"PERMEABILITY, PUNCTURE, AND SHEAR STRENGTH TESTING OF COMPOSITE LINER SYSTEMS UNDER HIGH NORMAL LOADS"

Geosynthetics, including geomembranes and GCLs, are seeing increased usage in mining applications, such as tailings impoundments and heap leach pads. These applications can involve extreme conditions, such as aggressive chemical environments and enormous compressive loads. Heap leach heights can reach 180 meters (600 feet), corresponding to normal loads of up to 3450 kPa (500 psi) on the leach pad liner system. Such loads exceed the limits of most standard laboratory testing devices, making it difficult to properly evaluate the behavior of geosynthetic materials in these applications. The attached paper, presented at the Tailings and Mine Waste '09 conference, presents the following laboratory evaluations of geomembrane and GCL performance under high normal loads:

- **High-Load Puncture Testing.** Heap leach pad fills are typically constructed by placing a layer of angular, large-diameter drainage stone (overliner) over the leach pad liner. When under load, geomembranes are vulnerable to damage from these large stones. A high-load shop press was fabricated to test the puncture resistance of different geomembranes, both with and without underlying GCLs, in contact with drainage stone under normal loads ranging from 1290 kPa (188 psi) to 5172 kPa (750 psi). In addition to normal load, other variables examined included geomembrane type and thickness, and GCL type.

- **High-Load Permeability Testing.** Copper heap leaching requires the use of low-pH sulfuric acid solutions. Past research and experience have shown that GCL hydraulic performance can be negatively impacted by low pH or high ionic strength solutions. However, research has also shown that the effects of aggressive solutions on a GCL's hydraulic performance lessen at higher normal loads. A high-load rigid wall permeameter was constructed to test the long-term compatibility/permeability of GCL samples in contact with an acidic copper pregnant leach solution. The GCL samples were subjected to a hydraulic head of 1.3 meters (4.4 feet), and normal loads ranging from 34.5 to 3447 kPa (5 to 500 psi), to simulate the typical operational stages of a copper heap leach facility.

- **High-Load Interface Shear Testing.** Direct shear testing of geosynthetics is typically limited to loads less than 690 kPa (100 psi), which falls far short of the loads expected in a tall heap leach pad. To address this data gap, a series of interface shear tests was performed between a textured geomembrane and a needlepunch-reinforced GCL, at normal loads ranging from 517 to 2758 kPa (75 to 400 psi).

The results of high-load puncture testing showed that geomembranes alone are expected to experience more puncture damage (puncturing and/or strain deformation past yield) than a geomembrane with an underlying GCL or a geomembrane covered by a protective geotextile cushion. The protection offered by a GCL is comparable to that of a 540 g/m^2 (16 oz/yd^2) nonwoven cushioning geotextile placed above the geomembrane. The GCL's benefit, in terms of reducing biaxial strains in the geomembrane, appears to be greater at higher normal stresses.

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Although protective measures (either GCL below or cushioning geotextile above the geomembrane) show reduced typical strain values, these measures may not be enough to protect the geomembrane from puncture in all cases, especially where sharp crushed rock particles happen to be aligned with a sharp point or edge in direct contact with the geomembrane.

Increased stress relaxation (due to slower loading rates and higher in-situ temperatures) in the field suggests that laboratory testing may provide conservative results in terms of geomembrane strain behavior.

High-load permeability testing of a GCL in contact with an acidic, high-ionic strength copper PLS shows a decrease in hydraulic conductivity with increasing confining stress. Additionally, a GCL sample with a 1-cm^2 puncture showed the ability to self-heal under high normal loads and maintain a low permeability ($<10^{-7}$ cm/sec), even while in contact with the PLS.

High-load direct shear testing of geomembrane/GCL liner components showed peak secant friction angles of 19 to 20 degrees and large displacement secant friction angles of 6 to 7 degrees at 2758 kPa (400 psi) normal stress. To minimize the potential for internal failure/rupture of the GCL (and residual conditions representative of unreinforced hydrated bentonite), a GCL with high peel strength is recommended for heap leach liner applications where extremely high normal stresses are expected.

A feasibility study of two lining alternatives for an example copper heap leach pad estimated that a geomembrane/GCL composite liner would be expected to allow only one-tenth as much leakage as a geomembrane/compacted soil composite. The resulting improvement in PLS capture is expected to result in a significant increase in copper recovery and increased revenue (potentially millions of dollars per year).

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PERMEABILITY, PUNCTURE, AND SHEAR STRENGTH TESTING OF COMPOSITE LINER SYSTEMS UNDER HIGH NORMAL LOADS

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INTRODUCTION

Geosynthetics, including geomembranes and geosynthetic clay liners (GCLs), are seeing increased usage in mining applications, such as tailings impoundments and heap leach pads. These applications can involve extreme conditions such as aggressive chemical environments and enormous compressive loads. Heap leach heights can reach 180 meters (600 feet), corresponding to normal loads of up to 3450 kPa (500 psi) on the leach pad liner system. Such loads exceed the limits of most standard laboratory testing devices, making it difficult to properly evaluate the behavior of geosynthetic materials in these applications. To address this limitation, CETCO and Tetra Tech performed the following laboratory evaluations of geomembrane and GCL performance under high normal loads:

