GEOMEMBRANE PUNCTURE POTENTIAL AND HYDRAULIC PERFORMANCE IN MINING APPLICATIONS

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The attached paper discusses a laboratory puncture testing program involving various geomembranes placed in direct contact with different drainage media under high loads, both with and without underlying GCLs. Variables being examined include: geomembrane type and thickness, GCL type, normal load, and drainage stone size. Preliminary test results have shown that geomembrane/GCL composite liners are subject to less puncture damage (i.e., lower defect frequency and/or smaller puncture sizes) than geomembrane liners alone. The paper also presents a feasibility study of two lining alternatives, geomembrane/compacted soil and geomembrane/GCL composites. The feasibility study compares technical effectiveness and cost effectiveness based on cost savings associated with improved metal recovery rates afforded by improved containment. This information is intended for mining companies and engineers in evaluating lining options and allowable stone sizes.

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EVALUATION OF GEOMEMBRANE PUNCTURE POTENTIAL AND HYDRAULIC PERFORMANCE IN MINING APPLICATIONS

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ABSTRACT: Lining systems in mining applications often consist of a geomembrane underlain by either a soil liner or a geosynthetic clay liner (GCL). Geomembranes are vulnerable to damage from large stones both in the soil subgrade and in the overlying drainage layer. Although guidance has been developed for minimizing geomembrane puncture, this past work has focused on subgrade protrusions in municipal solid waste applications. There has been limited information regarding puncture performance in mining applications, where extreme loads are encountered and angular, large-diameter crushed ore is often used as the drainage medium above the geomembrane. This paper discusses a laboratory puncture testing program involving various geomembranes placed in direct contact with different drainage media under high loads, both with and without underlying GCLs. Variables being examined include: geomembrane type and thickness, GCL type, normal load, and drainage stone size. Preliminary test results have shown that geomembrane/GCL composite liners are subject to less puncture damage (i.e., lower defect frequency and/or smaller puncture sizes) than geomembrane liners alone. This paper also presents a feasibility study of two lining alternatives, geomembrane/compacted soil and geomembrane/GCL composites. The feasibility study compares technical effectiveness and cost effectiveness based on cost savings associated with improved metal recovery rates afforded by improved containment. This information is intended for mining companies and engineers in evaluating lining options and allowable stone sizes.

1 INTRODUCTION

Geomembranes have been used in the mining industry since the early 1970s in solution and evaporation ponds, tailings impoundments, and heap leach pads. Traditionally, heap leach pad lining systems have consisted of a single geomembrane liner placed directly over a prepared subgrade of locally available soil. Heap fills are constructed by placing a layer of highly-permeable drainage stone (overliner) over the geomembrane. Crushed ore is then placed on the leach pad in 15- to 30-foot (3- to 10-m) thick lifts, sometimes reaching final heights of several hundred feet. The crushed ore is irrigated with a chemical solution which dissolves the precious metals from the ore. The nature of the chemical leaching solution depends on the metal being targeted. Low pH sulfuric acid solutions are generally used to leach copper and nickel; high pH cyanide solutions are used to leach gold and silver. The metal-laden pregnant leach solution (PLS) passes down through the ore pile and is captured in a drainage system. Metals are extracted from the leach solution and the solution is then recycled back onto the leach pile.

When under load, geomembranes are vulnerable to damage from large stones both in the soil subgrade and in the overlying drainage layer. Although intact geomembranes are virtually impermeable, installed geomembranes will have a small number of holes due to imperfect seams or damage during construction and filling operations. These holes serve as open pathways for leakage into the soil below. The leakage rate through each hole increases as the hole size and hydraulic head on the hole increase, and as the permeability of the layer under the geomembrane increases.

