Discussion of “Analysis of a Large Database of GCL Internal Shear Strength Results” by Jorge G. Zornberg, John S. McCartney, and Robert H. Swan Jr.

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The paper by Zornberg, McCartney, and Swan in the March issue of the *Journal* was read with great interest and the authors are to be congratulated on sharing this wealth of information performed over the years by an independent, third party, commercial testing laboratory. It is truly encouraging to see this type of information being made public.

Of the many interesting and informative segments of the total amount of information presented, the lack of relationship of peak internal GCL shear strength versus tension peel strength was particularly noticed. Fig. 12 of the original paper shows this information, where the response at 34.5 kPa normal stress is perfectly flat, there is a barely perceptible increase at 137.9 kPa, and only a nominal increase at 310.3 kPa. Clearly, the discusser agrees with the authors that the results suggest “that τ_p is not very sensitive to the peel strength.” In fact, looking at the data presented (for all intents and purposes), these two parameters are not related at all.

The authors’ explanation for this lack of response states, “This is consistent with results reported by Richardson (1997).” However, in looking at the reference cited, Richardson shows a very strong response of increasing internal shear strength with increasing peel strength. Furthermore, it occurs at both low and high normal stresses. Richardson even concludes that the peel strength must exceed a minimum specific value giving some credibility to its significance.

The Richardson trend of increasing peak shear strength with increasing peel strength has been the “tacit” assumption by many (including the discusser) in the design and use of reinforced GCLs. It is shown often in manufacturer’s brochures and literature. Commentary in this regard by the authors would be appreciated.

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The authors have presented an extensive and valuable study on the internal shear strength of geosynthetic clay liners (GCLs). The discusser has also performed extensive tests of these materials and can comment on several topics related to the paper. These topics include analysis of another large database of GCL shear strengths, shear-induced excess pore pressures, the relationship between peak internal shear strength and peel strength for needle-punched GCLs, and large-displacement versus residual shear strengths.

Another Large Database on GCL Shear Strengths

Chiu and Fox (2004) published the analysis of a large database of internal and interface GCL shear strengths, including results from the discusser’s own tests, published test data, and unpublished test data provided by two GCL manufacturers (CETCO, Arlington Heights, Ill.; and Gundle/SLT Environmental Lining Technology, Inc. (GSE), Houston). The vast majority of test results were obtained using 300×300 mm direct shear devices, with most of the tests conducted according to ASTM D 6243. The database only included test data that showed good quality shear stress (τ) versus shear displacement relationships (see Fox et al. 2004 for examples) and data from laboratories that are known for quality geosynthetic shear testing. Some of the test data in the authors’ database are also found in the Chiu and Fox database.

An example from the Chiu and Fox database is shown in Fig. 1 for peak internal shear strengths (τ_p) of dry and hydrated needle-punched (NP) GCLs. Power law regression for the hydrated data gives the following equation

$$\tau_p(\text{kPa}) = 6.4(\sigma_{n,s},\text{kPa})^{0.59} \quad (2 \leqslant \sigma_{n,s} \leqslant 2760 \text{ kPa}) \qquad (1)$$

where $\sigma_{n,s}$=shearing normal stress. A nonlinear failure envelope defined by Eq. (1) is shown in Fig. 1. The authors’ failure envelope for GCL *A* (c=46.6 kPa, ϕ=18.7°) is shown for comparison in Fig. 1(b). The nonlinear regression analysis permitted a nonzero intercept but, in this case, produced a zero intercept for hydrated NP GCLs. This surprising result is contrary to the authors’ test results in Fig. 4(c) of the original paper, but is consistent with the characterization of needle-punched reinforcement as essentially frictional (Gilbert et al. 1996; Fox et al. 1998). Fig. 1 further indicates that dry and hydrated NP GCLs in this database have similar peak strengths at low normal stress. Peak internal shear strengths of unreinforced and NP GCLs often yield nonlinear failure envelopes. Thus, a nonlinear equation such as Eq. (1) provides an alternative to the conventional linear failure envelope for the characterization of shear strength over a large normal stress range.

Shear-Induced Excess Pore Pressures

The authors present interesting data on the effect of shear displacement rate (SDR) on peak shear strength for GCL *A* at normal stresses above and below the swell pressure (approximately 100 to 160 kPa). Fig. 6(c) of the paper shows that peak shear strength increased with increasing SDR at low normal stress ($\sigma_{n,s}$=50 kPa) and decreased with increasing SDR at high normal stress ($\sigma_{n,s}$=520 kPa).

