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# Effect of Shear Displacement Rate on the Internal Shear Strength of GCLs

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## *Abstract*

A series of large-scale direct shear strength tests were conducted to evaluate the effect of shear displacement rate on the internal shear strength of reinforced GCLs. Specifically, the tests were conducted using shear displacement rates ranging from 0.0015 to 1.0 mm/min and using normal stresses ranging from 50 to 520 kPa. The peak internal shear strength was found to increase with decreasing shear displacement rates for high normal stresses, while the opposite trend was observed for low normal stresses. Interpretation of these results, involving indirect evaluation of shear-induced pore water pressures, is proposed to explain this apparently counterintuitive trend. In addition, a decreasing large-displacement shear strength was noted with increasing shear displacement rate for tests at all normal stresses. Future research is geared toward the verification of the trends in peak and large-displacement for other GCLs over a wider range of shear displacement rates.

## *Introduction*

The internal shear strength of geosynthetic clay liners (GCLs) is being evaluated as part of a research program at the University of Texas at Austin. 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). Stability is a major concern for side slopes in bottom liner or cover systems that include GCLs because of the very low shear strength of hydrated sodium bentonite. In particular, the failure surface of a liner system may develop internally (within the GCL), either through its bentonite core or along the bentonite/carrier geosynthetic interface.

The primary goal of laboratory characterization of the internal shear strength of geosynthetic clay liners (GCLs) is to replicate behavior noted in the field. However, specifications for laboratory testing must balance the need for representative conditions with practical time and cost restraints. An important variable in laboratory shear strength testing is the shear displacement rate (SDR). The shear displacement rate affects the pore water pressures in the sodium bentonite generated by shearing. In addition to specimen hydration and consolidation, the shear displacement rate determines the overall required testing time. Previous studies have primarily focused on the response of tests conducted under relatively low normal stresses (*i.e.*, less than 100 kPa), and have reported an increasing peak shear strength with increasing *SDR*. This finding suggests that the most conservative (*i.e.*, lowest) peak shear strength would be obtained from a test conducted at a very low SDR (*e.g.*, less than 1.0 mm/min). However, this conclusion may not necessarily be true for GCLs sheared under higher normal stresses. This study extends the knowledge base by investigating the effect of *SDR* on the internal shear strength of GCLs using tests conducted under both comparatively low and high normal stresses. Specifically, SDRs ranging from 1.0 to 0.0015 mm/min were used in this study, corresponding to shearing times of 1.25 hours to 35 days.

### *Database*

**Data Source**. A database of commercial large-scale direct shear tests was used as a source for this study (GCLSS). The tests were performed between 1997 and 2003 by SGI Testing Services (SGI), formerly the Soil-Geosynthetic Interaction laboratory of GeoSyntec Consultants. SGI is an accredited testing facility. It should be noted that procedures used for all GCL-GM interface direct shear tests are consistent with *ASTM D6243* (ASTM 1998), even though this standard was only approved in 1998.

**Materials**. Direct shear test results in the GCLSS database used in this study include two reinforced GCLs and one unreinforced GCL. The reinforced GCLs are Bentomat ST, referred herein as GCL *A*, and Bentofix NS, referred herein as GCL *C*. GCLs *A* and *C* consist of a bentonite layer between a woven and a nonwoven carrier geotextile, reinforced internally by pulling fibers from the nonwoven carrier geotextile through the woven geotextile using a needling board. In GCL *A* the fiber reinforcements are left entangled on the surface of the woven carrier geotextile, while in GCL *C* the carrier geotextiles are thermal-locked to the lower corner geotextile. The unreinforced GCL is Claymax 200R, referred herein as GCL *F*. GCL *F* consists of a bentonite layer containing a water soluble adhesive between a woven and a nonwoven carrier geotextile.

**Testing Equipment and Procedures**. Large-scale direct shear devices with top and bottom shear boxes with dimensions of 305 mm by 305 mm in plan and 75 mm in depth were used in this study. A constant *SDR* was applied to the bottom shear box using a mechanical screw drive system and the resultant shear load was measured on the top shear box. Figure 1 shows the configuration of the direct shear equipment used for GCL internal shear strength testing.

The hydration process used in this study is a two-stage procedure in which GCL specimens were placed under a specified hydration normal stress ($\sigma_h$) outside the direct shear device and soaked in tap water during the specified hydration time ($t_h$). The hydration normal stress, $\sigma_h$ was often specified to equal the shearing normal stress ($\sigma_n$). In this case, shearing was conducted immediately after hydration. The peak shear strength ($\tau_p$) and large displacement shear strength ($\tau_{ld}$) were recorded. If a $\sigma_h$ smaller than the $\sigma_n$ was specified, pore pressures were allowed to dissipate during a consolidation period ($t_c$) before shearing. Additional details on the testing procedures are presented by McCartney *et al.* (2002).

