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Design and application of the geomembrane supported GCL in one-product and encapsulated composite liner systems

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ABSTRACT: Since 1994, the geomembrane supported GCL (GM-GCL) has increasingly been used as a one-product composite liner and encapsulated bentonite composite liner in waste landfills across the USA, Europe, and Asia as an alternative to conventional geomembrane-compacted clay composite liners. This is primarily due to its superior hydraulic performance in response to leakage through defects in the geomembrane, effective sealing at its overlapped seams, and economic savings derived by its lower cost of installation. This paper discusses the general design and performance considerations when utilizing the GM-GCL as a one-product composite liner, focusing on: (1) hydraulic performance (e.g. composite liner leakage), (2) slope stability, and (3) installation issues and construction quality assurance (CQA).

1 INTRODUCTION

1.1 *Benefits of a one-product composite liner*

Conventional composite liner applications in waste containment industries often require a composite liner comprised of a geomembrane that overlays a low permeability compacted clay liner (CCL). Since their introduction to waste containment applications in 1985, GCLs have commonly been utilized to replace all or part of the CCL layer. The one-product composite GM-GCL discussed in this paper is comprised of a thin layer of sodium montmorillonite clay (bentonite) mixed with a water-based adhesive that attaches it to a polyethylene geomembrane. This product has been used as a one-product composite liner and in encapsulated bentonite composite liners in bottom liner and cap applications in the United States, effectively replacing both the geomembrane and compacted clay components of traditional prescriptive composite liners. Given the documented effective hydraulic sealing provided by the GM-GCL, the ease of its installation, and the cost savings made possible by the simplicity of installing a single product, the GM-GCL provides an effective alternative to conventional geomembrane and compacted clay liner installations.

1.2 *Installation configurations*

There are two general design configurations for the GM-GCL product (Fig. 1):

1. *Single composite mode.* In this installation, the bentonite side of the material is generally installed face down and the geomembrane side face up, to form a one-product composite (geomembrane-clay) liner. Normally, the overlaps are not mechanically joined but are overlapped for self-sealing, as shown in Figure 1a. It is also possible to weld the geomembrane components together utilizing conventional geomembrane welding techniques, including either dual-track hot-wedge welding (Fig. 1b) or extrusion welding procedures. Additional details and configurations are discussed in Thiel et al. (2001).
2. *Encapsulated mode*. In this installation, a supplemental geomembrane is installed against the bentonite side of the material, as shown in Figure 1c. In this application, the GM-GCL product is usually installed with the bentonite side face up and the geomembrane side facing against the subgrade, with a supplemental geomembrane installed over the bentonite surface. This configuration, however, can also be reversed so

