Improving the performance of mining infrastructure through the judicious use of geosynthetics

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ABSTRACT: The use of geosynthetics within the mining industry is not as extensive as within some other industries, such as the hazardous and municipal solid waste industries. However, in certain, very specific applications, the volumes used can be very large, such as in the lining of heap leach pads. This particular application provides two conditions of extreme loading for geosynthetics: extremely large normal loads and severe chemical exposure. The performance of geomembranes in these applications could be useful indicators of likely success in other applications. In applications such as containment of mining waste, where the potential volumes of geosynthetics usage are enormous, application rates remain low. This is attributed to the lack of internationally enforceable legislation requiring the lining of sites storing mining waste. Current areas of application in the mining industry are described in the paper, and suggestions made regarding improvements in awareness and training that could be facilitated by the International Geosynthetics Society. Needs are identified for improved testing techniques and associated performance criteria that are specific to the mining industry, such as heap leach pad liners. Without the confidence provided by such research, it is understandable that mining practitioners are sometimes reluctant to specify the use of geosynthetics in large, critical mining infrastructure projects.

1 INTRODUCTION

Mining is the backbone of many economies around the world, including developed countries such as Australia. In many developing countries it provides more than 50% of the export earnings, for example Papua New Guinea, where it is 66%. The mining life cycle, which includes exploration, construction, operation and finally closure results in the use of enormous volumes of resources such as cement, aggregate, diesel and electricity. Although relatively minor in comparison, the utilisation of geosynthetic products is increasing rapidly and there is enormous potential to increase this utilisation in the mining industry. Indeed, Smith (2008) suggests an increase of about 50% in the use of geosynthetics in the mining industry over the next decade is likely. Impediments appear to be the lack of knowledge of many mining industry personnel about geosynthetics, and the lack of enforceable legislation in many countries that allow environmental impacts of the mining process to proceed virtually unchecked. The primary recommendation from this paper is a call for a concerted campaign by the IGS to develop a strategy to improve the knowledge and understanding of the potential application of geosynthetic products within the mining industry.

This paper concentrates on current applications of geosynthetics in mining, focusing largely on the unusual and unique aspects of these applications that differentiate them from other, perhaps more traditional applications. The paper does not discuss in detail aspects of geosynthetics performance, such as conventional filtration, reinforcing or durability testing, unless these are specific to the mining application under discussion, or are entirely unique.

2 SCALE OF MINING

In Chile, many copper mines produce over 100,000 tonnes of tailings per day, with the Escondida mine alone producing approximately 230,000 tonnes per day. As will be explained later in this paper, the potential applications of geosynthetics in mining are enormous; however, current usage is far below what it could be. Reasons for this are many, and some of the key issues are discussed in the paper.

3 PRODUCTION VERSUS PROTECTION

When one considers the enormous volumes of mining waste produced annually, and the potential risks (particularly environmental risks) associated with storage of these wastes, it is striking to note that the vast majority of geosynthetics usage in the industry is not related to this application. It is related to production activities. This is not entirely surprising, because companies are in the business of mining to make a profit and anything that improves productivity is likely to be embraced. Environmental protection on the other hand, is simply a cost and generates no income stream. It would be naïve to expect companies to spend money on lining waste storage facilities unless compelled to do so by government regulation (with some notable exceptions, as discussed later). The paper therefore distinguishes between production applications and protection applications.

3.1 *Heap leach facilities*

Heap leach facilities are probably the single biggest user of geosynthetics in the mining industry, certainly in South America and the United States. In this process, crushed ore (which is usually first 'agglomerated' – the process of binding smaller particles into larger clusters) is transported (usually by conveyor) to an area that has been prepared with a geomembrane liner, above which are located a system of drainage pipes. These pipes are typically 10 to 15 cm diameter, spaced at about 2m centres. The agglomerated ore is often pre-treated with a solution (concentrated sulphuric acid in the case of copper) and then placed and spread on the geomembrane liner. Dilute sulphuric acid (at a concentration of around 2% and a pH of about 2) is then supplied to the surface of the agglomerated ore through either sprinkler irrigators, or a system of drip irrigators, the latter reducing evaporation rates quite dramatically. As the acid gradually percolates through the ore it dissolves the precious metal, producing what is known as a 'pregnant solution'. The percolation process may take a few weeks and the pregnant solution is recovered during this time and sent to a solvent extraction plant for metal recovery. As the product of mining in this case is the pregnant solution, it is imperative that losses through the underliner system are minimised (preferably eliminated) and recovery is maximised.

The liner materials typically used in these applications are HDPE, LLDPE, PVC and PP geomembranes, Table 1 lists their advantages and disadvantages. Use has also been made of Bituminous Geomembranes (BGM) and ethylene propylene dieneter polymer (EPDM), although no recent examples of these could be found. Within the mining environment, geomembrane liners often become exposed to severe conditions which could affect performance of the liner. These conditions include high stress/strain levels, exposure to acid or basic process solutions, and harsh environmental conditions, such as ultraviolet radiation and high temperature extremes. Under these harsh conditions, the ability of the geomembrane liner to remain flexible and provide solution containment may become impaired. Use of HDPE geomembranes is therefore tending to become predominant due to their excellent resistance to solvents and chemicals brought about by their high crystallinity (40 to 60%); by comparison

Table 1. Advantages and disadvantages of commonly used geomembranes (modified from Scheirs, 2009)

Geomembrane	Advantages	Disadvantages
HDPE	• Broad chemical resistance • Good weld strength • Good low temperature properties	• Potential for stress cracking • High degree of thermal expansion • Poor puncture resistance • Poor multiaxial-strain resistance
LLDPE	• Better flexibility than HDPE • Better layflat than HDPE • Good multiaxial strain properties	• Inferior UV resistance to HDPE • Inferior chemical resistance to HDPE
fPP	• Can be factory fabricated and folded so fewer field fabricated seams • Excellent multiaxial properties • Good conformability • Broad seaming temperature window	• Limited resistance to hydrocarbons and chlorinated water
PVC	• Good workability and layflat behaviour • Easy to seam • Can be folded so fewer field fabricated seams	• Poor resistance to UV and ozone unless specially formulated • Poor resistance to weathering • Poor performance at high and low temperatures

Figure 1. Photograph of a chemically attacked geomembrane. Note loss of ductility and thinning. The polymer became sticky and perished (courtesy of ExcelPlas Geomembrane Testing).

LLDPE geomembranes have an average of 15%-30% crystallinity whereas PVC geomembranes have 0% crystallinity and fPP geomembranes about 5% crystallinity. Furthermore, HDPE does not posses any functional groups in its structure which favour potential chemical attack. Chemical attacks can be detrimental to the longevity of the geomembranes (Figure 1). Highly crystalline polymers, such as HDPEs, tend to be rigid, high melting and less affected by solvent penetration. Crystallinity makes a polymer strong, but also lowers its impact resistance and increases its susceptibility to environmental stress cracking; whereas, a decrease in polymer crystallinity as in the case of LLDPE relative to HDPE, is associated with decreasing mechanical stiffness and chemical resistance (Scheirs, 2009).

When assessing the performance of geomembrane liners or geopipes (see later section) under harsh mining conditions, it is important to view the performance life in terms of the life of the mine. Mining facilities often have a life on the order of 10 to 50 years, after which the mine is reclaimed to minimize environmental impact and to promote long-term environmental stability. Whereas it is difficult to assign a life to geomembrane liners and geopipes in these environments, experience from actual mines in continuous operation for nearly 20 years, has indicated these materials are resilient and able to perform as designed.

Heap leach pads are generally constructed utilizing as much as possible the natural topography of the site in a variety of climates ranging from arctic (temperatures as low as -30°C), tropical wet (rainfall exceeding in some cases 2.5 m/y) to dry Saharan climates (temperatures as high as +50°C) and at altitudes above 4000 m (High Andes of South America). The pad area is cut and filled as required, and trimmed to achieve a desired slope of 0.5 to 1%. HDPE or LLDPE are normally used for the base of the pad with the liner being between 1-1.5 mm thick over the pad and between 2 - 3 mm thick in the sumps and drains. Directly over the liner are installed (generally HDPE) drainage pipes, which are coved by a layer of about 60 cm granular protective soil layer to protect the geomembrane liner-pipe system during ore stacking. Contrary to the practice in the landfill industry, geotextile protection layers are seldom used in heap leach pads.

The geomembrane lining material is used to retain chemical solution used to dissolve minerals from ore, and to allow the leachate to be collected and refined. Heap leaching presents a combination of extreme base pressures and high moisture/acidity conditions on the geomembrane not present in any other containment application. These extreme conditions push the envelope of known geomembrane performance often beyond the recommended general design limits, including 150-180 m high heaps, equipment loading of up to 53 tons per wheel, coarse rock overliner, concentrated acid exposure, hydraulic heads of up to 60 m, liquefaction potential and harsh arid climates with daily temperature extremes (Thiel and Smith, 2004). The combined action of sulfuric acid and temperatures reaching 70°C on an exposed geomembrane surface can seriously soften most liner materials. Furthermore the dumping of ore on the liner necessitates a strong membrane that is resistant to abrasions and punctures. Finally the steep, angular design of the collecting ponds requires a strong, durable product. For lined mining facilities subjected to moderate to high loads (greater than 300 kPa), geomembrane materials such as HDPE, LLDPE, and (to a lesser extent) PVC are used, mainly because of industry experience with these materials and documented performance from constructed mine facilities. However, geomembrane-lined heap leach facilities are being designed with ore heights approaching 200 m, resulting in normal stresses in excess of 3.3 MPa (Lupo and Morrison, 2007) presenting, in this respect, new challenges to the geosynthetics industry.

3.1.1 *Geomembrane liner performance under high loads*

Geomembrane liners, when used in the design of heap leach pads, tailings storage facilities, or overburden storage facilities, are often exposed to high loading conditions. These loading conditions are beyond those typically encountered in civil applications, such as landfills.