A low-permeability layer is often used beneath the geomembrane to form a composite liner. The low-permeability material beneath the geomembrane can be either a compacted soil (clay or silt) liner or a geosynthetic clay liner (GCL). Compacted soil liners are typically constructed within a specific range of water contents and dry unit weights to achieve a maximum hydraulic conductivity of either 1×10^{-6} or 1×10^{-7} cm/sec, depending on performance and regulatory requirements. GCLs are factory-manufactured liners consisting of sodium bentonite, with a laboratory-certified hydraulic conductivity of 5×10^{-9} cm/sec. Several factors affect the rate of leakage through composite systems, including the number of holes in the overlying geomembrane, the hydraulic conductivity of the underlying soil layer, and the contact quality between the geomembrane and the low-permeability layer (Giroud, 1997). Based on liner leakage measurements collected by the USEPA at 287 landfill cells spanning 91 sites (Bonaparte and Daniel, 2002), GCL-based composite liner systems have been shown to allow less leakage than clay-based composite liner systems.

2 LITERATURE REVIEW

Narejo et al (1996), Koerner et al. (1996), and Wilson-Fahmy et al (1996) developed guidance for addressing puncture damage due to subgrade protrusions below the geomembrane in municipal solid waste applications. Their design guidance involves selection of a cushioning geotextile to limit elongation of the geomembrane past the yield point, which helps avoid short-term puncturing of the geomembrane. European environmental agencies employ a more stringent approach, where local strains in the geomembrane are restricted to less than 0.25 percent, to not only avoid short-term puncturing, but to also avoid stress cracking of the geomembrane over long periods of time. Cylinder tests were first developed in Germany for 100-mil (2.5-mm) thick smooth HDPE geomembranes in contact with 0.6 to 1.25-inch (16 mm to 32 mm) drainage aggregate. The cylinder tests are used as site-specific performance tests to assess the effectiveness of geotextile protection layers over geomembranes in several European countries (Seeger and Muller, 1996) and (UK Environmental Agency, 2006). A load is applied to simulate the waste loading for a particular landfill with safety factors applied to account for different temperatures and test durations. They used safety factors ranging from 1.50 for a test at 40°C for 1000 hrs to 2.50 for a test at 20°C for 100 hrs (Seeger and Muller, 1996).

There has been limited information published related to puncture performance in mining applications, such as heap fills, where extreme loads are encountered and crushed rock is often used as the drainage medium above the geomembrane. For the particle sizes and high loads involved in heap leach applications, the design approaches discussed above for solid waste applications would result in unrealistically heavy geotextile layers. For example, assuming a 500-foot (152 m) high heap, and 1-inch (25 mm) diameter angular drainage stone over the geomembrane, the design guidance developed by Koerner et al (1996) would require a 130 oz/yd^2 (4.4 kg/m^2) cushioning nonwoven geotextile over the geomembrane to maintain a factor of safety of 3.0 against puncture damage. Unfortunately, the heaviest weight nonwoven geotextile that is readily available in the U.S. marketplace is perhaps only 32 oz/yd^2 (1.1 kg/m^2). The reality is that cushioning geotextiles are rarely, if ever, used in leach pad applications due to cost and stability considerations (Thiel and Smith, 2003). Additionally, 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, so maintenance of a defect-free geomembrane over the long-term may not be a critical design priority.

Considering the recent price increases in precious and commodity metals, there may now be a stronger incentive to limit geomembrane punctures and 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.

Narejo et al (2007) and Heerten (1994), have found that GCLs can serve as effective cushions, minimizing the puncture damage in geomembranes. Compacted soil liners are not expected to offer the same protection; in fact, under the high normal loads seen at heap leach pads, any coarse particles in the compacted soil subgrade present increased puncture risks. Also, since the rate of leakage through defects in a composite liner system decreases with decreasing hydraulic conductivity of the underlying soil layer, GCL-based composite liner systems are expected to allow less leakage than soil-based composite liner systems should a puncture occur (Narejo et al, 2002). A comparison of expected leakage rates through both geomembrane/soil and geomembrane/GCL composite liner systems will be presented later in this paper.