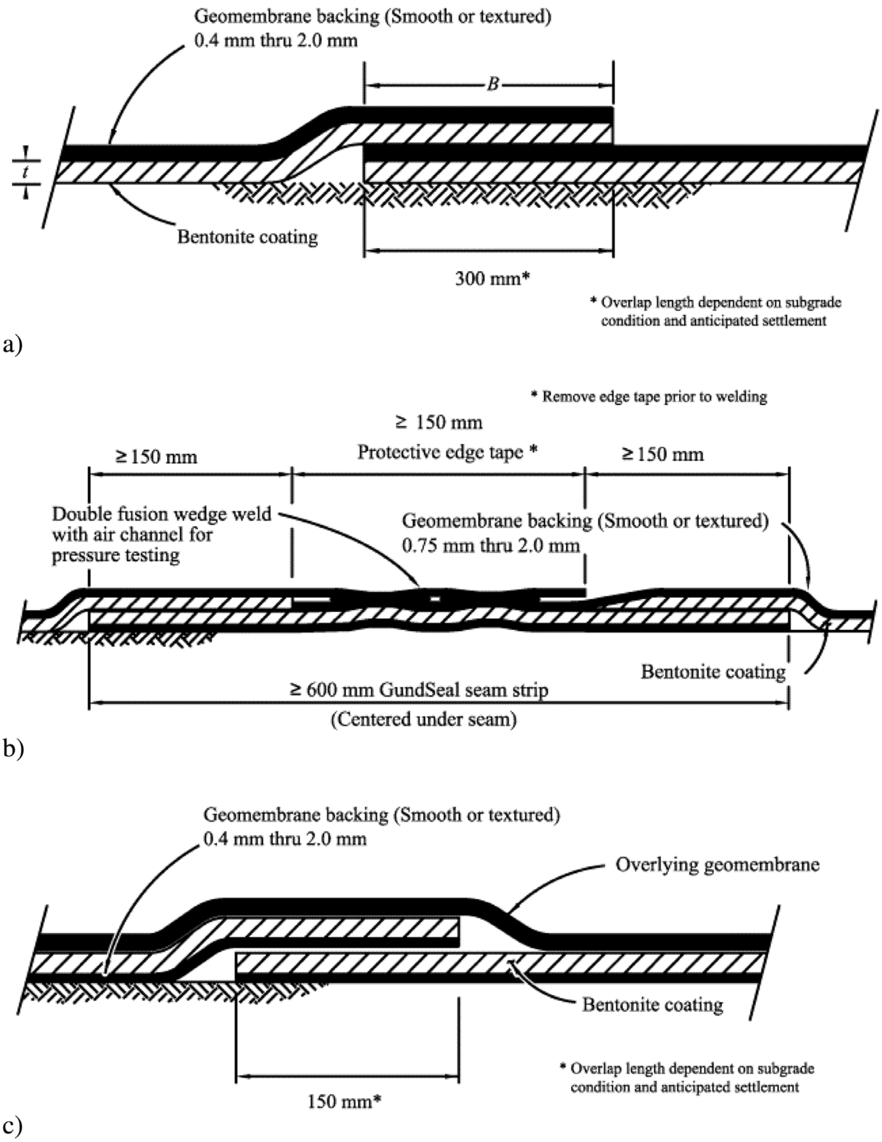

Figure 1. Typical GM-GCL Installation Options. a) Overlapped GM-GCL, shingle seams. b) Double wedge fusion welded GM-GCL seams. c) Encapsulated GM-GCL.

that the GM-GCL is deployed on top of a previously deployed geomembrane, with the bentonite side face down. The encapsulated design mode offers the following distinct performance advantages: (1) improved fluid containment; (2) improved bentonite durability during construction by preventing pre-hydration of the bentonite; and (3) improved slope stability.

1.3 *Overview of design issues for GM-GCL application*

Whether it is used as a bottom liner or cover, as a single-composite liner or in encapsulated bentonite mode, three fundamental design issues should be considered for GCL applications:

1. *Performance as a fluid barrier.* Since providing a fluid barrier is the main objective of a composite liner system, the design practitioner must have the means to evaluate potential leakage for a given design application. This issue is addressed in Section 2 of this paper.
2. *Slope stability.* Geosynthetics in cover and liner systems typically have layers and interfaces that provide the critical slip plane for slope stability. It is important that the designer understand the limitations and shear strength properties of all layers and their associated interfaces, and that relevant local and global stability analyses be performed. This is discussed in Section 3.
3. *Installation and durability.* Understanding how a project is constructed, and the construction advantages and limitations for the various materials proposed in a project, is critical to a sound design. Inappropriate construction practices can defeat any product or design intent. Key construction procedures and limitations are described in Section 4.

2 ENVIRONMENTAL PROTECTION AGAINST LEAKAGE

The hydraulic performance of a GM-GCL composite liner can be evaluated using standard accepted leakage models. Leakage may result from (1) defects in the primary geomembrane resulting primarily from installation damage, (2) coincident defects in the upper and lower geomembranes in encapsulated GM-GCL installations, and (3) seepage at overlapped GM-GCL seams when the geomembrane seams are not welded. The general approach and design equations for evaluating composite liner leakage, and environmental protection comparisons between a GM-GCL liner and an equivalent GM-compacted clay liner are presented below.