Let us first consider the data at low normal stress. The data in Fig. 6(c) is consistent with published results from Fox et al. (1998). Eid and Stark (1997) and Gilbert et al. (1997) also showed similar trends for hydrated unreinforced GCLs. The data of Eid et al. (1999) for hydrated NP GCLs is more complicated, with maximum peak strengths indicated at intermediate values of displacement rate. An increase in shear strength with increasing displacement rate can be attributed to shear-induced porewater

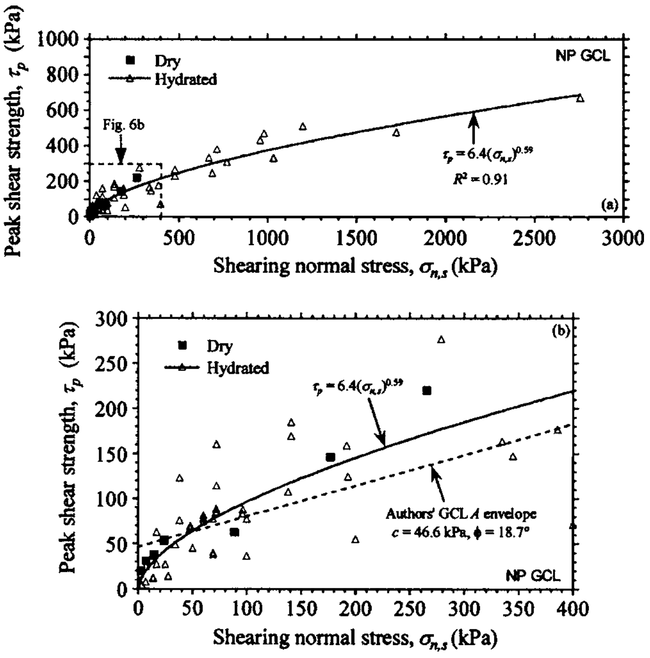

Fig. 1. (a) Peak internal shear strengths for NP GCLs; (b) detail at low normal stress

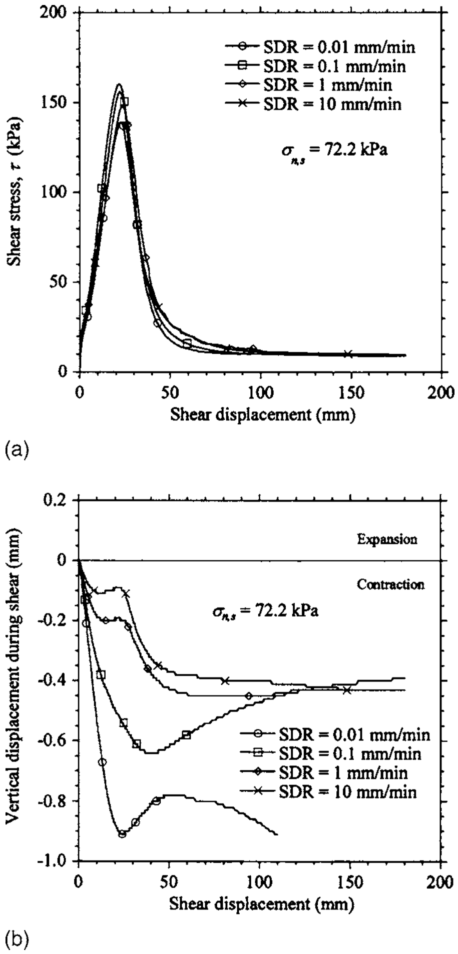

Fig. 2. Direct shear test results for GCL *A* at four displacement rates: (a) stress-displacement curves; (b) volume change data

