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GRI-GCL5*

Standard Guide for

"Design Considerations for Geosynthetic Clay Liners (GCLs) in Various Applications"

1. Scope

1.1 This guide covers most major design procedures necessary for the application of geosynthetic clay liners (GCLs) in civil and environmental engineering projects. It describes the major design categories, some suggested parameters for consideration, and the relevant test methods to be utilized. This guide is not all encompassing and is not meant to address unique and/or extreme project specific requirements.

1.2 This guide is intended to aid designers and users of GCLs in establishing the possible adequacy of a candidate GCL to limit fluid migration and remain stable within the structure or system under consideration.

1.3 Units – The values stated in SI units are to be regarded as the standard. No other units of measurement are included in this standard.

1.4 This guide offers a set of instructions for performing one or more specific operations. This document cannot replace specialized education or related experience and must be used in conjunction with professional judgment. Not all aspects of this guide may be applicable in all circumstances. This GRI standard is

*This GRI standard is developed by the Geosynthetic Research Institute through consultation and review by the member organizations. This guide will be reviewed approximately every 2-years, or on an as-required basis. In this regard, it is subject to change at any time. The most recent revision date is the effective version.

not intended to represent or replace the standard-of-care by which the adequacy of given professional services must be judged, nor should this document be applied without consideration of a project's many unique aspects. The word "Standard" in the title of this document means only that the document has been approved according to the GRI adoption process.

1.5 This standard does not purport to address all of the safety concerns, if any, associated with its use. It is the responsibility of the user of this standard to establish appropriate safety and health practices and determine the applicability of regulatory limitations prior to use.

2. Referenced Documents

2.1 ASTM Standards

- D 4439 Terminology for Geosynthetics
- D 4833 Test Method for Index Puncture of Geomembranes and Related Products
- D 5887 Test Method for Measurement of Index Flux through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter
- D 5888 Practice for Storage and Handling of Geosynthetic Clay Liners
- D 5889 Practice for Quality Control of Geosynthetic Clay Liners
- D 5890 Test Method for Swell Index of the Clay Mineral Component of Geosynthetic Clay Liners
- D 5891 Test Method for Fluid Loss of the Clay Component of Geosynthetic Clay Liners
- D 6072 Guide for Obtaining Samples of Geosynthetic Clay Liners
- D 6102 Guide for Installation of Geosynthetic Clay Liners
- D 6141 Guide for Screening the Clay Portion of a GCL for Chemical Compatibility to Liquids
- D 6241 Test Method for the Static Puncture Strength of Geosynthetics Using a 50-mm Probe
- D 6243 Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method
- D 6495 Guide for Acceptance Testing Requirements for Geosynthetic Clay Liners
- D 6496 Test Method for Determining Average Bonding Peel Strength Between the Top and Bottom Layers of Needle-Punched Geosynthetic Clay Liners
- D 6766 Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids
- D 6768 Test Method for Tensile Strength of Geosynthetic Clay Liners

2.2 GRI Standard

- GCL3 Specification for Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)

2.3 ISO Standards

ISO 10318 Geosynthetics – Terms and Definitions
ISO 12236 Test Method for Geosynthetics Static Puncture Test (CBR Test)

3. Terminology

3.1 Definitions

3.1.1 Geosynthetic Definitions:

3.1.1.1 adhered geosynthetic clay liner (GCL), n—GCL product in which the clay component is bonded to a film or membrane by adhesion.

3.1.1.2 coated GCL, n—GCL product with at least one layer of a synthetic substance applied to the GCL as a fluid and allowed to solidify.

3.1.1.3 geomembrane, n—essentially impermeable geosynthetic composed of one or more synthetic sheets. The common acronym is "GM".

3.1.1.4 geosynthetic clay liner, n—factory manufactured geosynthetic hydraulic barrier consisting of clay supported by geotextiles or geomembranes, or both, that are held together by needling, stitching, or chemical adhesives . The common acronym is "GCL".

Note 1: GCL's are also called geosynthetic barriers-clay (GBR-C). GCL's and GBR-C's are precisely the same type of geosynthetics and the difference is merely terminology.

3.1.1.5 geotextile, n—a permeable geosynthetic comprised entirely of textiles.

3.1.1.6 laminated GCL, n—GCL product with at least one geofilm or geomembrane layer superimposed and bonded to the GCL by an adhesive usually under heat and pressure.

3.1.1.7 multicomponent GCL, n—GCL with an attached geofilm, coating, or relatively thin geomembrane thereby decreasing the hydraulic conductivity or protecting the clay core or both.

3.1.1.8 needle-punched GCL, n—reinforced GCL manufactured using barbed needles that punch fibers from a nonwoven cover geotextile through the clay core and carrier geotextile so as to bond the components together and increase internal shear strength.

Note 2: The carrier (lower) geotextile is generally either a woven slit film geotextile or another nonwoven needlepunched geotextile.

3.1.1.9 reinforced GCL, n—GCL that has discrete fibers, yarns or filaments attaching the upper and lower geotextile to one another so as to increase the internal shear strength.

3.1.1.10 stitch-bonded GCL, n—reinforced GCL manufactured by stitching yarns or threads that are passed through the cover geosynthetic, the clay core, and the carrier geosynthetic to increase the internal shear strength.

Note 3: Stitch bonding creates a directional orientation; therefore, the direction of allowable shear transfer is predetermined.

3.1.1.11 unreinforced GCL, n—GCL that does not have a discrete components (such as needle-punched fibers or stitch-bonded yarns) to increase internal shear strength.

3.1.2 Organizational Definitions

3.1.2.1 installer, n—party who installs, or facilitates installation of, any materials purchased from manufacturers or suppliers.

3.1.2.2 manufacturer, n—group, corporation, partnership, or individual that manufactures a product.

3.1.2.3 purchaser, n—person, company, or organization that purchases materials or work to be performed.

3.1.2.4 supplier, n—party who supplies material or services.

3.1.3 Quality Definitions:

3.1.3.1 quality assurance, QA, n—all those planned or systematic actions performed by the purchaser necessary to provide confidence that a material, product, system, or service will satisfy given needs. For geosynthetics, QA applies to both manufacturing and construction thereby becoming MQA and CQA, respectively.

3.1.3.2 quality control, QC, n—planned system of activities performed by the manufacturer or installer whose purpose is to provide a level of quality that meets the needs of users; also, the use of such a system. For geosynthetics, QC applies to both manufacturing and construction thereby becoming MQC and CQC, respectively.

4. Summary of Guide

4.1 This guide presents many key design criteria that should be addressed for proper hydraulic and mechanical performance of a GCL such as the calculation of leakage rates and shear stability. There are many other issues that will be presented as well. In general, the designer should go beyond this guide into the idiosyncrasies of the product-specific and site-specific considerations. GCLs in this guide are products fabricated using a bentonite clay layer sandwiched between geotextiles (occasionally a laminate or a coating is added to the upper geotextile) or to a geomembranes and are used to limit the movement of fluids and/or gases. Table 1 suggests various applications, with ratings from 1-important to 4-not relevant, and selected criteria that might be applicable for design consideration. In all cases, product-specific and site-specific conditions can, and should, prevail.

4.2 This guide does not address installation criteria, i.e., CQC and CQA. These are independent activities and are invariably site specific. They are performed after the design process is essentially complete. Current standards and or documents are Guide D 6102, Practice D 5889, Guide D 6495, and Specification GRI-GCL3). See also Daniel and Koerner (2007) as well as manufacturers' recommendations on GCL installation issues.