Puncture

Heap leach pad fills are typically constructed by placing a layer of angular, large-diameter drainage rock (overliner) over the leach pad liner. Under load, geomembranes are vulnerable to damage from these large stones. There is evidence that liners at various facilities, including hazardous waste landfills, municipal landfills, surface impoundments, and mining heap leach facilities can experience leakage, and thus multiple liners, backup systems and monitoring systems are routinely included. Considering the recent price increases in precious and commodity metals, there may now be a stronger incentive to limit geomembrane punctures and pregnant leach solution (PLS) loss through liner systems in mining applications. Higher metals prices are also driving mining companies to design facilities that may be closer to populated or environmentally sensitive areas. As a result, there is a trend toward improving the containment capabilities of lining systems installed in mines. A high-load shop press was fabricated to test the puncture resistance of different geomembranes, both with and without underlying GCLs, in contact with drainage rock under normal loads ranging from 1290 kPa (188 psi) to 5172 kPa (750 psi). These loads correspond to approximate ore heights of 45 to 183 meters (150 to 600 feet), with a factor of safety of 1.5. In addition to normal load, other variables examined included geomembrane type and thickness, GCL type, loading rate, and loading duration.

Permeability

Copper heap leaching requires the use of low-pH sulfuric acid solutions. Past research and experience have shown that GCL hydraulic performance can be negatively impacted by low pH or high ionic strength solutions (Jo et al., 2001). However, research has also shown that the effects of aggressive solutions on a GCL's hydraulic performance lessen at higher normal loads (Daniel, 2000 and Thiel and Criley, 2005). A high-load, rigid wall permeameter was constructed to test the long-term compatibility/permeability of GCL samples in contact with an acidic copper pregnant leach solution (PLS). The GCL samples were subjected to a hydraulic head of 1.4 meters (4.6 feet), and normal loads ranging from 34.5 to 3447 kPa (5 to 500 psi), to simulate the typical operational stages of a copper heap leach facility.

Shear Strength

Direct shear testing of geosynthetics is typically limited to loads less than 690 kPa (100 psi), representing 36 m (120 ft) of ore, which falls short of the maximum loads expected in many heap leach pads. To address this data gap, a series of interface shear tests was performed between a needlepunch-reinforced GCL and different textured geomembranes, at normal loads ranging from 517 to 2758 kPa (75 to 400 psi).

LABORATORY TESTING DETAILS

Puncture Testing

A description of the high-load puncture testing system is provided in Athanassopoulos et al. (2008). A high-load shop press capable of exerting loads up to 667 kN (150,000 lbs) was fabricated for this study. This maximum load, distributed over a 0.093-m^2 (1-ft^2) sample area, corresponds to possible pressures as high as 7184 kPa (1042 psi). A maximum test pressure of 5172 kPa (750 psi) was selected for this study, as it corresponds to 183 m (600 feet) of ore, with a factor of safety of 1.5.

Table 1 provides a summary of the different types of liner components (geomembranes, GCLs, and geotextiles) used in this study. The liner components were placed inside a custom-fabricated HDPE test cylinder with an inside diameter of 344 mm (13.54 in) and a wall thickness of 72 mm (2.85 in). A layer of standard commercial mortar sand was placed in the cylinder first and tamped in place to serve as the bedding layer. Where specified, a GCL was then placed over the sand layer, followed by the geomembrane. To be representative of field conditions, the GCL samples were slightly moistened with tap water to increase the bentonite moisture content from 35% (typical as-manufactured value for Bentomat) to a test moisture content of approximately 50%. As shown in USEPA (1996), even GCLs placed on dry subgrade soils see an increase in moisture content within several weeks of installation. Moistening the GCL provides conservative puncture testing conditions, since hydrated bentonite would be expected to provide less cushioning. A 230-mm (9-in) thick layer of 50-mm (2-in) minus crushed stone was then placed over the geomembrane. One test incorporated a heavy (540 g/m^2, or 16 oz/yd^2) nonwoven geotextile between the geomembrane and the drainage aggregate, to evaluate the geotextile's role as a protective cushion. The final layer was a thick steel loading plate, intended to uniformly distribute the applied load across the sample area. The loading plate was equipped with two dial gauges (left and right) accurate to 0.025 mm (0.001 inch) to monitor vertical displacement over time.

After each liner cross-section was stacked within the test column, the entire assembly was placed on the high-load shop press, and loaded gradually in increments of approximately 200 kPa (30 psi) every 15 to 20 minutes, until the specified test pressure was reached. The gradual increase in applied load was intended to allow some bedding down of the stone and to partially simulate the increase in load that would occur on site. Selected tests were repeated at a faster loading rate of 479 kPa (69 psi) every 10 minutes, to assess the possible effect of loading rate on geomembrane straining.

Once the full load was applied, load and dial gage readings were taken every 20 minutes for the first ten hours, and every 12 hours thereafter.

To be consistent with common past practice in the mining industry, a puncture test duration of 48 hours was used for all tests, with the exception of one, which was loaded for two weeks. Dial gauge readings over time showed that vertical displacements stabilized within 0.05 to 0.1 mm after approximately 48 hrs of loading (Figure 1), indicating that the selected puncture test duration is appropriate.

After loading, the geomembrane samples were removed and visually examined over a light table for signs of puncturing. In addition to punctures, other signs of distress, including yielding in the geomembrane (defined as permanent indentations in the geomembrane which do not recover after removal of the pressure) were also recorded.

