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Internal and interface shear strengths of needle-punched geosynthetic clay liners

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ABSTRACT: This paper presents a study of the internal shear strength of needle-punched geosynthetic clay liners (GCLs) and the interface shear strengths of needle-punched GCLs with geomembranes (GMs). Peak strength envelopes for internal shear are often nonlinear and are related to GCL peel strength. Residual internal shear strength is equal to that of hydrated bentonite. Peak strength envelopes for textured GM/GCL interfaces can be linear, bilinear, or nonlinear. Textured GM/GCL interface shear strength will be higher on the nonwoven side of a GCL than on the woven side. Different types of GM texturing (e.g., laminated, coextruded) have relatively little effect on interface shear strength. Relative magnitudes of post-peak strength reduction for needle-punched GCLs, from highest to lowest, are: GCL > textured GM/GCL (nonwoven side) > textured GM/GCL (woven side) > smooth GM/GCL. Will have French abstract here for final version.

1 INTRODUCTION

Geosynthetic clay liners (GCLs) are commonly used as hydraulic barriers in the construction of waste containment and other facilities, such as landfills, impoundments, lagoons, reservoirs, ponds, canals, and tank farms (Koerner 1997). Unreinforced GCLs (i.e. adhesive-bonded) are held together by chemical adhesives. Reinforced GCLs incorporate stitches (i.e. stitch-bonded) or needle-punched fibers (i.e. needle-punched) between carrier geotextiles (GTs) to transmit shear stress across the bentonite layer. GCLs can be placed singly or, more commonly, adjacent to a compacted clay liner (CCL) or geomembrane (GM) to act as a composite liner. Since these applications often involve side slopes, stability of GCLs is an important consideration for design due to the low shear strength of hydrated bentonite. For high shear stress applications (such as landfill side slopes), a reinforced GCL must be used or an unreinforced GCL must be encapsulated (i.e. placed between two GMs) to prevent hydration. In either case, both the internal shear strength of the GCL and interface shear strengths between the GCL and adjacent materials need to be considered for stability analysis.

Although the internal shear strength of GCLs continues to persist as an issue of concern, there are no known examples of internal failures of reinforced GCLs within constructed facilities. On the other hand, GM/GCL interface failures have been documented for landfill cover systems and similar installations under low normal stress (USEPA 1996, Daniel et al. 1998). The most common GCL interfaces are GM/GCL, drainage geocomposite/GCL, and GCL/soil. Shear strengths of GCLs and GCL interfaces are measured using laboratory direct shear tests and are dependent on many variables (see discussions by Smith and Criley 1995, Frobel 1996, Fox et al. 1997, Gilbert et al. 1997, and Stark 1997). As such, final design strength parameters must be obtained from product-specific testing under hydration and shear conditions closely matching those expected in the field.

This paper presents data on the internal shear strength of needle-punched GCLs and the interface shear strength between needle-punched GCLs and GMs. This combination is the most common GCL composite liner currently used in landfill construction. The data has been obtained from the literature, the GCL database of the Colloid Environmental Technologies Company (CETCO, Arlington Heights, Illinois, USA), and the authors' own tests. This paper began, in part, as a state-of-the-art report (Fox 2001) written for the Los Angeles County Sanitation District to provide typical values of shear strength parameters for GCLs and GCL interfaces that are currently used in landfill bottom liner systems for Los Angeles County, California.

2 INTERNAL SHEAR STRENGTH

2.1 *Published data*

Table 1 summarizes currently available sources of published data on internal shear strength of needle-punched GCLs. The normal stress (σ_n) range and maximum shear displacement (δ_{max}) are indicated. Shear strength values are reported as peak (τ_p), large displacement (τ_{ld}), corresponding to a specific displacement (δ), and residual (τ_r), for which no further strength reduction occurs with continuing displacement.

