HDPE being deployed on a secondary GCL on the west sump area of the Monticello mixed waste repository in Utah.

GCL internal shear strength requirements

By Gregory N. Richardson

THIS PAPER REVIEWS THE REQUIREMENTS FOR internal shear strength of geosynthetic clay liners (GCLs) from a waste containment designer's perspective. This is a particularly important design concern, given the wide range of commercial GCL structures, their associated shear strengths, and a lack of standardization of laboratory shear testing procedures.

The information presented here is from the author's own projects and from previously published references. These include *GFR's* on-going educational series on GCLs, in which Robert M. Koerner (1996b) presented an overview of GCLs, David E. Daniel (1996) reviewed their hydraulic properties and Kent von Maubeuge (1996) reviewed manufacturer quality-control measures.

This paper reviews the components of available GCLs, their relative contribution to the internal shear strength of a GCL, and the available test data on GCL internal shear strength. It also examines the short- and long-term shear stresses that engineers typically encounter in the design of landfill liner systems and final covers. This includes construction, operational, and long-term service loadings. The paper also addresses construction quality-assurance (CQA) methods to ensure the adequacy of the internal shear strength of GCLs delivered to the site. In conclusion, it reviews typical specifications reflecting internal shear strength considerations and presents the author's opinion regarding where the consideration of GCL internal shear strength is important.

GCL types

Koerner's overview of GCLs shows they can be divided into the following types:

- granular bentonite bonded to a geomembrane using a water-soluble adhesive
- granular bentonite bonded between geotextiles using stitching to connect the two geotextiles
- granular bentonite bonded between geotextiles using a water-soluble adhesive and stitched to physically connect the two geotextiles
- granular bentonite between geotextiles needlepunched together.

The first two GCL types are *unreinforced* and are limited to relatively flat site applications that do not present significant shear stresses or differential bearing pressures to the GCL. The latter two GCL types are *reinforced* and are the focus of this article.

The internal shear strength of reinforced GCLs will be influenced by the following components if present: the bentonite clay, needled or stitched fibers that penetrate through the thickness of the GCL, and, possibly, an adhesive used to bond the clay to the geotextiles. Each of these components provides an internal shear strength that is affected by the clay's degree of hydration, the normal load acting on the GCL, and the shear strain that has occurred across the GCL. Unfortunately, the precise details on each of these components for a given GCL is not available to the designer. Laboratory tests performed on GCLs measure the simultaneous contribution of all internal shear strength components and do not provide a clear understanding of internal mechanisms.

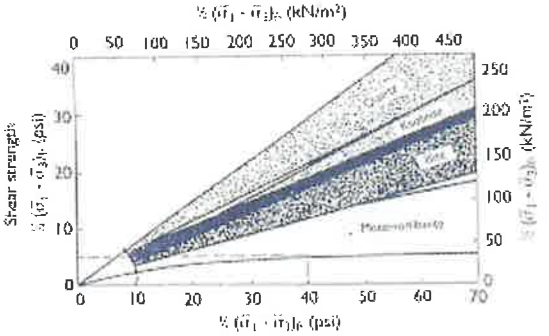

Figure 1. Ranges in effective stress failure envelopes for pure clay minerals and quartz (Olson, 1974).

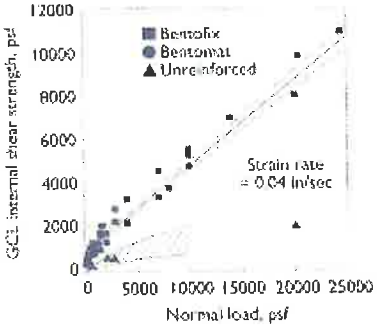

Figure 2. GCL peak shear strength vs. normal load.

The clay, exclusively bentonite, that forms the GCL's hydraulic barrier component has a hydrated shear strength that is influenced by the degree of hydration and the normal loading. The hydrated strength properties are relevant to long-term loading conditions. As with all clay properties, the internal shear strength of the bentonite is strongly influenced by water content and normal loading conditions.