A summary of some high loads applications on geomembrane liners at actual mining projects in presented in Table 2. There are several important ob servations that can be made from this table, the first high load applications is HDPE and LLDPE;

Table 2. Summary of high loads on geomembrane liners in operation

Geomembrane liner type	Maximum fill height over liner (m)	Maximum vertical stress (MPa)
2.5mm LLDPE	180	4.5
2.0mm LLDPE	150	2.7
2.0mm LLDPE	180	3.2
1.5mm HDPE	150	2.7
1.5mm LLDPE	180	3.3
2.0mm HDPE	90	1.6
1.5mm LLDPE	90	1.7
1.5mm LLDPE	68	1.2
1.5mm HDPE	45	0.8
2.0mm HDPE	90	1.6
2.0mm HDPE	75	1.2
1.5mm HDPE	60	1.0
2.0mm HDPE	75	1.1
2.0mm HDPE	90	1.4

the second is the liner thickness ranges from 1.5 to 2.5 is that the most common material to be used under mm, but varies from site to site. Experience from mining projects with very high loads has shown that geomembrane liner performance is a function of liner thickness, the geomembrane type, the types of materials immediately above and below the liner, and foundation settlement. The variation in the types of materials present at each site, dictates the type and thickness of the geomembrane liner that is matched with the anticipated high loads.

Based on experience at actual sites with high loads on geomembrane liners, Lupo and Morrison (2007) developed a design matrix, reproduced in Table 3, providing a general guideline for geomembrane liner selection based on the applied load and characteristics of the foundation, overliner materials and liner bedding materials. This table may be used as a general starting point for geomembrane selection (type and thickness). However, specific testing should be conducted to assess geomembrane liner performance for the given site conditions. As noted in Table 2, the liner thickness and type varies even for the same applied loads, which reflects the variability of materials (foundation, underliner, overliner) present at each site.

Table 3. Geomembrane liner design matrix (Lupo and Morrison, 2007)

Foundation conditions*	Liner bedding soil†	Overliner material‡	Effective normal stress (MPa)§		
			<0.5	0.5< <1.2	>1.2
Firm or high stiffness	Coarse-grained	Coarse-grained	2mm LLDPE or HDPE	2mm LLDPE or HDPE	2.5mm LLDPE or HDPE
		Fine-grained	1.5mm LLDPE or HDPE	2mm LLDPE or HDPE	2.5mm LLDPE or HDPE
	Fine-grained	Coarse-grained	1.5mm LLDPE or HDPE	1.5mm LLDPE or HDPE	2mm LLDPE or HDPE
		Fine-grained	1mm LLDPE or HDPE	1.5mm LLDPE or HDPE	2mm LLDPE or HDPE
Soft or low stiffness	Coarse-grained	Coarse-grained	2mm LLDPE	2mm LLDPE	2.5mm LLDPE
		Fine-grained	1.5mm LLDPE	2mm LLDPE	2.5mm LLDPE
	Fine-grained	Coarse-grained	2mm LLDPE	2mm LLDPE	2.5mm LLDPE
		Fine-grained	1.5mm LLDPE	2mm LLDPE	2.5mm LLDPE

*Description of foundation conditions is a relative measure of stiffness. The foundation conditions need to be investigated and tested to determine compatibility with the geomembrane

†Liner bedding soil refers to the soil in direct contact with the underside of the geomembrane. Testing and design calculations are required to assess compatibility with the geomembrane

‡Overliner refers to the material placed directly onto the geomembrane. Testing and design calculations are required to assess compatibility with the geomembrane

§Effective normal stress is the maximum stress onto the geomembrane due to the ore and other externally applied loads.

A critical issue with the performance of the geomembrane liner under high load is the compatibility of liner type and thickness with the site conditions (foundation), materials to be used for the liner bedding and overliner, and the applied load. In other words, there needs to be compatibility between all of the elements used within the liner system. Installation of a geomembrane liner that is not compatible with the site conditions and loading may lead to failure.

Lupo (2008) discusses the importance of compatibility between the different liner system elements and presents flow diagrams that illustrate the logic for assessing liner bedding and overliner for heap leach pad, reproduced here as Figures 2 and 3, respectively. While these flow diagrams are primarily structured toward the design of heap leach pads, the same basic logic is used for the design of bottom liners for tailings storage facilities and overburden storage facilities.

As noted in Figure 3, a geomembrane liner puncture test is often conducted to assess performance of the overall liner system under load. The most common geomembrane liner puncture test used in mining applications is the cylinder test, as described in Environmental Agency (2006), Brachman *et al.* (2000), Lupo & Morrison (2007) and Thiel & Smith (2004).These tests allow the overall performance of the entire liner system under load to be evaluated under highly confined conditions. A schematic of a testing frame and configuration is presented in Figure 4.

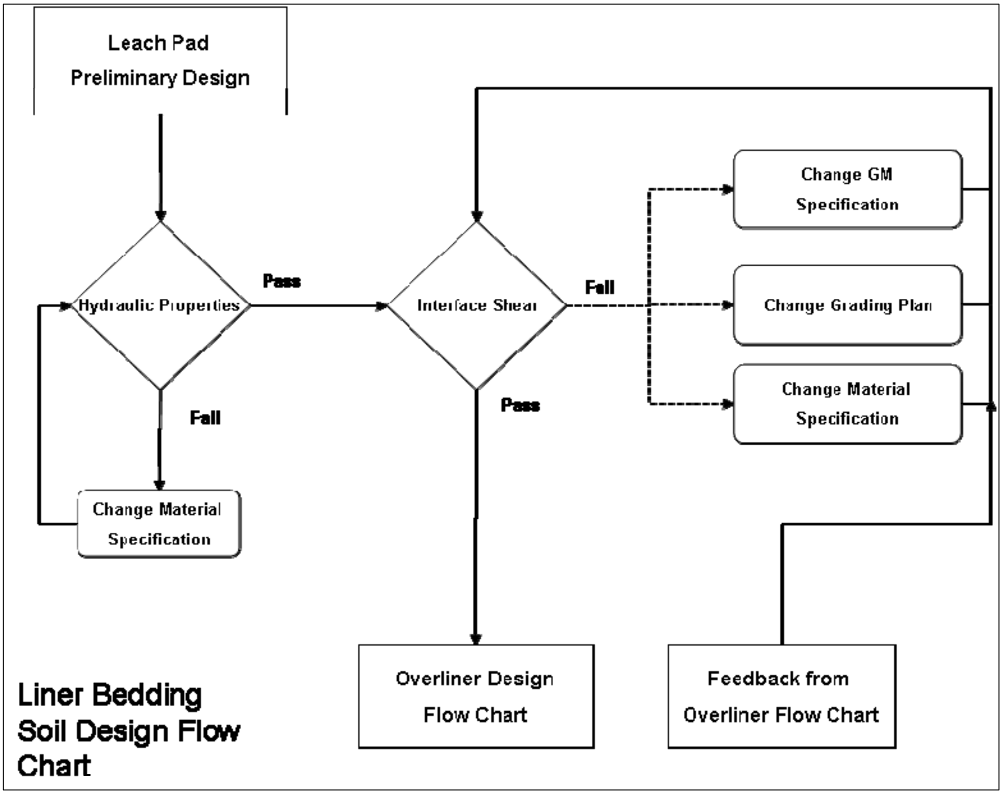

Figure 2 Liner bedding design logic (after Lupo, 2008).

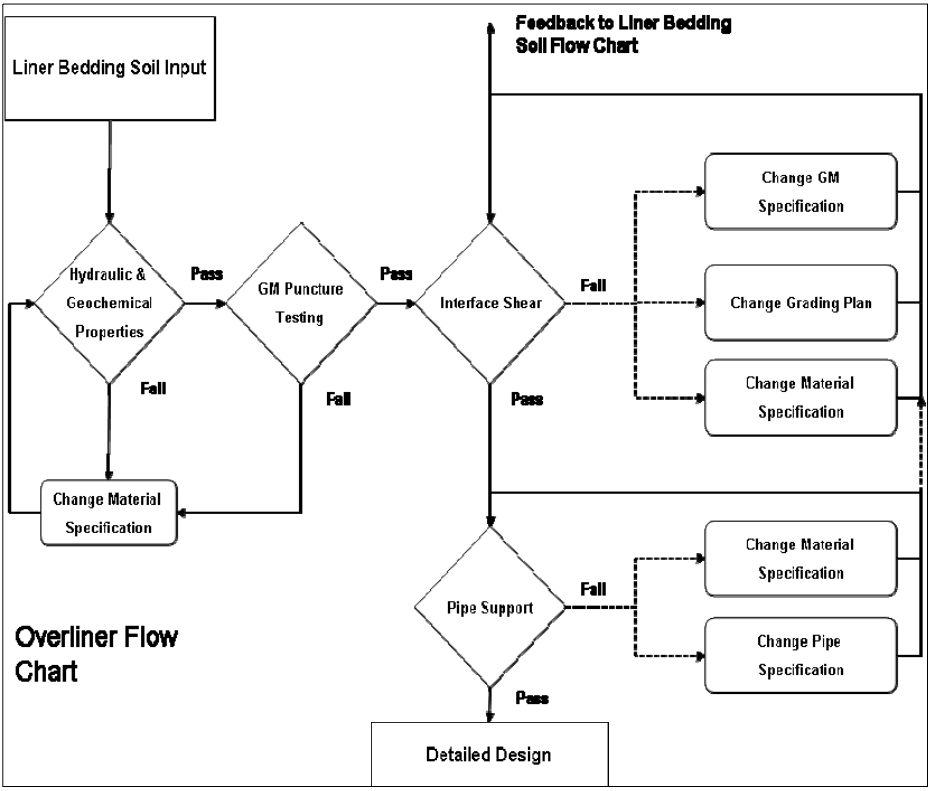

Figure 3 Overliner design logic (after Lupo, 2008).