Richardson (1997) is the only reference in Table 1 that presents GCL internal shear strengths for high normal stress. The failure envelope for the internal strength of two needle-punched GCLs (Fig. 1) is approximately linear for σ_n = 80 to 1200 kPa. The corresponding peak shear strength parameters are c_p = 40.7 kPa and ϕ_p = 21.6°. The linearity of this data suggests that friction angles obtained at low σ_n can be used to approximate shear strength at higher σ_n for needle-punched GCLs.

Fox et al. (1998) presented the most complete study of the internal shear strength of GCLs. In this work, the shear behavior of three types of GCLs are compared, an aggressive specimen gripping system was used without clamping (to avoid progressive failure effects), residual shear strengths (δ = 200 mm) were obtained, and shear rate effects and mechanisms of shear strength mobilization were investigated. Figure 2 shows a plot of peak and residual failure envelopes for the three GCL products. Material from two rolls of the needle-punched GCL (Bentomat ST), having different peel strengths, was tested and both failure envelopes are shown. The adhesive-bonded GCL (Claymax 200R) has the lowest peak strength at any σ_n. At low σ_n, τ_p val-

Table 1. Published data on internal shear strength of needle-punched GCLs.

Reference	σ_n range (kPa)	Reported shear strengths, (δ_{max}, mm)	Comments
Fuller 1995	10-345	τ_p, τ_{ld} (102)	Specimen clamping may have affected results
Stark and Eid 1996	17	τ_p, τ_{ld} (< 100)	Ring shear, rate effects, strength mechanisms
Gilbert et al. 1996	3-69	τ_p, τ_{ld} (43)	Strength mechanisms
Siebken et al. 1997	34-670	τ_p, τ_{ld} (50)	Thermally-locked GCL
Richardson 1997	0-1200	τ_p, τ_{ld} (unspec.)	High normal stress, peel strength vs. shear strength
Fox et al. 1998	7-279	τ_p, τ_r (200)	Large direct shear machine, no clamping, rate effects, strength mechanisms

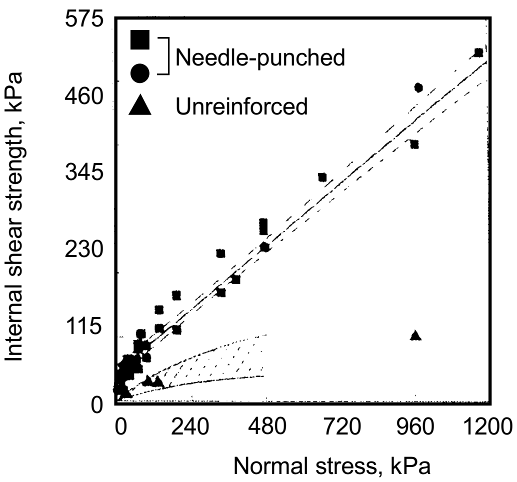

Figure 1. Failure envelopes for two needle-punched GCLs (Figure 2 from Richardson 1997).

ues for the stitch-bonded (Claymax 600SP) and needle-punched GCLs are comparable. As σ_n increased, the needle-punched GCL was the stronger product. Peak shear strength envelopes for the needle-punched GCL showed good correlation with peel strengths obtained from wide-width peel tests (102 × 254 mm specimens). The τ_r values for all three GCLs were in close agreement, indicating that geosynthetic reinforcement did not affect residual shear strength. Both peak and residual failure envelopes for the needle-punched GCL are modestly non-linear, having a tangent friction angle that decreased with increasing σ_n. Unlike Figure 1, Figure 2 indicates that it may be unconservative to extrapolate linear failure envelopes to higher normal stresses for needle-punched GCLs.