A method similar to the one recommended by the UK Environment Agency (2006) was used to quantify the extent of geomembrane deformation for comparison purposes. The five areas of greatest deformation (taking into account both

Table 1. Materials Tested

Material Designation	Description	Manufacturer
<u>Geomembranes</u>		
60-mil LLDPE-S	1.5-mm smooth LLDPE	Polyflex
80-mil LLDPE-S	2.0-mm smooth LLDPE	Polyflex
60-mil HDPE-S	1.5-mm smooth LLDPE	Polyflex
60-mil LLDPE-T1	1.5-mm textured (co-extruded) LLDPE	Polyflex
60-mil LLDPE-T2	1.5-mm textured (embossed) LLDPE	Agru America
<u>Geosynthetic Clay Liners</u>		
Bentomat ST	3.6 kg/m^2 bentonite, needlepunched between woven and nonwoven geotextiles	CETCO
Bentomat STM	2.4 kg/m^2 bentonite, needlepunched between woven and nonwoven geotextiles	CETCO
Bentomat DN	3.6 kg/m^2 bentonite, needlepunched between two nonwoven geotextiles	CETCO
<u>Geotextiles</u>		
GEOTEX 1701	540 g/m^2 nonwoven geotextile	Propex

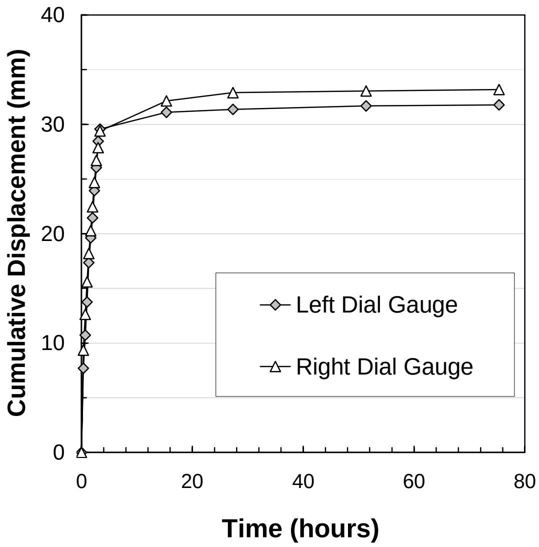

Figure 1. Geomembrane Deformation Readings

depth and steepness of the sides) were identified and selected for more detailed strain measurements. Indentations within 25 mm (1 in) of the sheet edge were not selected, due to possible edge effects. Two perpendicular axes, intersecting at the deepest point, were marked on each indentation (Figure 2). Vertical deformation was measured along the two perpendicular axes using digital calipers and a dial gauge (commonly used for asperity height measurements of geomembrane texturing, per GRI-GM-17). Starting at one edge of the indentation and working along each of the axes, the vertical deformation was measured at 2.5-mm horizontal intervals until the opposite edge of the indentation was reached. The edge of the indentation was defined as a point where two consecutive readings had a vertical height difference less than or equal to 0.05 mm. The measuring procedure was repeated along the second axis, and then for the remaining indentations, until all ten axes on each geomembrane sample were measured.

From these measurements, incremental strains (across each discrete 2.5-mm interval) and average strains (across the entire indentation) along the two axes of each indentation were calculated using the method recommended by the UK Environment Agency, (2006):

$$\varepsilon_{inc} = \frac{\sqrt{x^2 + \Delta y^2} - x}{x} \qquad (1)$$

$$\varepsilon_{average} = \frac{\sum \varepsilon_{inc}}{n} \qquad (2)$$

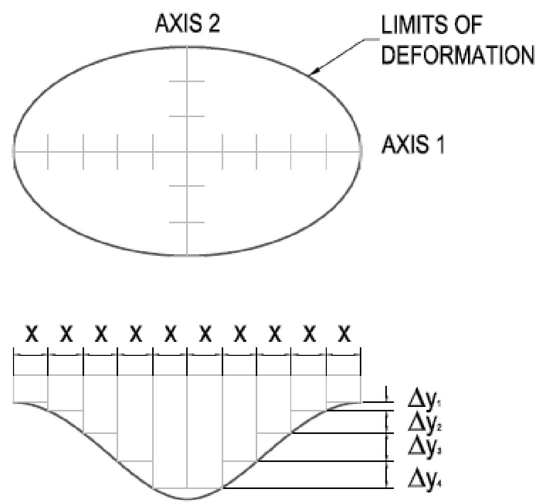

Figure 2. Geomembrane Deformation Measurement Method

Permeability/Compatibility Testing

Copper heap leaching requires the use of low-pH sulfuric acid solutions. To evaluate the long-term compatibility a GCL in contact with an acidic pregnant leach solution (PLS) under high loads, a rigid wall permeameter was constructed for this study. The permeameter was fabricated of stainless steel to withstand both the high pressures and the harsh permeant chemistry. The permeameter was placed on a shop press capable of exerting loads up to 45 kN (10,000 lbs). This load, distributed over a 100-mm diameter circular sample (0.0081-m^2 sample area), corresponds to a maximum possible pressure as high as 5172 kPa (750 psi). Effective stresses ranging from 34.5 to 3166 kPa (5 to 459 psi) were selected for the GCL permeability testing program, corresponding to 1.8 to 183 m (6 to 600 feet) of ore, with a PLS head of 1.4 m (4.6 feet).

Permeability/compatibility tests were performed on an intact GCL sample and a sample of GCL that had been pierced by a large stone during one of the high-load puncture tests (Test No. 4). Using digital calipers, the area of the hole was estimated at approximately 1 cm^2. The punctured GCL sample was tested to evaluate sodium bentonite's potential for self-healing under heap leach liner conditions.

The acidic copper PLS was collected from an active copper leach pad in the southwestern U.S. The results of a chemical analysis on the copper PLS are summarized in Table 2.

