SUMMARY: Geosynthetic Clay Liners (GCL) are mainly used in landfill caps and closures. In these applications the capping system is exposed to low confining stresses, differential settlement, possible temperature effects and to shear stress on slopes. Installed GCLs must not only withstand the mentioned stresses, but also withstand the installation procedure without any harm. These important design factors as well as the durability aspect are topic in this publication.

INTRODUCTION
A Geosynthetic Clay Liner (GCL) is according to ASTM D 4439 a manufactured hydraulic barrier consisting of clay bonded to a layer or layers of geosynthetic materials. A GCL is also known as a bentonite liner, bentonite mat, or according to the latest published ISO 10318 standard a Clay Geosynthetic Barrier (GBR-C). A recently published document from the Geosynthetic Research Institute, Folsom, Philadelphia (2005) GRI-GCL3 “Standard Specification for Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)” divides the GCLs into two groups, the unreinforced and reinforced GCLs. One type of reinforcing GCLs is needle-punching. Hereby a set quantity of high swelling sodium bentonite is confined between two geotextiles and the geotextiles are then needle-punched together through the intermediate bentonite layer (Fig. 1), securing the bentonite in place and reinforcing the otherwise weak layer of clay (when hydrated). The carrier layer is either a woven or a combination woven/nonwoven geotextile which allows for good anchorage of fibres.

The main purpose of a geosynthetic clay liner (GCL) is to reduce/limit the flow of liquid through the GCL or barrier system. GCLs are mostly used to replace a compacted clay liner (CCL) or soil barrier. High swelling sodium bentonite typically acts as the primary sealing element. In landfill applications, typically municipal solid waste landfills, GCLs are also used in combination...
with a geomembrane and replace the CCL in the landfill base and/or caps. For the purposes of this paper, a geomembrane is considered to have a thickness of \( \geq 1 \) mm (40 mils). Thinner membranes are termed more accurately as a plastic sheeting, foil, film or tarp.

**LANDFILL CAPS AND CLOSURES**

Geosynthetic clay liners (GCLs) are used either as a sole hydraulic barrier or as part of a composite lining system in combination with a geomembrane (Figure 2). The function is to inhibit the flow of precipitation into the landfill as well as to prevent the escape of any gasses into the environment. In this application, the permeation rate of water through the GCL is influenced by the water head acting on the GCL and the presence or absence of an overlying geomembrane. Typically the water head is limited to the thickness of the drainage collection system (in general less than 30 cm for sand/gravel, resp. 1 cm for geosynthetic drainage systems). Therefore a functioning geosynthetic drainage system will allow less permeation through a liner system due to the lower hydraulic gradient on the liner system, compared to thicker mineral drainage systems. The calculation of the hydraulic conductivity of a GCL is typically based on laboratory tests based on a flux rate according to ASTM D5887, DIN 18130, or any other adequate test method. They should in any case simulate on-site conditions (i.e. confining stress, hydraulic gradient, etc.).

![Figure 2: Idealized solid waste cap with various geosynthetic components](image)

In a cap or cover application, the GCL performance subsequent to differential settlement is another important design criterion. According to LaGatta (1997), a mineral barrier or compacted clay liner normally cannot withstand strains greater than 3 %, whereas a reinforced GCL can withstand strains as great as 15 %. Needlepunched GCLs with nonwovens as both a cover and
carrier layer have been tested at up to 30 % surface elongation and were still able to maintain the original low permittivity (Uni Hannover, 1993).

While in many cases the stresses are low (the typical confining stress is in the range of 10 kN/m² and 50 kN/m²), the shear strength of cap components must also be considered an important design issue. Heerten et al. (1995) and von Maubeuge et al. (1998) have shown that needlepunched GCLs have a correlation between internal shear stress and the GCL peel bonding strength under defined conditions. The stability of the GCL is influenced by the slope angle $\beta$, the normal load gradients, and the interface friction value $\varphi$, 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 location dependent and are less of a concern with a thickness of cover material over the GCL greater than 0.75 m. Larger cover layers benefit the sealing performance of the GCL. In landfill cap and cover applications where the GCL is installed in a composite lining system, e.g. under a geomembrane the gas permeability of the GCL is not a critical issue. However, in a stand-alone application, the performance of a GCL as a single liner should be investigated, due to the fact that desiccation of the bentonite under a water content of approx. 65% (see figure 6) might cause an increase of the gas permeation through the GCL.

DESIGN IN LANDFILL CAPS
GCLs must be properly designed in a manner consistent with anticipated field hydraulic and mechanical forces. This practice suggests the types of analysis and testing required to achieve acceptable levels of field performance. Minimum design factors of safety are recommended but it should be recognized that the designer may need to adjust the level of performance to reflect the criticality of the application.

THE BENTONITE COMPONENT
Looking at the bentonite specific standards, especially the ones quoted in ASTM D5889 "Standard Practice for Quality Control of GCLs", ASTM D6495 "Standard Guide for Acceptance Testing Requirements for GCLs", and GRI-GCL3 from the Geosynthetic Research Institute it is obvious that only two test methods are frequently being requested as a quality control measurement. These are ASTM D5890 "Standard Test Method for Swell Index of Clay Mineral Component of GCLs" and ASTM D5891 "Standard Test Method for Fluid Loss of Clay Component of GCLs". While not critical for other applications of bentonite, the bentonite in a GCL must act as a hydraulic barrier. It is the high swelling properties that provide sodium bentonite’s unique sealing qualities. As the clay hydrates and swells, the path for water to flow though becomes complex as the clay platelets intersperse. The most important test to evaluate the sealing qualities of bentonite in a GCL is a permeability or flux test. This test is ASTM D5887 "Standard Test Method for Measurement of Index Flux Through Saturated Geosynthetic Clay Liner Specimens Using a Flexible Wall Permeameter". The test method ASTM D5887 is a bentonite related test method but is mainly used on the finished GCL and not the bentonite property. Additionally the manufacturing process and the use of additives such as polymers and glues can affect the hydraulic conductivity of the bentonite. It is therefore not considered as a test method to determine the bentonite quality as a quick and simple test procedure. However it is recommended to test the bentonite on its own if glues and additives are used. In cases where the GCLs have a membrane, film or coating attached to the geotextile component or where the bentonite is attached solely to such a component a reported hydraulic conductivity of less than $5 \times 10^{-12}$ m/s does not say much about the bentonite quality due to the fact that the influencing factor of the hydraulic conductivity is the film, coating or membrane. In cases like these it is recommended to request the same amount of testing being done on the bentonite on its own because the dominant sealing factor in a GCL is the bentonite and not the film, coating or membrane. This fact was recognised by the geosynthetics experts in CEN and ISO who defined the GCL, resp. GBR-C as: "a factory-assembled structure of geosynthetic materials in the form..."
of a sheet which acts as a barrier. The barrier function is essentially fulfilled by clay. It is used in contact with soil and/or other materials in geotechnical and civil engineering applications" (ISO 10318 definition of clay geosynthetic barrier (GBR-C)). Bentonite is the key component for a GCL. The function is to maintain a low hydraulic conductivity in the hydrated state. It is therefore understandable that the bentonite component undergoes a stringent quality control process before the bentonite is used for the production of the GCL. The following test procedures describe the state of the art bentonite testing used for GCLs. It must be understood that these tests are not stand-alone tests and in the GCL industry the result of one single test does not allow an interpretation of the bentonite. However, taking all results together into account, they allow a determination of an expected performance of the bentonite.