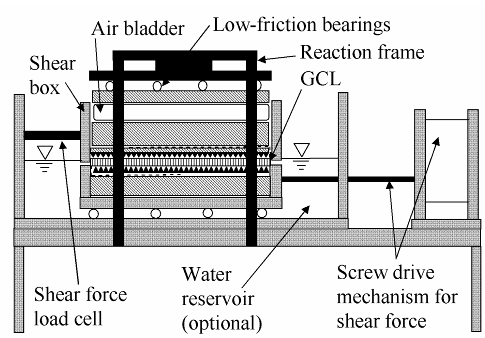


**Fig. 1. Direct shear device.**

***Results and Analysis***

This ongoing study builds on the results reported by Zornberg *et al.* (2004), who presented the results of a single GCL product. Also, the effect of SDR on large-displacement shear strength is being evaluated as part of this ongoing investigation. Figure 2 shows the peak shear strength results for GCLs *A* and *C* from direct shear tests conducted under a normal stress of 50 kPa using a range of SDRs. The GCLs tested within each series of tests were obtained from the same manufacturing lots, so material variability is assumed to be low. McCartney *et al.* (2004) identified that shear strength variability in same-lot GCL specimens is significantly lower than that in different-lot specimens, and can be quantified by a coefficient of variation of less than 0.1. The value of $\tau_p$ for GCL *A* increases at a rate of approximately 12 kPa per log cycle of *SDR*, while the value of $\tau_p$ for GCL C increases at a rate of less than 1 kPa per log cycle for tests conducted at $\sigma_n$ = 50 kPa. Explanations in the literature proposed to justify the trend of increasing $\tau_p$ with increasing *SDR* conducted under relatively low $\sigma_n$ have included shear-induced pore water pressures, secondary creep, undrained frictional resistance of bentonite at low water content, and *SDR*-dependent pullout behavior of fibers.

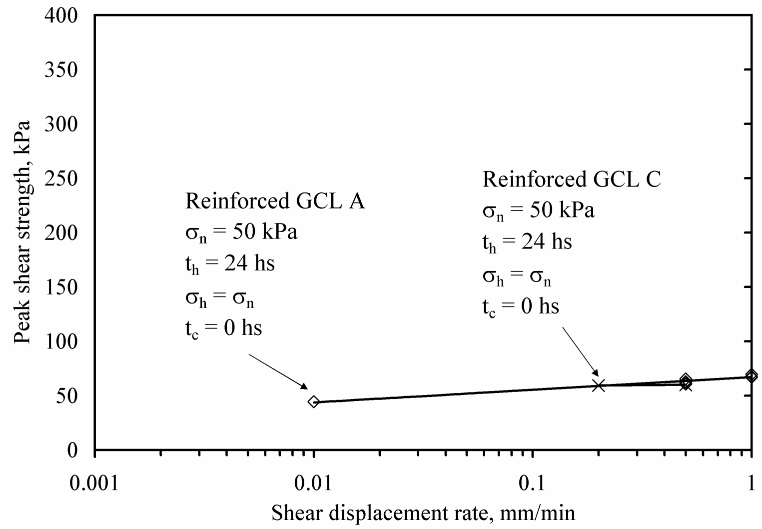


**Fig. 2. Peak shear strength of GCLs as a function of SDR for comparatively low normal stresses (i.e., 50 kPa).**

Figure 3 shows the peak shear strength results for GCLs *A*, *C*, and *F* from direct shear tests conducted under comparatively high normal stresses ($\sigma_n$ ranging from 200 to 520 kPa) using a range of SDRs. Again, the GCLs tested within each series of tests were obtained from the same manufacturing lots, to minimize material variability. Contrary to the findings for low normal stress, a decreasing trend in peak shear strength with increasing SDR is observed for all three GCLs. The value of $\tau_p$ for GCL *A* decreases at a rate of approximately 15 kPa per log cycle of *SDR* for tests conducted at $\sigma_n$ = 520 kPa, the value of $\tau_p$ for GCL *C* decreases at a rate of approximately 50 kPa per log cycle for tests conducted at $\sigma_n$ = 190 kPa, and the value of $\tau_p$ for unreinforced GCL *F* decreases at a rate of approximately 5 kPa per log cycle for tests conducted at $\sigma_n$ = 275.8 kPa.