Table 2. Copper PLS Chemistry

pH	1.8
Electrical Conductivity	37000 μmhos/cm
Aluminum	5044 ppm
Calcium	262 ppm
Copper	802 ppm
Iron	1788 ppm
Magnesium	498 ppm
Zinc	198 ppm

The GCL permeability/compatibility tests were performed in accordance with a modified version of ASTM D6766, the Standard Test Method for Evaluation of Hydraulic Properties of Geosynthetic Clay Liners Permeated with Potentially Incompatible Liquids. The as-manufactured moisture content of the GCLs tested is approximately 35%, with additional moisture absorption from subgrade soils likely soon after installation. Accordingly, the GCL samples in this study were initially moistened with a small volume of tap water, to attain a starting moisture content of 50%, and then fully hydrated with the copper PLS for 48 hours. After hydrating with PLS, a hydraulic head of 13.8 kPa (2 psi) was applied to drive PLS flow through the GCL. Permeability testing was performed at effective stresses ranging from 34.5 to 3166 kPa (5 to 459 psi), to simulate the range of typical operational stages of a copper heap leach facility. Testing continued until specific termination criteria (steady-state flow and chemical equilibrium) were established between the effluent and influent. Flow and water quality measurements were collected periodically to monitor termination criteria throughout the testing period.

Interface Shear Strength Testing

Considering the potentially high normal loads involved in some mining applications, there have been concerns expressed over the interface shear strength between geosynthetic liner components. Past shear testing of geosynthetics has typically been limited to loads less than 690 kPa (100 psi), which falls short of the loads expected in a tall heap leach pad. To address this data gap, a series of interface shear tests was performed between different textured geomembranes and needlepunch-reinforced GCLs, at normal stresses ranging from 517 to 2758 kPa (75 to 400 psi). In order to improve friction between geomembranes and adjacent soils or geosynthetics, geomembranes are often manufactured with surface texturing. The two most common geomembrane texturing processes are co-extruded texturing and embossed texturing. In this study, the shear performance of both types of textured geomembranes were evaluated against Bentomat DN, a high-peel strength, needlepunch-reinforced GCL consisting of 3.6 kg/m^2 of bentonite between two nonwoven geotextiles.

The geomembrane/GCL interface shear testing was performed in accordance with a modified version of ASTM D6243, the Standard Test Method for Determining the Internal and Interface Shear Resistance of Geosynthetic Clay Liner by the Direct Shear Method. Instead of the standard 300-mm by 300-mm (12-in by 12-in) shear box, testing was performed in a smaller 150-mm by 150-mm (6-in by 6-in) box, to allow application of higher normal stresses. Past testing by Olsta and Swan (2001) has demonstrated good correlation between these two shear box sizes.

RESULTS

Puncture Testing

The results of the high-load puncture testing program are summarized in Table 3. An inspection of the post-test geomembrane samples revealed significant yielding (i.e., permanent set deformations), with almost all of the samples subjected to stresses greater than 2586 kPa (375 psi) experiencing over 300 permanent deformations per m^2 (>30 per ft^2). Two of the geomembrane samples tested at the highest normal stress, 5172 kPa (750 psi), were also punctured, with holes ranging from 1.5 to 7.5 mm in diameter. Table 3 includes both “typical” geomembrane strains (an average of the overall strains from the five deepest indentations) and “peak” geomembrane strains (the overall strain associated with the deepest indentation on each geomembrane). For simplicity, incremental strains (local strains between two adjacent points on a single indentation) are not shown. In some of the deeper indentations and punctures, incremental strains in excess of 100% were calculated.

<u>Effect of GCL.</u> The calculated geomembrane strains in Table 3 show that the tests involving a GCL layer beneath the geomembrane (Test Nos. 1, 5, 7, 9, 13, 15) tended to show lower typical strains than geomembranes tested alone under the same conditions. The reduction in geomembrane strain afforded by an underlying GCL is also shown in Figure 3, which presents a plot of typical

geomembrane strains with respect to normal stress for all tests involving 1.5-mm LLDPE geomembranes. Additionally, tests involving 2-mm LLDPE and 1.5-mm HDPE geomembrane samples showed significant improvement (greater than 50% reduction in strain) when a GCL was placed under the geomembrane. However, Table 3 also shows that peak strains and maximum deformation depths were much more variable, and likely depend more on the random orientation of the crushed rock particles in direct contact with the geomembrane than the subgrade beneath the geomembrane. Punctures and deformations due to sharp rock edges or points that happen to be in direct contact with the geomembrane could not be fully mitigated by the GCL (or, as discussed below, by a cushioning geotextile) due to the small contact areas and high stresses involved.

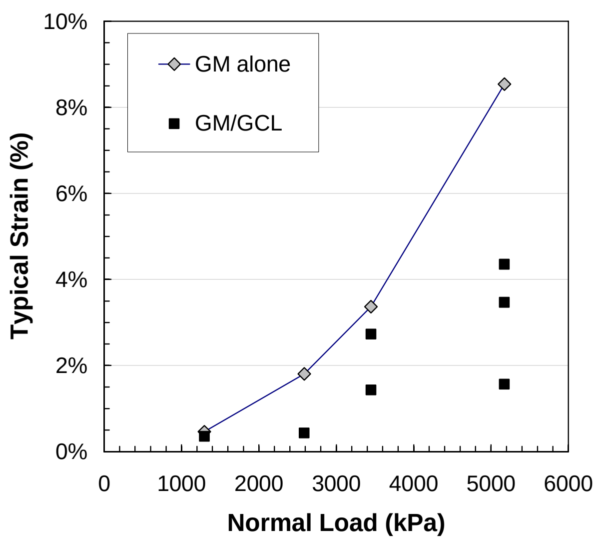

Figure 3. Geomembrane Strain vs. Normal Stress

Effect of GCL Weight. Geomembrane strain measurements show that the GCL bentonite mass (either 2.4 or 3.6 kg/m^2) does appear to impact the extent of geomembrane straining, with the heavier-weight GCL allowing slightly lower strains. To be conservative, the lighter-weight GCL (Bentomat STM, commonly used in mining applications) was used in the remaining tests involving GCLs.