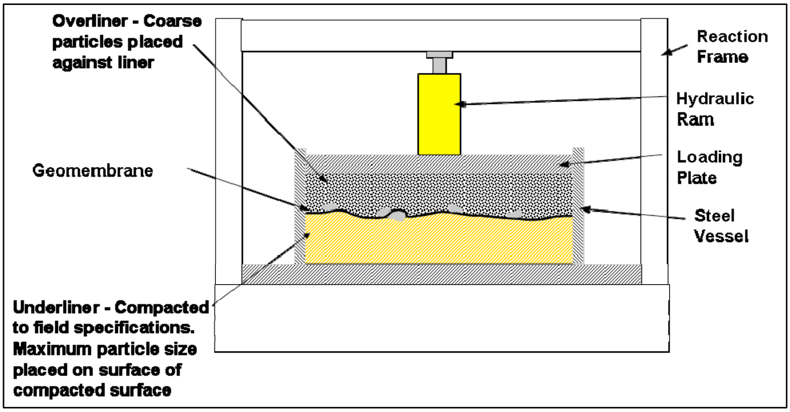

Figure 4 Cylinder test for liner puncture

The testing frame for the liner puncture test consists of a rigid vessel (either cylindrical or a rectangular box) with a loading ram and platens on either end. The testing procedure consists of constructing the liner system under consideration using the same specifications as those to be used in the design of the facility. The liner system is then loaded under the anticipated loading conditions. Upon completion of the test, the geomembrane liner is inspected for punctures, both visually and by applying a vacuum (vacuum pressure of 70mmHg).

The magnitude of the applied load and the time the load is kept on the liner system varies depending on the application and the designer's experience. For example, the Environmental Agency (2006) guidance recommends a maximum load 2.25 times the overburden pressure for tests at 20˚C lasting 1,000 hours, or a maximum load 2.5 times the overburden pressure for tests at 20˚C lasting 100 hours. However, many tests for mining applications are run using only the maximum load held for 24 hours. It is important to note that some geomembrane liner puncture tests have been run to simulate over 300 m of ore (6 MPa) with failure.

One of the shortcomings from running the cylinder tests to assess the performance of a geomembrane liner under load, is the time component. The cylinder tests are short compared to the life of mining facility, which can be on the order of 10 to 50 years. Much of our understanding of geomembrane liner performance under high loads comes from experience in the mining industry. The majority of lined heap leach facilities with high loads (greater than 1.2 MPa) operating around the world today were constructed in the early 1990s, providing approximately 18 to 20 years of continuous operational experience. Of these mining operations, only a few have experienced problems with geomembrane liner performance, and most of these were due to poor construction quality assurance or liner incompatibility rather than the high applied loads. Continued monitoring will extend our knowledge of long-term geomembrane liner performance under high loads.

3.1.2 *Compatibility with acid and alkaline solutions*

Since geomembrane liners are used as barriers to contain process solutions, they may have long-term exposure to high acid or base solutions at mining facilities. For example, geomembrane liners are often used in copper, nickel, or uranium heap leach pads. These types of ores are typically processed (leached) by dripping dilute acid solutions through the ore to leach the contained metal. These acidic solutions, with a pH of 1 or 2, accumulate at base on the leach pad, on the geomembrane liner. Geomembrane liners are also used in gold and silver heap leach pads, where the ores are leached with dilute cyanide solutions with pH values of 10 or more. Under these conditions, geomembrane liners may be exposed to acid or basic solutions for periods exceeding 20 years, or more.

A number of studies have been conducted to assess the performance of geomembrane liners exposed to municipal and industrial landfill solutions, but few studies have been completed for geomembranes exposed to the high acid and basic environments that are common at mining facilities. Gulec et al. (2004) conducted a series of laboratory tests on a 1.5 mm HDPE geomembrane exposed to a synthetic acid mine drainage solution with a pH of 2.1, acid water with a pH 2.1, and deionised water. These tests were conducted at three different temperatures (60°C, 40°C and 20°C). Their results showed that the HDPE was resistant to short-term degradation caused by acid mine drainage. However, their study also noted a faster antioxidant depletion rate in synthetic acid mine drainage than in the acid water or deionised water. Presumably, the greater antioxidant depletion rate was attrributed to the additional metal concentrations in the synthetic acid mine drainage solution. This would imply that long-term exposure could result in degradation of the geomembrane, although it is not possible to quantify the time period based on their results.

Mitchell (1985) examined the compatibility of PVC (thickness = 0.76 mm) and HDPE (thickness=1.0 mm) geomembranes with a simulated leachate from a uranium mill (pH=1.5 to 2.5) and also with the same leachate saturated initially with kerosene, an extractant used in uranium recovery process, at temperatures ranging from 18^{o}C to 78^{o}C for up to 126 days. Tests involved two sided exposure by immersion and column test with axial loading to mimic conditions in an acid leach uranium tailings pond (i.e one sided exposure under loading stress). The tensile breaking strength of immersed PVC declined in all cases after exposure for 30 days. After 120 days, the tensile forces were 0 to 12% below the original value. The 126 days exposure in aging columns showed +5.6, 0 and +2.8% changes in tensile strength when aged at 18, 48 and 78^{o}C, respectively. The elongation at break of immersed samples generally was greater than with virgin material. After 120 days, elongation was increased by 8 to 15% except for the 50^{o}C samples not exposed to traces of kerosene which exhibited a loss in elongation. The HDPE tensile yield force was found to be below the original value in the immersion tests, whereas the simulated field exposures at 47 and 76^{o}C produced tensile yield strengths 4 to 9% greater than the original value. Elongation at yield declined at 30 days exposure except for the sample at 50^{o}C with kerosene. At 120 days the elongation at yield was about 10% above the original value except the 23^{o}C sample without kerosene for which elongation at yield was unchanged from the original value. The simulated field exposures samples had 7 to 9% increase in elongation similar to the immersed samples. Inconsistency in the results between the two test methods was put to the test conditions which included stresses being present during simulated field exposure and samples being dry when tested. Of the materials tested, HDPE was found to be the most stable with its tear strength changing less than 6%, and tensile strength changing less than 10%, from their original values. However, this test program did not consider OIT.

Table 4: Mechanical properties of HDPE, LLDPE and PVC geomembranes after exposure to 98% sulfuric acid for 120 days, (%change from original), (modified from Thiel and Smith, 2004, Scheirs, 2009).

		Materials		
Property	Standard	HDPE (thickness=1.5 mm)	LLDPE (Thickness 1.5 mm)	PVC (thickness = 0.75 mm)
Tensile strength at yield (%)	ASTM D638/D882	2 (MD) -4 (XMD)	0 (MD) 0 (XMD)	173 (MD) 188 (XMD)
Tensile strength at break (%)	"	-4 (MD) -4 (XMD)	-7 (MD) -11 (XMD)	54 (MD) 54 (XMD)
Elongation at yield (%)	"	-5 (MD) -5 (XMD)	-10 (MD) 9 (XMD)	NA
Elongation at break (%)	"	5 (MD) 0 (XMD)	-7 (MD) -12 (XMD)	-66 (MD) -76 (XMD)
Puncture resistance (%)	ASTM D4833	-3	1	130
Tear resistance (%)	ASTM D1004	-3 (MD) 2 (XMD)	-5 (MD) -5 (XMD)	107 (MD) 112 (XMD)
Hardness (%)	ASTM D2240	0	5	31 (indicates loss of plasticizer)
OIT (%)	ASTM D3895	-64 (indicate loss of antioxidant)	-73 (indicate loss of antioxidant)	NA

Note: MD= machine direction, XMD=cross machine direction, for PVC, tensile strength at 'yield' was taken at 100% elongation as the yield point is indeterminate; OIT is only applicable for polyethylene.

Thiel and Smith (2004) evaluated the compatibility of HDPE, LLDPE and PVC geomembranes with concentrated sulfuric acid (H_2SO_4), at the upper limit of what may be added to the ore, over a 120-day exposure programme in the laboratory. Samples of each geomembrane were exposed to 98% H_2SO_4 solutions at 50°C. Samples were then tested each 30 days for retention of physical properties. Table 4 shows that both HDPE and LLDPE geomembranes and in particular their additive packages are adversely affected by the acid. Both types of polyethylene geomembranes performed very well given the aggressive environment with tensile strength and elongation properties after 120 days generally within 10% of the original conditions. However, they exhibited losses in oxidation induction time (OIT) of 73% for LLDPE and 64% for HDPE. Oxidation is generally regarded as the key degradation mechanism affecting the long term durability of polyolefin geomembranes. Their oxidation stability/resistance can be determined by the oxidative induction time (OIT) test (ASTM D3895, ASTM D5885). OIT is a key indicator for longevity and loss of OIT is a precursor to failure by ageing (Thiel and Smith, 2004). Depending on cure periods, cycle times and design life, cumulative exposures of up to 10 months are possible but 4–6 months is probably more typical. Since an OIT reduction of 64–73% was measured in 4 months the longevity of the geomembrane must be a concern for these pre-curing applications. However, Scheirs (2009) indicated that this problem could be solved by using co-extruded HDPE with a top layer made with an additive package specifically formulated for this environment (e.g. acid-tolerant non-basic HALS stabilizers).

PVC exhibited drastic loss of flexibility (i.e., a negative change percentage), within the first 30 days. The increase in tensile strength for PVC was accompanied by a reduction in elongation, which means that the material has lost plasticizer and is becoming brittle in just 30 days (Table 5). It was observed that the immersion solution turned very dark in the first 24 h, suggesting a very rapid leaching of plasticizers. Thiel and Smith (2004) concluded that PVC was not suitable for use in concentrated acid pre-curing operations, even for relatively short exposure periods. However, they indicated that thicker PVC may be suitable for short term applications, but this needs to be demonstrated. Furthermore, Thiel and Smith (2004) indicated that these tests results should not be considered as universally applicable and that project specific testing to be performed for the actual material to be installed. Denis and Marcotte (2009) pointed out that recent technical developments and industry standards have now adorned PVC with the same specification rigour and design algorithm approaches associated with HDPE for heap leaching.

Table 5: Mechanical properties of PVC geomembranes after exposure to 98% sulfuric acid at different immersion times, (%change from original), (modified from Thiel and Smith, 2004, Scheirs, 2009).

		Immersion time (days)		
Property	Standard	30	60	120
Tensile strength at break (%)	ASTM D882	31 (MD) 27 (XMD)	62 (MD) 40 (XMD)	54 (MD) 54 (XMD)
Elongation at break (%)	“	-58 (MD) -74 (XMD)	-71(MD) -75 (XMD)	-66 (MD) -76 (XMD)
Puncture resistance (%)	ASTM D4833	129	120	130
Tear resistance (%)	ASTM D1004	119 (MD) 122 (XMD)	122 (MD) 110 (XMD)	107 (MD) 112 (XMD)
Seam shear elongation (%)	ASTM D6392	-90	-94	-86

Note: MD= machine direction, XMD=cross machine direction,.