Sodium bentonite is commonly distinguished by it’s ability to swell several times it’s natural volume - when exposed to water. The test method used for quantifying the swelling property for use in GCLs is ASTM D5890 - Standard Test Method for Swell Index of Clay Mineral Component of Geosynthetic Clay Liners. This index test is useful for establishing the relative quality of a clay for use in a GCL. The current industry standard is 24 ml. For most environmental applications, sodium bentonite is also evaluated for use based upon it’s ability to create a seal. This test is ASTM D5891 - Standard Test Method for Fluid Loss of Clay Component of Geosynthetic Clay Liners. Many consider this index test to be a quick qualitative test, suggesting the bentonite’s ability to work effectively in a GCL. The current industry standard is < 18 ml and Fig 3 shows a relatively good correlation to the hydraulic conductivity.

\[
y = 1E-13e^{0.3433x}
\]

\[R^2 = 0.5042\]

Figure 3: Correlation of Fluid Loss (ASTM D5891) to hydraulic Conductivity according to ASTM 5887 (von Maubeuge (2004))

The Methylene Blue methodology describes how the absorption of a methylene blue solution is determined and gives a cation absorption value. The current ASTM standards C837 and D2330 are not considered to be suitable for the GCL industry. The German VDG P 96 Bestimmung des Methylenblau Wertes (Determination of the Methylene Blue Value) and the Dutch CUR Methyleenblauw-waare (Methylene Blue Values) method are mostly used and standard practice. This method is occasionally used by GCL manufacturers to determine the absorption capacity and the percentage of montmorillonite.

With an X-Ray Diffraction (XRD) the identification of mineral species and the quantitative estimation of their relative portions is possible but an exact quantification usually requires several complementary analyses. This method is occasionally used by GCL manufacturers to
determine the montmorillonite content in the bentonite but the presence of non-swelling illite partially accounts for a discrepancy in results (higher montmorillonite content). This method is not applicable for GCL specifications, especially because there are no standardized test methods available and results, resp. interpretation can vary from testing person to testing person. However the method is applicable to fingerprint and identify mineral species within the bentonite.

Landis et al. (2004) published a new method in 2004 with which it seems to be possible to fingerprint bentonites better than with the above described methods. The authors believe the combined utility of $^{13}$C/$^{12}$C and $^{18}$O/$^{16}$O isotope geochemistry is a promising tool for fingerprinting bentonite by means of an isotopic signature and should be developed as a standard QC tool.

An important value for a GCL is the mass per unit area of the bentonite. In earlier days the value was set at 4,900 g/m² but it was not specified at which moisture content. This caused a bit of confusion in the market because several manufacturers add water to the bentonite during the manufacturing process. In comparing GCL products with similar mass per unit areas, GCLs with higher moisture content will have a lower amount of bentonite compared to 0 % moisture content. For this reason ASTM D5993 “Standard Test Method for Measuring Mass per Unit of GCLs” was created and it describes that the mass per unit area of the bentonite is to be reported at a dry moisture content (at 0 % moisture). Therefore the reported values determined after this method are all comparable with each other.

GCL manufacturers are ideally looking for one simple test which allows an interpretation, whether the supplied bentonite meets their bentonite criteria and acts as a long-term sealing barrier. Up to date the author is not aware of such single test. The current practice is to use several tests for bentonite identification but is currently limited to as few as two tests (Swell Index and Fluid Loss, e.g. according to ASTM D5889 "Standard Practice for Quality Control of GCLs"). From the authors’ experience a high swellable sodium bentonite which meets the five criteria in Table 1 will pass the maximum hydraulic conductivity of $< 5 \times 10^{-11}$ m/s (according to ASTM D5887), even though it can be admitted that single tests do not necessarily show a good correlation to the hydraulic conductivity:

Table 1. Bentonite requirements for a sodium bentonite (hydraulic conductivity of $< 5 \times 10^{-11}$ m/s). (von Maubeuge 2002)

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Standard</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mass per unit area</td>
<td>ASTM D5993</td>
<td>$&gt; 3,500$ g/m² (@ 10 % moisture content)</td>
</tr>
<tr>
<td>Swell index</td>
<td>ASTM D5890</td>
<td>24 ml</td>
</tr>
<tr>
<td>Fluid Loss</td>
<td>ASTM D5891</td>
<td>$&lt; 18$ ml</td>
</tr>
<tr>
<td>Enslin Neff</td>
<td>DIN 18132</td>
<td>$&gt; 550%$</td>
</tr>
<tr>
<td>Methylene Blue content</td>
<td>CUR 33</td>
<td>$&gt; 300$ mg/g</td>
</tr>
</tbody>
</table>