3 PREVIOUS GEOMEMBRANE PUNCTURE TESTING

Two of the authors have overseen geomembrane testing programs for several large heap leach pad projects throughout the world. A summary of these studies is shown in Table 1. Many of these tests involved single HDPE or LLDPE geomembrane liners placed over compacted site soils, covered with different drainage media, and then subjected to normal loads between 180 and 625 psi (1241 and 4309 kPa). For one project, a copper heap leach pad in the southwestern United States, single geomembrane and geomembrane/GCL composite liners were tested in contact with 0.5 to 1.5-inch (13 to 38 mm) drainage stone at normal loads as high as 585 psi (4033 kPa). The majority of the tests resulted in “major” to “severe” yielding and puncturing of 60-mil and 80-mil (1.5-mm and 2.0-mm) LLDPE geomembranes, with the exception of the layer tested with a GCL between the 60-mil LLDPE and the bedding layer. That test resulted in only “minor” to “moderate” yielding of the LLDPE. The results indicated that with a protective GCL layer between the LLDPE and the bedding layer, a 60-mil LLDPE geomembrane could be specified rather than a bulkier and less cost effective 80-mil geomembrane, and provide improved hydraulic performance. Photographs of the geomembrane samples are shown in Figure 1.

4 PROPOSED GEOMEMBRANE AND GCL PUNCTURE TESTING PROGRAM

Based on the test results discussed above and the authors’ experience, it appears that geomembrane/GCL composite liners for heap leach pads may have less severe puncture damage from overlying drainage media than geomembrane liners used alone. For the purposes of the research presented in this paper, “less severe puncture damage” is defined as lower defect frequency and/or smaller puncture sizes. In order to investigate the puncture behavior of geomembranes and composite liners further, a high-load static puncture testing program has been initiated. The testing program involves various geomembranes, both with and without underlying GCLs, placed in contact with different drainage aggregate and tested at normal loads up to 750 psi (5171 kPa). Variables examined include: geomembrane type and thickness, GCL type, normal load, drainage stone size, and test duration. The intent of these tests is to more rigorously evaluate the puncture potential of geomembranes used in heap leach pad applications with ultimate ore heights of up to 600 feet (183 meters), assuming a factor of safety of 1.50.

Geomembrane samples will be placed over a standardized sand bedding layer (such as Ottawa sand), covered with the coarse-grained drainage aggregate, and loaded with a Material Testing System (MTS) equipped with Linear Variable Distance Transducers (LVDTs) to monitor displacement. A conceptual diagram of the load system is shown in Figure 2. The typical test duration will be 48 hours, with some tests up to two weeks possible. After loading, the geomembrane sample will be removed and examined for punctures, both visually and with a vacuum test. In addition to punctures, other signs of distress, including yielding in the geomembrane (defined as indentations in the geomembrane which do not recover after removal of the pressure) will also be recorded. Yield deformation will be reported as “None”, “Minor”, “Moderate”, “Major” or “Severe”, which are specific terms defined by the number of yield points observed as well as the size of each yield point.

Table 1. Summary of Previous Geomembrane Puncture Testing

Upper Material	Geomem-brane	Lower Material	Normal Stress	Yielding					Puncture?	
				None	A	B	C	D	N	Y
Mexico Heap Leach										
Gravel (1”)	60-mil LLDPE	Site Silt	180 psi	X					X	
Gravel (2”)	60-mil LLDPE	Site Silt	180 psi			X	X		X	
Gravel (minus 2”)	60-mil LLDPE	Stock-piles	300 psi		X	X			X	
Ore (3/4”)	60-mil LLDPE	Stock-piles	300 psi		X	X			X	
Ore (1-1/2”)	60-mil LLDPE	Stock-piles	300 psi			X	X		X	
Ore (1-1/2”)	60-mil LLDPE	CL/CH	300 psi			X	X	X	X	
Gravel	60-mil LLDPE	Site Silt	180 psi	X					X	
Turkey Heap Leach										
Ore (mi-nus 1”)	60-mil LLDPE	Sandy CH	214 psi		X				X	
Southwest USA Heap Leach										
Ore (1.5” to 0.5”)	60-mil LLDPE	Clay	417 psi		X				X	
Ore (1.5” to 0.5”)	60-mil LLDPE	Clay	625 psi		X				X	
Ore (1.5” to 0.5”)	80-mil LLDPE	Clay	625 psi			X	X		X	
Mongolia Heap Leach										
Lean Clay	60-mil LLDPE	Minus 2” crushed rock	256 psi		X	X	X		X	
Southwest USA Heap Leach										
Crushed Ore (1.5” to 0.5”)	60-mil LLDPE	Minus 0.5” Bedding	312 psi		X				X	
Crushed Ore (1.5” to 0.5”)	60-mil LLDPE	Minus 0.5” Bedding	585 psi				X	X		X
Crushed Ore (1.5” to 0.5”)	60-mil LLDPE and GCL	Minus 0.5” Bedding	585 psi		X	X			X	
Crushed Ore (1.5” to 0.5”)	80-mil LLDPE	Minus 0.5” Bedding	585 psi				X		X	
Crushed Ore (mi-nus 1”)	60-mil LLDPE	Minus 0.5” Bedding	312 psi		X				X	
Ore (mi-nus 1”)	60-mil LLDPE	Minus 0.5” Bedding	585 psi			X			X	