Gulec et al. (2004) evaluated how the exposure to acid mine drainage (AMD) from metallic mine wastes affected the polymer properties of HDPE geomembranes. Geomembrane samples were immersed for 22 months in synthetic AMD at temperatures ranging from 20°C to 60°C. The synthetic AMD contained Fe (1500 mg/l), Zn (350 mg/l), Cu (35 mg/l), SO_4 (4500 mg/l) and Ca (200 mg/l) and was prepared to achieve pH of 2.1. Results of the melt flow index (MFI) and Fourier transform infrared spectrum (FTIR) showed that exposure to AMD had little effect on the polymer properties. However, it was observed that the MFI was higher that for exposure to DI water suggesting that some alteration of the polymer might have occurred. The antioxidant depletion rates of HDPE geomembranes after immersion, in synthetic AMD were compared with results reported for municipal solid waste MSW leachate. Their work indicated that the antioxidant depletion rate for exposure to MSW leachate is two to four times higher than the rate for AMD exposure.

Gassner and Scheirs (2010) conducted a series of tests on HDPE (thickness 2.5 mm) and PVC geomembranes (thickness 0.76 mm) considered for base lining and/or capping systems in an alkaline environment. The geomembranes were immersed in high pH mining residues (pH = 12.4 to 12.7 and TDS = 15,000 to 23,000 mg/L) at temperatures of 50°C and 82°C, respectively. Their results are summarized in Table 6. The changes measured relate to an immersion period of 28 days for the mechanical testing samples and 56 days for the plasticiser and antioxidant content testing at 82°C.

Table 6: Measured changes in geomembrane samples

	HDPE		PVC	
	unexposed	exposed	unexposed	exposed
Plasticiser (%)			33.8	27.6
HP OIT (mins) at 150 deg.C	355	240		
S-OIT (mins) at 200 deg C	161	119		
Tensile elongation (%)	700	630	330	260

Hindered amine light stabilisers (HALS) package was used for the HDPE samples and the plasticiser for the PVC samples was dioctylphthalate. The PVC geomembrane samples showed a reduction in elongation indicating that the material has lost plasticizer or has been degraded via ester hydrolysis by the residue. It was estimated that based on the measured rates of depletion the plasticiser content in the geomembrane may reduce from 33.8 % to 17 % in 18 years. The testing also indicated that there was loss of phenolic antioxidants of the HDPE geomembrane samples as indicated by the significant drop in the standard OIT (S-OIT) values. The hindered amine stabilisers were less affected by the alkaline residue as reflected by the higher percentage retained high pressure OIT (HP-OIT) results. It should be noted that not all HDPE geomembranes are the same, Jeon et al (2007) showed that an HDPE geomembrane was more susceptible to alkaline solutions (antioxidant depletion rate was faster) because it was stabilised with phenolic and phosphates antioxidant.

As described by Viebke et al. (1994) and Hsuan and Koerner (1998), the oxidative degradation of HDPE geomembrane can be divided into three distinct stages: Stage I, depletion time of antioxidants; Stage II, induction time to onset of polymer degradation; and Stage III, degradation of the polymer to decrease some property or properties to an arbitrary level (e.g. to 50% of the original value). Therefore, any testing program to assess the performance of geomembranes to mining process solutions, should consider changes to the OIT. Rowe et al (2008) found that antioxidants were depleted at a faster rate in geomembranes exposed to acidic (pH 4) solutions as compared those exposed to basic (pH 10) solutions.

As presented above, the results from laboratory test programs on geomembrane materials indicate that under high acid conditions (at concentrations above that used at mines), only minor degradation occured in the mechanical properties of HDPE and LLDPE, while PVC degraded significantly. Some level of OIT reduction occurred in all geomembrane materials exposed to acid solutions. Very little testing has been done to assess performance of geomembranes exposed to basic solutions. Of the work that has been conducted (Rowe et al, 2008), very little affect has been noted due to exposure to basic solutions.

In North America, South America, and Australia, HDPE geomembranes are the most common liner material used in operating mines with acidic process solutions, like copper heap leach pads or tailings storage facilities. Some of these mines have been in continuous operation for over 18 years and have shown no indication of geomembrane liner degradation. In mining operations with basic process solutions, like gold heap leach pads or tailings storage facilities, HPDE, LLDPE, and PVC are commonly used as liner materials. Of these materials, only PVC has shown to degrade. However, the degradation was attributed to exposure to high ultraviolet radiation rather than exposure to basic process solutions.

According to Scheirs (2009), HDPE and fPP geomembranes are resistant to sulfuric acid (H_2SO_4) up to concentrations of 70%. Concentrations of acid greater than 80% even at room temperature can cause oxidation. While HDPE and fPP are resistant to concentrated hydrochloric acid (HCl) and hydrofluoric acid (HF), there is some diffusion of HCl (at concentrations >20%) and HF (concentrations >40%) which does not damage the geomembrane but causes secondary damage (corrosion) of the base substrates (e.g. concrete or metal tanks).

3.2 *Performance of geopipes under high loads*

Geopipes are used extensively in mining operations for solution conveyance and solution collection. The geopipes are generally constructed from Polyethylene (PE) or PVC, and are available as smooth (solid wall) or corrugated wall pipes. Solid wall pipes are commonly used in applications where internal pressures, between 340 to 1,760 kPa, are present and/or where the pipe may be subjected to high external loads. Corrugated PE (CPe) pipes are available as single-walled, double-walled, and triple-walled pipes. Corrugated wall pipes provide a light-weight alternative to solid wall pipe, and may be used in applications with high external loads.

For applications with high internal pressures (mainly solution conveyance), geopipes are not buried or are only nominally covered with soil. This allows the geopipe to be easily inspected and repaired. In solution collection applications, such as underdrains, heap leach pad collection pipes, and tailing storage facility drainage pipes, geopipes are buried to allow placement of materials over the pipe. While the pipe itself may not be buried to a great depth, the thickness of the material placed over the pipe can be significant, leading to the development of a high stress field around the pipe. Currently, there are several mines that have geopipes covered with 200 meters of material or more.

Traditional methods for the design of buried geopipes follow from work of Marston and Anderson (1913) and Spangler (1941), which consider pipes with shallow burial depth. The work by Spangler (1941) was later revised into what is known as the Iowa Method and the Modified Iowa method (USDA 1990), and has been a standard for design for a number of years. These methods generally consider the following performance criteria:

- Pipe Wall Crushing: Wall crushing occurs when the wall stress exceeds the long-term compressive strength of pipe material;
- Pipe Wall Buckling: Wall buckling occurs when the total soil pressure exceeds the pipe critical buckling pressure; and
- Ring Deflection; typically, pipe deflection is calculated using the Modified Iowa method (USDA 1990). The design limit for ring deflection is commonly assumed to be approximately 5 percent; Krizek (1990) reports that this value was derived from the inspections of numerous pipe installations, where the average deflection before failure was determined to about 20 percent of the pipe diameter; assuming a safety factor of 4, results in design ring deflection of 5 percent.

A number of field stress measurements and laboratory studies conducted by Adams *et al.* (1988), Reeve *et al.* (1981), Shad *et al.* (1993), Watkins (1990), Watkins *et al.* (1987) and Watkins & Reeve (1979) have demonstrated that, due to arching within the soil column above the pipe, the pressure at the pipe crown can be significantly lower than that predicted by the Modified Iowa method, thereby reducing the pipe deflection. This phenomena is illustrated in Figure 5.

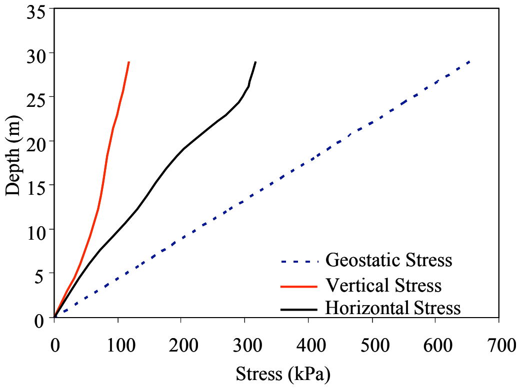

Figure 5. Stress arch above pipe (after Adams *et al.* 1988)

The affect of stress arching around pipes has been the subject of several studies by Adams *et al.* (1988), Reeve *et al.* (1981), Sargand *et al.* (1993), Selig (1990), Valsangkar & Britto (1978), Watkins (1990), Watkins *et al.* (1987) and Watkins & Reeve (1979). More recently, Brachman et al (2008) conducted laboratory tests on geopipes up to 200 kPa with different pipe envelopes. Their testing program also showed a close relationship between pipe deformation and pipe envelope quality (type of material and level of compaction). Figure 6 shows the generalized behavior of the geopipe to external loading, as a fucntion of pipe stiffness and the stiffness (density) of the pipe envelope material (the material around the pipe).

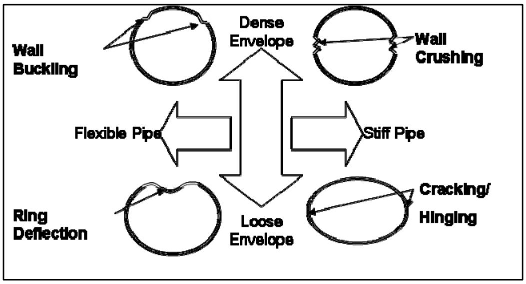

Figure 6 Pipe and pipe envelope interaction (from Watkins & Reeve 1979)

Figure 7 presents a summary of field-scale tests completed on various size and type of geopipes. It is important to note that the pipes presented in Figure 7 did not collapse, even though the deflections exceeded 5 percent in most cases.