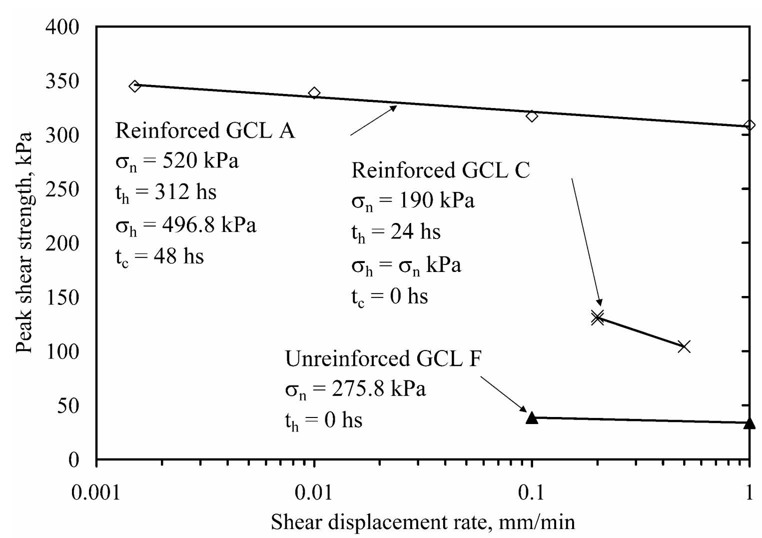


**Fig. 3. Peak shear strength of GCLs as a function of SDR for comparatively high normal stresses (*i.e.*, approximately above 200 kPa).**

The different trends in peak shear strength tests conducted under both low and high $\sigma_n$ suggests that the observed trends are related to the generation of shear-induced pore water pressures. Shear-induced pore water pressures are expected to be negative in tests conducted under low $\sigma_n$ (*i.e.,* below the swell pressure of GCLs). Consequently, increasing *SDR* will lead to increasingly negative pore water pressures and thus higher $\tau_p$. On the other hand, shear-induced pore water pressures are expected to be positive in tests conducted under high $\sigma_n$ (*i.e.,* above the swell pressure of GCLs). In this case, increasing *SDR* will lead to increasingly positive pore water pressures and thus lower $\tau_p$.

Figure 4 shows the trend in large-displacement shear strength results for GCL A from direct shear tests conducted under low and high $\sigma_n$. Since no shear-induced pore water pressures are expected (positive or negative) for constant volume conditions, the same residual shear strength is anticipated for different *SDR*s. Residual shear strength was not achieved for the tests reported in Figure 4 after a shear displacement of 75 mm. However, the decreasing trend in large-displacement shear strength with increasing SDR at low and high normal stresses suggests that the tests conducted under high SDR are closer to residual conditions for a given shear displacement (75 mm).

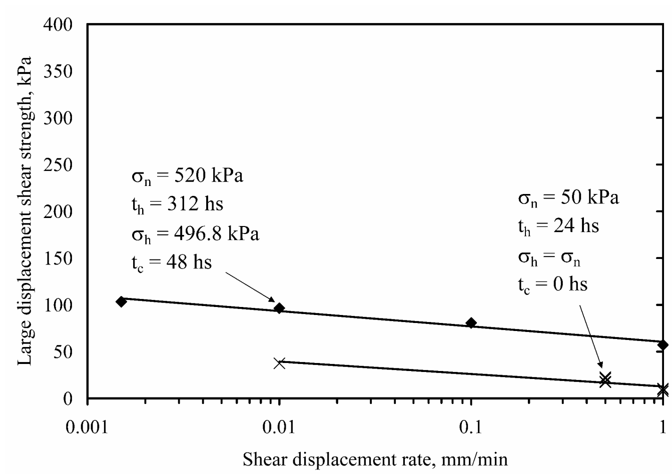


**Fig. 4. Large-displacement shear strength of GCL A as a function of SDR for comparatively low (i.e., 50 kPa) and high normal stresses (i.e., 520 kPa).**

***Discussion of Ongoing Research***

The peak shear strength of both unreinforced and reinforced GCLs was observed to increase with increasing *SDR* for tests conducted under low normal stress, while the opposite trend was observed under high normal stress. This behavior suggests the generation of negative shear-induced pore water pressures under low normal stress (below the swell pressure) and of positive pore water pressures under normal stress. Consequently, if design is governed by peak shear strength, test specification involving comparatively high SDR are acceptable if the normal stress of interest is relatively high, as the test will lead to conservative (*i.e.*, lower) shear strength values. However, tests should still be specified with sufficiently low shear displacement rate (*e.g.*, 0.1 mm/min) if the normal stress of interest is relatively low. The large-displacement shear strength of reinforced GCLs was observed to be closer to the residual shear strength conditions for a given shear displacement for faster SDRs under low and high normal stresses. Consequently, if design is governed by large-displacement shear strength, direct shear tests conducted using high *SDR* should be adequate for internal shear strength characterization as they provide conservative large-displacement shear strength values. Future research will involve additional testing of other GCLs and shear displacement rates to provide verification of the important trends in peak and large displacement shear strength observed in this study.

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