Effect of Geomembrane Type. Table 3 also shows that the type of geomembrane plays a role in puncture performance. The peak and typical indentation depths and strains in the 1.5-mm HDPE geomembranes (Tests No. 15 and 16) were consistently less than those seen in the same thickness LLDPE geomembranes subjected to the same test conditions (Test 9, 10, and 11). This difference is not surprising, considering the different microstructures of HDPE and LLDPE. Although HDPE's semi-crystalline structure gives it greater strength and chemical resistance than LLDPE, this structure also makes HDPE more susceptible to stress cracking, and subject to failure at lower strains than LLDPE (Peggs et al., 2005).

Effect of Geomembrane Thickness. The strain values in Table 3 suggest that geomembrane thickness does not appear to influence the extent of straining. Peak and typical strains measured in 1.5-mm LLDPE and 2.0-mm LLDPE geomembrane samples tested under the same test conditions were almost identical. This finding is consistent with Brachman and Gudina (2008), who observed that geomembrane strain was not significantly affected by geomembrane thickness, possibly due to the small geomembrane stiffness relative to the subgrade.

Effect of Test Duration. All of the puncture tests were run for 48 hours, with the exception of Test No. 4. Test No. 4 involved the same liner cross-section and test conditions as Test No. 3, except the test duration was extended to 2 weeks. A cursory comparison of Test No. 3 and 4 results might conclude that test duration plays a large role in geomembrane strain and puncture performance. However, it is important to note that the Test No. 4 results were skewed by a large (7.5-mm) hole in the geomembrane. Inspection of the post-test sample showed that a sharp 50-mm rock was driven through both the geomembrane and the underlying GCL. The puncture appears to have occurred instantaneously and was not related to the increased test duration. If the deformation associated with this large puncture is not included in the strain calculations, Test No. 4 would have a peak strain of 10% and a typical strain of 3.6%, much closer to the Test No. 3 values. This finding, together with the fact that vertical displacements in all tests stabilized within 48 hrs of loading (see example in Figure 1), suggest that test duration is not as critical a test variable as normal load, rock size, shape, and random orientation of the crushed rock on top of the geomembrane.

Effect of Loading Rate. Test Nos. 10 and 11 involved the same liner cross-section and test conditions, with the exception of loading rate. Test No. 10 was loaded at a faster rate than any other test (478 kPa, or 69 psi increments every 20 minutes), whereas Test No. 11 was

Table 3. Summary Of Geomembrane Puncture Testing Results

	Liner Cross-section	Normal Stress (kPa)	Holes (dia.)	Max. Depth (mm)	Average Depth (mm)	Peak Strain (%)	Typical Strain (%)
1	60-mil LLDPE-S (alone)	5172	2 and 2 mm	5.6	4.0	25.7%	8.5%
2	60-mil LLDPE-S over Bentomat ST	5172	--	4.5	3.2	3.0%	1.6%
3	60-mil LLDPE-S over Bentomat STM	5172	--	4.4	3.8	6.4%	3.5%
4	60-mil LLDPE-S over Bentomat STM [(1)]	5172	1.5 and 7.5 mm	8.6	4.9	12.5%	4.4%
5	60-mil LLDPE-S (alone)	2586	--	4.0	2.3	3.3%	1.8%
6	60-mil LLDPE-S over Bentomat STM	2586	--	2.3	1.4	0.6%	0.4%
7	60-mil LLDPE-S (alone)	1297	--	1.9	0.9	0.7%	0.5%
8	60-mil LLDPE-S over Bentomat STM	1297	--	3.3	2.6	0.5%	0.4%
9	60-mil LLDPE-S (alone)	3448	--	5.0	3.8	6.4%	3.4%
10	60-mil LLDPE-S over Bentomat STM [(2)]	3448	--	4.7	3.5	4.6%	2.7%
11	60-mil LLDPE-S over Bentomat STM	3448	--	3.7	3.1	3.4%	1.4%
12	60-mil LLDPE-S under 540 g/m^2 geotextile	3448	--	4.1	2.2	9.0%	1.8%
13	80-mil LLDPE-S (alone)	3448	--	4.9	3.2	6.2%	3.4%
14	80-mil LLDPE-S over Bentomat STM	3448	--	2.7	2.1	3.4%	1.1%
15	60-mil HDPE-S (alone)	3448	--	4.2	2.9	4.6%	2.6%
16	60-mil HDPE-S over Bentomat STM	3448	--	2.9	2.2	1.8%	1.1%

All tests performed with a mortar sand subgrade and a 50-mm (2-inch) minus crushed rock overliner.
[(1)] Two-week test duration.
[(2)] Load applied at a faster rate (479 kPa every 10 minutes).

loaded at less than half this rate, 192 kPa (27 psi) every 20 minutes, comparable to the remaining tests. Deformation depths and strains were greater in the geomembrane sample that was loaded faster, likely because stress relaxation was minimized. As discussed by Peggs et al. (2005), because of stress relaxation, slower applied strains will result in lower geomembrane stresses. Peggs et al. also showed that stress relaxation will increase as temperature increases. Together, these factors suggest that in a heap leach liner, where loads are applied over months or years, and elevated in-situ temperatures are common, stresses will not likely build to the same extent as in geomembrane samples tested in the laboratory. For this reason, laboratory testing could be considered to provide conservative results in terms of geomembrane strain behavior.