2.2 *Unpublished data*

Figure 3 shows peak and large displacement internal shear strength failure envelopes for three needle-punched GCL products. GCL-1 (Bentomat ST) is a woven/nonwoven needle-punched GCL having a peel strength of 109 N. GCL-2 (Bentomat CL) is manufactured by laminating a thin geomembrane onto the woven side of the GCL-1 product. GCL-3 (Bentomat DN) is a nonwoven/nonwoven needle-punched GCL. GCL-1 and GCL-3 have similar shear strengths, whereas GCL-2 shows

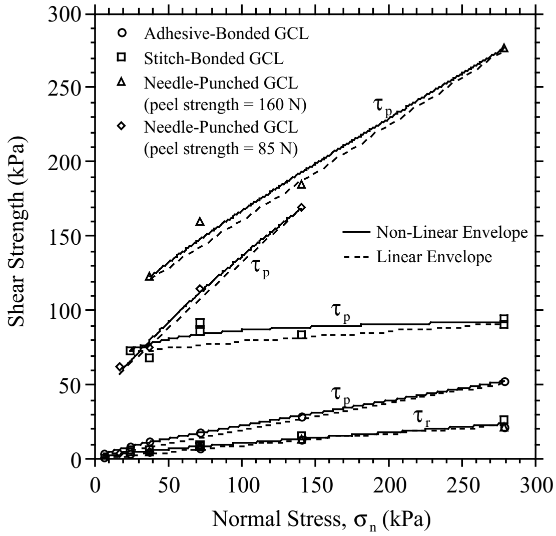

Figure 2. Peak and residual failure envelopes for three GCL products (Fox et al. 1998).

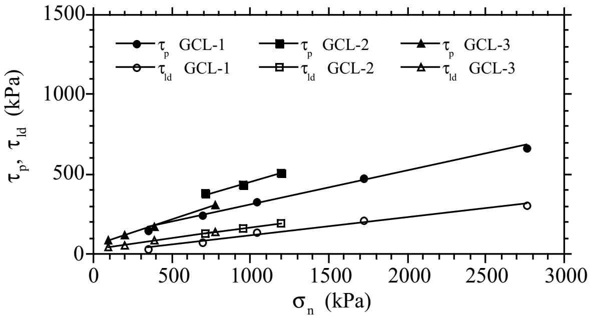

Figure 3. Peak and large displacement failure envelopes for three needle-punched GCL products (tests performed by Geosyntec Consultants, Atlanta, Georgia, USA).

higher shear strength over the limited normal stress range tested. The GM lamination process apparently increased the pullout resistance of needle-punched fibers from the woven geotextile of GCL-2. Similar to Figure 1, the envelopes for GCL-1 and GCL-3 are approximately linear over a large stress range.

3 GM/GCL INTERFACE SHEAR STRENGTH

3.1 *Published data*

Five papers, listed in Table 2, present data on GM/GCL interface shear strength. Peak (c_p, ϕ_p) and large displacement (c_{ld}, ϕ_{ld}) shear strength parameters are provided for woven (W) and nonwoven (NW) sides of needle-punched GCLs sheared against smooth (SM), laminated (LM), and coextruded (CX) geomembranes. Strength parameters vary widely from study to study, further illustrating the need for project-specific testing for design purposes. For GT-supported GCLs, the influence of product type on interface shear strength is more closely related to the type of carrier GTs than to the type of reinforcement. However, needle-punched fibers extending through a woven GT may increase interface shear strength for the woven side of a W/NW needle-punched GCL (Triplett and Fox 2001).

Depending on the relative values of internal and interface shear strengths, a critical normal stress (σ_c) may exist at which the mode of failure changes from internal shear to interface shear. Interface failures occur for $\sigma_n < \sigma_c$ and internal failures occur for $\sigma_n > \sigma_c$. Two of the five studies listed in Table 2 report the existence of such a critical stress for a textured GM/needle-punched GCL (woven GT) interface. Byrne (1994) reported

Table 2. Published data on interface shear strength between GMs and needle-punched GCLs.