The shear strength of hydrated clays was evaluated by Olson (1974) who produced the effective stress failure envelopes shown on **Figure 1.** Bentonite is a sodium montmorillonite—the most active of the montmorillonites. Here activity refers to the ratio of the clays plasticity index, PI, to the percentage of soil particles passing a No. 200 sieve (0.074 mm). From Olson's work we can see that the lower limit of the effective shear strength ($\frac{1}{2}\bar{\sigma}_1 - \bar{\sigma}_3$) of montmorillonite clays is greater than 5 psi (720 psf) at a normal load of approximately 40 psi (5760 psf).

This strength can be increased by decreasing the percentage of bentonite in the clay but at a cost of increased permeability. At lower normal loads, the degree of hydration increases and the shear strength decreases to zero at no normal load. At higher normal loads, the lower limit for the shear strength can be assumed to be approximately 5 psi (720 psf). Swelling pressures of bentonite can easily reach 2000 to 4000 psf (Gromoko, 1974). This may control the equilibrium water content and, therefore, the shear strength at low normal loads if a ready supply of moisture is available.

Clay soils experience time-dependent deformation, or creep, under constant shear loads. In general, the potential for significant creep increases with higher clay content and clay activity. Unfortunately, the bentonite used in GCLs is relatively pure, and the most active clay known to man. Thus the potential for creep deformation is high. Typically, potential creep deformations are controlled by using a generous factor of safety to limit the shear stress acting on the clay to significantly less than the peak shear strength.

Both the polymers associated with the needled fibers and the bentonite may creep, i.e., deform, when subjected to long-term loadings. Recent published reports by Koerner (1996) and Trauger et al. (1996) have shown that the majority of internal shear displacements occur during the first 100 hours of loading. Essentially, if field conditions do not change and the GCL installation survives the initial week of loading, the GCL is stable. This is certainly the observation that has come out of the recent GCL slope tests performed over the past two years in Cincinnati by EPA (Scranton, 1996).

Stitched or needled fibers that penetrate through the thickness of a reinforced GCL contribute to shear strength as the two geotextile surfaces move differentially apart. The amount of shear strength added by the fibers at low strains may also be influenced by the anchorage or tensioning of the fibers to the geotextiles. The Bentofix product, for example, uses a proprietary process to thermally lock the needled fibers to the geotextile surfaces. Such fibers may develop a larger shear resistance at a smaller relative displacement of the two geotextiles than those simply needled through.

A similar stiffening of the GCL may occur in stitched GCLs if the tension in the stitching is increased. At present, no data exists to clearly show the relationship between needling and stitching variables. **Figure 2** shows the contribution of the needled reinforcement fibers of current reinforced GCLs to the peak shear strength of a GCL. Here the internal total stress peak shear strength data available to the author is compared to the effective shear strength of the montmorillonite. The higher peak shear strength of the GCLs must be due to the contribution of the needled fibers and, possibly, the rate of shear.

The test data shown was obtained at a shear rate of 0.04 in./min. (1 mm/min). Note that the heat-set fibers of the Bentofix appear to function the same as those simply needled in the Bentomat. Scranton (1996) has reported that the shear strength (total stress) of the GCL decreases as the strain rate decreases to approximately 0.01 to 0.0001 mm/min. The reduction in strength due to strain rate was less than approximately one-third. Even with the strain rate reduction in strength, the contribution of the needled fibers is very significant across the full range of normal loads.

Continued shear of a reinforced GCL beyond the peak stress point produces a lower residual strength. **Figure 3** plots the residual shear strengths for Bentofix and Bentomat products as a function of normal load. The residual total strengths are compared with Olson's effective stress failure envelope for montmorillonite and the peak strength values of an unreinforced GCL. Data presented by Scranton (1996) indicates that the residual strength of an un-

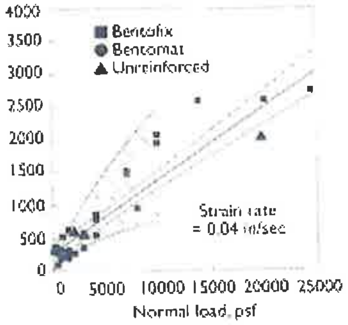

Figure 3. GCL residual shear strength vs. normal load.