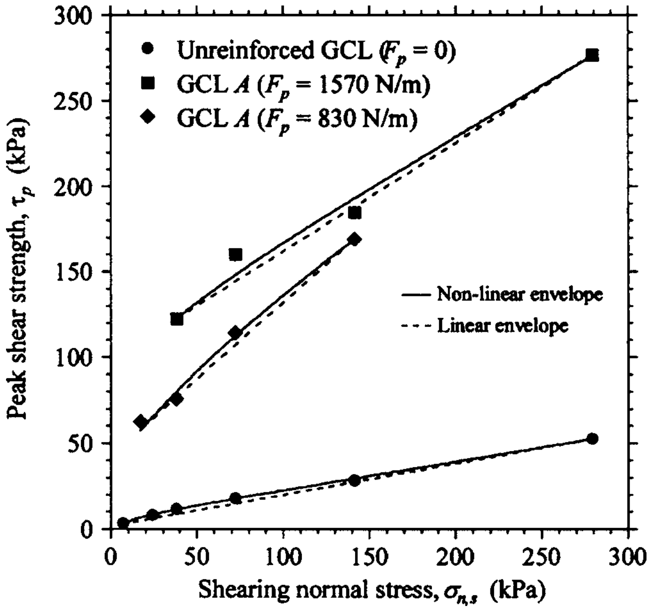

Fig. 3. Peak strength failure envelopes for three GCL rolls with different peel strengths

suctions (i.e., negative pore pressures), creep of the bentonite and/or geosynthetic components, or rapid pullout effects for the reinforcement during shear. Fox et al. (1998) attributed the displacement rate effect to drained creep of the hydrated bentonite because: (1) the failure surface for each test was immediately adjacent to a drainage boundary and thus any pore pressures/suctions would have been small, and (2) residual strengths showed the same general displacement rate effect as peak strengths, which eliminates possible explanations associated with the geosynthetic reinforcement.

The authors attributed the effects in Fig. 6(c) to shear-induced excess pore pressures. In the case of $\sigma_{n,s}=50$ kPa, this suggests that progressively larger porewater suctions occurred on the failure surface as the SDR was increased. Two requirements must be satisfied for this hypothesis to be correct. First, the failure surface must be sufficiently far from a drainage boundary to sustain such suctions. The authors state that, consistent with the observations of Gilbert et al. (1996) and Fox et al. (1998), the failure of unreinforced and NP GCLs typically occurred at the bentonite/carrier geotextile interface. Any comments on the ability of this interface to sustain significant porewater suctions in the authors' tests would be welcome. Second, the GCL specimen must exhibit a tendency for expansive behavior during shear. Fig. 2 shows the stress-displacement curves and vertical displacement data for the Fox et al. (1998) variable shear displacement rate tests at $\sigma_{n,s}=72.2$ kPa, which were not provided in the original publication. The measured vertical displacements correspond to vertical displacement of the loading plate and are equal to changes in thickness of the GCL specimen during shear. The data clearly indicate that volumetric contraction occurred at each displacement rate. The data also show that the maximum amount of volumetric contraction increased with decreasing displacement rate, which almost certainly resulted from the additional time available for consolidation at the slower rates. Consolidation occurs because the mean stress increases during shear up to the peak strength for a direct shear test. Corresponding measurements of GCL internal pore pressure taken at the middle of the bentonite using needles, although quantitatively unreliable, yielded a positive value (2 to 18 kPa) at peak strength for each test. Thus, the authors' hypothesis that porewater suctions are responsible for progressively larger shear strengths with increasing SDR at low normal stresses is not supported by data from the Fox et al. (1998) testing program.

We now consider the authors' high normal stress tests ($\sigma_{n,s}=520$ kPa). In this case, the GCL specimens were consolidated to a higher normal stress and thus had lower hydraulic conductivity. It is possible that the lower hydraulic conductivity, combined with a stronger tendency toward contractive behavior, produced significant positive excess pore pressures on the failure surfaces for these tests. Higher displacement rates allowed less time for pore pressure dissipation and thus the peak shear strengths were reduced accordingly. Another factor must also be considered. The GCL specimens were hydrated at 496.8 kPa for 312 h and then consolidated to 520 kPa for 48 h. The consolidation time (48 h) may not have been sufficient to allow for complete excess pore pressure dissipation prior to shearing. Thus, the specimens sheared at higher rates may have had progressively larger residual pore pressures from the consolidation stage when peak strengths were reached.

This section suggests that the explanation for SDR effects may be more complicated than that provided by the authors and that different mechanisms may govern SDR effects at low and high normal stress levels. More research is needed on this important issue.