Reference	Interface GT/ Interface GM	σ_n range (kPa)	Peak c_p (kPa), ϕ_p	Lg. Displ. c_{ld} (kPa), ϕ_{ld} (δ_{max}, mm)
Byrne 1994	W/textured HDPE		23.9, 18°	23.9, 9° (51)
Gilbert et al. 1996	W/SM HDPE	3.5-69	0, 8.4°	0, 8.1° (43)
	W/textured HDPE	3.5-69	ϕ_o = 30° [a] $\Delta\phi$ = -4.7° [a]	ϕ_o = 9.8° [a] $\Delta\phi$ = -16° [a] (43)
	W/textured HDPE	3.5-345	ϕ_o = 25° [a] $\Delta\phi$ = -9.5° [a]	ϕ_o = 13° [a] $\Delta\phi$ = -12° [a] (43)
Hewitt et al. 1997	NW/textured LLDPE	69-310	18.5, 21.5°	24.0, 2.4° (76)
		103-414	15.5, 25.2° [b]	15.5, 14.1° [b] (76)
Daniel et al. 1998	W/textured HDPE	17	0, 23° [c]	0, 21° [c] (50)
	NW/textured HDPE	17	0, 37° [c]	0, 24° [c] (50)
	NW/textured HDPE	17	0, 29° [c]	0, 22° [c] (50)
Triplett and Fox 2001	W/SM HDPE	6.9-127 127-486	0.3, 9.8° 0.3, 9.8°	0.3, 8.1° 3.0, 6.9° (200)
	NW/SM HDPE	6.9-127 127-486	0.4, 9.9° 0.4, 9.9°	0.6, 9.2° 5.8, 6.9° (200)
	W/LM HDPE	6.9-124 124-486	2.2, 21.6° 22.0, 13.3°	1.0, 12.7° 15.7, 6.6° (200)
	NW/LM HDPE	6.9-69.6 69.6-279	7.4, 31.7° 7.4, 31.7°	2.3, 18.5° 11.8, 11.2° (200)
	W/CX HDPE	6.9-71.9 71.9-279	0, 23.7° 0, 23.7°	0, 15.0° 4.9, 11.3° (200)
	NW/CX HDPE	6.9-135 135-279	7.2, 28.3° 7.2, 28.3°	3.4, 14.4° 16.0, 9.3° (200)

[a]parameters refer to: $\tau_f = \sigma_n \tan[\phi_o + \Delta\phi \log(\sigma_n/P_a)]$, where P_a = 1 atm.
[b]hydrated under σ_n = 6.9 kPa
[c]secant friction angle through origin

interface failures for σ_n < 95.8 kPa and internal failures for $\sigma_n \geq$ 95.8 kPa. The data of Gilbert et al. (1996) indicate a value of σ_c between 13.8 and 27.6 kPa. A critical normal stress exists only for textured GMs because no internal failures have been reported for needle-punched GCLs sheared against smooth GMs.

Triplett and Fox (2001) presented the most comprehensive study of the shear strength of HDPE GM/needle-punched GCL interfaces. Peak interface shear strength failure envelopes are shown in Figure 4a. Each failure envelope, with the exception of LM/W, is approximately linear, whereas the LM/W envelope is approximately bilinear. The SM/W and SM/NW interfaces had nearly identical peak strengths at all stress levels. The resulting ϕ_p value of 9.8° is larger than the value of ϕ_p = 8.4° reported by Gilbert et al. (1996) for similar materials. The textured GM interfaces were stronger than the smooth GM interfaces. Peak shear strengths for the textured GM/NW interfaces were consistently higher than those measured for the textured GM/W interfaces. Differences in peak strength for the two textured GM products sheared against the NW GT were relatively minor, with the strength of the LM/NW interface approximately 10-15% higher than that for the CX/NW interface. A different behavior