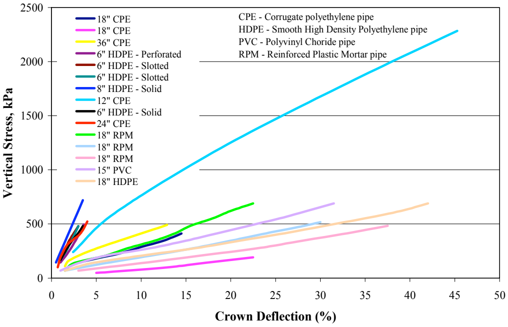

Figure 7. Measured pipe deformation from deep burial field tests

It is clear from Figures 6 and 7, that design of geopipes for high loading conditions must consider the pipe material as well as the pipe envelope. Methods such as those presented by Burns & Richard (1964) and Höeg (1968), use closed form, plane-strain solutions for thin, circular conduits buried in an elastic soil. These methods assume the geopipes are embedded in an infinite field of homogenous pipe envelope material. In spite of this simplification, these equations are useful for design as they consider the interaction between the geopipe and the pipe envelope. These methods have been used by Brachman et al. (2001) and Lupo (2001) to assess the performance of plastic pipes under high overburden pressures.

Numerical methods have also been used to analyses geopipe performance under various loading conditions. For example, Katona (1988) used a finite-element soil-structure code to determine the maximum burial depth for CPe pipe up to 760mm diameter. In this analysis, the maximum burial depth was determined to develop no more than 7.5% ring deflection. Using this criterion, the maximum calculated burial depths for CPe pipes were found to be approximately 10m for most pipe sizes. This study highlights the importance of defining the acceptable design/performance criteria for the geopipe. The design/performance criteria will likely vary depending on the type of facility, hydraulic considerations (head and flow rates), stability, and construction materials. For example, in some mine facilities, high ring deflections (up to 20%) may be acceptable, as long as the geopipe has sufficient flow capacity. In these cases, the design/performance criteria must consider minimum open area (for solution flow), maximum crown deflections, type of pipe envelope materials, and construction method. The construction method is critical, as many pipes have failed at mines due directly to poor pipe and pipe envelope placement and compaction. It is also important to note that often an arbitrary value, such as 5 percent (a traditional value based on stiff pipe design), is selected for acceptable pipe deflection. A low deflection limit of 5 percent can easily be exceeded in most construction applications, but with no adverse affect on the pipe. Recent work by Brachman et al. (2008) also indicates that the pipe deflection limit of 5 percent may be unnecessarily conservative. The acceptable deflection should be based on the desired performance based on engineering calculations, not an arbitrary value.

Figure 8 Wall crushing in geopipe

To assess the performance of geopipes under load, a number of unpublished field investigations using video surveysof buried pipes have been completed. Experience gathered from these investigations at mine sites has shown that the performance of the pipe envelope primarily governs the geopipe response. Figure 7 presents a photograph of a geopipe with signficant wall crushing due to high loading conditions. This crushing occurred as a result of poor compaction around the pipe envelope.

Given these observations, careful consideration should be given to the quality and compressibility of the pipe envelope material. For example, Figure 8 presents a family of compression curves from some pipe envelope materials. As shown, fresh crushed rock provides a relative “stiff” material, with a vertical compression of less than 7 percent at 2.5MPa. At the same vertical stress level, a well graded gravel had a compression of nearly 15 percent, while a weathered crushed rock had a vertical compression of over 20%. If one makes a simple assumption that the pipe ring deflection is equivalent to the vertical strain of the pipe envelope, the fresh crushed rock would be recommended to minimize ring deflection of the pipe and provide sufficient arching support.

It is important to consider that the pipe section shown in Figure 8 may appear unacceptable. However if the pipe can still effectively convey flow and perform as required, the appearance of the pipe is immaterial. On a final note, the authors are aware of at least nine locations where fragments of PE pipe were found in the pipe discharge. Video surveys of these pipes found areas where portions of the pipe appeared to fail in a brittle fashion, which is unusual for PE pipe behavior.

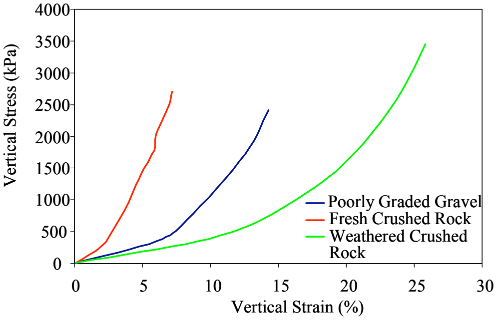

Figure 9. Pipe envelope compressibility

3.3 *Storage tanks*

In an effort to reduce costs the stainless steel tanks used by many mines to process pregnant copper, nickel, and uranium leachates in the solvent extraction and electrowinning (SX/EW) phases have been replaced by concrete basins lined with thick high density polyethylene (HDPE) geomembrane. The concrete nominally provides the strength while the geomembrane simply acts as a barrier to protect the concrete from the process solutions. Swelling of the HDPE and other polyolefin liners can occur due to absorption of organic components (namely kerosene) from solvent extraction (SX) process solutions such as that used in copper and uranium ore extraction. This absorption causes large bulges to form thereby placing peel stresses on critical welds (e.g. between the loose liner and anchored liner). This can also lead to cracking along heat affected areas of the welds. Another consequence of the absorption and swelling of organics is that repair work on the cracked weld would be very difficult (Peggs, 2007, 2010).

3.3.1 *Case Study, uranium mine liquor (Scheirs, 2009)*

An HDPE stud liner in a uranium mine underwent significant swelling due to diffusion of kerosene into the polyethylene. Precedents should have alerted the material supplier to potential compatibility problems between polyethylene and organic liquids. It should have been apparent to the materials supplier that HDPE has a tendency to soak up kerosene and expand. If the HDPE is constrained or is installed as a 'tight fit' (as in this concrete tank application), then the expansion will set up resultant stresses in the liner structure that can lead to failure, especially at the heat-affected area of welds.

An HDPE stud liner is known to absorb kerosene from mine process solutions resulting in swelling, bowing and the development of blisters in the liners on the walls and floors. This swelling leads to stressing of critical welds and separation of the studs from the back surface of the sheet. Attempts to repair swollen liners are compromised by the evolution of absorbed organic vapours as the base liner has been heated during repair welding.

An HDPE Stud liner exposed to a solvent extraction (SX) solution at an operating temperature of 45–55 °C is likely to fail by stress cracking due to:

- Swelling-induced stresses imposed on the weld region by the swelling and volumetric expansion of the HDPE sheets and pull-off of the studs/anchors.
- Swelling-induced stresses leading to shear and peel forces acting on the adjacent welds.

It should be emphasized that kerosene does not directly chemically attack the liner itself, but rather it provides the conditions for other agents to accelerate the degradation of the HDPE. In particular, kerosene swells the HDPE and therefore increases its permeability. The solubility parameter for kerosene is in the range 15.6–15.8 $(MPa)^{1/2}$ whereas the solubility parameter for polyethylene is 16.4 $(MPa)^{1/2}$; therefore polyethylene has a high affinity for kerosene. The antioxidant and stabilizer additives are an essential formulant in HDPE and these are susceptible to extraction by good solvents (kerosene is an excellent solvent). The loss of antioxidants by solvent extraction renders the HDPE susceptible to thermal oxidation.

3.4 *Lining of evaporation ponds*

Probably the largest installation of a PVC geomembrane in the world is in the rather unlikely location near the Atacama desert in Chile, at an elevation of about 2130m (see Berube et al., 2007, and Rollin et al., 2010). The company Sociedad Quimica y Minera de Chile S.A. (SQM) extracts components such as potassium and lithium salts by pumping the highly saline groundwater into lined evaporation ponds, allowing excess water to evaporate and recovering the resulting salt deposits, before starting the process again. In this application it is extremely important (from a commercial viewpoint) that the lining system does not leak at all, as it takes approximately one year to yield approximately 1m of salt (Berube et al., 2007). The flexibility of PVC geomembranes has resulted in this produce becoming the preferred option in this application, where chemical compatibility with the highly saline water does not appear to be a problem.

3.5 *Applications in waste containment*

Mining produces enormous volumes of waste material annually. In Australia, for example, the annual production of mining waste is about 1.8 billion tonnes, which dwarfs the annual volume of municipal solid waste by a factor of about 120. The waste is in one of two primary forms; waste rock and tailings. In any mining operation, in order to access the valuable, mineral bearing rock, it is first necessary to strip or excavate non-mineral bearing rock. This rock, which has been fragmented during the drilling, blasting and excavating process, is dumped in dedicated storage areas, known as waste rock dumps. These dumps often exceed 200m in height, and there is currently a dump in the planning stages that will exceed 700m in height from the toe to crest (Valenzuela et al., 2008). Tailings are the by-product of the crushing, milling and chemical extraction process used to recover the valuable mineral being mined. Tailings are generally sand sized or finer, and are managed by pumping at low solids contents and depositing into purpose-built impoundments, known as Tailings Storage Facilities (TSFs). These TSFs are characterised by the very large volumes of entrained and impounded water, and have often been associated with catastrophic failures leading to multiple fatalities (Blight and Fourie, 2005). If one considers that in order to recover a gram or two of gold, one tonne of mineral bearing rock must be crushed and processed, and at least another tonne of waste rock is produced, an idea can be gained of the enormity of the waste management problem faced by the mining industry.

To give some examples: in the phosphate industry in Florida, USA, the tailings have very low solid contents (of the order of 3% to 6% solids) and consolidation to the required solids content of 20 to 25% may take several decades (Shang and Lo, 1997). As far back as 1972, Vasan (1972) indicated that the volumes of tailings produced by the phosphate mining industry in Florida had exceeded 6 billion tonnes of fluid tailings. The bauxite residue produced from just one (of many) aluminium plants in Western Australia produces over 4 million tonnes of red mud annually. The mud is deposited at a solids content of around 56% and has a pH in excess of 12, with elevated levels of sodium hydroxide in addition to other salts. A key feature of currently used technology for the management of mine tailings is the use of water as the medium of transport. The solid tailings are mixed with water and pumped to the tailings storage facility (TSF), sometimes over large distances (in excess of 5km). This requires pumping in turbulent flow mode, which necessitates relatively low solids concentrations; these may be as low as 3% in exceptional circumstances (phosphate wastes), but more typically are around 20% solids. Upon deposition, large volumes of water separate out from the solid material, and this water must be stored and managed in such a way that it poses no risk to the environment. There is usually a substantial head difference between the elevated pond level and the surrounding ground surface, resulting in flow occurring, either towards the outer slope of the TSF if downward drainage is impeded, or down and into the subsurface, if drainage is not impeded. The kind of facility most analogous to a TSF is a landfill, with the major difference being that in a landfill an adequate drainage system is installed to ensure that the head on the underlining system is restricted, usually to around 0.3m. In a TSF, this is not the case, with the full hydraulic head acting on a liner system (if indeed a liner is present).