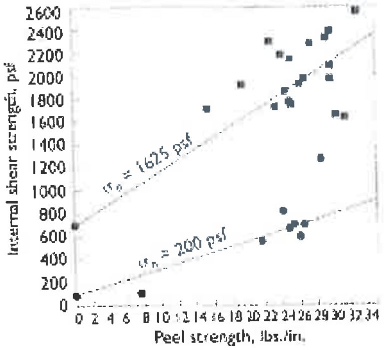

Figure 4. GCL peel vs. internal peak shear strength.

reinforced GCL is approximately 1.0 to 0.6 times the peak strength. The data on Figure 3 shows that the shear strength of a reinforced GCL approaches that of an unreinforced GCL at large internal shear displacements. This also was observed by Gilbert et al. (1996).

No theoretical method has been advanced for predicting the shear strength contribution of the reinforcing fibers that penetrate through the thickness of the GCL. The bonding of the needled fibers to the geotextiles or the stitching tension must be sufficient to prevent them from easily pulling free under the swelling pressures generated by the hydrating bentonite. Swelling pressures of bentonite may control the tension in the reinforcing fibers at low normal pressures. Swelling pressures may dissipate if the surrounding geotextiles are porous enough for the bentonite to extrude through. It has been the author's experience that the current reinforced GCLs which provide a minimum internal shear strength of 500 psf have sufficient reinforcing fiber tension to prevent full hydration of the bentonite.

On previous projects, the author has used the peel strength of the nonhydrated GCL as an index to the internal shear strength of a hydrated GCL. Peel strength was selected because it approximately quantifies the strength of the needled fibers, the bonding of the needled fibers to the geotextiles, and the resistance to swell by the bentonite. The test is performed as a modified ASTM D 4632 using a 4- to 8-inch-wide sample. Unfortunately, the modified peel test does not simulate the correct differential movement of the geotextiles or provide a uniform strain of the needled fibers in the sample. These shortcomings make the peel strength an index and not a true measure of internal shear strength.

Figure 4 presents data relating peel strength (ASTM D 4632) to internal shear strength of the Bentofix and Bentomat products for two normal loads. Both GCLs have a peel strength typically exceeding 15 lbs./in. At low normal pressures, the needled fibers prevent free swelling of the bentonite. Thus, they contribute to the internal shear strength of the GCL by both bridging between the geotextiles and by limiting hydration of the bentonite. Figure 4 indicates that the peak internal shear strength of these GCLs should be approximately 450 psf at a normal load of 200 psf. This is slightly less than the manufacturer's specifications for both GCLs, i.e., 500 psf. Unfortunately, peel strength data

An installation crew deploys a secondary HDPE liner over a secondary GCL on the floor of the Monticello mixed-waste repository.

Placing GCL in the west upslope trench of the Monticello repository.

is not provided with most internal shear strength data so it is difficult to extend this chart with available published data. In the author's opinion, peel strength is an important property that must be clearly defined in the project specifications and verified during construction quality assurance for reinforced GCLs.

GCL design considerations

The designer must be aware of field conditions that can lead to the failure of a GCL barrier within a liner system or final cover. Failure may result from either inadequate internal shear strength that leads to a stability problem or from relocation, i.e., squeezing, of the bentonite that leads to a liquid containment failure. The following considerations are meant to illustrate these considerations, and should not be thought of as comprehensive.

Construction

It has been the author's experience that, next to a shaman's chant, leaving exposed GCLs on the ground is one of the best means of producing a design storm at a site. All GCL manufacturers recommend that the GCL be covered with at least 12 inches of soil immediately after placement. This soil cover may be a sand as used in lateral drainage systems on final covers. The soil cover limits hydration of the bentonite from the free access of surface water to the GCL and provides a small normal stress.