2.1 *Leakage modes*

2.1.1 *Defects in composite liner geomembranes*

Empirical modeling and field observations (Giroud & Badu-Tweneboah 1992; Giroud 1997) have resulted in the Equation (1) for estimating leakage through a hole in the geomembrane portion of a composite liner. The empirical equation takes the following form:

$$Q = C[1 + 0.1(h_w/t)^{0.95}]a^{0.1}h_w^{0.9}k_s^{0.74} \tag{1}$$

[For $h_w < 3$ m, and defect diameter $a \leq 5 \times 10^{-4}$ m^2 (25 mm dia.)]
where: Q = rate of leakage through a defect (m^3/s); C = a constant related to the quality of the intimate contact between the geomembrane and its underlying clay liner; h_w = head of liquid on top of the geomembrane (m); t = thickness of the soil component of the composite liner (m); a = area of defect in geomembrane (m^2); and k_s = hydraulic conductivity of the underlying clay liner soil (m/s). The basis for Equation (1) is referenced in the U.S. EPA Technical Manual (1993), and is incorporated into the latest versions of the HELP computer model (U.S. EPA 1994) used for predicting landfill leachate generation and leakage.

2.1.2 *Defects in encapsulated bentonite system*

For an encapsulated design (Fig. 1c), the size of the defect in the lower geomembrane would control leakage, and leakage would occur when an event caused coincident defects in the upper and lower geomembranes. In this case, Darcy's law controls the advective flow rate through a defect of a given size. The leakage equation would take the following form:

$$Q = k_s i a \tag{2}$$

where: Q = leakage (m^3/s); k_s = hydraulic conductivity of the bentonite; i = hydraulic gradient (liquid head h_w/bentonite thickness t); and a = area of coincident defects through an encapsulated liner system (m^2).

2.1.3 *Seepage at overlapped (unwelded) GM-GCL seams*

In the case of overlapped seams (Fig. 1a), liquid will seep directly into and possibly through the overlaps. Therefore, the seepage rate through overlapped GM-GCL seams must be quantified in a leakage evaluation.

Due to the weight of its bentonite coating, an installed GM-GCL lays flat on the subgrade. This virtually eliminates wrinkles and results in excellent contact between overlapped panels at their seam areas. For a typical GM-GCL overlap distance of 300 mm, it would take more than 5 years before seepage would begin through the overlap with a fluid build-up of up to 300 mm. Steady-state leakage would most likely take several more years to develop (Thiel et al. 2001). This seam performance is based on data provided by the large-scale tank tests reported by Estornell & Daniel (1992) and the Cincinnati U.S. EPA GCL test Plot "P" exhumed after 4.5 years of performance (Daniel 2001).

Leakage per unit length due to seepage along a saturated GM-GCL overlap is calculated in accordance with Darcy's law as follows (Thiel et al. 2001):

$$Q = k_s(h_w/B)t \tag{3}$$

where Q = flow rate per unit length (m^3/s m); k_s = hydraulic conductivity of the bentonite (m/s); h_w = head on top of the liner (m); B = width of overlap (m); and t = thickness of the bentonite (m).

To determine leakage due to seepage at overlap seams, the total linear length of seam for a given project must be calculated. The general length of overlap seams (S) in an installation area (A) is (Thiel et al. 2001):

$$S = A(1/L + 1/W) \tag{4}$$

where L = average length of panels less overlap (typically 51.2 m for the GM-GCL); W = average width of panels less overlap [typically 5.0 m for the GM-GCL]. Applying equation (4) to a typical GM-GCL installation thus results in approximately 2200 m of overlap seam per hectare of lined area. The actual length of overlap seam would increase slightly if the complexity of the installation increased due to structures, for example, or irregularities. Total leakage at overlapped seams is subsequently determined by multiplying Q by the length of seam S.

2.2 *Factors affecting leakage*

2.2.1 *Intimate contact "C-value"*

Equation (1) contains the factor C which accounts for the degree of intimate contact between the geomembrane and adjacent clay. Most of the empirical formulas and recommendations developed to date have been for compacted clay liners. Empirical studies indicate that compacted clay liner installations with good construction quality assurance achieve what would be considered a "good" liner contact rating, resulting in a C-value of 0.21. Without good construction quality control and quality assurance, the hydraulic contact between a geomembrane and a compacted clay liner might be "poor", resulting in a C-value for Equation (1) of 1.15.