According to Majid et al (1998), a typical plant producing oil from bitumen-impregnated sands, currently producing 100,000 barrels of synthetic crude oil per day requires the processing of 100,000 m^3 of ore, resulting in a reject stream (tailings) that consists of 100,000 m^3 of coarse sand (which usually contains residual bitumen), 2,000 m^3 of coke, 100 m^3 of fly ash and 20,000 m^3 of fine tailings consisting of bitumen impregnated material that is predominantly clay, at a solids content of about 30%. The implication of this latter statistic is that very large volumes of water are locked up in these fine tailings, water that cannot be released to the environment without treatment. Many tailings streams can pose significant environmental risks. Examples include the very high pH of bauxite residue, heavy metals associated with base metal mines, and the potential for the generation of acidic drainage water if the tailings contain appreciable quantities of sulphidic minerals and have no intrinsic buffering capacity.

Aside from the enormous volumes of mine tailings produced annually, an equal (or usually greater) volume of waste rock is also produced. To illustrate the problem, a current nickel mine in Western Australia required the removal of 80m of overburden soil and barren rock before the ore body was exposed. Remembering that the slopes of the excavated pit have to be sufficiently shallow to ensure a slope stability problem does not ensue, the ratio of waste rock to ore that is mined (termed the stripping ratio) can sometimes be significantly greater than one. Environmental problems occur when some, or all, of the waste rock contains minerals such as pyrite or other sulphide minerals. When exposed to oxygen and water, these minerals oxidise and form what is effectively a dilute sulphuric acid. This acid drainage will seep out of the water rock dump over an extended period of time, certainly throughout the operational phase of the dump, and even beyond if not prevented by techniques such as preventing infiltration from rainwater (more of this later). The magnitude and frequency of acid drainage releases depends on the climatic conditions at the site in question. Thus although waste rock dumps do not have the same intrinsic problems of excessive water as do TSFs, there is a potential risk associated with the issue of acid drainage to be considered.

3.5.1 *Lining of waste storage facilities*

As might be expected, the storage of these very large volumes of waste rock and tailings results in storage facilities that cover very large areas of land. Some of the oilsands TSFs exceed 100 hectares, and areas exceeding 120 hectares are not uncommon in base metal, gold and platinum mining operations. Given these extremely large volumes, and the potential for release of contaminants into the environment, it is surprising to find that relatively little has been written about the application of geosynthetics to mine waste storage applications. Even more interesting, and perhaps also surprising, is the relative laxity of many countries regulations when it comes to managing the impacts of mining. Many jurisdictions do not require any form of underliner to a TSF, much less an underliner for waste rock dumps. The reason for this apparent anomaly appears to have been anchored in the argument that installing an underliner is uneconomical. In other industries this argument has been rejected, so it is open to speculation why it should not be the case for the mining industry. Arguments in favour of the omission of underliners (aside from the very real cost implications) include the resulting requirement for effective (and long-lasting) underdrainage systems to maximise consolidation of tailings and the resulting strength gain, the implementation of active management systems to collect and remove excess water, and the recent move to much higher density tailings (thickened or paste tailings), where the volume of water is low enough to be retained by the inherent water retention capacity of the tailings itself.

There are very few examples of lined TSFs internationally. Exceptions are the bauxite residue disposal sites, where the very high pH and salt load of the leachate, often coupled with the proximity to residential areas, has resulted in mining companies such as Alcoa World Alumina and BHP-Billiton voluntarily implementing the installation of lining systems. Other examples include Newmont operations in Ghana, west Africa, but the overriding majority of current (and planned) TSFs will not have an underliner installed.

A lining system below a TSF will not have the same issues of ultra high loading common to the heap leach application, but issues of chemical compatibility with extreme pH solutions still exist (Rose and Cravotta, 1999), and appropriate compatibility testing programmes are essential, as with any application of geosynthetics in critical conditions. Although they are unlikely to be used in heap leach applications (because of installation and strength concerns) geosynthetic clay liners (GCLs) may offer a viable alternative in future waste storage facility lining systems. As with all clay- or bentonite-based lining systems, leachate incompatibility can reduce expected swelling and increase internal pore size and connectivity, therefore increasing advective transfer of the pore fluid as well as diffusion of contaminants. Hydraulic performance of GCLs depends in most cases on the k_{sat} of the bentonite. In general, laboratory k_{sat} to water of different types of geotextile-supported GCL varies between $\sim 2 \times 10^{-12}$ and 2×10^{-10} m s^{-1} (Bouazza et al., 2002), depending on the applied confining stress. Swelling under confinement from overburden pressures (and also the physical bonding within the GCL itself) decreases hydraulic conductivity, improving performance as an environmental barrier.

The ability of bentonite to maintain a gel state with low hydraulic conductivity can be seriously impaired when exposed to leachates of excessive ionic strength (>0.3 M), elevated temperatures (>60 ^{o}C) and either strongly acid or strongly alkaline pH (Gates et al, 2009). While there is very little research literature available directly related to mining applications of bentonite and/or GCLs, predictions can be made regarding the performance of GCLs under these conditions (Bouazza et al., 2006; Gates et al., 2009, Hornsey et al., 2009). Elevated temperatures increase the hydraulic conductivity of GCLs due mainly to the evolution of the permeant viscosity with temperature, but also probably due to a redistribution of intra-and interparticle pores (Bouazza et al., 2008). High ionic strength results in flocculation, aggregation and increased porosity of the bentonite thereby increasing hydraulic flux (Shackelford et al., 2000; Likos et al., 2009) and the presence of high dissolved salt load itself causes a strong diffusion gradient (Shackelford et al. 2000). Some treatments are available that improve bentonite swelling in high ionic strength (eg, Katsumi et al., 2008).

Acid attack of clays has been used to advantage industrially (e.g. Gates et al., 2002), but less is known directly regarding the effect of strongly acid pH on performance of GCLs. We can assume, however, that in general pH<3-4 will have detrimental effects on bentonite performance due mainly to dissolution of smectite (Jozefaciuk and Matyka-Sarzynska, 2006; Gates et al., 2009; Shaw et al., 2009). Maintaining the GCL in a hydrated state prior to contact with the leachate will likely slow the ingress of acid and extend its useful lifetime (Shackelford et al., 2000; Gates et al., 2009). In general, we urge a cautious approach in the use of GCLs as barriers to strongly acid leachates. More information is available regarding the effects of alkaline pH on barrier performance. While, strongly alkaline pH solutions (>pH 12) cause dissolution induced transformations of smectite (Gates et al., 2009), if sufficient silica is available and the hydraulic flux is initially low, precipitation reactions can result in pore filling and maintenance of good barrier performance (Benson et al., 2008; 2009; Gates and Bouazza, 2009). Indeed, Lange et al. (2007) have shown that GCLs might provide a significant benefit, demonstrating marked retention of various metals following permeation with two different mine waters.

Specifications regarding the use of geosynthetics vary from country to country fall in two general categories, either specifications of their minimum properties or how they should be produced, transported and installed, or alternatively, rules on their use in specific applications. This distinction is usually referred to as the prescription versus performance debate.

In Brazil, the Brazilian Association of Technical Standards (ABNT - Associação Brasileira de Normas Técnicas) issued rules that shall be respected by the industry to produce, to transport and to install geosynthetics, in general, or geotextiles or geomembranes in particular. Items such as composition, properties, production control, testing procedures, etc. are part of these standards. Rules NBR 12.569/2003; NBR 12.553/2003; NBR 12.592/2003; NBR 12.568/2003; NBR 15.227/2005; NBR 12.593/1992; NBR 12.824/1993 are examples of rules about geosynthetics in general or geotextiles, geomembranes, in particular.

Related to specific applications, normally one sees references to the use of geomembranes as a part of lining systems, in landfills or ponds, both to contain the residues or water or to cover them. In Brazil, residues are classified according to the rules of ABNT, specifically NBR 10004 (NBR - Brazilian Standard). This rule defines residues as hazardous (Class I) or non-hazardous (Class II). Class II is subdivided in non-inerts (Class IIA) and inerts (Class IIB). Deposits of hazardous residues shall be designed and constructed according to rules ABNT NBR 8418, December/1983, "Presenting hazardous industrial landfills designs", and NBR 10157, December/1987, "Hazardous residues landfills - criteria for design, construction and operation". Rule NBR 10157 specifies, in its item 5.2, that the lower lining system must show the following profile, from top to bottom:

- upper drainage layer to remove percolated water, above the liner
- liner
- leak detection layer

It is interesting to note that the Brazilian regulations do not specify how this liner has to be constructed or what materials shall be used. In ABNT rule NBR 8418, item 5.1.8.4, there is a reference about the possibility of using "artificial lining system" or "the use of clay as a lining material".

Brazilian waste storage sites, whether storing hazardous residues or not, can be constructed with or without geomembranes, with or without composite liners. Even this latter situation is not "against the rules". To counteract this situation, design companies adopt practices and standards from other countries (such as from Europe or North America) for use in Brazil, normally searching for the "best available technology", to protect the client and to satisfy the environmental agencies. In general, one can say that in Brazil the majority of geomembrane applications are of the HDPE type, and normally 1.5 mm (60 mils) thick. In only some projects are double composite liners used. In both cases it is common to use the American standards. Although these rules are not laws in Brazil, it is likely that judges will follow them because of a lack of appropriate legislation. In such circumstances, it is their understanding that they represent the law, so they have the force of the law.