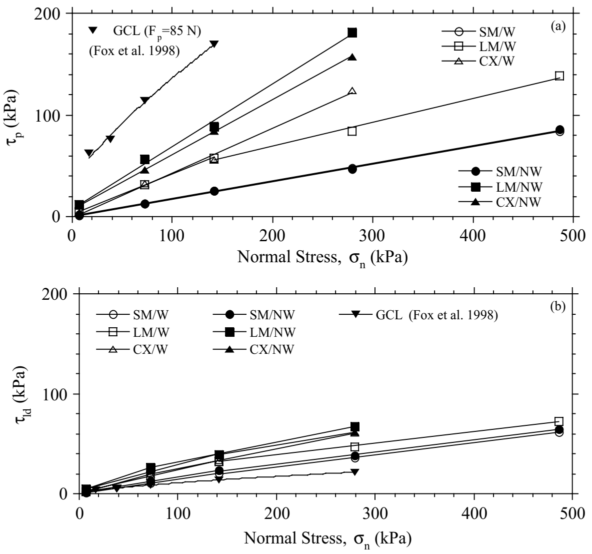

Figure 4. (a) Peak shear strengths and (b) large displacement shear strengths for GM/needle-punched GCL interfaces (Triplett and Fox 2001).

was observed for the textured GM/W interfaces. The LM/W and CX/W interfaces had similar peak strengths for normal stresses up to 141 kPa. The failure envelopes then diverge at higher normal stresses, with LM/W yielding lower shear strengths and a bilinear envelope

Figure 4a also shows the internal peak strength failure envelope for the same needle-punched GCL product (from Fox et al. 1998). The peel strength of this material was 85 N, which is lower than the value of 94 N for the GCL material used in the Triplett and Fox study. The failure envelope for the GCL material for the interface strength tests would therefore be expected to be somewhat higher than the envelope shown in Figure 4a. Peak shear strength values for all interfaces are substantially less than the peak strength of the GCL itself. This is consistent with the observation that all failure planes were located at the interfaces and none were located within the GCL.

Large displacement (200 mm) failure envelopes, each approximated as bilinear, are shown in Figure 4b. The envelopes follow trends with respect to normal stress and interface type that are similar to those in Figure 4a for peak shear strength. The difference between shear strengths of smooth and textured GM interfaces at δ = 200 mm is less than corresponding differences at peak strength, presumably due to higher levels of damage that occur for textured GM interfaces.

The residual shear strength failure envelope for the same needle-punched GCL product (Fox et al. 1998) is also shown in Figure 4b. Considering that residual shear strength does not vary with peel strength, the GCL failure envelope shown in Figure 4b should represent a close approximation for the GCL material in the Triplett and Fox study. With the exception of the SM/W and SM/NW interfaces at σ_n = 6.9 kPa, τ_{ld} values for all interfaces exceeded the residual shear strength of the GCL. Thus, if the GCL specimens had failed internally, all values of τ_{ld} would have been controlled by the residual shear strength of the hydrated bentonite.

Smooth GM/needle-punched GCL interfaces show little post-peak strength reduction (τ_{ld}/τ_p), whereas textured GM/needle-punched GCL interfaces show larger reductions. This results from the higher level of damage that occurs during shear for a textured GM and the adjacent GCL. Gilbert et al. (1996) obtained τ_{ld}/τ_p values ranging from 0.57 to 0.70, whereas Byrne (1994) measured τ_{ld}/τ_p ranging from 0.59 to 0.76 for a similar interface. Triplett and Fox (2001) reported values of τ_{ld}/τ_p ranging from 0.37 to 0.61 for textured GM/needle-punched

GCL interfaces. Post-peak strength reductions for textured GM/needle-punched GCL interfaces are generally less than those for internal shear strength of needle-punched GCLs.