Giroud (Thiel et al. 2001) evaluated the contact C-factor between the bentonite component of the GM-GCL and an adjacent geomembrane by analyzing the approaches developed and expounded by Rowe (1998), Foose et al. (2001) and Harpur et al. (1993). Using the results published in those references, Thiel et al. (2001) recommend a conservative value of $C = 0.01$ for contact between the bentonite component of the GM-GCL and an adjacent geomembrane.

Note that the C-value for the GM-GCL is not applicable for other types of GCLs. This exclusion is justified by the much smaller amount of bentonite wetting observed in GM-GCLs compared to geotextile encased GCLs in tests performed by Estornell & Daniel (1992), and in the lower interface transmissivity shown in tests performed by Harpur et al. (1993).

2.2.2 *Hydraulic conductivity*

The hydraulic conductivity of sodium bentonite in GCLs is affected by (1) the level of normal stress applied to the GCL, and (2) chemical alterations caused by different permeating liquids that may increase the hydraulic conductivity of sodium bentonite. Guidance to selecting the appropriate hydraulic conductivity value(s) for a project-specific GCL application and liquid is presented by Thiel et al. (2001).

Typical hydraulic conductivity values for sodium bentonite, when exposed to tap water and compatible dipolar liquids, range from 5×10^{-11} m/s to 9×10^{-13} m/s under normal loads ranging from 5 kPa to 500 kPa, respectively. Bentonite's hydraulic conductivity may be increased to as high as 1×10^{-8} m/s by leachates that contain high cation concentrations, such as from incinerator ash (Thiel et al. 2001). Therefore, project-specific normal loads and leachate compatibility must be evaluated when deriving the appropriate hydraulic conductivity values.

2.2.3 *Project specific design assumptions*

1. *Liquid head build-up, h_w.* The build-up may vary from less than 25 mm for cap applications, up to 300 mm for regulated allowable build-up above bottom liners, and elevated liquid head for secondary containment leakage events and impoundment applications.
2. *Defect area, a, and frequency of defects per unit area.* Industry average standards for estimating defects in an installed geomembrane assume that approximately two to ten 100 mm^2 holes per ha exist after a geomembrane

is deployed and covered with soil. The number and size of these defects can be reduced through more thorough CQA procedures, such as the use of an electric defect-detection survey after the overlying soil has been placed. The quality of installation and the assumed size and frequency of geomembrane defects should be evaluated on a project-specific basis.

3. *Clay liner thickness, t.* The thickness of compacted clay liners is generally given by prescriptive requirements. The thickness of the GCL bentonite layer is based on the mass loading of bentonite (standard 3700 g/m^2 at 0% moisture) at the design normal load. The thickness of the hydrated bentonite component of the GM-GCL as a function of effective compressive stress ranges from 8.5 mm to 3 mm for a normal load range from 10 kPa to 1000 kPa, respectively, as presented by Thiel et al. (2001).

2.3 *Leakage rate comparisons*

In evaluating hydraulic performance, each liner system is analyzed by utilizing the project-specific design criteria outlined above and applying the applicable leakage equations. The total potential leakage for the composite liner system is calculated by combining the leakage through the assumed frequency of geomembrane defects with the leakage at the overlapped seams, if the geomembrane seams are not welded.

Figure 2 presents an example of leakage rate comparison between the various GM-GCL configurations (overlapped seams, welded seams, and encapsulated bentonite alternatives) and a prescriptive U.S. EPA Subtitle D geomembrane-compacted clay composite liner for a typical landfill bottom liner application. For the calculations in this comparison, the design assumptions were: liquid head $h_w = 300$ mm; bentonite thickness $t_{bent} = 5$ mm; assumed area of defects $a = 0.0001$ m^2; defects per hectare $n = 10$; and overlap distance $B = 300$ mm. Design assumptions for the prescriptive compacted clay liner included thickness $t_{ccl} = 600$ mm and hydraulic conductivity $k_{ccl} = 1 \times 10^{-9}$ m/s.