Effect of Geotextile. Test No. 12, which included a heavy nonwoven geotextile over the geomembrane, showed a reduction in typical strains. However, the peak strain in this sample – corresponding to one deep indentation over a small contact area, indicative of a sharp rock driven into the geomembrane – was very high (9%). This shows that, similar to the tests involving GCLs, geomembrane protective measures may have limited benefit against rocks randomly aligned with a sharp edge or point perpendicular to, and in direct contact with, the geomembrane. This finding speaks to the uncertainty involved in geomembrane puncture protection systems in the field; if sharp rock particles happen to be aligned in a certain way, the geomembrane can be punctured even with standard protective measures in place.

This finding further shows that a low-permeability soil or GCL beneath the geomembrane is warranted, not only for the nominal puncture protection offered, but also to limit PLS leakage through the holes that may develop in the geomembrane.

Allowable Strain. None of the geomembranes tested would meet the total strain requirement of 0.25% required by German regulators (Seeger and Muller, 1996). However, this is the most stringent requirement known, intended to not only avoid short-term puncturing, but to also avoid stress cracking of the geomembrane over time. In their critique of the European puncture requirements, Peggs et al. (2005), pointed out that the 0.25% strain criterion was based on durability testing of HDPE pipes in the early 1980s. In these tests, stress was maintained constant (i.e., no stress relaxation) and the pipes were not intimately confined between two confining layers like a geomembrane in a liner system would be. Additionally, the tests did not address newer HDPE formulations with stress crack resistance, nor did they address other geomembrane types, like LLDPE, which are not subject to stress cracking. Due to these factors, Peggs et al. concluded that the European criteria were too restrictive. They proposed the following alternate allowable strains for geomembranes strained slowly between confining layers: 6-8% for smooth LLDPE and 10-12% for smooth HDPE. Almost every test in this study met these criteria, except for two tests at the highest normal stress (Test No. 1 and 4, at 5172 kPa), and surprisingly, the deepest indentation in the LLDPE geomembrane that was tested with a protective geotextile (Test No. 12, at 3448 kPa). This last finding speaks to the role played by variability in overliner rock position/alignment in affecting geomembrane puncture performance.

This variability in rock position, together with the high stresses involved, suggest that random puncturing of the geomembrane can take place in a heap leach liner setting, even if protective measures are in place. However, since heap fills typically operate over shorter periods of time (5 to 10 years) compared to solid waste landfills (more than 30 years), and are commonly built in less environmentally sensitive areas, maintenance of a completely defect-free geomembrane over the long-term may not be a critical design priority. In this case, rather than limiting strains to prevent long-term cracking, perhaps a most realistic strain criterion for geomembranes in heap leach liners is to tolerate elongation of the geomembrane past the yield point, but to prevent short-term puncturing of the geomembrane. This concept has been termed Level III protection (Narejo, 1995).

Overliner Puncture Behavior. During the tests with normal stresses greater than 3447 kPa (500 psi), significant fracturing of the drain rock was observed. Fracturing was so extensive that there was an accumulation of fines on top of the geomembrane, and in many cases these fines had been cemented together by the high stress. The reduction in particle size and introduction of fines on top of the liner are both expected to result in less geomembrane damage; although this finding is non-conservative, it is believed to be representative of conditions in the field. Another implication of the overliner particle size reduction is that it could likely result in a less permeable overliner in the field.

Permeability Testing

Table 4 and Figure 4 present the results of the high-load compatibility/permeability tests performed on both intact and punctured GCL samples. At low effective stress, the permeability of the intact GCL sample in contact with the copper PLS was approximately 1 x 10^{-6} cm/sec, showing the impact of the harsh PLS on the bentonite clay. As effective stress was increased to simulate increasingly higher ore heights on the liner system, the permeability decreased significantly, reaching a value of approximately 5 x 10^{-11} cm/sec at 1440 kPa (200 psi) effective stress. A least-squares linear regression of the results showed the permeability of an intact GCL in contact with this copper PLS can be expressed as:

$$\ln K \left(cm/s\right) = -10.414 - 0.0091\,\sigma'\left(kPa\right) \qquad (3)$$

The punctured GCL sample also showed a high permeability (> 10^{-7} cm/sec) at effective stresses up to 510 kPa (75 psi), evidence of preferential flow through the 1-cm^2 hole at the center of the sample. However, as effective stress increased further, sodium bentonite exuded into the open hole, forming a thin layer (~1 mm, compared to 3 mm in the remaining sample), partially sealing the hole. This self-sealing behavior appears to have brought the overall permeability of the punctured sample down to 5 x 10^{-8} cm/sec at 3165 kPa (459 psi) effective stress. This result demonstrates that even if a sharp rock in the overliner penetrates the geomembrane and GCL, bentonite's ability to swell (even the reduced swell in the presence of an acidic solution) may be able to effectively seal the puncture opening, limiting overall leakage through the liner system. Without the underlying GCL, the same size hole in a geomembrane could allow hundreds of liters per hectare per day of PLS leakage.