3.5.2 *Use in filtration applications.*

To provide some control over the capture and control of water within a TSF, geotextiles are often used as a component of a drainage system. Typical examples include the lining of drainage collection trenches, and the sleeving of drainage pipes. As with similar civil engineering applications, conventional rules of particle size compatibility and the need for correct installation procedures apply. Compatibility studies of geotextiles in contact with mine waste leachate or liquors are scarce and very limited information is available in literature. However, Gulec et al. (2005) indicated that that no major changes in the hydraulic and mechanical properties of polypropylene geotextiles were observed after immersion in AMD for 22 months. Similar results were reported by Grubb et al. (1999) who indicated that AMD did not reduce the retained strength of polyester geotextiles below 70% at 180 days. However, they observed that strength losses were greater and more rapid than for PET geotextiles exposed to concentrated acids and salt solutions for longer duration and/or higher temperatures. Grubb et al. (2001) reported on the short term mechanical durability of polyester (PET) and polypropylene (PP) geotextiles in an alkaline environment. PET and PP geotextiles samples (one light, 290 g/m^2, and 4 heavier, 420 to 560 g/m^2) were embedded in freshly deposited alkaline tailings with a pH of 11.3 and 178 mg/L total cyanide for one year. The average retained strength of the light PET geotextile was found to vary widely suggesting that alkaline pH of the tailings had an effect on its strength. However, the average retained strength of the heavier polyester geotextiles was found to be comparable to the polypropylene geotextiles for the range of conditions investigated. Grubb et al. (2001) concluded that PET geotextiles were not significantly more susceptible to deterioration by the alkaline tailings than the PP geotextiles. However, the large body of work available in literature suggests that alkaline agents with high pH can degrade the properties of polyester geotextiles via alkali-catalyzed hydrolysis and that PP geotextile properties are less affected in an alkaline environment.

A particular problem with many TSF drainage collection systems has been clogging of geotextiles with chemical precipitate (Legge et al., 2009). Although it is likely the problem would also occur with mineral drainage systems (such as gravels), the large surface area of some geotextiles may make them more susceptible to this problem. One simple solution has been to incorporate a U-bend in the drainage pipe, effectively excluding oxygen from the drainage pipe. There is also some evidence that the particular nature of tailings deposition, where a low solids content slurry is deposited against a geotextile, may result in a significant degree of particle intrusion and capture within the geotextile (in the case of a nonwoven product. Evidence of this was provided by Beirigo et al. (2009), who exhumed geotextiles from a TSF in Brazil. They found evidence of particle intrusion, as well as surface blinding, with a very noticeable heterogeneity to these occurrences. It is probably fair to say that the filtration application within a TSF may be amongst the most challenging filtration applications faced by geotextiles, primarily because of the high seepage forces and suspended particles that must be filtered.

3.5.3 *Use in underground backfilling operations.*

In hard rock mining, ore is recovered by drilling, blasting and removing rock in sequences of panels, which may be more than 100m and about 500m^2 in plan (although the sizes vary greatly, depending on the shape of the ore body being mined). These panels are referred to as stopes. If left unfilled, convergence of these stopes occurs, as the prevailing ground stresses squeezes rock into the voids. This movement, if left unchecked, can result in rockbursts and other falls of rock within the underground working environment; clearly this is a potentially dangerous situation. One of the techniques for reducing this risk is backfilling of the mine void using mine tailings. Although increasing use is being made of full-plant tailings, in which case cement is added to the tailings, the majority of backfilling operations use hydraulic backfill. This consists of tailings from which the finer fraction has been removed, leaving a backfill that is essentially a slightly silty sand, with d_{50} values of around 0.1mm (Fourie et al., 1994). A common procedure, particularly in the South African goldmines, is to pump a slurry of this backfill into large geotextile bags (of the order of 30m x 4m x1m in size), which then fill the mine void, much like a water-filled balloon. Water begins to seep through the geotextile bag immediately that backfilling starts, and the prime considerations relating to worker safety underground is that the geotextile bags do not rupture, in order to allow the backfill time to consolidate and become self-supporting, and that seepage of solid particles through the geotextile bag into the underground workings is minimised.

Fourie and Blight (1996) describe the development of a testing protocol to determine the suitability of various geotextiles for this application, and demonstrated that the knitted HDPE multifilament product that was currently being used was in fact unsuitable because of the out-of-plane stretching that occurred when subjected to a lateral pressure, and that woven polypropylene geotextiles performed far better. This particular application proves unusual, in that the design requirement was not to retain 100% of solid particles, because this would mean the geotextile would have to be very slow draining, resulting in the backfill material remaining in a fluid, saturated state for far longer than was acceptable on safety grounds. A compromise had to be reached between drainage rate and percentage retention of solid particles.

3.6 *Use of geosynthetics in cover systems.*

Mining companies are becoming acutely aware of the financial costs of decommissioning and closing mining operations. The large multinational company BHP-Billiton has, for example, reportedly made provision for over $5½ billion in closure costs across the company. A large proportion of the closure costs are usually consumed by the construction of covers over the waste rock dumps, TSFs, and heap leach pads (if present). The primary function of these cover systems is to minimise, if not eliminate, seepage of contaminated water into the environment; other functions are to prevent erosion of the stored waste material and to ensure that the desired final land use (be it agriculture, recreation, wilderness, etc) is achieved.

Contrary to the situation with municipal solid waste landfills, the use of geosynthetics in cover systems is limited. This is for good reason; the requirements for acceptable closure of mine waste disposal sites are usually couched in terms of, ‘designing for perpetuity’, whatever that means. A consequence of this requirement is that regulators are reluctant to permit cover systems that incorporate synthetic materials, preferring to rely on natural materials and the evolution of vegetated profiles, in the absence of engineered solutions.

Long term risks associated with the storage of mine waste continue to be a concern for the mining industry. Acid mine drainage (AMD) from sulphidic waste rock piles and mine tailings are a significant source of environmental contamination due to potentially high concentrations of SO_4, Fe and contaminant metals in addition to low pH. Oxygen is essential for the oxidation of sulphides. Simple calculations can demonstrate that the availability of oxygen controls the oxidation rate of sulphidic waste (Gibson and Ritchie, 1991; Ritchie, 1994). For example, a 50 t sulphidic waste rock pile has a sulphur concentration of 2 wt./%. The waste heaps, therefore, contains 1 t of sulphur which will require 1.75 t of oxygen for its oxidation to sulphate. A 50 t waste pile with a porosity of 0.3 contains approximately 8 x 10^{-3} of oxygen, which is only 1/200 of the 1.75 t needed for complete oxidation (Gibson and Ritchie, 1991). Therefore to accomplish complete oxidation of the waste, oxygen must travel into the heap from the atmosphere.

Engineered cover systems are sometimes used in sulphide bearing waste storage facilities to separate buried waste from the surface environment. In this case, the cover system will have two main objectives: 1) to reduce or control water infiltration; and 2) to limit oxygen ingress into sulphide bearing mine waste. The design of such cover systems is, in most cases, site specific and depends usually on the climatic conditions prevailing at a given mine site. In areas where humid climates tend to prevail, the conventional approach to cover systems (usually multi-layered systems) is to construct a “resistive barrier” that utilises a liner with a low saturated hydraulic conductivity (i.e., compacted clay liner or geosynthetic clay liner) or composite liners (i.e compacted clay liner or geosynthetic clay liner + geomembrane), in combination with a number of other soil layers, to reduce or control the water infiltrations and oxygen ingress into the waste. In this respect, geosynthetic clay liners have been increasingly included in the construction of mine cover systems as replacement to soil resistive barriers, at least in humid or wet climates (Aubertin et al., 1997, Kim and Benson, 2004, Renken et al., 2005). Oxygen diffusion through GCLs plays an important role in the assessment of the effectiveness of the cover system in minimizing oxygen migration. This movement will tend to occur through the air filled pores if the porous medium is partially saturated whereas in a highly saturated medium it will occur partly in the gaseous phase and partly in the liquid phase. Both mechanisms of transport are reviewed in detail in Aubertin et al. (2000).

Bouazza and Rahman (2007) reported on the variation of oxygen diffusion against the degree of saturation of three GCLs referred to as GCL1, GCL2, and GCL3, respectively (Figure 10). These GCLs consisted of essentially dry bentonite (powder in GCL1 or granular in GCL2) sandwiched between polypropylene geotextiles. The geotextiles are held together as a composite material by needle-punching for GCL1 and GCL2, whereas GCL3 is stitch bonded. The test results shown in Figure 10 indicate that the decrease of gas diffusion is associated with an increase in degree of saturation. A decrease of around 4 orders of magnitude in the diffusion coefficient is observed as the degree of saturation increased from 20% to 97%, this is in line with the fact that the diffusion coefficient of oxygen in water ($D_{aw}= 2.2\text{x}10^{-9}$ m^2/s) is much lower than in air ($D_a = 1.8\text{x}10^{-5}$ m^2/s). It also appears from Figure 10 that GCL3 achieved a higher diffusion coefficient than GCL1 and GCL2. This might be caused by the way that GCLs are held together as a composite material. Stitch bonding is used in GCL3, whereas needle punching is used in GCL1 and GCL2. As GCL3 hydrates, the bentonite will tend to become partly confined along the stitch lines, and swell freely between them. This results in zones (along the stitches) with less bentonite available to mitigate gas diffusion. In contrast, the bentonite will tend to swell uniformly in the needle punched GCLs. Notwithstanding the variations observed between the two types of GCLs, the diffusion coefficient was found to vary by two orders of magnitude for water saturation varying from 20% to approximately 80%. Whereas for S >80% a change of only 15 % in saturation was needed to achieve an additional two orders of magnitude variation in the diffusion coefficient. This indicates that GCLs should have a high degree of saturation to be effective as a barrier against oxygen. Once again, the proximity of the GCL within a cover system means that it is likely to be subjected to cyclic wetting and drying cycles, and particularly in arid and semi-arid climates the ability of the GCL to remain hydrated may be a cause for concern.