Geomembrane Yielding Descriptions, based on size and number of yield points:
A = Minor; B = Moderate; C = Major; D = Severe.

Figure 1. Comparison of 60-mil (1.5 mm) LLDPE Geomembrane tested in contact with 1/2" to 1” (12 to 25 mm) rock at 585 psi (4033 kPa) for 48 hours, both with (left) and without (right) underlying GCL.

Geomembrane sample with underlying GCL experienced less severe (minor to moderate) yielding, and no punctures. Geomembrane tested without GCL experienced severe yielding and one puncture (circled).

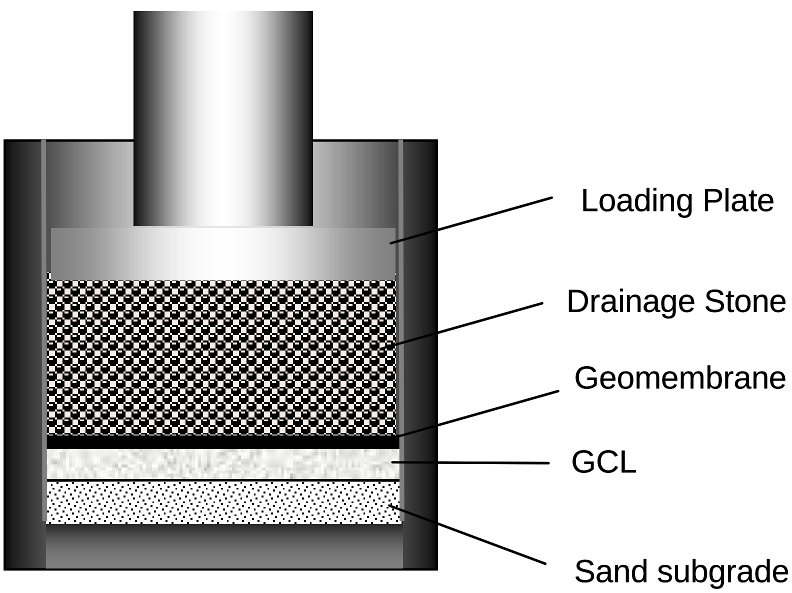

Figure 2. Conceptual Diagram of Geomembrane/GCL Loading System

A separate testing program, involving long-term compatibility/hydraulic conductivity testing of GCL samples in contact with an aggressive, low-pH synthetic copper leach solution is also being performed. The tests will follow 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 GCL samples will be hydrated with synthetic leachate under low effective stress and then subjected to a hydraulic head of 2 psi (13.8 kPa) to drive the flow of leach solution through the samples. Testing will be performed at confining pressures ranging from 5 to 500 psi (34.5 to 3447 kPa), to simulate the range of typical operational stages of a copper heap leach facility. The method recommends that testing continue until specific termination criteria (steady-state flow and chemical equilibrium) be established between the effluent and influent. Accordingly, flow and water quality measurements will be collected daily to monitor termination criteria during the testing period.

5 HEAP LEACH PAD LINER FEASIBILITY STUDY

A comparison of expected hydraulic performance and metal recovery was performed for potential leach pad liner options at an example copper heap leach project. Two scenarios were analyzed: (1) a 60-mil HDPE geomembrane overlying a GCL; and (2) a 60-mil HDPE geomembrane overlying a 1-foot thick layer of compacted soil with a permeability of 1×10^{-6} cm/sec. (State mining regulatory agencies in the western United States commonly require the low-permeability soil layer beneath the geomembrane to have a maximum hydraulic conductivity of 1×10^{-6} cm/sec). A copper heap leach has been selected as a "worst-case" example due to potential GCL chemical compatibility concerns between the acidic PLS and the bentonite in the underlying GCL. A gold heap leach, which employs a high-pH dilute cyanide solution, has been shown to be compatible with sodium bentonite (CETCO, 2000), and is therefore expected to result in a low long-term GCL hydraulic conductivity (on the order of 5×10^{-9} cm/sec).

