $\sigma_h = \sigma_n$. Hydration using $\sigma_h < \sigma_n$ has been reported to lead to bentonite extrusion from the GCL as well as changes in the fiber reinforcement characteristics (Triplett and Fox 2001). The lower shear strength observed in GCL-GM interfaces hydrated using σ_h less than σ_n indicates increased sodium bentonite extrusion at lower σ_h. Even if extruded sodium bentonite is consolidated, it still lubricates the GCL-GM interface.

5 CONCLUSIONS

A database of GCL internal and GCL interface shear strength tests was analyzed in this study in order to assess the impact of specimen conditioning (hydration and consolidation) on the shear strength of GCLs. The following conclusions may be drawn from this study:

1. Specifications for laboratory shear strength testing procedures should replicate the GCL field conditions.
2. Unhydrated conditions led to the highest GCL internal and GCL-GM interface shear strength. This can be attributed not only to the lack of swelling of the sodium bentonite but also to the absence of shear-induced pore water pressures and little sodium bentonite extrusion.
3. Hydration conducted using $\sigma_h = \sigma_n$ showed a decreasing GCL internal peak shear strength with increasing t_h. However, no further decrease was observed for t_h beyond 48 hs. Hydration conducted using a constant, small σ_h (without subsequent consolidation) led to lower peak shear strength than hydration conducted using $\sigma_h = \sigma_n$. However, hydration conducted using a constant, relatively low σ_h with subsequent consolidation led to peak shear strength similar to that obtained if hydration is conducted using $\sigma_h = \sigma_n$.
4. Evaluation of the effect of the conditioning procedures on the shear strength indicated that conditioning has a greater effect on the sodium bentonite pore water pressures than on the reinforcing fibers.

5. Hydration conducted using $\sigma_h = \sigma_n$ showed a decreasing GCL-GM peak shear strength with increasing t_h. However, no significant decrease was observed for t_h beyond 1 hs. A t_h of at least 24 hs is still recommended for uniform hydration. Hydration conducted using a constant, small σ_h (without subsequent consolidation) led to lower peak shear strength than hydration conducted using $\sigma_h = \sigma_n$ even if the interface was subsequently consolidated, most likely due to greater sodium bentonite extrusion during hydration.
6. GCL internal and GCL-GM interface large-displacement shear strength was found to be insensitive to conditioning procedures.
7. The evaluations in this study indicate that GCLs should be placed under a high normal stress before they are allowed to hydrate in the field. This prevents sodium bentonite swelling and the corresponding loss in shear strength due to fiber reinforcement pullout and changes in soil structure. In addition, the need to consolidate the GCL when the normal stress is increased is eliminated, which leads to time and cost savings.

REFERENCES

American Society of Testing and Materials. (1998). "Standard Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method." ASTM D6243. West Conshohocken, Pennsylvania.

Fox, P. J., Rowland, M. G., and Scheithe, J. R. (1998). "Internal Shear Strength of Three Geosynthetic Clay Liners." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 124(10), 933-944.

Gilbert, R. B., Scranton, H. B., and Daniel, D. E. (1997). "Shear Strength Testing for Geosynthetic Clay Liners." *Testing and Acceptance Criteria for Geosynthetic Clay Liners*, L. Well, ed., American Society for Testing and Materials, Philadelphia, 121-138.

McCartney, J.S., Zornberg, J.G., and Swan, R.H. (2002). "Internal and Interface Shear Strength of Geosynthetic Clay Liners (GCLs). " Geotechnical Research Report, Department of Civil, Environmental and Architectural Engineering, University of Colorado at Boulder, 471 p.

Stark, T. D., and Eid, H. T. (1996). "Shear Behavior of a Reinforced Geosynthetic Clay Liner." *Geosynthetics International*, IFAI, 3(6), 771-785.

Triplett, E. J., and Fox, P. J. (2001). "Shear Strength of HDPE Geomembrane/Geosynthetic Clay Liner Interfaces." *Journal of Geotechnical and Geoenvironmental Engineering*, ASCE, 127(6), 543-552.

Zornberg, J.G., McCartney, J.S., and Swan, R.H. (2004). "Analysis of a Large Database of GCL Internal Shear Strength Results. " Accepted for publication in the *ASCE Journal of Geotechnical and Geoenvironmental Engineering*.