As shown in Figure 2, the simple-overlap design with the one-product composite liner will environmentally out-perform a prescriptive Subtitle D liner (geomembrane over 600 mm compacted clay layer) even when its bentonite's hydraulic conductivity is increased to $k_{bent} = 1 \times 10^{-9}$ m/s. The environmental performance of the GM-GCL encapsulated design is exceptional, with estimated leakage rates between 100 and 100,000 times lower than the prescriptive geomembrane-compacted clay liner (showing as nearly zero leakage on the graphical scale in Figure 2), depending on the hydraulic conductivity of the bentonite.

The hydraulic analysis presented above can be adapted to all potential design applications in order to evaluate the environmental performance and equivalency of a GCL as compared to conventional geomembrane-compacted clay composite liner systems for a project-specific set of design parameters.

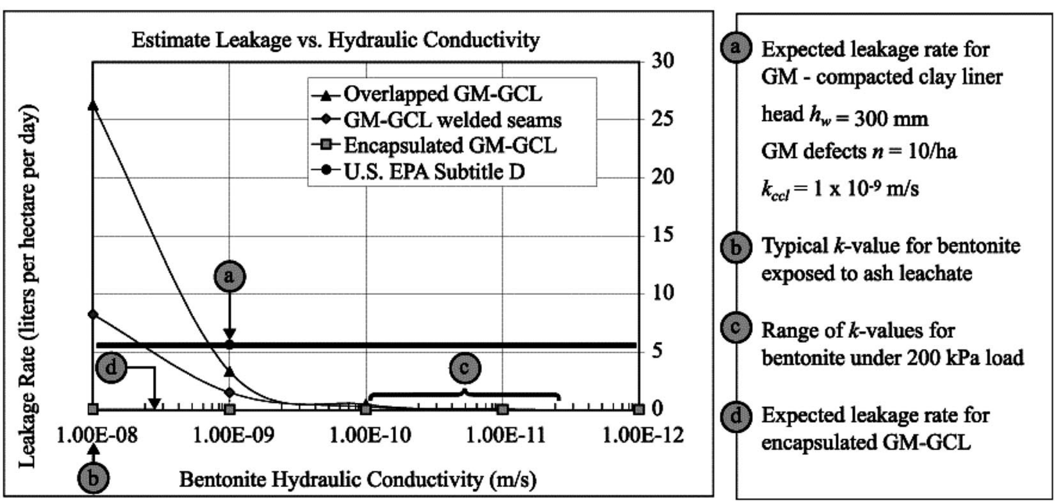

Figure 2. A comparison of hydraulic performance of example composite bottom liner systems with (a) GM-GCL alternative liners, and (b) U.S. EPA subtitle D composite bottom liner.

3 SLOPE STABILITY

3.1 *GM-GCL stability considerations*

Determining whether a slope will remain stable or not requires an understanding of the slope geometry, the unit weights and shear strengths of the materials within and under the slope, pore pressures, and external loadings. Geosynthetics, such as geomembranes and GCLs, generally provide a preferential slip plane along which a slope failure may occur. For a GM-GCL, the unreinforced bentonite layer is an obvious location to evaluate for the critical slip plane.

Since the shear strength properties of bentonite have been the subject of investigation and study for many decades, it is possible to assume the shear strength properties of bentonite with a great degree of confidence. This is, however, not usually the case with most natural soils and geosynthetics. Recommended shear strength curves and equations for dry and hydrated bentonite are presented by Thiel et al. (2001).

When using the GM-GCL in the single-composite mode, the bentonite is exposed to subgrade moisture. In this case, slope stability analyses should always be performed assuming the fully hydrated shear strength properties of the bentonite. Depending on the construction and subgrade conditions, the designer may wish to select either the peak hydrated shear strength, the residual hydrated shear strength, or something in between. Slope stability conditions for the GM-GCL can be improved by using the encapsulated design approach (Fig. 1c), which protects the bentonite from hydration. Some details of this approach are discussed in the next section.

Whichever approach is selected as the design basis that will provide an acceptable factor of safety defined by the designer, the authors recommend that an additional analysis be performed representing long-term, worst-case conditions using the residual, fully-hydrated shear strength of the bentonite, and that the results achieve a factor of safety at least greater than unity.