In cases in which the hydraulic conductivity value of $5 \times 10^{-11}$ m/s was not met, at least one or more of the requirements in Table 1 were not achieved. However in single tests it was possible that a bentonite met the required hydraulic conductivity of $< 5 \cdot 10^{-11}$ m/s (according to ASTM D5887) but did not meet the swell index or the Enslin Neff value. This fact reinforces even more the need to specify more than just two bentonite test methods, since the hydraulic conductivity is the most important requirement, a long running test (usually $> 14$ days) is recommended to be tested once every week according to ASTM D5889 "Standard Practice for Manufacturing Quality Control of GCLs". Von Maubeuge et al. published a new possible test method in 2004 to determine the hydraulic conductivity performance as a quality control test, which allows the determination of the bentonite performance in a much shorter time period. However, it has not yet been discussed in any standardisation group.
THE GEOTEXTILE COMPONENTS

Daniel (2000) mentioned that another key to achieving consistent hydraulic integrity over the long-term is to prevent loss of bentonite and to avoid penetrations or fracturing of the GCL. Estornell et al. (1992) have recognized bentonite migration into an underlying geonet was not observed when a heavier (356 g/m²) nonwoven geotextile was used as a filter layer between the GCL and the geocomposite.

Examining the geotextile mass per unit area for one GCL, it can be seen that the mass per unit area for the underlying carrier geotextile component of the GCL was much heavier during the early days of GCL development - in the range of 300 to 800 g/m² (Heerten, 2000). In all cases, a scrim (slit film woven) reinforcement was incorporated in the carrier layer of this product. This concept (use of the slit film woven) evolved from turbulence tests to simulate high hydraulic loading that indicated a scrim reinforced nonwoven prevented bentonite loss better than thin nonwovens by themselves. It is for this same reason that one manufacturer generally recommends the slit-film woven or scrim reinforced nonwoven geotextile be installed down-gradient.

Gilbert et al. (1997) have also witnessed bentonite extrusion through thinner nonwovens and select wovens and state as follows:

"... for GCLs with bentonite encased between geotextiles, the bentonite passes through the geotextiles into adjacent interfaces and affects the interface strength. Bentonite extrusion is normally associated with woven geotextiles although it has been observed for thin (i.e. mass per unit area less than 220 g/m²) nonwoven geotextiles as well... Not only did bentonite extrude through the woven geotextile, but a smooth geomembrane that was adjacent to the woven geotextiles was also smeared with bentonite after hydration."

Generalizing, there are two probable causes for all bentonite extrusion. One is the bentonite extrusion through thin geotextile components due to the simple swelling pressure of the bentonite. In this case, the extrusion could cause surface lubrication and reduce the interface friction angle to adjacent surfaces such as a geomembrane and even soils as evidenced by the EPA Cincinnati shear test plots (Koerner 1996). This form of bentonite extrusion is typically limited to very small amounts of bentonite and takes place during the first few months of hydration. As it is only a viscous “film" that is created, an impact on the hydraulic conductivity is not to be expected.

The second category of bentonite extrusion is thought to occur due to higher hydraulic gradients. In these situations, the extrusion will only occur when the underlying layer is highly porous soil, coarse sand or gravel. Extrusion is also possible in cases where the underlying component is a drainage layer such as geotextile or geocomposite drainage net. Careful selection of subgrade soils and geotextiles is therefore recommended. Gradient driven bentonite extrusion would tend to have more direct consequences as it could lead to bentonite thinning or even an increase to the hydraulic conductivity.

Thicker nonwovens or a scrim (slit film woven) reinforced carrier layers can prevent bentonite extrusion in both cases described, while sandy gravel, sand or clay as a subgrade can be used when installing a GCL over soil subgrades.

Currently used geotextile components of standard GCL products are in the range of 220 g/m² for the nonwoven components and 110 g/m² for the woven components. These mass per unit areas could be considered the lowest tolerable levels for composite liner applications requiring shear strength of the interfaces and for all moderate to high gradient applications.
While many consider GCLs to be a “commodity” product based upon their economics, the steps that are taken to engineer a GCL into a project would suggest otherwise. When using a GCL, the designer should be aware of the influences the environment may have on the GCL as well as the technical requirements of the GCL product, including the geotextile components. For example, in an application where the GCL is installed in combination with a geomembrane on a slope steeper than 3h:1v, interface and internal shear strengths are relevant. However, this same application would not suggest precautions be taken to address a high hydraulic gradient. Conversely, in applications where the GCL will act as a sole hydraulic barrier component, the bentonite encapsulation and choice of geotextiles is of much greater importance.

THE GEOSYNTHETIC CLAY LINER

The characterisation of the single components are an important tool to define the type of GCL needed for the application and should be seriously considered in specifications. Not only does it help to describe the GCL type and the performance it should be designed for, it is also a valuable tool for the contractor, designer or owner to compare GCL products which each other, based on the same requirements and not needing to revert to the manufacturer requesting more information on the GCL type. A clear specification which the designer, owner and/or operator should follow will increase the performance of the GCL and not risk poorer performance.

HYDRAULIC PROPERTIES

The test method ASTM D5887 is typically used to determine the flux rate through a GCL. It therefore takes into account the entire GCL product. However the use of additives such as polymers and glues can affect the hydraulic conductivity of the bentonite, but their long-term performance is not necessarily longterm. In cases where the GCLs have a membrane, film or coating attached to the geotextile component or where the bentonite is attached solely to such a component a reported hydraulic conductivity of less than $5 \times 10^{-12} \text{ m/s}$ does not say much about the bentonite quality due to the fact that the influencing factor of the hydraulic conductivity is the film, coating or membrane. In both of these cases it is recommended to request the same amount of testing being done solely on the bentonite.

For ASTM D5887 test or DIN 18130 the flux rate $q$, of fluid movement through a saturated GCL is measured in a flexible permeameter using the test method. The flux rate $q$, of fluid movement through a saturated GCL is measured in a flexible permeameter using the test method D5887 test. The flux rate is measured under a given normal load. The thickness $t$, of the saturated bentonite, which is needed for the calculation from flux to hydraulic conductivity, depends on the normal load and is measured in this test. Knowing the flux rate and bentonite thickness, the hydraulic conductivity of the bentonite portion of the GCL can be evaluated by using the calculation methods in ASTM D5887, e.g.: Constant Head or Falling Head and Constant Rate of Flow Test.