For alternative liner systems, the GCL must be covered by a geomembrane that, in turn, must be seamed and eventually covered itself by the leachate collection system. Placement of the leachate collection system may not occur for many weeks after placement of the GCL. If an unreinforced GCL, i.e., peel strength equal to zero, is exposed to water under these conditions, the internal shear strength of the GCL will be less than 100 psf, as shown on Figure 4. The consistency of such clay is 'very soft' such that the bentonite will have the consistency and properties of a stiff grease and have a very low bearing capacity.

Even with a 2-foot cover over the GCL, the contact pressure generated by a typical rubber-tired off-road truck, e.g. Cat D25D (contact stress = 1870 psf), will greatly exceed the bearing capacity of hydrated bentonite ($q_{allow} = N_c \times c = 5.5 \times 150$ psf

GCL INTERNAL SHEAR STRENGTH REQUIREMENTS

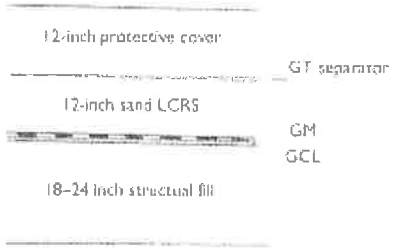

Figure 5. GCL alternative Subtitle D liner.

= 825 psf)). This can cause lateral displacement of the bentonite and damage to the hydraulic integrity of the GCL. The author has avoided these concerns by not using unreinforced GCLs—even on low slope applications—when the potential for full hydration and surface traffic exists. Bearing capacity considerations should be reviewed by the designer before an unreinforced GCL is selected for a final cover applications.

Operations

Figure 5 shows a typical alternative liner system designed and permitted by the author. As installed, the GCL initially has a normal load acting on it of only 180 to 200 psf. Figure 4 indicates that the reinforced GCLs have a peak internal shear strength of approximately 450 psf, and an unreinforced GCL less than 200 psf when hydrated under such loads. As in the construction consideration, typical landfill traffic on the completed protective cover can generate excessive normal loads on the unreinforced GCL prior to placement of the first lift of waste. Here again, the author will not use an unreinforced GCL for alternative liner systems unless it can be assured that full hydration can be avoided. Once a lift of waste is placed over the liner system, the potential for a bearing-capacity problem with the unreinforced GCL diminishes.

A majority of the landfills being designed by the author will require an initial soil access ramp. Once sufficient waste is placed within the landfill, so that access is possible across the waste, the ramp is removed and used as daily cover. The stability of the soil ramp depends on the internal shear strength of the GCL used in the liner system. **Figure 6** shows the sliding factor of safety for a 15 percent grade soil ramp as a function of the GCL internal shear strength and side slope angle. The geometry and assumed soil properties are also shown for clarification. The internal shear strength of the GCL must be maintained higher than 200 psf to ensure stability of the ramp. Note

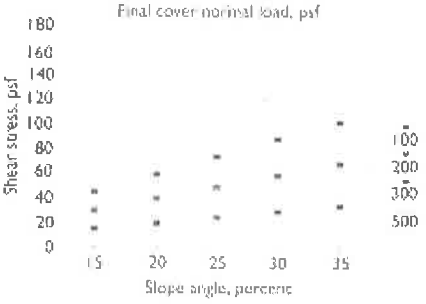

Figure 7. GCL alternative Subtitle D liner.

that the ramp's stability is dependent on the GCL strength, both on the side slope and over a portion of the bottom. Here again, the use of an unreinforced GCL can lead to failure of the landfill liner system and should be avoided if a potential for free hydration of the GCL exists.

Long-term

The GCL data on Figure 2 shows that, under the high normal loads generated by the weight of refuse, the internal shear strength of a GCL is very high. Because of this high shear strength, the author has never encountered long-term, post-closure slope stability problems in the GCL-lined facilities he has evaluated. However, this cannot be said of the final covers that incorporate a GCL barrier. Typical normal loads acting on a GCL barrier in a final cover system typically range from 200 to 300 psf. These loads are less than the swelling pressure generated by the bentonite. The long-term strength of the GCL, therefore, is going to be heavily dependent on the strength of the needled fibers that penetrate through the thickness of the GCL.