Relationship between Peak Internal Shear Strength and Peel Strength

Fig. 12 of the original paper shows that peak shear strength is essentially independent of peel strength for the authors' database. This is particularly interesting considering that peel strengths vary by a factor of approximately 5 for the tests conducted. A lack of correlation between peel strength (F_p) and peak strength is not supported by some data sets. Fig. 3 shows three failure envelopes from Fox et al. (1998), one for an unreinforced GCL with presumably zero peel strength ($F_p=0$), and two for different rolls of GCL *A* having different peel strengths ($F_p=85$ N/102 mm$=830$ N/m and $F_p=160$ N/102mm$=1570$ N/m). In this study, peel strengths were taken as peak values from 102 × 254 mm specimens that were tested using wide-width grips. The failure envelopes indicate that higher peel strengths produce higher τ_p values. The authors' data set is far more extensive than Fig. 3 and clearly supports the authors' conclusion. It is, however, difficult to understand why peel strength would have essentially no correlation with peak strength since both values are primarily affected by the interlocking of needle-punched fibers from the cover geotextile with the carrier geotextile. Any additional comments regarding the test results in Fig. 12 would be welcome.

Large-Displacement versus Residual Shear Strengths

The authors conclude that large-displacement shear strengths of unreinforced GCLs ($\phi_{ld}=5.3°$) are consistently lower than those of reinforced GCLs ($\phi_{ld}=7.8°$). This is reasonable since the last vestiges of reinforcement are still carrying load at the authors' typical termination displacement of 75 mm. The quality of the specimen gripping system can also have an important effect on the amount of load-carrying reinforcement that remains at large displacements (Fox et al. 1997a; Fox and Stark 2004). Standard 300 × 300 mm direct shear devices generally do not allow sufficient travel to measure internal residual shear strengths of reinforced GCLs (Fox et al. 1997b).

Using a large direct shear machine with a maximum shear displacement of 203 mm, Fox et al. (1998) showed that residual strengths of both unreinforced and reinforced GCLs are equal to the residual strength of hydrated bentonite ($\phi_r=4$ to $5°$). Thus, the authors' distinction between large displacement strengths for unreinforced and reinforced GCLs does not hold for residual strengths. This may be important because it is unconservative to use large-displacement shear strengths for designs which must remain stable under true residual conditions.

The authors are to be commended for their significant contribution to our knowledge of the internal shear strength of GCLs. Continued research and discussion will no doubt provide further insights into the shear behavior of these composite geosynthetic materials.

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The writers would like to thank Dr. Robert Koerner for his interest in the paper and for raising important issues concerning the relationship between GCL internal peak shear strength and peel strength. Peel strength testing was first proposed to provide an index of the density (and possibly the contribution) of fiber reinforcements in needle-punched GCLs, and has often been used to support the design of liner systems involving GCLs (Heerten et al. 1995; von Maubeuge and Eberle 1998; Mackey and von Maubeuge 1999; Eichenaur and Reither 2002; von Maubeuge and Ehrenberg 2002). It should be noted that the current standard testing procedure (ASTM D6496) for the peel strength test was only established in 2000 (Mackey and von Maubeuge 1999), so most data reported in the literature was obtained using a modified version of the grab tensile load test for geotextiles (ASTM D4632). This may have compromised the development and interpretation of correlations between GCL internal peak shear strength and peel strength. The development of standard tests will facilitate proper use of such correlations in QA/QC programs.

The peel strength testing program in this study was originally aimed at quantifying the variability of peel strength results as a means to explain the variability in GCL internal peak shear strength (τ_p). Based on information reported in the literature, the writers had anticipated a positive correlation between τ_p and peel strength. Yet, they found the lack of correlation reported in the paper and, consequently, no conclusions could be drawn regarding the effect of the peel strength variability on that of τ_p. The information presented in Fig. 12 of the original paper should be replaced by Fig. 1(a) presented here. It should be noted that Fig. 12 of the original paper incorrectly presented the peel strength data in units of N/cm. The correct units (N/m), as recommended by ASTM D6496, are used in the revised Fig. 1(a) presented herein. As shown in the figure and reported in the paper, there is no clear correlation between peel strength and τ_p. The peel strength results in Fig 1(a) range from 313 to 2244 N/m. The peel strength tests were conducted on specimens from Subsets V3d, V4d, annd V5d (Table 4), which were manufactured in 2002. The peak shear strength results from this subset tended to have lower shear strength than GCLs from other years, as indicated in Fig. 11 of the original paper. A total of 13 of the 15 rolls tested for shear strength values were also tested for peel strength. A total of 5 individual peel strength values from each roll are shown in Fig. 1(a), even though ASTM D6496 recommends reporting the average peel strength from the 5 individual peel strength values. Such average results are presented in Fig. 1(b). Yet, consistent with the observations drawn from the results in Fig. 1(a), the average results show no clear correlation between peel strength and τ_p. The average peel strength results in Fig. 1(b) range from 484 to 1998 N/m. The minimum average peel strength specified by the GCL *A* manufacturer is 440 N/m, as obtained via ASTM D6496 (or a minimum average peel strength of 650 N/m obtained via ASTM D4632).