Table 1 – Subjective Ratings for Importance of Various Criteria of Common GCL Applications

Criterion	Landfill Covers	Landfill Base Seals	Dams/Dykes (GCL only)	Waterways (GCL only)	Surface Impoundments (GCL only)	Environmental Protection	Secondary Containment	Waste Covers
Hydraulic Conductivity - GCL - Seam	 1 1	 1 2	 1 1	 1 1	 1 1	 1 1	 1 1	 1 1
Long-term stability - Geotextile - Geofilm or Geomembrane - Bentonite	 1 1 1	 1 1 1	 1 1 1	 1 1 1	 1 1 1	 1 1 1	 1 1 1	 1 1 1
Intimate contact Contaminant flow	3 3	1 1	4 4	4 4	4 4	GCL only: 4; Comp: 1 GCL only: 4; Comp:1	GCL only: 4; Comp: 1 GCL only: 4; Comp:1	
Diffusion	3	1	4	4	4	2	GCL only: 4 Comp: 2	4
Settlement	1	2	3	3	2	3	2	1
Behavior - Freeze/thaw - Dry/wet	 2 1	 4 (1 if not frost protected) 4 (2 if not protected against dry/wet cycles)	 1 1	 1 3	 1 2	 2 2	 1 1	 1 1
Shear - Internal - Interface	 1 1	 1 1	 1 1	 1 1	 1 1	 1 1	 1 1	 1 1
Puncture Resistance - Fine cover - Sandy gravel - Coarse cover	 3 2 1	Normally covered with geomembrane	 3 2 1	 3 2 1	 3 2 1	 3 2 1	 3 2 1	 3 2 1
Internal Erosion - GT < 250 g/m^2 - GT > 270 g/m^2	 4 4	 3 3	 1 2	 1 2	 1 2	 1 2	 1 2	 1 2
Bearing behavior (installation) 30/60/90 cm Cover Soil thickness	1/2/3	Normally GM covered	1/2/3	1/2/3	1/2/3	1/2/3	1/2/3	1/2/3
Root penetration	1	4	2	2	2	1	1	1

1 – important 2 – project dependent requirement 3 – rarely required 4 – not relevant GM – geomembrane GT – geotextile [Comp = Composite GM/GCL liners]

5. Major GCL Applications

5.1 This guide describes the major issues, as well as selected related design issues, and the various types of GCL tests for the following applications.

Note 4: Multicomponent GCLs might improve the performance over a standard GCLs in a specific application. However, they might only be suitable for short- or mid-term use.

Note 5: A geomembrane overlying a GCL, i.e., a GM/GCL composite, is always an alternative for long-term use in most applications.

5.1.1 Landfill Covers (or Caps) and Remediation Barriers—GCLs are used to inhibit the ingress of water and the escape of fluids and/or gases in the construction of solid or industrial waste facility cover or to cap contaminated soil. The typical confining stress is in the range of 10 and 50 kN/m^2. Hydraulic gradients are typically less than 50.

5.1.2 Landfill Base (or Bottom) Liners—GCLs are used to limit the escape of landfill leachate or gases in the construction of solid waste storage, heap leach pads, and disposal site base liners and to inhibit the ingress of groundwater. Confining stresses vary greatly, e.g., 100 and 1000 kN/m^2. The hydraulic head acting on the GCL in a well performing landfill base liner is usually regulated to be less than 300 mm. Thus, for a typical GCL thickness of 7 to 10 mm, the hydraulic gradient is typically less than 50. That said, conditions vary widely.

5.1.3 Canals, Streams, or Waterways Liners and Surface Impoundments or Ponds—In applications in which a significant water head is maintained, GCLs are generally used in combination with an existing soil barrier or in combination with a geomembrane, i.e., a GM/GCL composite. Under certain conditions they can be used alone. In all cases, the function of the GCL is to reduce seepage through the system thereby reducing water loss from the waterway or storage impoundment. The typical soil stress is less than 50 kN/m^2, however, the head acting on the GCL invariably exceeds 1 m. As a result, the hydraulic gradient is then higher than 100 and can even be 1000, or more, depending on site specific conditions.

5.1.4 Environmental Protection—The function of the GCL in these applications is to inhibit hazardous liquids or constituents resulting from vehicle, railway, or airline incidents from entering a sensitive location in the local environment. A GCL as the sole hydraulic barrier or a GM/GCL composite will often be used. The typical confining stress is in the range of 50 kN/m^2 and the hydraulic gradient is often less than 50.

5.1.5 Secondary Containment—The function of the GCL in this application is to inhibit hazardous liquids or constituents stored in storage tanks, silos or similar containments from entering the local environment. The concern is over leakage or failure of the storage facility which is the primary containment. The typical confining stress is in the range of 25 kN/m^2, whereas the hydraulic gradient is often less than 150.

5.1.6 Covers for Mine Wastes, Tailings, Coal Ash, etc.—Since most residues from mining, incineration and combustion rarely have liner systems beneath them (the notable exception being heap leach mining) emphasis is to be placed on the cover. In this regard, there is similarity with landfill covers in that confining stresses are in the range of 10 to 50 kN/m^2 and the hydraulic gradient is typically less than 50. One notable exception from landfill covers is the enormous size and scale of these waste piles. Another is the regulatory setting which is generally other than an environmental agency.

Note 6: GCL's are regularly used for waterproofing of underground concrete structures but such applications are not the topic of this guide.

6. Significance and Use

6.1 Introduction—GCLs (by themselves or with other geosynthetics and/or soils) must be properly designed in a manner consistent with anticipated field mechanical and hydraulic forces. For example, a GCL will only function properly if hydrated and under a confining stress. This guide suggests the types of analyses and testing required to achieve an acceptable level of field performance. Where minimum design factors-of-safety are recommended, it must be recognized that the designer has the responsibility to adjust the level of performance to reflect the criticality and permeance of the site-specific application.

6.2 Landfill Covers (or Caps)—Figure 1 shows a common usage of GCL within a final cover. Generally a GM/GCL composite will be the barrier, but in some cases, a multicomponent GCL may be used. In this application, the flux rate of fluid leakage through the GCL is influenced by the head of water acting on the GCL and the presence or absence of an overlying geomembrane. Typically, the head should be limited to the thickness of the overlying drainage collection system (in general, less than 300 mm for sand or gravel, and 1 cm for geosynthetic drainage systems). The flux rate of the GCL can be carried out with water as described in Test Method D 5887. The mechanical stability of the GCL is mainly influenced by the slope, the confining stress and the interface friction angle with adjacent layers. Additionally, the performance of the GCL is influenced by the elongation performance of the GCL during differential settlement. Freeze/thaw effects as well as dry/wet effects in this application are dependent on the location's climatic conditions and cover soil type and thickness. Although 1.0 m of soil cover may be sufficient, larger thicknesses may be required to prevent freezing of the bentonite clay component in the GCL. Thicker cover layers also benefit the sealing performance of the GCL; Bouazza (2002). In landfill cover (cap) applications in which the GCL is installed in a composite lining system, for example under a geomembrane, the gas permeability of the GCL is not a critical issue. However, in a GCL-only application, the performance of a GCL as a single clay component must be investigated because of the fact that desiccation of the bentonite can cause an increase of the gas permeation through the GCL; Vangpaisal and Bouazza (2001).

6.3 Landfill Liners—Figure 1 also shows the common usage of a GCL within a landfill base seal beneath the waste mass. In essentially all landfill liner applications, the GCL underlays a geomembrane forming a composite lining system i.e., a GM/GCL composite liner. In this application, the flux rate of fluid leakage through the GCL is influenced by the head of fluid acting on the GCL and the presence or absence of an overlying geomembrane. Essentially all regulations require that the head be limited to the thickness of the leachate collection layer or the leachate detection layer. This is typically 300 mm. In a composite lining system, for example, the flux rate of leachate leakage through the GCL is caused by defects in the geomembrane during installation or cover soil placement. The size and number of defects in the geomembrane is dependent upon good CQC and CQA and the proper design of the protection layer. The flux rate of the GCL can be carried out with water as described in Test Method D 5887 for short-term conditions simulating the initial landfill phase with no or very little waste over the leachate collection system. For the long-term, in many cases, if the GCL meets GRI-GCL3, no other long-term testing is necessary. However, in certain cases it may be necessary to use site-specific leachate as the permeation liquid or an approved synthetic leachate per D 6766. It may not be practical to replicate the hydraulic gradient as well as the confining stress to simulate on-site conditions. A lower confining stress will shorten the test time and yield a conservative result. A U.S. Environmental Protection Agency (EPA) study (Bonaparte, et al., 2002) indicates that GM/GCL composite liners have only nominal leakage (measurably less than geomembranes alone or GM/CCL composite liners) through the primary liners of 279 double lined landfill cells that were evaluated. Additionally, diffusion through the GM/GCL or GCL alone should be considered in design if deemed a concern, e.g., in cases of long lasting hydraulic head or high VOC concentrations, etc. Freeze/thaw effects as well as dry/wet effects are, in this application, only a design issue during the installation phase and are felt not to be an issue once the thickness of cover material over the GCL is greater than the first lift of waste, e.g., 3 to 5 m. The mechanical stability of GCL's is influenced by the slope, normal loads, and the interface friction with adjacent layers. The internal shear strength of reinforced GCLs should be investigated using site-specific conditions and product-specific samples and, perhaps more importantly, the interface shear strengths according to site-specific conditions for both materials above and below the GCL. See Gilbert, et al. (1996) and Fox, et al. (2002). In all cases, the appropriate test method is ASTM D 6243.