Table 4. GCL Permeability Results

Effective Stress (kPa)	Intact GCL (cm/sec)	GCL w/ 1-cm^2 hole (cm/sec)
35	--	6.8E-6
234	2.1E-6	1.7E-6
510	9.8E-7	1.1E-6
821	7.9E-9	1.8E-7
1131	2.1E-9	1.0E-7
1441	4.9E-11	8.4E-8
3165	--	4.9E-8

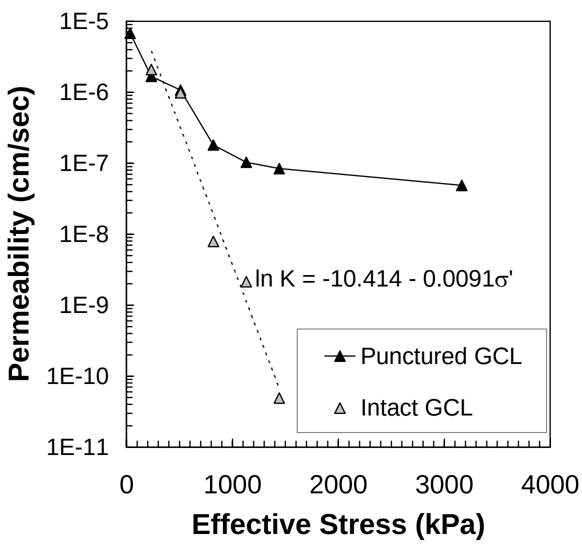

Figure 4. GCL Permeability With Copper PLS

Interface Shear Strength Testing

As shown in Figure 5, interface testing between Bentomat DN and an LLDPE geomembrane with embossed texturing found a peak secant friction angle of 20 degrees and a large-displacement secant friction angle of 7 degrees, for normal loads up to 2758 kPa (400 psi). Testing between Bentomat DN and an LLDPE geomembrane with co-extruded texturing found a peak secant friction angle of 19 degrees and a large-displacement secant friction angle of 6 degrees. These angles are much higher than those expected for unreinforced, hydrated bentonite (less than 4 degrees at these loads), indicating that the GCL's internal reinforcement had not ruptured during testing. Inspection of the post-test samples verified that, with only one exception, the reinforcement in all of the GCL samples had remained intact, and that sliding had only occurred between the geomembrane and the GCL. The GCL sample tested against the co-extruded textured geomembrane at 2759 kPa (400 psi) experienced partial internal failure.

To minimize the potential for internal failure/rupture of the GCL (and residual conditions representative of unreinforced hydrated bentonite), a GCL with high peel strength (>900 N/m by ASTM D6496) is recommended for heap leach liner applications where extremely high loads are expected.

Past direct shear tests performed by Breitenbach and Swan (1999) under high fill loads showed that geomembrane interfaces with underlying and overlying soils gain strength with time, due to (1) high-load deformation, or dimpling, of the geomembrane, increasing the interface contact area; and (2) reduction in excess soil porewater pressures over time. They estimated a 5-degree increase in friction angle due to these factors. Since the high-load shear tests performed in this study did not include overliner and underliner soils, it is plausible that the actual peak shear strengths in the field will be higher than those reported in Figure 5.

DISCUSSION

The findings of the high-load puncture and high-load permeability testing presented above were used to revisit the leakage calculations presented in Athanassopoulos et al. (2008), and based on Giroud's equations (1997). The evaluation compared the expected hydraulic performance and metal recovery of two potential liner options at a hypothetical copper heap leach site: (1) a 1.5-mm HDPE geomembrane overlying a GCL; and (2) a 1.5-mm HDPE geomembrane overlying a 0.3-m thick layer of compacted soil with a permeability of 1×10^{-6} cm/sec. The analysis assumed circular geomembrane punctures with a diameter of 2 mm, a puncture frequency of 10 per m^2 (based on the punctures per ft^2 found during testing at the highest loads) for both the GCL and compacted soil options, and a conservative GCL permeability of 5×10^{-8} cm/sec (corresponding to the measured permeability of the punctured GCL sample in contact with copper PLS under high loads).

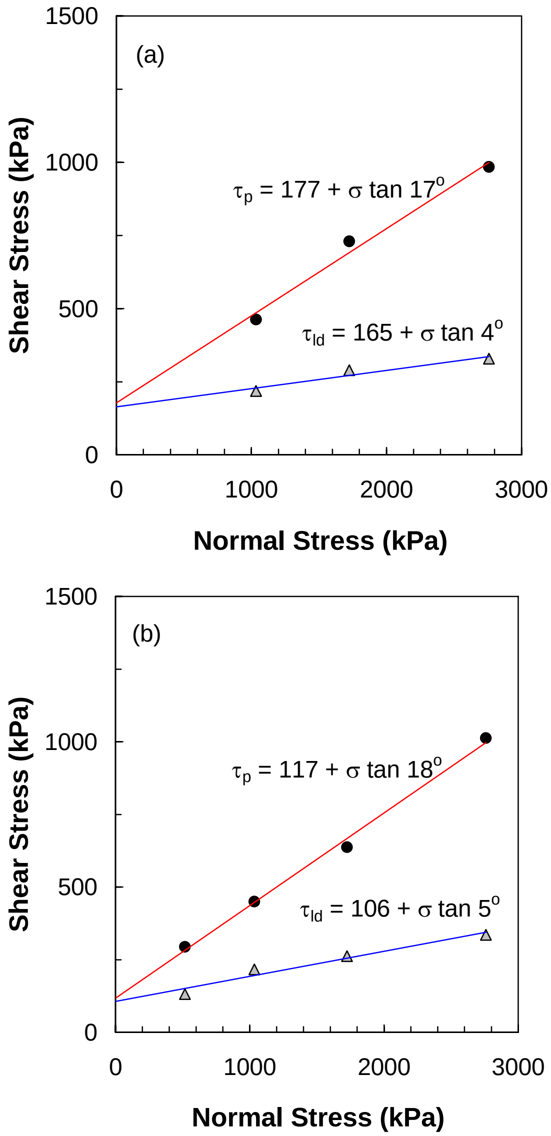

Figure 5. Geomembrane/GCL Shear Strength Envelopes: (a) geomembrane with co-extruded texturing; (b) geomembrane with embossed texturing