The relationship between peel strength and peek shear strength is expected to be affected by many variables, including those that affect GCL internal shear strength (e.g., normal stress, shear displacement rate, and bentonite hydration), and those that affect needle-punched fiber-reinforcement characteristics (e.g., the par-

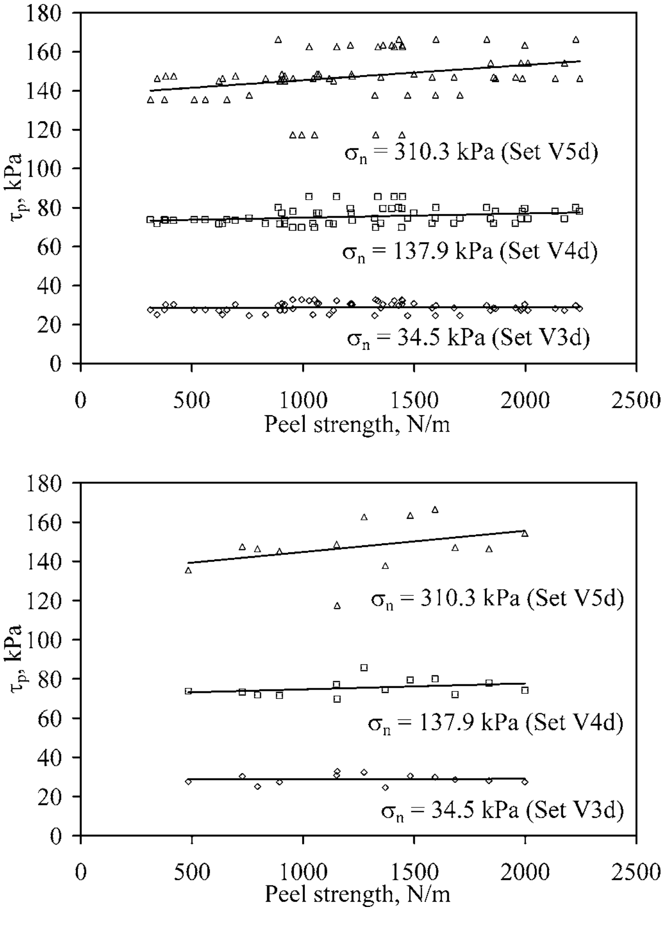

Fig. 1. Relationship between peel strength values and τ_p for needle-punched GCL *A*: (a) individual peel strength results; (b) average peel strength from specimens in each roll. Note: Peel strength was obtained using 100-mm-wide specimens. Figure 1(a) replaces Fig. 12 in the paper.

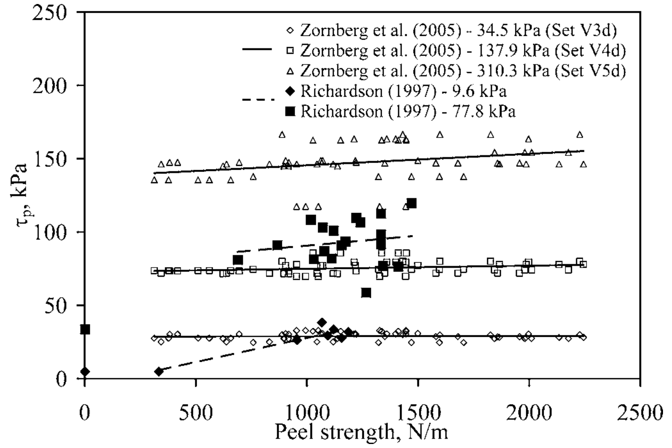

Fig. 2. Relationship between peel strength and τ_p for needle-punched GCLs from Zornberg et al. (2005) and Richardson (1997). Notes: Peel strength obtained using 100-mm-wide specimens; units in Richardson's data account for 25.4-mm-wide grips; best-fit lines for Richardson (1997) do not include the data points with zero peel strength.