3.2 *Unpublished data*

Figure 5a shows five additional peak strength failure envelopes for textured HDPE GM/needle-punched GCL interfaces. A corresponding plot of large displacement shear strengths is shown in Figure 5b. The τ_p values in Figure 5a are comparable to those in Figure 4a at the same normal stress. However, values of τ_{ld} in Figure 5b are generally larger than those in Figure 4b, which is probably due to differences in maximum displacement for the respective shearing machines. The data generally confirm the previous observation that shear strengths for GM/GCL(NW) interfaces are higher than for GM/GCL(W) interfaces. GM type again appears to be a secondary issue, although CX interfaces are somewhat stronger than LM interfaces in Figure 5a (opposite to the trend observed in Figure 4a). Internal GCL failures occurred for only one series of GM/GCL tests, giving a value of σ_c between 193 and 386 kPa. As many of the envelopes are modestly nonlinear in Figure 5, the fitted lines must only be considered a first approximation (especially for the test series in which σ_c was exceeded).

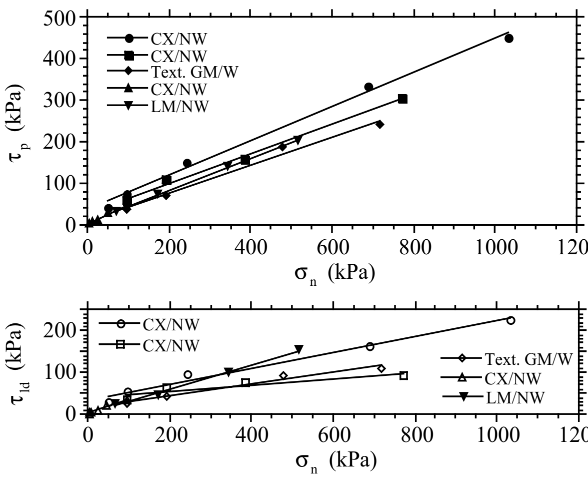

Figure 5. (a) Peak shear strengths and (b) large displacement shear strengths for textured GM/needle-punched GCL interfaces (tests performed by AGP Laboratories, CETCO, Geosyntec Consultants, TRI/Environmental).

4 CONCLUSIONS

Internal shear strength tests of needle-punched GCLs often yield non-linear peak strength failure envelopes. Needle-punched and stitch-bonded GCLs typically have similar peak strengths under low normal stress conditions (e.g., landfill cover system). Needle-punched GCLs usually have higher peak shear strengths than stitch-bonded GCLs under high normal stress conditions (e.g., landfill bottom liner system). Woven/nonwoven and double nonwoven GCLs have similar internal shear strength, whereas limited data indicates that a woven/nonwoven GCL with a GM laminated to the woven side has higher internal strength. The residual shear strength of needle-punched GCLs is equal to that of hydrated bentonite.

Shear strength tests of textured GM/needle-punched GCL interfaces can yield linear, bilinear, or non-linear peak strength envelopes, depending on the materials and the normal stress range. Interface shear strengths for textured GMs placed against the nonwoven side of a woven/nonwoven GCL are usually higher than those corresponding to the woven side. By comparison, differences in peak shear strengths for laminated GM/GCL and coextruded GM/GCL interfaces are relatively less. Little data is available on the residual shear strength of textured GM/GCL interfaces due to the limited maximum displacement of direct shear machines.

Needle-punched GCLs and GCL interfaces show post-peak strength reduction. Thus, the available shear strength will decrease if peak strength is exceeded, leading to the potential for large displacements. Relative reductions in shear strength after peak, ranging from highest to lowest, are: GCL > textured GM/GCL (nonwoven side) > textured GM/GCL (woven side) > smooth GM/GCL.

Linear envelopes are commonly fitted to nonlinear data. Unconservative fitting practices must be avoided in such cases. Shear strength parameters should not, in general, be extrapolated outside of the normal stress range for which they were obtained. Reported values of GCL internal and interface shear strengths are highly variable, due to material variations and differences in testing equipment and procedures over time. As a result, shear strength parameters for design purposes must be obtained using project-specific materials tested under conditions closely simulating those expected in the field.

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