For cover veneer systems, Thiel et al. (2001) have illustrated how slopes as steep as 1(H):3(V) and over 30 m long can remain stable when utilizing a GM-GCL and assuming hydrated unreinforced bentonite shear strength. For much longer slopes, however, the maximum allowable slope angle may need to be reduced. A full-scale demonstration project in Cincinnati, Ohio (Koerner et al. 1996) has demonstrated that the GM-GCL, with hydrated unreinforced bentonite overlaid by a 900 mm thick cover soil, has remained stable on an "infinite" (i.e. no toe buttressing or top anchorage) 1(H):3(V) slope for more than seven years. Even so, the authors of the U.S. EPA research-demonstration project do not recommend this slope configuration for final design. The practical limitations for cover veneer slope designs are discussed by Thiel et al. (2001).

For bottom liner systems, designers should be particularly sensitive to the variation in effective normal stress over the length of the critical failure surface. They must also be sure to account for the non-linear characteristics of the bentonite shear-strength envelope in the analyses.

3.2 *Encapsulated bentonite hydration*

In the encapsulated design, the bentonite in the GM-GCL is installed at its factory-produced moisture content of approximately 25%, which preserves its "dry" shear strength of the bentonite. Over time, however, encapsulated bentonite can hydrate from a relatively dry state, to one that is more saturated. From the point of view of shear strength, relatively dry means that the bentonite is drier than 35% moisture. Moisture contents above 40%–50% will result in reduced bentonite shear strength (Daniel et al. 1993). By estimating the fraction of the installed bentonite area that may become hydrated, the global shear strength of the bentonite layer can be prorated (i.e. % of dry area vs. % of hydrated area). With a given relative hydrated vs. dry area of bentonite in an encapsulated GM-GCL installation, a design methodology can be applied to prorate the shear strength over the design life of a project. The approach of prorating shear strength for encapsulated GCLs has been successfully applied in several landfill designs since 1994 for projects in the Western USA. A case history outlining the prorated shear strength design methodology is presented by Thiel & Erickson (2001).

After the installation of encapsulated GM-GCL, there are two potential hydration mechanisms that could result in a localized increase in bentonite moisture: (1) moisture entering through defects in the upper and/or lower geomembranes, and (2) subgrade moisture seeping through the overlapped GM-GCL seams. Thiel et al. (2001) discuss potential hydration from water diffusion through the geomembranes and conclude that this hydration mechanism is insignificant.

3.2.1 *Hydration from above and below through geomembrane defects*

The method for calculating hydration rates in encapsulated bentonite due to a hole in an adjacent geomembrane was developed by Giroud and described in Thiel et al. (2001). Examples are presented showing how the radius of hydrated bentonite would be less than 500 mm over a period of 250 years in a typical bottom liner under 300 mm of liquid head. Relative to one hectare, the hydrated area beneath a single 10 mm diameter defect is calculated to be less than 0.008% of the total area. Thus, assuming there are 10 randomly located geomembrane defects per hectare in both the bottom and top geomembranes (a very conservative assumption), the total number of defects per hectare would be 20, the percent of the total area that becomes hydrated would be $20 \times 0.008\% = 0.16\%$. This degree of hydration beneath occasional imperfections in the geomembrane is essentially negligible assuming good contact between the geomembranes and the bentonite. Greater lateral spreading and bentonite hydration could, however, be produced by wrinkles in the overlying geomembrane.

This analysis assumes a continuous head of water; if conditions were comparatively dry, the hydration would be less. Therefore, it is conservative to assume that 5% of the total installed bentonite area might become hydrated due to geomembrane defects over a 250 year design life.