5.1 *Flow through Geomembrane Defects*

Theoretical leakage calculations were performed using the semi-empirical Giroud equations (1997). These equations are similar to the equations used in the Hydrologic Evaluation of Landfill Performance (HELP) model, which were also developed by Giroud (Schroeder et al, 1994). Since geomembranes are virtually impermeable, the only significant liquid migration through the composite liner system will occur through geomembrane defects. HELP provides estimates for the number of installation defects (caused by installation quality, equipment, and surface preparation) that can be expected when the geomembrane is placed using good, fair, and poor installation practice and QA/QC. HELP recommends an installation defect diameter of 1 cm^2.

At this time, defect frequencies corresponding to "fair" installation quality (4 to 10 per acre, or 10 to 25 per hectare) will be used for both liner options presented in this paper. The authors feel that this is a reasonable assumption, considering the high loads involved, the common use of crushed rock for overliner, and the fact that heap leach construction projects may not follow the same strict construction quality assurance (CQA) as landfill liner projects. In addition, considering that GCLs have been shown to be effective geomembrane cushions, allowing less puncture damage (Figure 1), the geomembrane/GCL liner option will be assumed to have fewer installation defects (4 defects/acre) compared to the geomembrane/soil liner option (10 defects/acre). Each installation defect will be assumed to be circular, with an area of 1 cm^2. A list of the assumptions used in this example feasibility study is presented in Table 2. The defect assumptions will be re-examined after the ongoing laboratory puncture testing program discussed above has been completed.

5.2 *Interface Flow*

Where defects are present, the liquid will pass through the defect, and then flow laterally in the space between the geomembrane and low-permeability soil layer before infiltrating through the soil (Giroud, 1997). The radius of this "interface flow" is dependant upon the quality of contact between the geomembrane and the low-permeability soil. Composite liner components in good contact (no geomembrane wrinkles, well-prepared, smooth subgrade) will permit less interface flow (and therefore, less overall leakage) than those components in poor contact. The contact quality factor is a coefficient introduced to account for the effects of interface flow. Giroud provides estimates of 0.21 and 1.15 for good and poor contact quality, respectively. Giroud states that good contact should be assumed with GCLs, since they are usually installed flat and, when under pressure, bentonite will exude through the surrounding geotextiles, forming a hydraulic seal with the geomembrane.

Table 2. Liner Leakage Calculations

	60-mil LLDPE/ compacted soil	**60-mil LLDPE/GCL (1×10^{-7} cm/sec)**	**60-mil LLDPE/GCL (5×10^{-9} cm/sec)**
Soil hydraulic conductivity	1×10^{-6} cm/sec	1×10^{-7} cm/sec	5×10^{-9} cm/sec
Soil thickness	1 ft (0.3048 m)	0.02 ft (0.006 m)	0.02 ft (0.006 m)
Hydraulic head	1 ft (0.3048 m)	1 ft (0.3048 m)	1 ft (0.3048 m)
Contact quality factor	1.15	0.21	0.21
Number of defects	10 per acre (25 per hectare)	4 per acre (10 per hectare)	4 per acre (10 per hectare)
Size of each defect	1 cm^2	1 cm^2	1 cm^2
Liner leakage	47 gpad (442 lphd)	3 gpad (28 lphd)	0.3 gpad (2.9 lphd)

Note: gpad = gallons per acre per day. lphd = liters per hectare per day.
Calculations performed using the methodology in Giroud (1997).