Increasing confining stress on a porous material, such as highly compressible hydrated sodium bentonite, decreases the hydraulic conductivity as shown in figure 4. With increasing confining stress several effects of high swellable sodium bentonites can be prevented, such as shrinkage of the bentonite creating cracks which might increase the hydraulic conductivity. These effects can occur due to dehydration of the bentonite or due to e.g. high concentrated calcium solutions which are extremely aggressive to sodium bentonite. Higher confining stresses however overcome this effect and the hydraulic conductivity is hardly affected. However these effects take place if the landfill cover soil thickness is over 1.50 m and root penetration is totally prevented. In e.g. landfill base seals GCLs subjected to high confining stresses are far less vulnerable to increases in hydraulic conductivity than GCLs in low confining stress applications (less than 20 kPa). However once a GCL in a landfill cover is overlayed by a geomembrane of thickness > 1.0 mm, the desiccation issue of a GCL and the root penetration is very much reduced to not being a design issue.
The flow rate of liquids that pass through a GCL or GCL/Geomembrane composite must be quantified to allow evaluation of the effectiveness of a GCL barrier system. The leakage rate, \( Q \), through a hydrated GCL can be calculated from Darcy’s Law as follows:

\[
Q = k \left( \frac{(h + t_{GCL})}{t_{GCL}} \right) A
\]

where \( k \) is the permeability of the bentonite, \( t_{GCL} \) is the effective thickness of the GCL, \( h \) is the height of the liquid above the GCL, and \( A \) is area.

The leakage through a GCL/Geomembrane (GM) composite, based on a defect in the geomembrane, is calculated by the following equations (Giroud, 1997):

\[
Q = 0.976 C_{qo} \left[ 1 + 0.1 \left( \frac{h}{t_{GCL}} \right)^{0.92} \right] d^{0.2} h^{0.9} k_{GCL}^{0.74}
\]

where \( d \) = hole diameter [m]; \( h \) = liquid head on top of the geomembrane [m]; \( k_{GCL} \) = hydraulic conductivity of the GCL [m/s]; \( t_{GCL} \) = thickness of the bentonite layer in the GCL [m]; and \( C_{qo} \) = contact quality factor for a circular hole. This results in the rate of leakage \( Q \) [m^3/s]. The contact quality factor \( C_{qo} \) is dimensionless, where \( C_{qo \, good} \) = value of \( C_{qo} \) in the case of good contact conditions; and \( C_{qo \, poor} \) = value of \( C_{qo} \) in the case of poor contact conditions. “Good” and “poor” contact conditions refer to the contact between the geomembrane and the GCL and are defined by Giroud (1997). In the case of a GCL he assumed the contact conditions between a GCL and a geomembrane to be good (\( C_{qo \, good} = 0.21 \)). Giroud further investigates the effect of the defect shape as well as the wetted area of the GCL. Figure 5 gives an example of the effects of the geomembrane defects and the leachate head.
Figure 5: Radius of the area of the GCL hydrated by leachate migrating through a defect in the geomembrane overlying the GCL as a function of leachate head and of geomembrane defect diameter (Giroud 1997)

IONIC EXCHANGE
If there is a supply of free available calcium or magnesium from the surrounding soil to the sodium bentonite of a GCL an ionic exchange within the bentonite can occur over a time period of approx. 2 years (Egloffstein et al. 2002). However several field studies simulating landfill covers were performed in the last years and have shown that an ionic exchange of bentonite does not critically influence the performance of a GCL if the landfill is properly designed (Bluemel et al. 2002 and Heerten 2000). This includes a minimum cover soil thickness of at least 0.75 m and a reduction of root penetration to the sealing system. In cases of landfill covers for municipal waste typically a HDPE geomembrane overlays the GCL and therefore performs as a root barrier, desiccation and ionic exchange protection and therefore increases the cover sealing system performance. In cases of a GCL stand-alone barrier system it is therefore recommended to closely investigate any effects the cover soil over GCLs has on the hydraulic conductivity or ensure an increased cover soil thickness.

GAS PERMEABILITY
Landfill cell gas emissions and odour control are now factors to consider when designing a landfill cap or gaining a permit. In the past years gas recovery and utilization technology has become an important issue for landfill caps. In a composite lining system (geomembrane
Figure 6: Variation of nitrogen gas permittivity with volumetric water content for confined hydration (Vangpaisal et al., 2001)

overlaying a GCL) there is less concern of a large amount of gas permeation. In the case of a GCL stand alone barrier, GCLs offer many advantages over compacted clay in capping situations - such as greater strain tolerance, less potential for desiccation and cracking, and improved control of rainfall infiltration (Eberle et al., 2003). Vangpaisal et al. (2001) have extensively studied the performance of GCLs with nitrogen gas (a non-reactive gas), further improving predictability of performance (Figures 6). Note that the normal in-situ moisture content of a GCL in a capping barrier system will be in excess of 80% by weight, (Eberle & von Maubeuge, 1998).

SHEAR STRENGTH

Internal shear strength. GCLs are commonly divided into reinforced and unreinforced structures (Geosynthetic Research Institute, 2005). In practical use an unreinforced GCL is not at all suitable for slope applications due to the low midplane friction angle of bentonite (in hydrated condition peak approx. 9°, residual about 4° to 5°). Therefore a minimum reinforcement is required to ensure short- and long-term shear strength. Table 1 in the Geosynthetic Research Institute Standard GRI-GCL3 recommends a minimum peel strength of 360 N/m for reinforced GCLs according to ASTM D6768. The peel strength of a GCL allows, according to Heerten et al (1995), Berald (1997), Mackey et al. (1999), and von Maubeuge et al. (2002), a correlation to shear test if compared correctly, due to the fact that these tests were carried out under similar conditions and peel tests were carried prior to the shear test. A generic comparison of shear data assuming that the GCL has a minimum peel strength and not having the actual peel value of the GCL would obviously not lead to a correlation (Zornberg et al. (2005)). It is logical that a higher amount of needlepunching, especially if the fibres are additionally thermally locked to the bottom geotextile component, as one manufacturer produces his product, would result in a higher peak shear strength of the GCL due to the contribution of the needled fibres. Needled fibres that penetrate through the thickness of a reinforced GCL contribute to shear strength as the geotextile surfaces move apart differentially. The amount of shear strength added by the fibres at low strains may also be influenced by the anchorage or tensioning of the fibres to the geotextiles. The contribution of the needled reinforcement fibers is very significant across the full range of normal loads. Additionally the testing conditions can highly influence the shear strength results (von Maubeuge et al., 2002).
Designers should typically specify a minimum peel strength to ensure adequate and consistent needling. The peel strength of a GCL is evaluated using ASTM D6496. But for shear testing it is also recommended to specify all conditions for the test.