Figure 7 shows the static-side slope shear stresses generated in a GCL barrier within the final cover. For a 4H:1V side slope, these typical shear stresses range from 50 to 80 psf. As indicated before, at these normal loads, the internal shear strength of an unreinforced GCL is less than 100 psf. In the author's opinion, this results in too low a factor of safety to ensure against long-term creep of the side

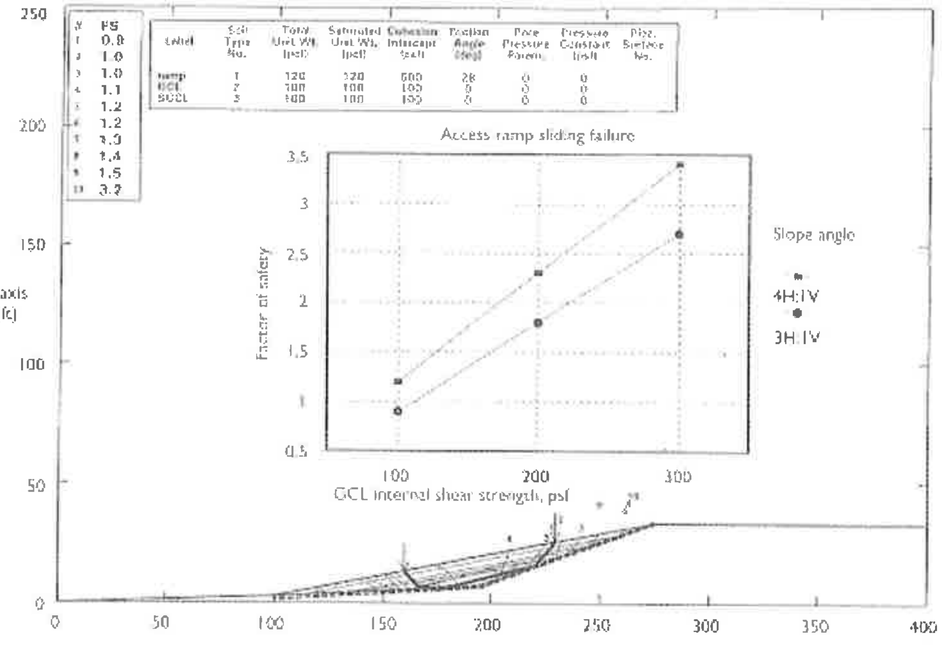

Figure 6. The sliding factor of safety for a 15 percent grade soil ramp as a function of the GCL internal shear strength and side slope angle.

slope cover. When added to the previously mentioned bearing capacity problem, it shows that unreinforced GCLs should not be used in landfill final cover systems on slopes greater than 10 percent.

Recommendations

The long-term internal shear strength of a GCL is important for the safe construction, operation, and long-term closure of a contemporary landfill. Under low normal loads, this internal shear strength is significantly influenced by the strength and bonding of the needled fibers that penetrate through the thickness of the GCL. The following are the author's recommendations regarding the use of GCLs in *landfill liner or final cover systems*:

- Only reinforced GCLs having an internal shear strength greater than 450 psf under normal loads (250 psf) should be used. *An unreinforced GCL should not be used unless free hydration of the GCL can be avoided with certainty.*
- The peel strength of the GCL must equal or exceed 15 lbs./in., as measured by ASTM D 4632 (preferably specified as a MARV) and should be verified in the field CQA program.
- The designer must consider both shear loads (slope stability) and traffic-related normal loads (bearing capacity) in the evaluation of a GCL in both liner and cover applications.

The author hopes this article will stimulate other designers to publish additional GCL project data that will lead to the development of better guidelines for ensuring the internal stability and hydraulic integrity of GCLs. GFR

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