6.4 Canals, Streams or Waterways Liners, and Surface Impoundment—The use of a GCL to inhibit water loss in these applications is shown in Figure 2. Since the confining stress is typically low (less than 50 kN/m^2) in these applications, the GCL performance is controlled by the hydraulic head and the subsoil conditions. The hydraulic conductivity of the GCL can generally be carried out using water as described in Test Method D 5887. The leakage rate should be determined by Darcy's Law (per Section 10.1.1) using site-specific conditions. The mechanical stability of the GCL is influenced by the slope, the confining stress, and the interface friction with adjacent layers. Internal shear strength should be considered under the low confined stress applications using ASTM D 6243 under site-specific and product-specific conditions. For projects using a GCL as the only barrier, the erosion stability of the bentonite (during wave action of the water) as well as the bentonite piping (affected by the high hydraulic water head and subsoil conditions) are issues to consider. Freeze/thaw effects must also be considered in areas of concern. Dry/wet effects are a concern when there is intermittent storage, for example, irrigation canals and storm water retention ponds. Roots have been known to grow through GCLs, particularly on side slopes, and thus an ongoing maintenance program should be recommended.

6.5 Environmental Protection—The use of a GCL to inhibit hazardous liquids or constituents resulting from vehicle, railway, or airline traffic from entering a sensitive location in infrastructure applications is shown in Figure 3. Since the confining stress is typically low (less than 50 kN/m^2) in these applications, the GCL performance is controlled by the hydraulic head, which is generally a liquid other than water. The hydraulic conductivity of the GCL should be carried out according to Test Method D 6766 with the site-specific liquid or agreed upon simulated liquids. The mechanical stability of the GCL is influenced by the slope, the confining stress, and the interface friction with adjacent layers and is to be evaluated using ASTM D 6243 under site-specific and product-specific conditions. Freeze/thaw effects as well as dry/wet cycles in these applications are location dependent and often of design concern.

6.6 Secondary Containment—The use of a GCL to provide secondary containment for storage tanks is shown in Figure 4. The function of the GCL in this application is to inhibit any hazardous liquids or constituents leaking from tanks, silos, or similar containments (including pipes) from entering the local environment. Since the confining stress it typically low (less than 50 kN/m^2) in these applications, the GCL performance is controlled by the hydraulic head, which is generally a liquid other than water. The hydraulic conductivity of the GCL should be carried out according to Test Method D 6766 with the site-specific liquid or agreed upon simulated liquid. The stability of the GCL is influenced by the slope, the confining stress, and the interface friction with adjacent layers. Freeze/thaw effects as well as dry/wet cycles in these applications are location dependent and are of design concern. Although project dependent, the GCL can be placed around the perimeter of tanks (proper sealing of the GCL against the tanks is obviously required) or completely under the tanks.

6.7 Covers for Mine Wastes, Tailings, Coal Ash, etc.—At many geographic locations the spoils of mining, combustion and incineration are deposited in huge piles which rarely have liners or liner systems beneath them. As shown in Figure 5 they also are rarely covered. The lack of a cover leads to infiltration of rainfall and snowmelt, as well as surface erosion from water or air. The December 22, 2008 coal flyash spill of the Tennessee Valley Authority in Kingston, Tennessee has prompted concern and activity in covering such sites. GCL's by themselves or GM/GCL composite barriers are being used as waterproofing barriers for such sites. Beyond simply supplying such a barrier, however, regulations vary greatly. Sometimes cover soil is placed directly on a GCL, otherwise a drainage layer can be included in the cross section and then cover soil. In all cases long-term erosion control must be considered. Site-specific conditions will prevail as well as regulatory concerns which are often in other than environmental protection departments. The typical confining stresses are in the range of 10 to 50 kN/m^2. Hydraulic gradients are typically less than 50.

7. Related Considerations

7.1 Manufacturing Quality Control—Practice D 5889 provides guidelines for the manufacturer quality control testing of GCLs to be performed by manufacturers before the GCL is shipped to the project site. The practice provides types and frequency of tests required.

7.2 Acceptance Testing—Guide D 6495 provides guidelines for the acceptance testing and conformance verifications of GCLs to be performed by the CQA engineer for the GCL material. The guide provides types and frequency of tests required.

7.3 Storage and Handling—Guide D 5888 provides guidelines for the proper storage and handling of GCLs received at the job site by the end user.

7.4 Installation Guidelines—Guide D 6102 provides directions for the installation of GCLs under field conditions typically preset in environmental lining applications. Also see Daniel and Koerner (2007) as well as manufacturers literature in this regard.

7.5 Obtaining Samples—Practice D 6072 covers procedures for sampling GCLs for the purpose of laboratory testing.

7.6 Chemical Compatibility—Guide D 6141 suggests procedures and test methods to be used in the evaluation of the ability of the clay portion of the GCL to resist change as a result of exposure to liquids.

8. GCL Strength Properties

8.1 Wide-Width Tensile Strength—GCL's, as a composite material, are occasionally placed under wide-width tensile stress conditions and must be evaluated accordingly. Steep short slopes of canals, ponds and secondary containment facilities are situations where the GCL is contained at the top of slope in an anchor trench and tensile stresses may be imposed along the length of the slope. Based on limit equilibrium there are several models available to determine the induced stresses which must be counterpointed against the GCL's tensile strength as measured in ASTM D 6768. Reduction factors on the GCL's ultimate strength are appropriate to apply; see GRI White Paper #4 (2005). The resulting factor-of-safety is assessed by the designer upon consideration of the criticality and permeance of the situation.

8.2 Internal Shear Strength—GCLs are commonly divided into reinforced and unreinforced types. The reinforced GCLs have fibers, threads or yarns that connect the upper and lower geotextiles that form the two exterior surfaces of the GCL. Therefore, the internal shear strength of GCLs will be greatly influenced by the needled or stitched fibers that penetrate through the thickness of the GCL. In its hydrated state the bentonite itself will offer some, but very limited, shear strength by itself. These various components provide an internal shear strength that can be impacted by the degree of hydration of the clay, the normal load acting on the GCL, the type and amount of fiber reinforcement and the shear strain that has occurred across the thickness of the GCL. Test Method D 6243 measures the simultaneous contribution of all of these internal shear strength components. That said, the cited test method is silent on the essential parameters necessary to properly perform the test. These include, but are not limited to, normal stresses, saturation conditions, liquid type, consolidation time, shearing rate, shearing distance, etc. These (and others) are site-specific conditions and are at the designer's discretion. This section will elaborate on various aspects of internal shear strength.

8.2.1 Bentonite Shear Strength—The clay, in particular, bentonite, that forms the hydraulic barrier component of GCL's has a hydrated shear strength that is influenced by the degree of hydration and the normal loading. The shear strength of hydrated clays has been evaluated by Olson (1974) who produced a series of effective stress failure envelopes. From Olson's work, the lower limit of the effective shear strength of bentonite clay is approximately 35 kPa at a normal load of approximately 275 kPa. This shear 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 somewhat higher normal loads, Daniel, et al. (1993) showed that the drained friction angle of the bentonite clay in GCLs approaches seven degrees. Data is not available at high and very high normal loads and site-specific testing is required for such sites.

8.2.2 Internal Reinforcement Strength—Needled punched fibers or stitched yarns that penetrate through the thickness of a reinforced GCL contribute the major portion of shear strength as the geotextile surfaces move differentially apart. The amount of shear strength added by the reinforcement at low strains may also be influenced by the anchorage or tensioning of the fibers to the geotextiles. The contribution of the reinforcing fibers of reinforced GCLs to the peak shear strength of a GCL is shown in Figure 6. Here the internal total stress peak shear strength data is compared to the effective shear strength of bentonite as determined by Olson, (1974). As expected, the majority of peak shear strength of the GCL is due to the contribution of the reinforcement fibers. This contribution is seen to be significant across the full range of normal loads. Recognizing that the internal shear strength testing of GCL's is intricate and time consuming (see Fox, et al., 2002) the peel strength test is used to evaluate consistency of the reinforcement at frequent intervals. The peel strength of a GCL is evaluated using Test Method D 6496.

8.2.3 Large Strain Internal Shear Strength—Continued shearing of a reinforced GCL beyond its peak stress produces a residual strength; see Figure 7a. The residual strengths are also compared with Olson's effective stress failure envelope for montmorillonite and the peak strength values of a unreinforced GCL; see Figure 7b. Data presented by Scranton (1996) indicates that the residual strength of an unreinforced GCL is from 60 to 100% of the peak strength. The data in Figure 7 clearly show that the shear strength of a reinforced GCL approaches that of an unreinforced GCL at large shear displacements. This was also observed by Gilbert, et al. (1996).