**Creep.** Both the polymers associated with the needled fibres and the bentonite may creep, i.e., deform, when subjected to long-term loadings. Published reports by Koerner et al. (1998) and Siebken et al. (1995) have shown that the majority of internal shear displacements occur during the first 100 hours of loading. Essentially, if field conditions do not change and the GCL installation survives the initial week of loading, the GCL is stable. This is certainly the observation that has come out of the GCL slope tests performed over the past years in Cincinnati by EPA, Daniel et al. (1996). At this site, reinforced GCLs have remained stable with little or no ongoing deformation on slopes as steep as 2H:1V which implies a minimum static slope stability factor of 1.5 when applied to 3H:1V slopes. The latest study by Mueller (2005) states that a GCL with defined resin properties and an anti-oxidant package of the fibres of a needle-punched GCL was stable in longterm creep tests and would be approved for a duration of > 400 years.

In April of 1994, NAUE constructed several large-scale creep shear devices to evaluate the behavior of a needle-punched woven/nonwoven GCLs, under simulated in-situ conditions of low normal load applications as seen in a landfill cap application. The testing program included the measurement of differential creep movement. The GCL being tested was mounted to a 1 m x 1 m test apparatus in the following cross section (top to bottom):

- 25 kN/m² steel plates
- 30 cm of 2 - 8 mm (0.32 - 0.32 in) crushed gravel contained in a steel box
- Bentofix GCL with carrier geotextile anchored to the bottom steel plate

Upon the initial loading of the specimen with the confining stress, a small amount of movement was measured in the system, associated with the settling of gravel in the steel box. While movement occurred, it was not creep or elongation in the needle-punched GCL. Regardless, it has been included in the final displacement figures to ensure the most conservative picture. With an initial value of 2.5 mm of movement, the final value shortly before dismantling the box was a total differential movement of 2.9 mm during the over 40,000 hour period (includes the shifting) and is shown in figure 7. The GCL is according to this study not prone to creep distortion under conditions replicating low-load/low stress applications described herein. While the creep resistance of a material is directly related to the needle-punched fibers themselves, similar testing on other GCLs from the same style reflects the same conclusion, that the GCLs are resistant to the long-term affects of constant strain under low normal loads.
Interface shear. For design it is obvious that one must consider, next to the internal shear strength of a GCL, the interfaces between its outer surfaces and adjacent materials, as well as all other interfaces of other adjacent liner components and their internal shear strengths. Assuming that the internal shear strength of the GCL might be the critical interface can cause a fatal slope slippage as has been published by Koerner et al. (1996). Underestimating the possible bentonite lubrication of the interface between an overlaying friction geomembrane and underlying woven side of a GCL by extruding bentonite can cause a reduction of the interface shear value and depending on the slope angle cause a slide due to a too low friction angle as has happened. For this reason it is not recommended to install a GCL with the woven side against the friction geomembrane on slopes with a slope angle less than 18° (without considering safety factors). In general it is recommended to use GCLs with nonwoven on both sides in slope applications, however due to latest findings the GRI-GCL3 standard “Standard Specification for Test Methods, Required Properties, and Testing Frequencies of Geosynthetic Clay Liners (GCLs)” recommends not to use GCLs with just a nonwoven on both sides (Note 2 of table 1 in GRI-GCL3: For both cap and carrier fabrics for nonwoven reinforced GCLs; one, or the other, must contain a scrim component of mass \( \geq 100 \text{ g/m}^2 \) for dimensional stability.)

Peak versus residual strength. It is often debated whether to design using the peak or the residual strength of the GCL. One must consider the type of GCL, the overall system behavior, and the specific conditions under which the GCL will be used. Design must consider the internal strength of the GCL product, the interfaces between its outer surfaces and adjacent materials, the interfaces of other adjacent liner components considering both short-term and long-term conditions, and the internal strengths of other liner components. The application will also influence the selection of design strength values. Typically 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 subjecting the system to a shear stress, sliding failure will occur when the applied shear stress exceeds the peak strength of the weakest material or interface. Once failure is initiated, displacement will continue along that slip plane (Marr et al., 2004). Design using the lowest peak strength assumes that the peak strength of the interfaces and materials do not change with time. Data from shear tests are obtained over a few hours. It is well known that polymeric materials in tension might fail in creep at lower stresses than their short-term tensile strength. Aging can also occur. 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. This approach has also been suggested.
by Marr et al. (2003). In the absence of long-term direct shear tests to determine the creep limit of the GCL polymers (i.e., the stress level above which the fibers will creep to failure within the design life of the project), a creep reduction factor of 3 has been recommended by Marr et al. (2004) based on creep reduction factors normally used for PP fibres in tension (Koerner, 1998). This value is considered somewhat conservative due to anticipated composite soil-fibre reinforcement interaction that is not present in conventional creep tests used to obtain the reduction factor of 3.

**SLOPE STABILITY EVALUATION**

The most conservative method of evaluating the stability of a GCL in the veneer type systems common to landfill liners and final cover systems is the infinite slope model. The pseudo-static factor of safety for the cover may be assessed using the following general equations for the stability of an infinite slope:

\[
FS = \tan\phi \left[ (I - u)/(\gamma \cdot z) \right] - k_s \cdot \tan \beta \cdot \tan \phi
\]

where FS - factor of safety, \( k_s \) - seismic coefficient, \( \gamma \) - unit weight of slope material(s), \( u \) - excess water or gas pressure on the slip surface, \( \beta \) - angle of internal friction of the assumed failure interface or surface. The internal and interface strengths are evaluated using e.g. ASTM D6243. The above equation yields the factor of safety for both cohesionless interfaces (cohesion = 0). Using the infinite slope equation, the static side-slope shear stresses generated on and within a GCL barrier can be predicted.