5.3 *GCL Hydraulic Conductivity*

Sulfuric acid solutions are typically used in copper heap leach pads to leach copper from the ore. This results in an acidic PLS containing high levels of sulfates, dissolved metals, and total dissolved solids (TDS). Jo et al. (2001) found that sodium bentonite samples exhibited approximately a 50 percent decrease in swell at pH values less than 3. As part of the same study, GCL permeability values on the order of 10^{-6} to 10^{-5} cm/sec were measured at pH values less than 2. However, Ruhl and Daniel (1997) found that when exposed to strong acid, a GCL's buffering capacity was not exhausted until after 15 pore volumes of flow. At the low water flow rates expected in a liner, it may take months or years for the first 15 pore volumes to flow through liner. By this time, the liner will likely be covered and compressed by several hundred feet of ore.

In addition to exhibiting low pH values, copper PLS contains high levels of dissolved sulfates and metals. High ionic strength solutions may be incompatible with sodium bentonite and can decrease a GCL’s hydraulic performance. Many researchers have observed decreasing swell and increasing hydraulic conductivity in GCLs exposed to high strength leachates and liquids containing high divalent cation concentrations (Jo et al, 2001, Kolstad et al, 2004, Shackelford et al, 2000).

The hydraulic conductivity of bentonite is dictated by not only the pore water chemistry, but also the compressive stress acting on the GCL. Daniel (2000) permeated GCLs with concentrated calcium chloride (5000 ppm) solutions at various confining pressures. At low compressive stress, the calcium solution had a dramatic effect on GCL performance. But as the pressure increased to 58 psi (400 kPa), the hydraulic conductivity to distilled water and concentrated calcium solution was virtually identical. These results are consistent with the findings of Thiel and Criley (2005), who found that at effective stresses greater than 58 to 72 psi (400 to 500 kPa), the hydraulic conductivity of a GCL is independent of the leachate chemistry. Since modern heap leach piles are typically several hundred feet high, the GCL will be under a very high confining pressure, and is therefore expected to maintain a relatively low hydraulic conductivity.

Shackelford et. al. (2000) and Jo et al (2004) have shown that prehydration of a GCL with clean water prior to exposure to high strength liquids can significantly improve the GCL's hydraulic conductivity. Considering that a GCL typically achieves hydration through moisture in the subgrade within weeks or months of placement, it is likely that a GCL used to line our example copper heap leach pad will be at least partially hydrated with subgrade moisture before it is exposed to any aggressive acidic PLS.

Considering the combined effects of low pH, high ionic strength, prehydration, and confining pressure, a GCL in this example application could be conservatively expected to exhibit a hydraulic conductivity less than 1×10^{-7} cm/sec, or an increase of almost two orders of magnitude from the value expected with clean water. As discussed above, to confirm this assumption, long-term compatibility/hydraulic conductivity testing of a GCL in contact with a synthetic copper PLS is currently underway, in accordance with a modified version of ASTM D6766. If the testing indicates that a GCL under high confining pressure is not impacted as strongly by the PLS, the disparity in leakage rates will be even greater. Accordingly, the calculations in Tables 2 and 3 were performed for two different GCL hydraulic conductivity values: 1×10^{-7} cm/sec (significant negative impact) and 5×10^{-9} cm/sec (little or no impact).

5.4 *Estimated Liner Leakage Rates and Recoverable Copper*

Giroud's equation requires knowledge of the hydraulic head on the liner system. For purposes of this calculation, it is assumed that the head is 1 foot (0.3 m), the regulatory requirement in many states. It should be noted that head levels can vary depending on annual rainfall, leach solution application/collection rates, and the type of fill (e.g., valley or heap). The calculations in Table 2 show that, even if the GCL's hydraulic conductivity increases to 10^{-7} cm/sec due to chemical interactions with the PLS, a geomembrane/GCL composite liner would be expected to allow less than one-tenth as much leakage as a geomembrane/one-foot thick compacted soil composite.

Based on a review of the literature (Drummond et. al. 2003, Thiel and Smith 2003, and Jergensen, 1999), copper PLS concentrations may range from 3000 to 7000 ppm. By multiplying the leakage rates with 3000 ppm of copper, estimates of the mass of copper escaping through each type of liner to the environment can also be made. These calculations, which are shown in Table 3, indicate that significantly more copper can be captured when using a GCL composite liner. Assuming an average copper price of $3.60 per pound ($7.92 per kg), and a recovery efficiency of 90 percent, the improved recovery rate afforded by a GCL represents an additional $1300 per acre per year of revenue ($3200 per hectare per year). For a large heap leach site of 200 acres (80 hectares), this represents several hundred thousands of dollars per year of added revenue.