8.2.4 Peak Versus Residual—It is often debated whether to design using the peak strength or the residual strength of a GCL. In this regard, one must consider the type of GCL, the overall system behavior, and the specific conditions under which the GCL will be used. One must also consider the internal strength of the GCL product, the interfaces against its outer surfaces, the interfaces of other adjacent liner components considering both short-term and long-term conditions, and the shear strengths of other liner components in the design. The application will also influence the selection of design strength values. Typically, at lower normal loads, the peak interface strength of a reinforced GCL with adjacent materials is less than the peak internal strength of the GCL. If these materials are sandwiched together to form the sealing system and then subjected to a shear stress, sliding will occur when the applied shear stress exceeds the peak strength of the weakest material or interface. It is likely that once failure is initiated, displacement will continue along that particular slip plane; Thiel (2001) and Marr and Christopher (2004). Design using the lowest peak strength assumes that the peak strength of the interfaces and materials do not change with time.

Note 7: There are several other possible interpretations of selecting design shear strength based on peak, residual, or even large-displacement conditions.

8.2.5 Creep—It is well known that polymeric materials in tension can fail in sustained load creep at lower stresses than their short-term tensile strength. Creep and aging of polymeric materials placed in tension are handled in reinforced soil applications by applying reduction factors to the peak strength of the materials; see GRI White Paper #4 (2005). In the absence of long-term direct shear tests to determine the creep limit of the GCL reinforcement fibers or yarns (that is, the stress level above which the reinforcement will creep to failure within the design life of the project), a creep reduction factor of three has been recommended by Marr and Christopher (2004) based on creep reduction factors normally used for polypropylene (PP) fibers in tension. This value might be somewhat conservative due to anticipated composite bentonite-to-fiber reinforcement interaction that is not present in conventional creep tests used to obtain the stated reduction factor. Published papers by Koerner, et al. (2001), Siebken, et al. (1995), Trauger, et al. (1995) and Zanzinger and Saathoff (2010) have shown that the majority of internal shear displacement occurs during the first 100 h of loading. In this regard, the initial 10 to 30 days after installation is critical. At the GCL landfill cover slope tests in Cincinnati (Scranton, 1996) reinforced GCLs have remained stable with little or no ongoing deformation on slopes as steep as 2H:1V since 1994. This implies a minimum slope stability factor of 1.5 when applied to 3H:1V slopes. Of course, these are at low normal stresses. Unfortunately, there are no similar studies conducted at high normal stresses. The latest study by Müller (2008) states that a GCL with defined resin properties and an antioxidant package of the fibers of a double sided needle-punched nonwoven GCL has a lower limit of functional durability of at least 250 years at 15°C.

8.3 Interface Shear Strengths—In addition to internal shear strength of GCL's, the designer must consider the interfaces between its outer surfaces and the adjacent materials (as well as all other interfaces of other adjacent liner components and their respective shear strengths). In all cases, it is recommended to test product-specific materials to be used in the design and the applying site-specific conditions. The basic test procedure is according to ASTM D 6243. It is important to recognize that this test method is silent on selection of important test variables such as type of liquid, saturation, consolidation time and load, displacement rate, amount of displacement, etc. These are important decisions which will significantly influence the test results.

8.3.1 Shear Strength of Nonreinforced Bentonite GCLs—For those GCLs which have bentonite bonded to a geomembrane, a critical interface will be against or within the bentonite. As mentioned previously if the bentonite is hydrated (as it will be under most situations), the shear strength will vary from approximately zero to seven degrees depending on the normal stress. As such, this type of GCL usually deploys a field placed geomembrane against the exposed surface of the bentonite thereby encapsulating the bentonite between two geomembranes. The encapsulated and relatively dry bentonite has a significantly higher shear strength than when hydrated. In this case emphasis is then transferred to the geomembrane (smooth or textured) surfaces.

8.3.2 Interfaces With Woven Geotextiles—The typical woven geotextile used with GCL's is of the slit (or split) film type. This material with whatever is placed against it must be evaluated for its shearing resistance. Again, site-specific and product-specific conditions must be used in conducting the direct shear test. It is important to communicate the orientation of this woven geotextile, i.e., up or down, to the field installer.

The designer must also assess whether or not hydrated bentonite might extrude through the openings between the filaments of the woven geotextile. Vukelic, et al. (2008) has evaluated this situation in the laboratory and found that the shear strength of the interface can decrease appreciably when hydrated bentonite extrudes through the fabric's openings onto the adjacent material.

8.3.3 Interfaces With Nonwoven Geotextiles—For the nonwoven geotextile component of GCLs, and for those GCL's with nonwoven geotextiles on both upper and lower surfaces, extrusion of hydrated bentonite to the opposing interface(s) is unlikely if the weight of the geotextile(s) is adequate. While at the discretion of the designer, the GRI-GCL3 specification calls for a minimum mass per unit area of nonwoven geotextiles of 200 g/m^2.

9. Stability Evaluations Containing GCL's

9.1 Overview—The conventional method of evaluating the mechanical stability of a mass of soil or solid waste is using limit equilibrium procedures so as to formulate a factor-of-safety (FS) against failure. This includes situations which have GCL's located somewhere within the potentially unstable mass. The concept is embodied in Eq. 1.

$$FS = \sum \frac{Resisting\ Forces\ or\ Moments}{Driving\ Forces\ or\ Moments} \tag{1}$$

All geotechnical engineering textbooks include information on the background and details of this approach. In the context of performing stability analyses which include geosynthetics (including GCL's), they are considered to be inclusions and very often form critical interfaces resulting in low, or even the lowest, FS-value.

Note 8: Details and procedures of stability analyses are so intricate and involved that it is beyond the scope of this guide. That said, its importance is paramount to the designer who must be properly educated and experienced in order to perform such analyses.

9.2 Stability of Large Masses—Slope stability analyses involving GCL's is necessary when dealing with large masses of materials such as landfills, waste piles, tailings piles, coal ash deposits, etc. While the fundamental factor-of-safety approach is traditional, an explicit formulation is usually not possible and a computer model becomes necessary. See Figure 10 for two very large landfill failures. Standard geotechnical engineering texts cover the situation and they should be used accordingly. For example, see Holtz and Kovacs (1981). It should be noted that the solutions are rarely explicit and a systematic search for the lowest FS-value requires a computer code to be used.

9.3 Stability of Veneer Layers—Relatively thin layers of soils, such as landfills and waste pile covers or leachate collection layers can translate gravitationally and the GCL must be evaluated accordingly. See Figure 11 for these types of slides. Koerner and Soong (2005) give such a procedure (there are others) for a number of possible scenarios. This is a special case of stability wherein an explicit solution for the FS-value is available.

9.4 Computer Codes for Stability Analyses—The most widely used soil stability computer codes often do not have provision for including layers of geosynthetics such as GCL's. While they can be adapted, the newer codes have such provisions. Of course, the designer must have interface shear strength values (internal and both external surfaces for GCL's) available for all interfaces as well as wide-width tension strengths. Reduction factors must be assessed and applied in many situations. The importance of properly determining the geosynthetic strengths (tensile and shear) is illustrated in Koerner and Soong (2000) who evaluated ten large landfill failures. All were translational along some particular geosynthetic interface. Conversely, without geosynthetics in the cross-section the failures were oftentimes rotational within the solid waste mass.

10. GCL Hydraulic Properties

10.1 The flow rate or flux, (q) of fluid movement through a saturated GCL is measured in a flexible permeameter according to ASTM D 5887. The flux is measured under a given normal load. The thickness of the saturated bentonite depends on the normal load and is measured in this test. Knowing the flux and bentonite thickness, the hydraulic conductivity (routinely called permeability) of the bentonite portion of the GCL can be evaluated by using the calculation methods given in D 5887.

10.1.1 GCL Barrier—The flow rate that liquids pass through a GCL can be quantified to evaluate the effectiveness of a GCL barrier system. The flow rate, Q, through a hydrated GCL is conventionally calculated using Darcy's Law as follows:

$$Q = K\,((h + t_{GCL})/t_{GCL})\,A \tag{2}$$

where:

Q = flow rate or flux, (cm^3/sec)
K = permeability of the bentonite, (cm/sec)
t_{GCL} = effective thickness of the GCL, (cm)
h = height of the liquid above the GCL (cm), and
A = total area (cm^2).

10.1.2 Geomembrane/GCL Composite Barrier—The flow rate through a GM/GCL composite, based on a defect in the geomembrane, is assumed to be similar to a GM/CCL composite for which the following equations have been derived, Giroud (1997).