ticular GCL carrier geotextiles, use of thermal locking, and quality of needle-punching). Tension in the fiber reinforcements is mobilized in a significantly different manner during the peel and direct shear tests. Specifically, direct shear tests mobilize tension in the fibers over the full area of the specimen and is thus highly sensitive to the confining pressure, while peel strength tests only mobilize tension along a single line of fibers. The writers attribute the potential lack of correlation to such differences in the mobilization of fiber tension. An important characteristic of the data presented in Fig. 1(a and b) here is that all direct shear tests were conducted by the same laboratory, using the same conditioning procedures (hydration during 168 h under a normal stress of 20.3 kPa, followed by consolidation during 48 h under the normal stress used during shearing) and same shear displacement rate (0.1 mm/min) in a testing program involving a single GCL product (with W–NW carrier geotextiles). While relevant data on peel strength has been reported in the literature (see below), the writers are not aware of other studies with the number of tests conducted under same GCL conditioning procedures as reported in Fig. 1(a and b) of this closure. In spite of the lack of cor-relation found in this study, caution should be used before generalizing this observation to GCLs with different conditioning procedures, shear displacement rates, and different carrier geotextile arrangements.

The discusser is correct in pointing out that Richardson (1997) concluded that there is a strong correlation between τ_p and peel strength. Accordingly, the writers take this opportunity to clarify that the comment made in the paper regarding the lack of correlation between τ_p and peel strength data is indeed based on the writers' reinterpretation of Richardson's data. Specifically, the writers noted that the trend line presented by Richardson (1997) (Fig. 4 in that paper) is highly dominated by two data points for GCLs with peel strength of 0 lb/in (i.e., unreinforced or poorly reinforced GCLs). If these two data points are neglected, it is hard to justify a trend between τ_p and peel strength. This lack of correlation is consistent with the findings based on the writers' own results. Fig. 2 shows the peel strength data reported by the authors along with that reported by Richardson (1997). The trend lines shown for data reported by Richardson (1997) were generated by the writers using standard regression techniques (least squares), but ignoring the two data points from unreinforced GCLs. It should be noted that the peel strength results reported by Richardson (1997) were obtained using a modified version of the grab tensile test for geotextiles (ASTM 4632). This standard uses 25.4-mm-wide clamps to peel 100-mm-wide GCL specimens. This previous peel strength standard may lead to higher values than those obtained using 100-mm-wide clamps (ASTM 6496), as used in the peel strength tests conducted by the writers. Although the results presented by Richardson (1997) at a normal stress of 9.6 kPa show an increasing trend due to the presence of a data point with low peel strength and low peak shear strength, the data shown in Fig. 2 here appears to suggest a lack of correlation between τ_p and peel strength.

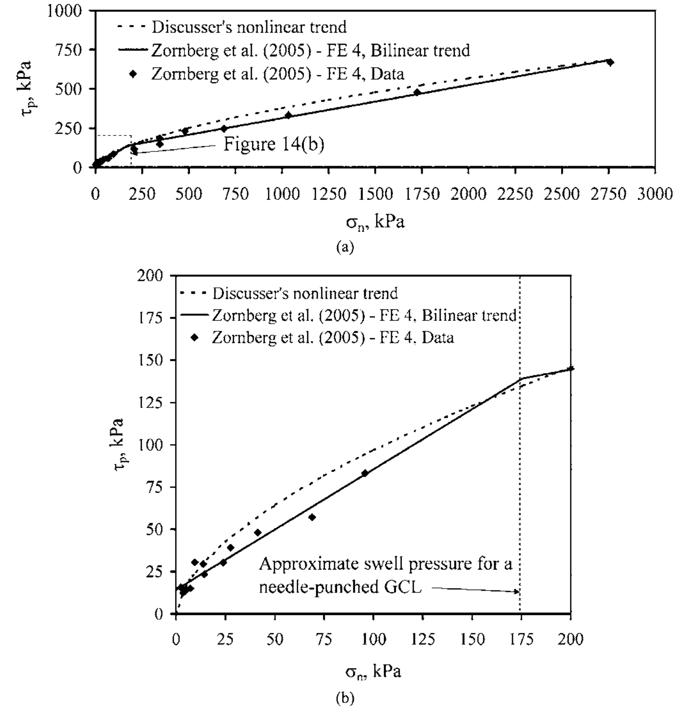

Fig. 3. Bilinear and nonlinear shear strength envelopes for needle-punched GCL *A* (t_h=48 h, σ_h=σ_n, SDR=10 mm/min) obtained using a wide range of σ_n: (a) full range of normal stresses; (b) low normal stresses