**INTERNAL BENTONITE EROSION**

The increasing use of geosynthetic clay liners as part of composite liner systems for landfills and as the sole liner for ponds and lagoons raises questions regarding the potential for internal erosion. 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 depth of fluid above the liner. The presence of large hydraulic gradients combined with clay soils that may be inadequately filtered creates the potential for internal erosion (i.e. the migration of fine particles out of the clay liner) and possible hydraulic failure of the liner. Relatively little research has addressed the subgrade requirements for GCLs and installation specifications generally report the same conditions for all GCLs. However, considering the many different products available, there is some question as to whether it is appropriate to apply a common specification to all products. A computer-controlled, constant flow rate, fixed ring hydraulic conductivity apparatus was utilized with modifications as described by Rowe et al. (2002) to investigate the GCL performance. The tests were performed in duplicate for five GCLs and three subgrades. The five different GCLs tested included 2 woven carriers, 1 nonwoven carrier and 2 scrim-reinforced carriers. The subgrades were sand, 6 mm gravel, and a geonet. The sand subgrade proved to be a very adequate subgrade when tested. GCLs placed directly over the 6 mm gravel experienced internal erosion and increases in hydraulic conductivity by at least one order of magnitude for GCLs with the woven, resp. the nonwoven side down. A scrim-reinforced nonwoven side down over the gravel did not suffer any detrimental effects at the tested hydraulic heads. GCLs placed directly over the geonet experienced internal erosion (bentonite loss) and increases in hydraulic conductivity by at least one order of magnitude. No differences have been noticed between powder or granular bentonite. The only product that did not exhibit any sign of internal erosion when tested over the geonet was the GCL with a scrim-reinforced nonwoven as carrier geotextile. However it must be noted that these results are only representative for carrier geotextiles that have wovens of 110 g/m², nonwovens of 220 g/m² and scrim reinforced nonwovens (scrim 100 g/m² and nonwoven 250 g/m²). Geosynthetics with a lower mass per unit area may create higher bentonite internal erosion as one would expect with coarser subgrades. Geosynthetics with a higher mass per unit area are more likely to be a bit
more stable against erosion as one would also expect with finer subgrades. Additionally the effect of the hydraulic gradient needs to be considered in a design as well.

**LONGTERM**

Geosynthetic Clay Liners (GCLs) are commonly reinforced with polypropylene (PP) fibres to improve their resistance to shear loads. Since the shear resistance is often used in the design of slopes, the long-term properties of the reinforcement can be the determining factor affecting the service lifetime of the slope. Therefore, it is important to understand the long-term behaviour of reinforced GCLs. Two possible failure mechanisms for the reinforcing fibres are creep rupture and oxidation. For this reason NAUE started a research program in 1999 to investigate these issues. One research part was carried out by the BAM and the second by TRI.

When the DIBt (Deutsches Institut für Bautechnik [German institute for construction engineering]) granted its approval for the use of Geosynthetic Clay Liners (GCLs) in class 1 landfills (1997/1998), it also ordered the manufacturers of these approved GCLs to submit proof of the continuous, internal, longterm shear strength over the five-year approval period. Over the 5 year period NAUE carried out several tests to proof the long-term performance for Bentofix GCLs. The tests additionally conducted the evaluation of the GCL continuous long-term shear strength in a joint effort with BAM (Bundesanstalt für Materialforschung und -prüfung [federal agency for materials research and testing]). This joint research project (which was open to participation of other GCL manufacturers) developed a test procedure (figure 8) for GCLs that is based on existing experiment models from BAM approval procedures for structured geomembranes. Experiments were conducted with a 50 kPa superimposed load at an incline of 2.5(H):1(V) in 80 °C hot water. The GCLs must withstand a test period of 365 days without shearing to ensure a minimum functional lifetime of 200 years. On 20 June 2005 the BAM submitted the appraisal about the long-term shear strength of the tested GCL from NAUE. This appraisal (MUELLER 2005) certifies that the GCL, based on the widely promulgated Arrhenius extrapolation, has exceeded the minimum functional lifetime rating and is now estimated to last for 400 years at 15 °C ambient temperature.

![Figure 8: Schematic view of a test equipment used to determine long-term shear strength.](image-url)
The results from the BAM experiments on the > 400 year functional lifetime of the tested GCL were independently complimented by a series of oven aging experiments designed to measure the oxidation rates of the fibres when exposed to air in a simulated landfill environment. The second research project was carried out at TRI (Thomas, 2004), a testing and research institute in Austin/Texas. This study involved using Arrhenius extrapolation methods to determine the oxidation rate of fibres when exposed to air at temperatures of 100°C, 90°C, 80°C, 70°C, and 60°C. The material tested was a needle-punched, nonwoven polypropylene Secutex® geotextile made from fibres used in the Bentofix® GCL. The specimens for oven exposure were approximately 5 cm x 15 cm. Over 500 specimens were cut and then were shuffled to try to minimize the effect of thickness variations in the material. Test specimens were exposed in forced-air ovens at temperatures of 100°C, 90°C, 80°C, and 70°C. The specimens were hung under racks with unfolded steel paper clips. The specimens were spread out evenly around the oven and they were not touching each other. Three different ovens were used to perform the four sets of exposures. The unexposed and exposed test specimens were evaluated by a strip tensile test. The test grips were 2.5 cm x 10 cm, the strain rate was 10 cm/min, and the initial gauge length was 7.5 cm. All tests were taken to failure and the maximum load and the strain at the maximum load were recorded. The aim of the study was to propose a generally accepted requirement that the tested geotextile should maintain over 50% of its strength when exposed to the tested condition, which was also the basis for the extrapolation. When these data were used to extrapolate THOMAS (2005), it was found that if the textiles were continuously exposed to fresh air in a high air-flow environment, the predicted service lifetime would be about 17.8 years at 15°C. However, since these were extreme and not realistic conditions the results were compared to oxidation rates found in 8% oxygen, which is believed to be the maximum concentration one would find in a buried application. In this case, the oxidation rate was 21 times slower than the rate found in air (21% oxygen). This means that the 17.8 year service lifetime would actually be 373 years in a buried application; agreeing very well with the results from the BAM. The results for these two independent studies clearly show the long term performance capabilities of the tested GCLs. However, one can be less conservative and assume that a remaining longterm tensile strength of 25% or even 10% would be sufficient. In this case the lifetime prediction for the tested GCLs would increase to 560 years, resp. 672 years. The full study will be published shortly.