Using these assumptions, the calculations show that a geomembrane/GCL composite liner would be expected to allow less than one-tenth as much leakage as a geomembrane/0.3-m thick compacted soil composite. By multiplying the leakage rates with 800 ppm of copper (from Table 2), a copper price of $4.40 per kilogram (as of July 2009), and a estimated recovery of 80%, copper recovery rates for each liner option can be calculated and compared. The example calculations show that because of the large disparity in leakage rates between the two liner options, the improved recovery rate afforded by adding a GCL below the geomembrane could potentially translate to millions of dollars per year of added revenue. This far exceeds the cost of the initial investment in the GCL for the heap leach pad liner system.

SUMMARY AND CONCLUSIONS

The results of high-load puncture testing showed that geomembranes alone are expected to experience more puncture damage (puncturing and/or strain deformation past yield) than a geomembrane with an underlying GCL or a geomembrane covered by a protective geotextile cushion. The protection offered by a GCL is comparable to that of a 540 g/m^2 nonwoven cushioning geotextile placed above the geomembrane. The GCL's benefit, in terms of reducing biaxial strains in the geomembrane, appears to be greater at higher normal stresses.

Although protective measures (either GCL below or cushioning geotextile above the geomembrane) show reduced typical strain values, these measures may not be enough to protect the geomembrane from puncture in all cases, especially where sharp crushed rock particles happen to be aligned with a sharp point or edge in direct contact with the geomembrane.

Increased stress relaxation (due to slower loading rates and higher in-situ temperatures) in the field suggests that laboratory testing may provide conservative results in terms of geomembrane strain behavior.

High-load permeability testing of a GCL in contact with an acidic, high-ionic strength copper PLS shows a decrease in hydraulic conductivity with increasing confining stress. Additionally, a GCL sample with a 1-cm^2 puncture showed the ability to self-heal under high normal loads and maintain a low permeability (<10^{-7} cm/sec), even while in contact with the PLS.

High-load direct shear testing of geomembrane/GCL liner components showed peak secant friction angles of 19 to 20 degrees and large displacement secant friction angles of 6 to 7 degrees at 2758 kPa (400 psi) normal stress. To minimize the potential for internal failure/rupture of the GCL (and residual conditions representative of unreinforced hydrated bentonite), a GCL with high peel strength (>900 N/m by ASTM D6496) is recommended for heap leach liner applications where extremely high normal stresses are expected.

A feasibility study of two lining alternatives for an example copper heap leach pad estimated that a geomembrane/GCL composite liner would be expected to allow only one-tenth as much leakage as a geomembrane/compacted soil composite. The resulting improvement in PLS capture is expected to result in a significant increase in copper recovery and increased revenue (potentially millions of dollars per year).

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REFERENCES

Athanassopoulos, C., Kohlman, A., Henderson, M., and J. Kaul. 2008. Evaluation Of Geomembrane Puncture Potential And Hydraulic Performance In Mining Applications. Tailings and Mine Waste, 2008.

Brachman, R.W.I, and Gudina, S. 2008. Gravel contacts and Geomembrane Strains for a GM/CCL composite liner. Geotextiles and Geomembranes, 26:448-459.

Breitenbach, A.J. and Swan, R.H. 1999. Influence of High Load Deformations on Geomembrane Liner Interface Strengths. Geosynthetics ’99, vol. 1, pp. 517-529.

Daniel, D. 2000. Hydraulic Durability of Geosynthetic Clay Liners. GRI-14, Conference on Hot Topics in Geosynthetics.

Giroud, J.P. 1997. Equations for Calculating the Rate of Liquid Migration Through Composite Liners Due to Geomembrane Defects. Geosynthetics International, 4 (3-4): 335-348.

Jo, H.Y., Katsumi, K., Benson, C.H., and T. Edil. 2001. Hydraulic Conductivity and Swelling of Nonprehydrated GCLs Permeated with Single-Species Salt Solutions. Journal of Geotechnical and Geoenvironmental Engineering, ASCE. 127 (7): 557-567.

Narejo, D. 1995. Three Levels of Geomembrane Puncture Protection. Geosynthetics International, 2(4): 765-769.

Olsta, J., and Swan, R. 2001. Internal Shear Strength Of A Geosynthetic Clay Liner At High Normal Loads. Tailings and Mine Waste, 2001.

Peggs, I. D., Schmucker, B., and Carey. P. 2005. Assessment of Maximum Allowable Strains in Polyethylene and Polypropylene Geomembranes. Geofrontiers 2005, Waste Containment and Remediation, Geo-Institute, ASCE.

Seeger, S., and Muller, W. 1996. Requirements and Testing of Protective Layer Systems for Geomembranes. Geotextiles and Geomembranes, 14:365-376.

Thiel, R. and Criley, K. 2005. Hydraulic Conductivity of a GCL Under Various High Effective Confining Stresses for Three Different Leachates. Geofrontiers 2005, Waste Containment and Remediation, Geo-Institute, ASCE.

UK Environmental Agency. 2006. A Methodology for Cylinder Testing of Protectors for Geomembranes on Landfill Sites.

USEPA. 1996. Report of 1995 Workshop on Geosynthetic Clay Liners, EPA/600/R-96/149. USEPA, ORD, Cincinnati, OH.