Additional factors not discussed above include a comparison of the installed costs of GCLs and compacted soil liners, as this is a highly variable, strongly site-specific consideration. The authors' experience at past sites, including a recent mine site in Nevada, has shown that the installed cost of a GCL is roughly equivalent to or lower than the installed cost of a compacted soil liner when the soil is transported from an off-site location, or when soil amendments such as bentonite are required. Another factor is the revenue gained through faster heap leach pad construction when using GCLs. GCLs can often be deployed at a faster rate than compacted low-permeability soil liners can be constructed, and offer a preferable working surface for deploying and welding the overlying geomembrane. Additionally, GCLs are factory-controlled materials, with consistent bentonite distribution and hydraulic performance. As such, GCLs are less likely than compacted soil liners to yield failing CQA test results. These factors suggest that GCLs allow for a shorter construction schedule and an earlier start to leaching operations. A final factor to consider when evaluating installed costs of GCLs and compacted soil liners is the potential for reduced screening operations when using a GCL-based composite liner system. If the laboratory puncture testing program described above confirms that a GCL will reduce puncture damage to the geomembrane from coarse-grained overliner materials, then a larger stone size may be allowable, resulting in fewer screening operations.

Table 3. Copper Recovery Calculations

	60-mil LLDPE/ compacted soil	**60-mil LLDPE/GCL (10^{-7} cm/sec)**	**60-mil LLDPE/GCL (5 x 10^{-9} cm/sec)**
Copper in PLS	3000 ppm	3000 ppm	3000 ppm
Copper lost due to leakage	433 lb / acre / yr (486 kg / ha / yr)	27 lb / acre / yr (30 kg / ha / yr)	3 lb / acre / yr (3.3 kg / ha / yr)
Copper price (June 2008)	\$3.60 / lb (\$7.92 / kg)	\$3.60 / lb (\$7.92 / kg)	\$3.60 / lb (\$7.92 / kg)
Copper recovery	90%	90%	90%
Cost of recoverable copper lost	\$1401 / acre / yr (\$3462 / ha / yr)	\$88 / acre / yr (\$217 / ha / yr)	\$10 / acre / yr (\$25 / ha / yr)
Gain in Revenue	--	\$1314 / acre / yr (\$3246 / ha / yr)	\$1392 / acre / yr (\$3438 / ha / yr)

6 CONCLUSIONS

Lining systems in mining applications can consist of a geomembrane underlain by either a soil liner or a GCL. When under load, geomembranes are vulnerable to damage from large stones both in the soil subgrade and in the overlying drainage layer. There has been limited information published regarding geomembrane puncture in mining applications, where extreme loads are encountered and angular, large-diameter crushed ore is often used as the drainage medium above the geomembrane. Considering the recent price increases in precious and commodity metals, and the increased environmental sensitivity of the mining industry, there may now be even stronger incentive to limit geomembrane punctures and PLS loss through the liner system in mining applications.

The author's experience and preliminary results of high-load static puncture tests have shown that geomembrane/GCL composite liners may be subject to less puncture damage than geomembrane liners alone over compacted soil subgrades. A feasibility study of two lining alternatives for an example copper heap leach pad was performed. Theoretical liner leakage calculations revealed that, for a reasonable set of assumptions at a typical copper heap leach, a geomembrane/GCL composite liner would be expected to allow only one-tenth as much leakage as a geomembrane/one-foot thick compacted soil composite. The resulting improvement in PLS capture is expected to result in a significant increase in copper recovery and increased revenue (potentially hundreds of thousands of dollars per year for large sites).

Ongoing and future work includes a laboratory puncture testing program involving various geomembranes placed in direct contact with different drainage media under high loads, both with and without underlying GCLs, and long-term compatibility/hydraulic conductivity testing of GCL samples in contact with an aggressive, low-pH synthetic copper leach solution, and shear strength testing under high loads. The results of this laboratory testing will be used to refine the calculations presented in this paper, with the end goal of providing mining companies and engineers with information to assist in their evaluations of potential lining options and optimizing allowable drainage stone sizes.

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