An evaluation was conducted by the writers of peel strength data reported for needle-punched GCLs (Berard 1997; Richardson 1997; Fox et al. 1998; Eid et al. 1999; Olsta and Crosson 1999; von Maubeuge and Lucas 2002; Zornberg et al. 2005). Unlike the trend observed in Figs. 1 and 2, several of the reported data sets do indicate an increasing τ_p with increasing peel strength (Olsta and Crosson 1999; von Maubeuge and Lucas 2002). Some of these studies did not report the product name, GCL carrier geotextile arrangement, bentonite hydration procedures, or use of thermal-locking along with their correlation. Interpretation is also hindered as some studies did not present the actual normal stresses used for the direct shear tests (von Maubeuge and Lucas 2002) while others present a limited number of data points (Berard 1997; Fox et al. 1998; Eid et al. 1999), or even different GCLs and different peel specimen widths (Richardson 1997). It is noted, though, that the data sets that reported increasing trends generally involved correlations using shear strength tests conducted under different normal stresses and did not ensure constant hydration procedures, both of which may contribute to the increasing trend. Probably the most appropriate use of peel strength

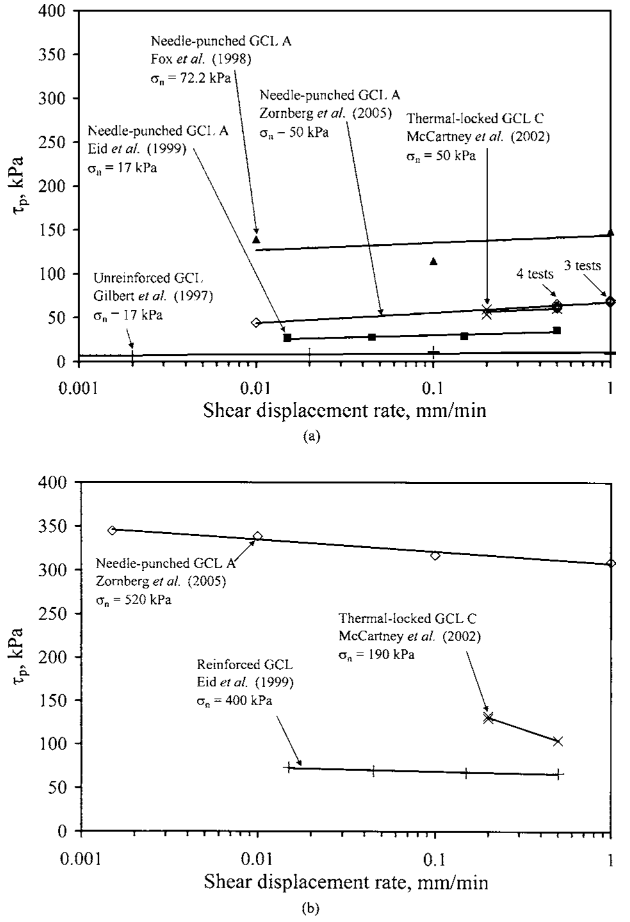

Fig. 4. Effect of SDR on peak shear strength of needle-punched GCL *A*: (a) summary trends for tests conducted under relatively low σ_n; (b) summary trends for tests conducted under relatively high σ_n

data would be for defining a minimum value to meet for quality control purposes, rather than for establishing correlations with peak shear strength (G. N. Richardson, personal communication, 2005).

In summary, the writers believe that further evaluation should be conducted on the potential correlation between τ_p and peel strength before peel strength is used as an index of GCL strength. A specific area that could be addressed in future research is the use of peel strength to infer the behavior of GCLs exposed to free hydration, as the significant swelling may cause rupture or pullout of the fiber reinforcements. A minimum value of peel strength was reported to ensure that GCLs exposed to free hydration remain serviceable (Richardson 2005). Free hydration can occur due to exposure to rain during installation or during service in landfill final covers with nominal cover (σ_n as low as 7 to 20 kPa). Correlations between τ_p and peel strength for free hydration of GCLs have not been covered in the technical literature, and pose testing problems for most laboratories due to the low normal loads. Low normal load applications are distinct from the typical service loads experienced by liner systems, and may be the applications where peel strength could be relied upon as an indicator of in-service τ_p (Richardson 2005). Product-specific direct shear test results should continue to be used until further data is generated showing the validity of correlations between τ_p and peel strength.