Figure 9: Lifetime prediction for Bentofix® GCL fibres when buried at 15°C
QUALITY CONTROLL AND INSTALLATION

It is standard practice to evaluate a design (and this includes the installation phase) assuming that the worst case conditions will exist. This is especially important with GCLs, as many performance parameters for certain GCLs are not clearly specified or ill defined. For geosynthetics as well as GCLs, the worst case conditions typically occur during installation and subsequent soil cover placement. In the past years several documents have been published which give the user a support for specification and installation. However, one must keep in mind that these are typically the bottom line of a compromise and not necessarily reflect the true minimum requirements which should be specified. It is therefore up to the designer, owner, installer or others involved to ensure, with their recommendations, the minimum requirements which are really needed for the GCL and its installation and try to avoid following the lowest price only.

- Manufacturing Quality Control: ASTM D5889 provides guidelines for the manufacturer quality control testing of GCLs to be performed by manufacturers before the GCL is shipped to project site. The standard provides types and frequency of tests required.
- Acceptance Testing: ASTM D6495 provides guidelines for the acceptance testing and verification of GCLs to be performed by manufacturers before the GCL is shipped to project site. The Standard provides types and frequency of tests required.
- Storage and Handling: ASTM D5888 provides guidelines for the proper storage and handling of GCLs received at the job site by the end user.
- Installation Guidelines: ASTM D6102 provides directions for the installation of GCLs under field conditions typically present in environmental lining applications.
- Obtaining Samples: ASTM D6072 covers procedures for sampling GCLs for the purpose of laboratory testing.

The following are some very generic installation guidelines which should be taken into consideration during the GCL installation:

- Each delivered individual GCL roll must be marked and numbered clearly with at least one label giving details about the specific GCL brand, type and roll number.
- The subsoil on which the GCL is stored and will be installed should be smooth, well compacted and free of sharp and protruding edges and soil depressions according to the given specifications.
- Vehicular traffic directly on the unrolled geosynthetic clay liner is prohibited unless a minimum sufficient soil coverage is installed. Exceptions can be made during the installation of geosynthetic components over the GCL if low-pressure ATVs are used. It must be ensured by the installer that no damage occurs to the GCL. Driving with these vehicles directly over pre-hydrated (in-field or during manufacturing) is strictly prohibited.
- GCLs should be overlapped (according to the roof tile principle) with a minimum of 30 cm for longitudinal overlaps and 50 cm for cross overlaps. Overlaps need to be bentonite augmented to ensure sealing of overlaps. (Note: Geosynthetic clay liner (GCL) panel separation, when placed beneath an exposed geomembrane, has occurred in at least five instances. Separation distances between adjacent panel edges are from 0 to 300 mm, except in one extreme case where they were significantly larger. The as-manufactured moisture content of the GCLs was 24% to 44% for four of the five cases. The nonwoven geotextiles used in the manufacture of these GCLs were of the needle-punched type, but none had any type of woven "scrim" reinforcement, i.e., they were not composite geotextiles. The possible cause: GCL shrinkage; perhaps accompanied by cyclic wetting and drying in unconfined condition. The recommendations: a) Do not leave GM/GCL composite liners exposed to the atmosphere. Soil backfilling with at least 300 mm (12 in.) of soil in a timely manner (which is very much site-specific) should be adequate in this regard, b) Do not use GCLs with needle-punched nonwoven geotextiles
on both sides unless one of the geotextiles is scrim reinforced, c) Increase the GCL overlap to compensate for the potential panel separation (for details: Geosynthetic Research Institute 2005a).) The authors of this paper additionally recommend specifying a bentonite moisture content of the GCL under 12%.

- GCLs should be covered with a minimum of 30 cm soil coverage. Soil type is GCL specific. In general a well graded soil is suitable (> 64 cm), however the finer the grains the better against any damage during installation. In case of frequent traffic over the GCL a cover soil thickness of > 0.60 m is recommended. Soil coverage of the GCL is prohibited in case of pre-hydrated geosynthetic clay liners caused by precipitation.
- Penetrations (e.g. pipes) must be sealed according to manufacturers recommendations.
- Repairs of possible damages should be carried out according to the GCL manufacturers recommendations, however with a minimum overlap from the damaged area of 0.50 m.

GCL VERSUS CCL PERFORMANCE

It is apparent from field data (Heerten, 2000; Bluemel 2003) that GCLs show advantageous behavior as compared with a CCL despite select frailties and limitations of both. As the use of composite liners in landfill caps and base seals has evolved, GCLs have been used in combination with an overlying geomembrane component in lieu of compacted clay based systems. The synergistic effect of the composite lining system is best achieved and ensured by the installation of two co-functional yet independent liners. The other major advantage of a composite lining system is that two sealing layers are installed independent of the other. One can therefore be confident that in a worst case scenario, it is virtually impossible to have two manufacturing or installation related defects lying on top of each other.

GCLs are designed for applications where a compacted clay liner (CCL) or a mineral sealing barrier is considered suitable. They are used to replace the relatively thick and hard and expensive to install compacted clay layers due to their numerous advantages when contrasted to a CCL as provided in Table 2. GCLs can be substituted for the CCL component without sacrificing the integrity of the design or loss of performance. While not discussed in this paper, GCLs in general show an equivalent and typically better performance at a lower cost than a CCL.