3.2.2 *Hydration from below through GM-GCL overlapped seams*

In the encapsulated mode, where the GM-GCL is deployed with the geomembrane face-down with overlapped seams against a soil subgrade, moisture will be absorbed into the exposed bentonite edge of the overlap due to the difference in matric suction between the bentonite and the subgrade soils. The extent and rate of wetting along the exposed bentonite edge of the overlap depend upon the water content of the soil in contact with the bentonite. The method for calculating the hydration rates along an exposed overlap GM-GCL seam edge was developed by Giroud and described in (Thiel et al. 2001). Examples are provided there, showing how the bentonite might become hydrated between 5–34% of its area over a period of 250 years, depending on the moisture content of the subgrade on which the liner was placed. Therefore, a conservative estimate of the total long-term (250 years) hydrated bentonite area resulting from geomembrane defects and overlap seams would range from $5 + 5 = 10\%$, to $5 + 34 = 39\%$.

3.3 *Slope stability analysis*

The shear strength along a slip plane within the bentonite of the encapsulated GM-GCL is a proration of both the hydrated and dry shear strength properties of bentonite. Given the random location of geomembrane defects, and mostly even spacing of overlapped GM-GCL seams, one can assume the hydration pattern in the bentonite area to be relatively uniformly distributed over a project area. Therefore, a weighted average for the global shear strength can be defined based on the hydrated and dry shear strengths of bentonite, and the corresponding assumed fractions of hydrated and dry areas.

For example, if the hydrated fraction $[Area_{(hydrated)}/Area_{(total)}]$ of the GM-GCL over the design life of a project is assumed to be 10%, Figure 3 illustrates the prorated design shear strength envelope for a high-normal load residual strength. This shear strength data were used for a landfill bottom liner system designed and constructed in 1994 with a subsequent expansion in 1997 (Thiel & Erickson 2001).

The factor of safety for a stability analysis using this approach is typically on the order of 1.5 or greater. Although this may satisfy the basic design requirements for slope stability, the authors recommend one additional requirement, which is that the factor of safety be greater than 1.0 assuming the bentonite is fully hydrated and has only residual shear strength. This latter condition is often the more critical.

4 INSTALLATION AND DURABILITY

The engineering assumptions made by designers are hinged on the geosynthetics' integrity being maintained through the construction process. Geosynthetics are generally specified and manufactured with adequate durability to survive construction and service loadings. Designers, installers, contractors, and operators must be aware, however, that there are limits to the level of abuse that geosynthetics can tolerate.

For the GM-GCL, there are three significant durability issues, all related to covering the liner with soil that could affect its fundamental design performance if the construction procedures are not closely monitored and followed.

4.1 *Soil covering in a timely manner*

The objective of covering a GCL in a "timely manner" is to prevent the bentonite from hydrating with no confining pressure. With an encapsulated GM-GCL, however, the issue is significantly reduced, if not eliminated altogether, as long as the bentonite is covered with the overlying geomembrane by the end of each working day.

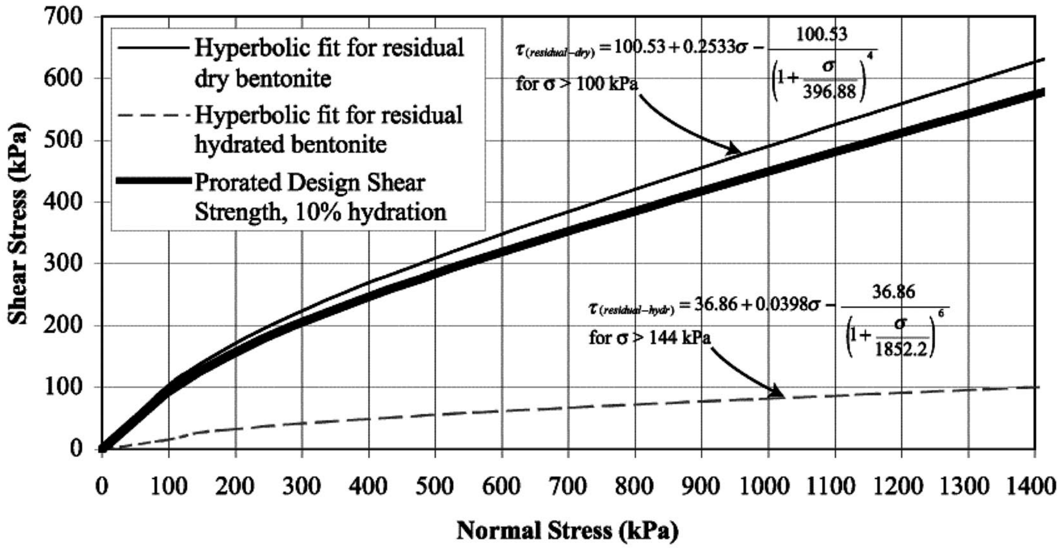

Figure 3. Prorated shear strength curve for encapsulated, partially-hydrated bentonite.