- Circular Defect, $Q = C_{qo}\, i_{avgo}\, a^{0.1}\, h^{0.9}\, K^{0.74}$ (3)
- Square Defect, $Q = C_{qo}\, i_{avgo}\, a^{0.2}\, h^{0.9}\, K^{0.74}$ (4)
- Infinitely Long Defect, $Q = C_{q4}\, b^{0.1}\, h^{0.45}\, K^{0.87}$ (5)
- Rectangular Defect, $Q = C_{qo}\, i_{avgo}\, b^{0.2}\, h^{0.9}\, K^{0.74} + C_{q4}\, (\mathbf{B} - b)\, b^{0.1}\, h^{0.45}\, K^{0.87}$ (6)

where:

C_{qo} = quality of GCL-geomembrane contact (C_{qogood} = 0.21, C_{qopoor} = 1.15),
i_{avdo} = average hydraulic gradient (dimensionless),
a = area of the defect (m^2)
h = head acting on the liner (m),
K = permeability of the GCL (m/sec),
b = side length of a square defect (m), and
C_{q4} = quality of geomembrane-to-GCL contact for the infinitely long case (C_{g4good} = 0.42, C_{q4poor} = 1.22).

10.1.3 Effects of Confining Stress on Permeability—Increasing confining stress on a porous material, such as highly compressible hydrated sodium bentonite, decreases the hydraulic conductivity as shown in Figure 8. With increasing confining stress, several detrimental aspects of hydrated sodium bentonites can be prevented; the main one being shrinkage of the bentonite creating cracks that would increase the hydraulic conductivity. These effects can occur as a result of dehydration of the bentonite or, for example, high concentrated calcium solutions that are extremely aggressive to sodium bentonite (see Section 10.2). Higher confining stresses mitigate this effect, and the hydraulic conductivity can possibly remain unchanged. In landfill liners beneath a waste mass, GCLs subjected to high confining stresses are felt to be less vulnerable to increases in hydraulic conductivity than GCLs in low confining stress applications, e.g., less than 20 kPa.

10.2 Cation Exchange

10.2.1 If a liquid containing significant electrolytes [for example, potassium (K+), calcium (Ca++), magnesium (Mg++), and aluminum (Al+++) cations] percolates down to and through a GCL, these positively charged cations will preferentially exchange with the sodium (Na+) cation in the bentonite of the as-manufactured GCL. This is referred to as cation exchange. It is somewhat controlled by the role of RMD, the ratio of monovalent to the square root of divalent ions. The phenomenon results in reduced swelling capacity (according to ASTM D 5890) and increased hydraulic conductivity of the bentonite. The higher the charge (or valence) of the cation, the more preferential and readily it will exchange with the Na+ cations within the bentonite structure. It should be recognized that most soils contain an abundance of salts that contain significant concentrations of K+, Ca++, Mg++, or Al+++. The least favorable cations with regard to exchange of Na+ in bentonite are the polyvalent cations. They have a charge of +2 or more.

Note 9: While there are several technical papers on the topic of cation exchange in sodium bentonite GCL's, the studies by Kolstad, et al. (2004, 2006) are quite comprehensive and illustrate the potential seriousness of the situation.

10.2.2 Free available calcium or magnesium from the surrounding soil will produce an ionic exchange within the sodium bentonite of the GCL within a time period of a few years depending upon site-specific conditions. It is, therefore, recommended to investigate closely the ionic content of the cover soil over GCLs, the cover soil thickness, and the type of bentonite for effects on the GCL's hydraulic conductivity.

10.2.3 ASTM Guide D6141 is used as a screening tool for determining the potential for a liquid or soil to impact a GCL insofar as ionic exchange is concerned. In D6141, sodium bentonite is tested for swell index (ASTM D5890) and fluid loss (ASTM D 5891) with a test liquid instead of deionized water. The test liquid is either the site-specific liquid or a synthetic liquid derived from the adjacent soil. Laboratory research by Jo, et al. (2001) has indicated that free swell tests can be a valuable tool for estimating how inorganic aqueous solutions affect the hydraulic conductivity of non-prehydrated GCL's, see Figure 9.

10.2.4 ASTM D 6766 is used to determine GCL long-term hydraulic conductivity when exposed to potentially incompatible liquids. Scenario 1 is used for those cases in which the GCL is expected to be prehydrated with water before exposure to the liquid. Scenario 2 is used for those cases in which the GCL is expected to be exposed to the site-specific liquid without any prehydration.

10.3 Diffusion of Inorganic and Organic Contaminants

10.3.1 Proper assessment of any barrier system containing potentially harmful pollutants requires a contaminant transport assessment of the barrier system, taking into account factors such as the service life of the collection system and the barrier system along with the surrounding hydrogeological setting. Such an analysis can be performed using a contaminant transport analysis program such as POLLUTE (1997). To perform such assessment, transport processes such as advective, diffusion, sorption, and biodegradation must be established for the barrier system of interest.

10.3.2 Diffusion, the movement of contaminants from areas of high concentration to areas of lower concentration, can be a significant transport phenomenon for low-hydraulic conductivity barrier systems such as those used at the base of municipal solid waste landfills. For the solutions that Goodall and Quigley (1977) tested, the GCL diffusion coefficients of inorganic and organic contaminants are equal to or lower than compacted clay liners. These include salt solutions at different concentrations and synthetic municipal solid waste leachate. Of course, there are site-specific conditions such as dry subgrade soils, which must be individually investigated. This suggests that when considering similar thickness barriers such as a 1-m thick compacted clay liner ($k = 10^{-9}$ m/s) versus 0.01-m-thick GCL ($k = 10^{-11}$ m/s) over an existing subgrade soil 0.99 m thick ($k = 5 \times 10^{-9}$ m/s), the diffusion transport will be equal to or better for the GCL system (provided the thickness of the two systems are similar). When considering similar hydration conditions, stress levels, and permeating fluids, the GCLs tested exhibited a linear relationship between final bulk GCL void ratios and diffusion coefficients. Even when a GCL was hydrated under low-stress conditions and subsequently consolidated to a lower final bulk GCL void ratio, it was the bulk GCL void ratio during diffusion testing that controlled the diffusion parameters. Generally, the diffusion coefficient was shown to decrease as the bulk GCL void ratio decreased. The final bulk GCL void ratio significantly affects the diffusion coefficient of the GCL; that is, the higher the void ratio, the higher the diffusion coefficient.

10.3.3 Organic diffusion results from Lake and Rowe (2004) show that the rates of contaminant migration proceeded through the hydrated GCL in the decreasing order of dichloromethane (DCM) > DCA > benzene >

trichloroethane (TCE), and toluene. This was attributed to varying degrees of sorption of DCA, benzene, TCE, and toluene to the geotextile component of the GCL as well as to the bentonite present in the GCL. Diffusion coefficients (Dt) deduced from volative organic compound (VOC) diffusion testing conducted on the GCLs at confining pressures lower than approximately 10 kPa range from approximately 2×10^{-10} m^2/s to 3×10^{-10} m^2/s. Based on the results presented for inorganic contaminants, these are expected to be upper bound values for the GCL with natural sodium bentonite since the bulk void ratio of a GCL installed for field conditions will be lower than that tested in the study. The effect of low temperature on diffusion of toluene through a needle-punched GCL was examined by Rowe, et al. (2007). Generally speaking, the lower temperatures used during testing resulted in lower rates of organic diffusion through the GCL. This influence of temperature can be critical in harsh northern regions as discussed by Li and Li (2001). The hydraulic properties of the GCL can result in a composite subgrade/GCL soil having very little hydraulic flow through the system. Since the diffusive properties of GCLs have been well established, a contaminant transport assessment of the barrier system can be performed to assess the performance of the proposed landfill barrier system and hydrogeologic setting.

11. Additional Design Considerations

11.1 Freeze/Thaw Cycling—The critical property of a hydrated GCLs insofar as freeze-thaw behavior is concerned is the increase in permeability. Daniel, et al. (1997) used a rectangular laboratory flow box and subjected the entire assembly to ten freeze-thaw cycles. The permeability showed a slight increased from 1.5×10^{-9} to 5.5×10^{-9} cm/sec. Kraus, et al. (1997) report no change in flexible wall permeability tests of the specimens evaluated after twenty freeze-thaw cycles. Podgorney and Bennett (2006) examined the long term performance of GCL's exposed to 150 freeze/thaw cycles and found no appreciable increase in permeability.