Table 2 - Advantages and Disadvantages of Clay Liners (according Daniel 1995)

<table>
<thead>
<tr>
<th>Material</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compacted Clay Liner</td>
<td>1. Long history of (successful?) use.</td>
<td>1. Susceptible to desiccation cracking.</td>
</tr>
<tr>
<td></td>
<td>2. Regulatory approval is virtually assured.</td>
<td>2. Must be protected from freezing.</td>
</tr>
<tr>
<td></td>
<td>3. Thickness ensures that layer will not be breached by puncture.</td>
<td>3. Very low resistance to cracking from differential settlement.</td>
</tr>
<tr>
<td></td>
<td>4. Thickness provides physical separation between waste and surface environment.</td>
<td>4. Difficult to compact soil above compressible waste.</td>
</tr>
<tr>
<td></td>
<td>5. Cost can be low if material is locally available.</td>
<td>5. Suitable quality borrow source not always locally available.</td>
</tr>
<tr>
<td></td>
<td>7. Familiar material to geologists and geotechnical engineers.</td>
<td>7. Slow construction.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9. Sensitive to construction.</td>
</tr>
<tr>
<td></td>
<td>2. Very low hydraulic conductivity to water if properly installed.</td>
<td>2. Potential concerns over interface shear strengths.</td>
</tr>
</tbody>
</table>
4. Excellent freeze-thaw resistance.
5. Can withstand large differential settlement.
7. Manufactured highly quality controlled consistency.
8. Low volume consumed by liner.
9. Easy to repair.
10. Not as sensitive to installation.

3. GCLs can be punctured during or after installation.
4. Dry bentonite (e.g., at time of installation) is not impermeable to gas.

In addition, it is important to mention the differences in re-hydration of a GCL compared to CCLs. If it is assumed that the GCL or the CCL has higher hydraulic conductivity values in a stiff consistency (IC = 1) and re-achieves a lower permeability once the consistency is soft (IC = 0.75), it is possible to calculate the amount of water the barrier needs to regain a low permeability (Table 9 indicates that a compacted clay liner has a moisture content of 11.5% with a stiff consistency (IC = 1.0) and a moisture content of 20.4% in a more or less very soft consistency (IC = 0). Therefore the moisture content difference between these two conditions is 8.9%. Assuming that the mass of the CCL is 975 kg/m³, Table 9 shows that the CCL needs 22 l/m² of water to be able to move from a stiff consistency to a soft consistency to allow re-hydration of a desiccated CCL and achieve (assuming a self-healing capability of the CCL) lower hydraulic conductivity through a sealing of cracks which occur during desiccation. It is clear that this can only occur with a high normal stress combined with the water if self-sealing properties of the clay components are missing.

Table 3 – Required amount of water (W_{req}) needed to allow rehydration and self-sealing of a 0.5 m thick CCL and a GCL with 5,000 g/m² bentonite (w = moisture content) (Reuter, 1999)

<table>
<thead>
<tr>
<th>Compacted clay liner (CCL)</th>
<th>Geosynthetic clay liner (GCL)</th>
</tr>
</thead>
<tbody>
<tr>
<td>w_{field desiccated} = 11.5%</td>
<td>w_{field desiccated} = 45.9%</td>
</tr>
<tr>
<td>w_{optimum} = 20.4%</td>
<td>w_{maximum} = 162.4%</td>
</tr>
<tr>
<td>w_{\Delta} = w_{field desiccated} – w_{optimum} = 8.9%</td>
<td>w_{\Delta} = w_{field desiccated} – w_{maximum} = 116.5%</td>
</tr>
</tbody>
</table>

w_{req} = (IC_{stiff} – IC_{soft}) • w_{\Delta}

w_{req} = 0.25 • 8.9% = 2.23%
V_{req} = thickness_{clay} • \gamma_{clay} • w_{req}/100
V_{req} = 0.5 m • 1,950 kg/m³ • 0.0223
= 21 kg/m² = 21 l/m²

On the other hand, the GCL has a water content of 45.9% (at IC = 1.0) in excavations carried out from 1996 to 1999 and achieves a maximum moisture content of 162.4%. Therefore the moisture content difference is 116.5% resulting in a moisture content of 29.13% (0.25 x 116.5) if the GCL changes from IC = 1.0 to 0.75 (from stiff to soft consistency). Assuming a mass of 5 kg/m² of bentonite in a GCL, it is clear that the bentonite of the GCL would only require 1.5 l/m² of water to change the consistency from stiff to smooth and to self-seal potential desiccation cracks which could have occurred under the normal load of 1 m cover soil.

The results from Table 3 show that a CCL once desiccated with cracking does not have the ability to absorb the necessary amount of water in a few days and distribute homogeneously over the entire area to achieve the soft consistency required to lower hydraulic conductivity. Due to the normally occurring water run-off in the drainage collection layer and the small amount of water permeating through the cover soil layer, it is even questionable if the CCL will ever be able to absorb the necessary amount of water to be able to self-seal.
If a GCL is to replace a compacted clay liner, there is no doubt that the bentonite of the GCL would perform for this application. It is the designer's responsibility to ensure that the surrounding conditions are suitable for the GCL, such as smooth subgrade surface, suitable cover soil material (the finer the better) and thickness (the thicker the better). But it is also the responsibility of the manufacturer to forgo a GCL project if, in their best judgement, the application design is not appropriate or the GCL will not allow for a successful installation.

**SUMMARY**

Geosynthetic Clay Liners (GCLs) are often used in landfill cap design as a stand alone liner or in combination with a geomembrane. They replace thick compacted clay liners due to many advantages, such as
- easy installation,
- low hydraulic conductivity,
- self healing capabilities,
- capable of withstanding differential settlement,
- shear performance,
- and cost effectiveness.

However, the designer should consider site specific conditions (soil material, slope angle, interface friction) and specify relevant characteristics to ensure a long-term and safe design. Current standard GCL properties could be on the lower limit, so that increasing some GCL properties (on the geotextile, bentonite and GCL) are in some cases recommended. Additionally the installation recommendations need to be looked at in detail in any landfill cap project. The Geosynthetic Research Institute, Folsom, has published a White paper and a GRI-GCL3 standard and has highlighted the necessity to consider several important topics, especially overlap separation under certain conditions of pre-hydrated GCLs. However, this topic can be solved by means of immediate soil coverage or an increasing overlap for these types of products.

Comparing a GCL landfill cap design with a compacted clay liner solution the authors of this paper come to the conclusion that a GCL, properly designed will out perform in short-term and long-term other landfill cap solutions with a mineral material performance wise and probably in most cases also cost wise.

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