How one defines "timely manner" depends upon the moisture conditions of the subgrade. Construction quality assurance (CQA) specifications should set maximum allowable exposure times before soil covering, and every instance of exceeding these exposure times should be verified by field inspection. The following general recommendations (Thiel et al. 2001) address the three basic moisture characteristics of agronomic soils, the intent being to cover the GM-GCL before bentonite hydration and migration due to construction loads would cause concern:

1. *If the subgrade is relatively dry* (approaching the "wilting point" moisture content that makes vegetation growth difficult), the GM-GCL should be covered within five days.
2. *If the subgrade is damp to moist* (approaching the "field capacity" moisture content that allows lush vegetation), the GM-GCL should be covered within 2-3 days.
3. *If the subgrade is moist to wet* (approaching saturation), it is advisable to cover the GM-GCL on the same day or the following morning.

4.2 *Soil covering in a careful manner*

The high level of performance demonstrated by composite liners with GCLs assumes that certain size defects in the geomembrane would be rendered benign by the underlying bentonite from the GCL. Very large defects through a GCL, however, might be beyond a GCLs sealing ability. Spinning wheels or tracks on construction equipment, for example, could rip a large gap in a geosynthetics-only lining system. Therefore, industry accepted construction installation and monitoring practices should be followed (such as those established by ASTM D6102, or the manufacturer's recommendations) to prevent these types of defects from occurring.

After a minimum 300 mm of soil is in place over the liner system, the potential for further construction- or operations-induced damage becomes remote. To ensure the liner system's integrity, therefore, it is crucial that the placement and spreading of the cover soil layer over the liner be properly executed. To eliminate the possibility of large through-liner defects for the project, two installation and monitoring practices should be followed.

1. Develop appropriate construction specifications that alert the installer, general contractor, and owner to the specific actions and activities should be taken and avoided.
2. Provide for a high level of construction quality control (CQC) and construction quality assurance (CQA) during liner deployment and covering operations. Typically, this involves having a ground-person directly monitor the cover soil placement operations.

4.3 *Thicker soil covering for high traffic areas and roads*

Hydrated bentonite may migrate and thin in response to differential stresses, depending on the magnitude of confinement and the degree of differential stress. With the GM-GCL encapsulated design and isolation of the bentonite from potential pre-hydration, this is of minimal concern. Areas above the liner system that experience heavy construction loads should be required to have adequate soil cover to protect the liner system beneath the wheel paths. At least 300 mm of cover soil is generally adequate for track equipment. For heavier traffic areas and haul routes, a minimum soil cover of 600 mm to 900 mm should be required, depending on the intensity of usage and the size of the equipment. The extra material on the haul routes can subsequently be spread out with a dozer at the end of the construction project.

5 SUMMARY AND CONCLUSIONS

The GM-GCL has been used as a one-product composite liner as an alternative to conventional geomembrane-compacted clay liners given its superior hydraulic performance as well as potential economic benefits derived from ease of installation. Designs utilizing a GM-GCL must evaluate the critical hydraulic, slope stability, and installation issues to ensure its long-term performance. This paper outlines various design approaches that can be used to evaluate a GM-GCL in its various installation configurations, ranging from simple overlapped seams to encapsulation of the bentonite between geomembranes.

For applications where the GM-GCL is used as a stand-alone one-product composite liner, the excellent lay-flat properties and minimal geomembrane wrinkles of the installed product, combined with its effective sealing properties at overlapped seams with compatible liquids, provide an effective and economical alternative to conventional welded geomembrane composite liner systems. Where slope stability becomes a concern, or greatly enhanced environmental protection is warranted, encapsulated GM-GCL liner systems can be highly effective.

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