While the moisture in the bentonite of the GCL can indeed freeze, causing disruption of the soil structure, upon thawing the bentonite is very self-healing and apparently returns to its original state. In this regard, it is fortunate that most GCLs have geotextile or geomembrane coverings so that fugitive soil particles cannot invade the bentonite structure during the expansion cycle. Thus, the bentonite does not become "contaminated" with adjacent soil particles.

11.2 Dry/Wet Cycling—The behavior of dry and wet cycles insofar as a GCL's permeability is concerned is important in many circumstances. This is particularly so when the duration and intensity of the dry cycle is sufficient to cause desiccation of the clay component of the GCL. Boardman and Daniel (1996) evaluated a single, albeit severe, dry-wet cycle on a number of GCLs and found essentially no change in the permeability. Testing by Benson and Meer (2009) indicates that multiple wet-dry cycles, in conjunction with sodium for calcium ion exchange, may adversely affect the hydraulic performance of GCLs.

Perhaps more significant than change in permeability is that shrinkage can case loss of overlap and even separation at the roll edges or ends. If this occurs in the field, friction with the underlying surface will prevent expansion back to the original overlapped condition. Thus cover soil, placed in a timely manner and sufficiently thick to resist shrinkage, is necessary; see Section 11.6 for exposed conditions.

11.3 Puncture and/or Squeezing Resistance—Due to the relative thinness of GCLs compared with CCLs, puncture and/or squeezing resistance concerns are understandably often voiced. There are a number of tests that can be used with GCLs, including ASTM D4833, which uses a 8.0 mm probe; ASTM D6241, which uses a CBR probe of 50 mm diameter; and ISO 12236, which also uses a 50 mm diameter probe. Although all of these tests are straightforward to perform, it is important to recognize the self-healing puncture characteristics of GCLs which contain bentonite. Puncture tests by themselves cannot reproduce this self-sealing mechanism, since the GCL is being used as a hydraulic barrier and puncture per se may not be a defeating, or even limiting, phenomenon.

Lateral squeezing, however, can occur if a nonpuncturing load is stationed on a GCL which has insufficient cover soil. The degree of squeezing is dependent on the bentonite's initial moisture content, the type of GCL and the applied normal stress and duration. Koerner and Narejo (1995) have investigated this situation and found that a minimum of 300 mm of soil cover above a GCL is necessary (U.S. Corps of Engineers use 450 mm) in order to have the potential failure planes be contained in the overlying soil. By so doing, lateral squeezing of the bentonite does not appear to occur.

11.4 Internal Bentonite Erosion—For projects using a GCL by itself, i.e., without an overlying geomembrane, questions regarding the potential for internal bentonite erosion when placed over coarse grained soils or on open structures such as a geonet arise. High hydraulic gradient applications such as ponds and lagoons are of concern in this regard. This is in part because of the nature of the application and in part because GCLs are relatively thin and so large hydraulic gradients may occur if there is a significant head of fluid acting on the liner. Relatively little research has addressed subgrade requirements for GCLs and installation specifications generally report the same conditions for all GCLs. Some work is reported by Fernandes (1989) with modifications as described by Rowe and Orsini (2003) to investigate the GCL internal erosion performance. In general, woven geotextiles on coarse subgrades resulted in bentonite erosion but nonwoven geotextiles did not. This same result occurred with the GCL placed directly over a geonet. However, these results were under controlled laboratory conditions and are only representative for the geotextiles evaluated. Geotextiles with a lower mass per unit area may create higher bentonite internal erosion as one would expect with coarser subgrades or over geonets. Geosynthetics with higher mass per unit area geotextiles are likely to be more protective against erosion. One would also expect this with finer subgrades. Additionally, the effect of the hydraulic gradient needs to be considered in such investigations.

Note 10: The bentonite erosion issue is somewhat mitigated when using a GM/GCL composite or multicomponent GCL instead of a GCL by itself.

11.5 Total Settlement and Differential Settlement—GCL's (as with all geosynthetics in a layered liner system) will often be subjected to total settlement and/or differential settlement. Of the various applications mentioned in Sections 5 and 6, landfill covers and waste covers are of the greatest concern.

Note 11: Depending upon site-specific subgrade conditions any, or all, of the applications of Sections 5 and 6 might be of concern in this regard but likely to a lesser extent than covers.

Typical landfills will settle 10% to 30% of their initial thicknesses, Spikula (1997), and waste piles are anticipated to do likewise. If a GCL is in the cover cross section it will necessarily settle likewise. In this regard, total settlement can probably be accommodated (depending on site-specific conditions like contouring), but differential settlement is of concern.

GCL's have been laboratory evaluated for their performance in an out-of-plane deformation mode thereby simulating differential settlement. LaGatta (1992) used large-scale tanks with deformable bases to measure water breakthrough. Values for different GCL's were from 10 to 15% tensile strain. Koerner, et al. (1996) used large cylinders of 1.0 m diameter to measure tensile failure with results for different GCL's ranging from 15 to 20% tensile strain. Of course, these values must be counterpointed against field anticipated differential settlement which involves estimates of the size, depth, and shape of the anticipated deformation(s). These are, of course, important and difficult design considerations.

11.6 GCL Panel Separation—Geosynthetic clay liner (GCL) panel separation, *when placed beneath an exposed geomembrane (GM)*, has occurred in at least five instances. Separation distances between adjacent panel edges were from 0 to 300 mm except in one extreme case where they were significantly larger, (GRI White Paper #5, 2005). Again it is emphasized that the geomembranes overlying the affected GCLs were exposed to the environment at all times; i.e., from the time of placement until the separation situation was observed (from 2 months to 5 years). This type of GCL panel separation is not envisioned to occur for the more common situation where timely soil cover is placed over a GM/GCL composite liner. The following three mechanisms have been investigated:

- Longitudinal slope tensioning of GCL.
- GCL contraction on relatively flat slopes.
- GCL shrinkage; perhaps accompanied by cyclic wetting and drying; see Thiel and Thiel (2009) and Thiel and Rowe (2010).

Recommendations to avoid or mitigate the effects of GCL panel separation are as follows, GRI White Paper #5 (2005);

- Do not leave the GM/GCL exposed.
- Increase the overlap distance beyond the common value of 150 mm.
- Protect and/or insulate the surface of the exposed geomembrane.
- Heat-tack the GCL panel overlaps, see Thiel and Rowe (2010).
- Use a woven scrim in one of the geotextiles if the GCL has two nonwoven geotextiles associated with it, i.e., if it is a double nonwoven.

11.7 Sodium Modified Bentonite—By far, the largest deposits of sodium bentonite are in Wyoming and North Dakota in north central USA. This is significant since sodium bentonite has an extremely high swell potential resulting in extremely low hydraulic conductivity. It is ideal for waterproofing in many applications, including the manufacture of GCL's. What is readily available, however, is many calcium bentonite deposits. In this regard, the bentonite industry has been successful in treating natural calcium bentonite with a sodium mixture thereby creating a modified sodium bentonite. It is sometimes referred to as a "peptizing" process. This modified sodium bentonite is being used to manufacture GCL's in many worldwide facilities.

A GCL designer should always be aware of the origin of the bentonite used for the specified product. Presently, the major tests used to indirectly assess the quality of the bentonite are swell index via ASTM D5890 and fluid loss via ASTM D5891. Both values are embodied in the GRI-GCL3 specification. Whether these tests are adequate to assure the efficiency and permeance of the sodium modified bentonite is to be determined.

It should be noted that there is presently (2011) several ongoing research efforts in modifying both sodium and calcium bentonites, primarily (but not exclusively) with polymer additives. The goals of these efforts are to reduce cation exchange. Of course, the long-term performance of these polymers needs to be addressed, as well as the environmental impact. If polymers are added they should be noted in the product data sheets.

Note 12: The practice of heat tacking the overlapped GCL edges and ends has been shown to be helpful in mitigating panel separation. It can be done using either hot air or a hot plate.

Research is ongoing in this regard. See Thiel and Rowe (2010).