The writers appreciate Dr. Patrick Fox's interest in the paper, as well as the relevant insights provided from a database he compiled on GCL internal shear strength results. Regarding the comparison of shear strength envelopes shown in Fig. 1 of the discussion, the writers agree with the discusser that nonlinear envelopes are well suited to represent the internal shear strength of GCLs. The writers would like to note that the GCL *A* envelope ($c=46.6$ kPa, $\phi=18.7°$) was in the paper for preliminary evaluation of different GCL types, but does not account for conditioning procedures or shear displacement rate. A representation of the internal shear strength of GCL *A* specimens with constant conditioning procedures ($t_h=48$ h, $\sigma_h=\sigma_n$) and constant shear displacement rate (1.0 mm/min) tested over a wide range of normal stresses was also presented in the paper (see Table 2 and Fig. 8). This set of GCL peak shear strength data was found to be represented well by a bilinear failure envelope shown in Fig. 8 of the original paper. The bilinear envelope compares well with the nonlinear failure envelope for a wide range of normal stresses presented by the discusser, as shown in Fig. 3. The break in the bilinear envelope at 175 kPa is consistent with the swell pressure of the reinforced GCLs, providing a physical significance to the bilinear trend. The scatter observed in the data shown in Fig. 1 by the discusser and Fig. 4 of the original paper reinforces the importance of quantifying the variability in GCL internal shear strength results.

The writers agree with the discusser that pore water pressure generation during shear may not be the only mechanism explaining the effect of shear displacement rate (SDR) on the peak GCL internal shear strength. The discusser points out that in order to have generation of shear-induced pore water pressures, as suggested by the writers, (1) the interface should be able to sustain pore water pressures, and (2) the GCL specimen should exhibit expansive vertical displacements during shearing. Regarding the first point, it is unlikely that a free drainage boundary would occur in direct shear tests on hydrated GCLs due to significant bentonite extrusion through the carrier geotextiles, which prevents free drainage from the shear plane, even when the shear plane is located at the bentonite/carrier geotextile interface. Regarding the second point, it should be noted that vertical displacements during shearing are affected by rotation of the principal stresses, continued hydration/consolidation of the GCL during shearing, and shear-induced volumetric changes. Only the last component (i.e., shear-induced volume changes) is associated with the issue under discussion (i.e., magnitude and sign of shear-induced pore water pressures). In addition, deformations along the shear plane in the direct shear test are not necessarily the same as the displacements measured at the top platen. Accordingly, evidence of shear-induced pore pressures is not directly related to the total vertical displacement measured in specimens sheared at different rates. The trend in vertical displacement shown in Fig.2(b) by the discusser, while dominated by continuous consolidation during shear, would also be consistent with an increasingly negative changes in shear-induced pore water pressures (i.e., reflected in a decreasing total, positive pore water pressure) as SDR increases. Also, although the mechanisms causing the observed SDR effects on GCL peak internal shear strength are difficult to quantify, the trends observed by the writers in Fig. 6(c) are consistent with those measured for other GCLs. Figs. 4(a and b) of this closure show the trends in peak shear strength reported in the literature and by the writers for other GCLs tested under low and high normal stresses (Eid et al. 1999; Gilbert et al. 1997; Fox et al. 2001; McCartney et al. 2002). The trend of increasing shear strength with increasing SDR under low normal stress and decreasing shear strength with increasing SDR under high normal stresses is observed in different GCLs. While the available information appears to point out a significant role of pore water pressures on the effect of SDR on shear strength, the writers agree with the discusser that these mechanisms are complex, and that this subject deserves further research.

The relevant issue raised by Dr. Fox on the relationship between peak internal shear strength and peel strength was provided in the previous discussion, which addresses the comments raised by Dr. Koerner.

Finally, regarding the use of large-displacement versus residual shear strengths, it should be pointed out that the large-displacement shear strength values presented in the paper were not intended to replace the use of residual shear strength values. However, the shear strength at a post-peak shear displacement of 75 mm may prove relevant in designs that account for post-peak shear strength loss without incorporating the conservatism associated with the use of residual shear strength. In such situations, recognizing that for a given displacement (*e.g.*, a large-displacement defined as 75 mm) the shear strength of reinforced GCLs remains higher than that of unreinforced GCLs may have important design implications.

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