12. Keywords

13.1 design; GCL; geosynthetic clay liner; internal shear strength; ion exchange; leakage; stability

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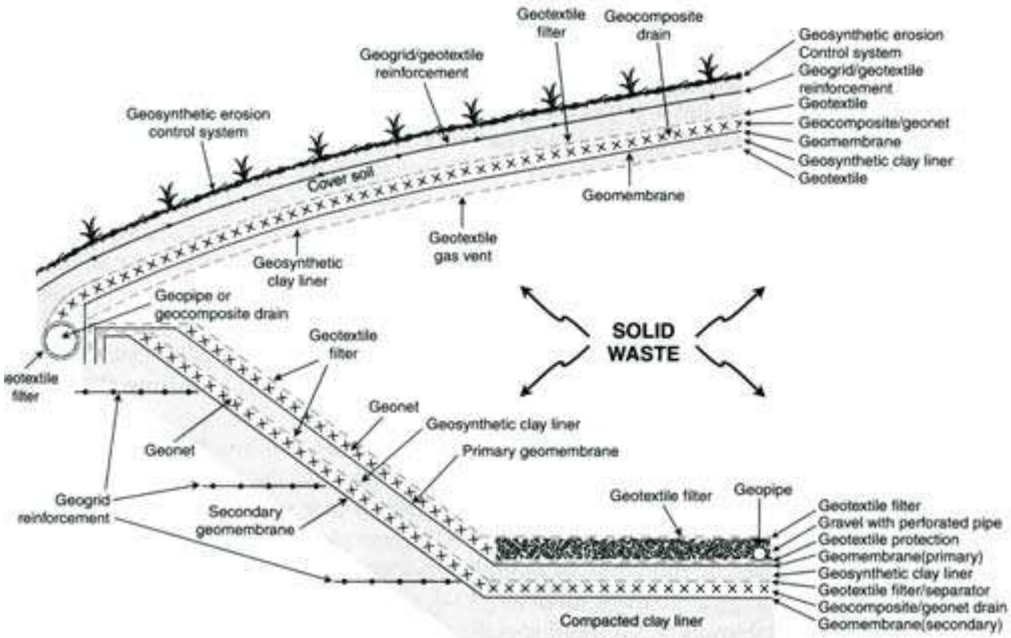


Fig. 1 – Solid Waste Containment System (Cover and Liner) with High Geosynthetic Utilization; Koerner (2005)

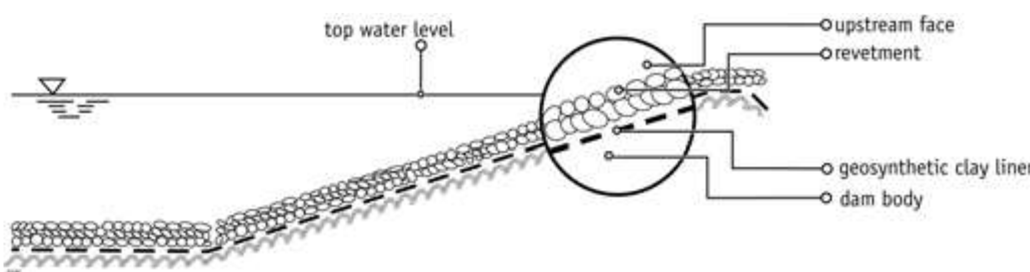


Fig. 2 – Canal Liner System with a Geosynthetic Clay Liner as the Hydraulic Sealing System

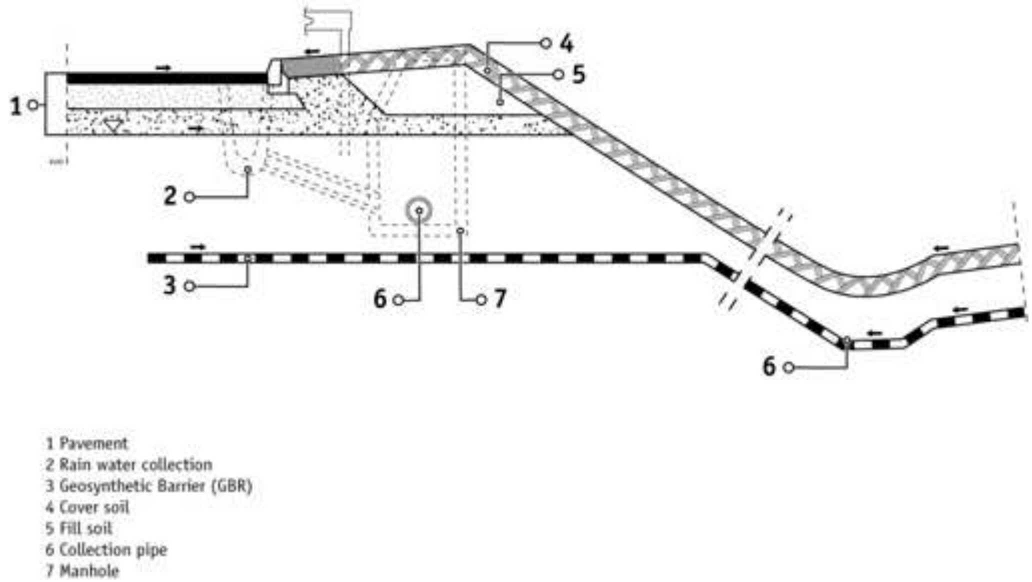


Fig. 3 – Environmental Protection Under a Road by Using a Geosynthetic Clay Liner as Groundwater Protection

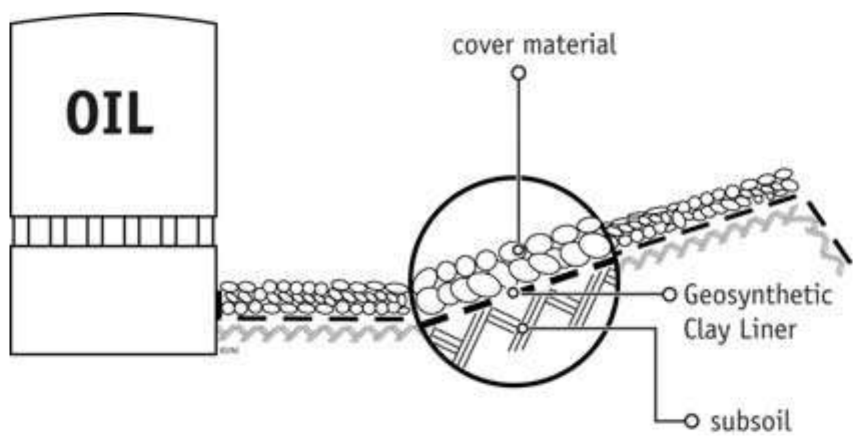


Fig. 4 – Secondary Containment System Using a Geosynthetic Clay Liner

Fig. 5 – Examples of Exposed Mine Waste and Canal Ash (Wikipedia)

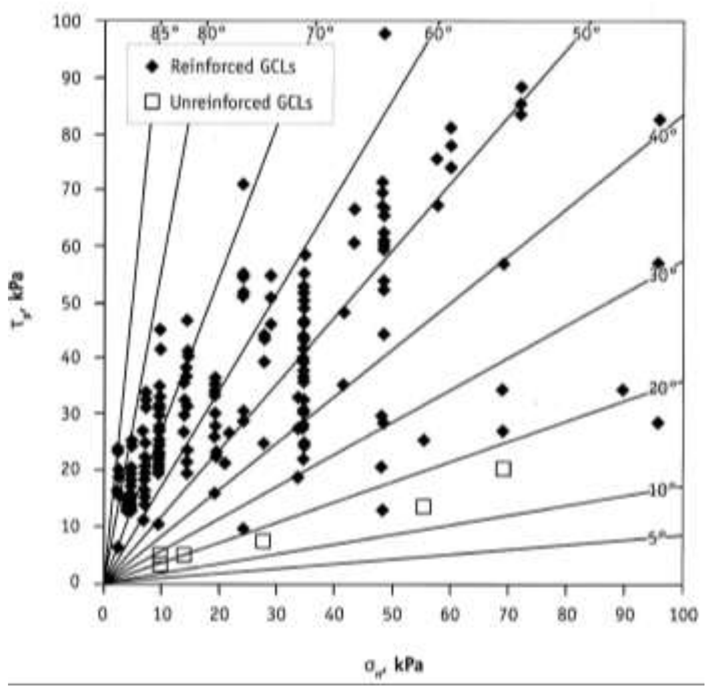
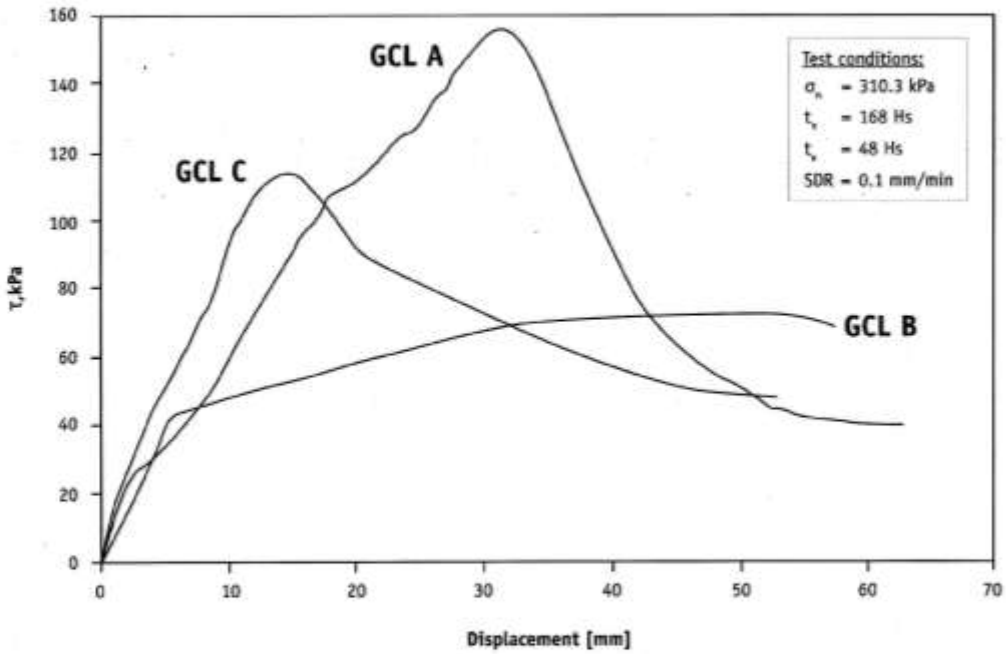
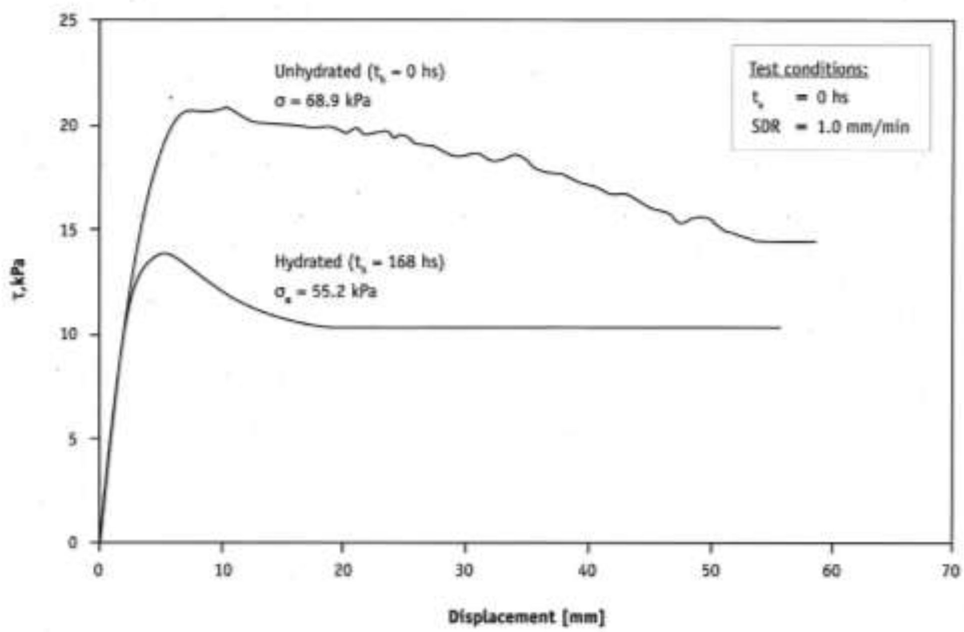


Fig. 6 – Peak Shear Strength Results for Reinforced and Unreinforced Geosynthetic Clay Liners; Zornberg, et al. (2005)



(a) Reinforced GCLs; "A" (needle punched), "B" (stitch bonded), and "C" (thermally locked)



(b) Unreinforced GCL "F"

Fig. 7 – Shear Stress Versus Displacement Curves for Different Reinforced and Unreinforced GCLs; Zornberg, et al. (2005)

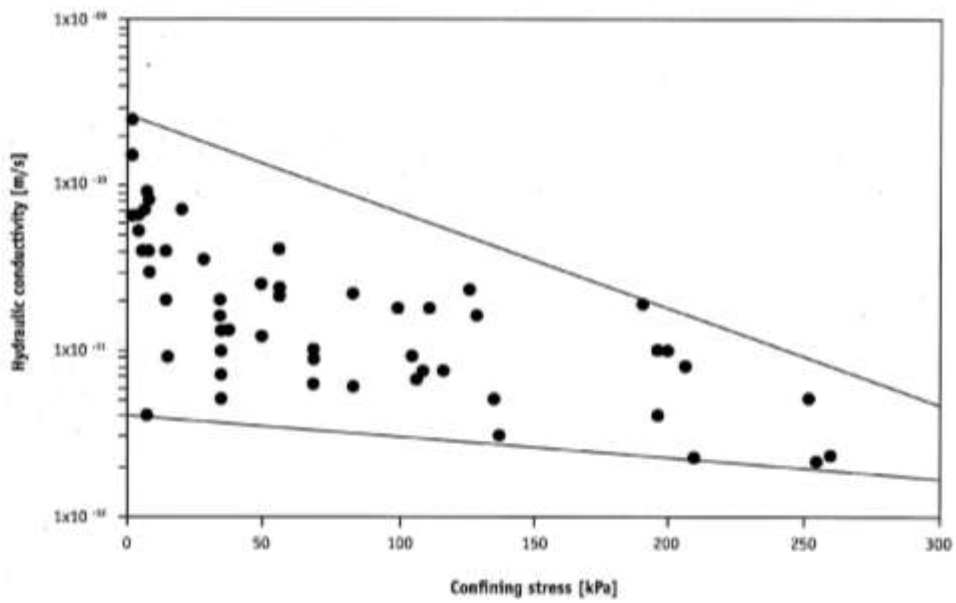


Fig. 8 – Variation of Hydraulic Conductivity Versus Confining Stress; Bouazza (2002)

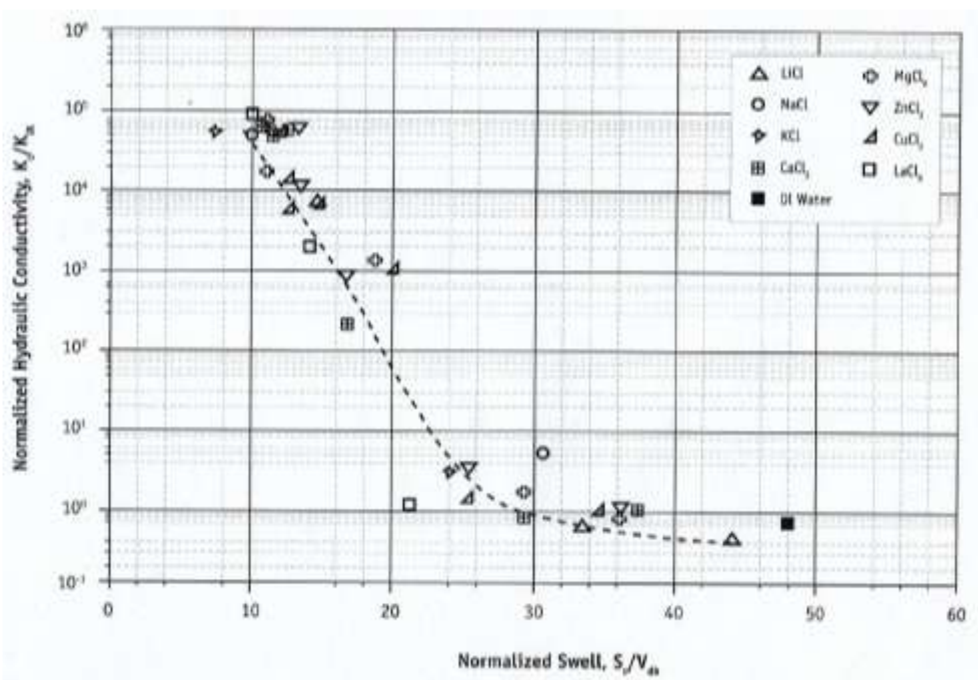


Fig. 9 – Correlation between Normalized Bentonite Free Swell and Hydraulic Conductivity; adapted from Jo, et al. (2001)

(a) Multiple rotational failure (500,000 m^3)

(b) Translational failure (1,000,000 m^3)

Fig. 10 – Two Large Stability Landfill Failures; Koerner and Soong (2000)

(a) Leachate collection slide

(b) Cover soil slide

Fig. 11 – Two Veneer Stability Slides at Landfills; Koerner and Soong (2005)