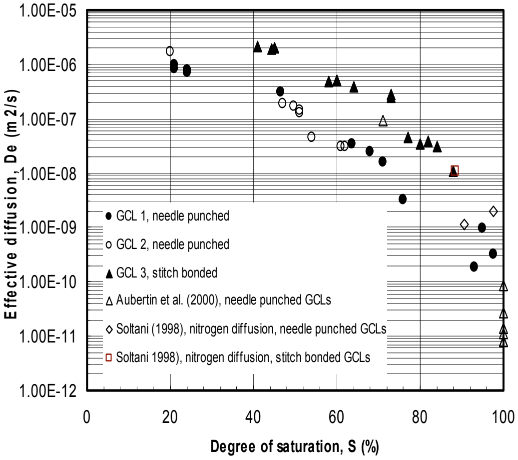

Figure 10. Effective diffusion coefficient of oxygen versus degree of saturation in different GCLs (from Bouazza and Rahman, 2007).

Soils traditionally used in mine covers are different in texture and are heavily dependent on the way they are placed and compacted (Yanful, 1993). Soils’ oxygen diffusion data collected from several studies reported in the literature seems to plot well above needle punched GCLs (Figure 11). A larger difference in terms of effective diffusion is noticed at the lower range of saturation where soils by nature contain larger air filled pores. At very high saturation (S≥90%) it seems that this difference is largely reduced and the variation between the two materials becomes minimal. In the case of the stitch bonded GCLs, their effective diffusion is close to that of soils reported in Figure 11 due to the fact that the stitch bonding tends to provide a preferential flow path to gas.

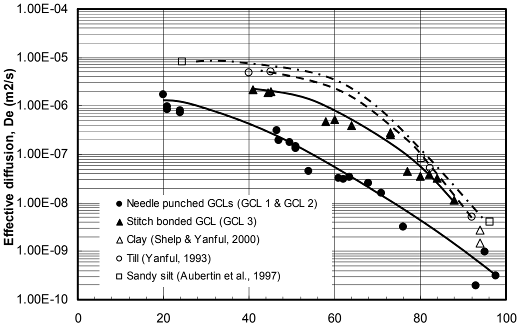

Figure 11. Effective diffusion coefficient of oxygen versus degree of saturation: comparison between present study and soils (from Bouazza and Rahman, 2007).

Numerous studies have been conducted on gas diffusion through soils, Rowe (2001) summarised the results of these studies in the form of a relationship relating the ratio of diffusion coefficients D_e/D_a (effective diffusion coefficient/ diffusion coefficient in air at the relevant temperature) to the degree of saturation (S) in soils. This relationship is given by:

$$D_e/D_a = \exp\left[-1.03\exp(0.017S)^{1.64}\right] \qquad [1]$$

Equation 1 is plotted in Figure 12 together with the results obtained by Bouazza and Rahman (2007) (normalised with respect to $D_a = 1.8\text{x}10^{-5}$ m^2/s at 20^{o}C). Equation 1 seems to capture the variations observed in stitch bonded GCLs. This was expected since their diffusion behaviour was close to the one encountered in conventional soils as shown in Figure 11. In the case of the needle punched GCLs, their experimental diffusion values are significantly lower than the values for soils, at the same degree of saturation, suggesting that they might provide a more robust barrier to oxygen. The reasons for such disparity could be due to the fact that equation 1 was developed specifically for conventional soils. Needle punched GCLs have a completely different structure where the randomly distributed fibres and bentonite are heavily intermingled to form a more homogeneous material with probably less pore space available for gas migration than for soils. Based on the data presented in Figure 12, a unique relationship between the effective diffusion of needle punched GCLs and degree of saturation appears to exist and can be described by the following equation (Bouazza and Rahman, 2007):

$$D_e/D_a = \exp\left[-2.00\exp(0.016S)^{1.10}\right] \qquad [2]$$

Notwithstanding the above, the general trend observed in GCLs is similar to that observed in soils, i.e. D_e/D_a was found to decrease significantly as the degree of saturation increased. Both empirical relationships (equations 1 and 2) between the effective diffusion and the degree of saturation can be used to obtain an estimate of the diffusion coefficient value for use in simulations, predictions or calculations of diffusive flux through cover systems containing stitch bonded or needle punched GCLs.

Capillary barrier cover systems can also be used to provide a proper capping of the mine waste (Bussiere et al., 2001, 2003, Yanful et al., 2003). These barriers usually consist of a fine grained soil layer sandwiched between two coarse grained soil layers. To work efficiently, the fine grained layer needs to remain saturated under drainage conditions. This can be achieved by the presence of the coarse grained layer underneath the fine grained layer. The role of the upper coarse grained layer is to drain water away and minimise loss of water by evaporation. A capillary barrier can also develop when an unsaturated fine-grained soil layer is underlain by another unsaturated porous material with relatively large-sized pores, such as a porous geosynthetic (e.g., a nonwoven geotextile) (Zornberg et al., 2009). The hydraulic conductivity of nonwoven geotextiles under unsaturated conditions is typically lower than that of most soils, working then as hydraulic barriers. The reason why nonwoven geotextiles are effective as hydraulic barriers for unsaturated soils is the same that makes them effective for separation, protection and drainage: their greater pore size than that of most soils. The specific phenomenon that resists the passage of water from an unsaturated soil into a nonwoven geotextile is referred to as the capillary break effect (Stormont and Anderson 1999).

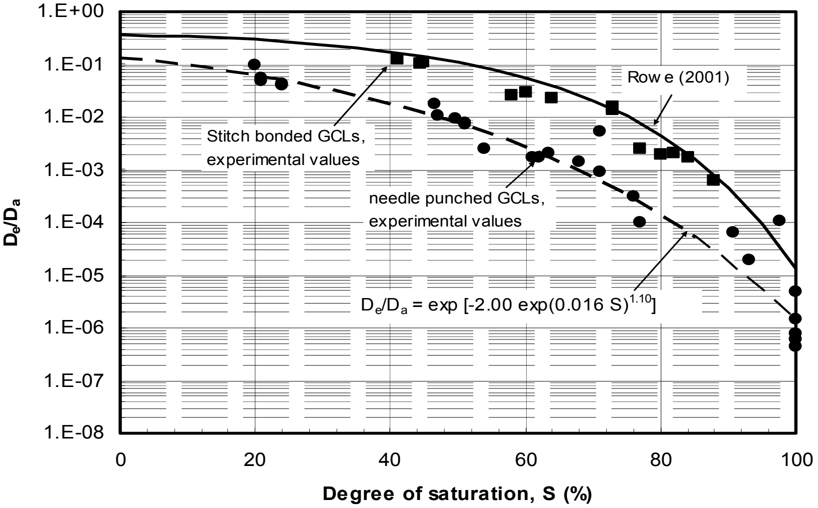

Figure 12. Diffusion coefficient as a function of degree of saturation (from Bouazza and Rahman, 2007)

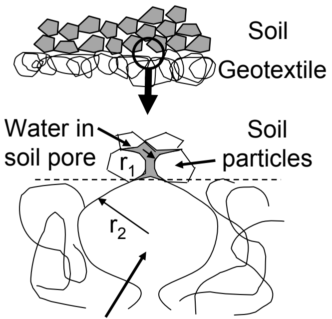

Figure 13. Schematic of capillary break effect at soil-geotextile interface (from Zornberg et al., 2009).

The capillary break effect is observed at the interface between fine-grained materials having relatively small pores and coarse-grained materials having relatively large pores, shown schematically in Figure 13. The air-water meniscus at the interface between the small and large pores must overcome the shift in radius from r_1 to r_2 to force air from the large pore. Inspection of Equation 3 indicates that the small soil pores of radius r_1 result in comparatively large suction, and water can only move to the larger geotextile pores when a significantly smaller suction (corresponding to the larger radius r_2 of the geotextile) develops in the system. In other words, the energy in the pore water has to be sufficient to permit it to break into the large pore. Macroscopically, the capillary break effect prevents a measurable amount of water from flowing from the soil into the nonwoven geotextile until reaching a critical suction close to zero (saturation). At this point, water is capable of "breaking" into the large pore from the small pore.

$$\psi = P_a - P_w = h_c \rho_w g = \frac{2\sigma_{aw} \cos\gamma}{R} \qquad [3]$$

Where, ψ is the matric suction, P_a is the pore air pressure, P_w is the pore water pressure, h_c is the height of capillary rise in a pipette of radius R, ρ_w is the density of water, g is the acceleration of gravity, σ_{aw} is the surface tension between water and air, and γ is the wetting contact angle (typically 10° for quartz minerals). Equation 1 assumes that air is under atmospheric pressure ($P_a = 0$) and indicates that the suction is inversely proportional to the pore radius R (note that all other variables are constants). Accordingly, for the same volumetric moisture content, a fine-grained soil (with comparatively small pore radii) will have a higher suction than a coarse-grained soil or a nonwoven geotextile (with comparatively large pore radii)

3.7 *Boutique applications*

The discussion so far has dealt with mining applications of geosynthetics that might be considered mainstream, i.e. relatively well established, are widely used and have a number of years in service. This section discusses applications that are either new or unproven, or have seen limited application. Notwithstanding this, some of these applications may turn out to become mainstream applications in the future, but it is suggested that at this time they are not.

3.7.1 *Geotextile tubes*

Newman et al (2004) describe experiments in which the viability of using large geotextile tubes for the dewatering of ultrafine tailings and wastewater sludge were evaluated. The project related to ongoing problems with storage capacity for fine tailings, and the need to find alternative techniques for solid-liquid separation. The material tested typically had 94% passing the 44µm particle size and exhibited very slow rates of drainage in the TSF. Initial experiments consisted of using 0.22 m^3 hanging geotextile bags, into which the tailings slurry was pumped at a solids content of between 5 and 14% solids. Drainage began to occur immediately on filling, and after 20 hours the slurry had consolidated to about 50% solids. These results prompted a larger experiment, in which a geotextile tube 60m long and 14.7m diameter was filled with slurry at a solids content of 7%. After about two weeks the solids content had increased to 65% solids and was according of very stiff consistency.

The technique clearly dewatered the tailings and might have been further developed had the mine not shut down due to poor metal prices. However, at $1.20 per cubic metre of slurry tested (remembering these are costs as at 2002, plus the slurry was only around 7% solids), it would be difficult to justify the technique on economic grounds at present.

3.7.2 *Electrokinetic dewatering*

The use of electrokinetic phenomena for the dewatering of soft clays and slurries is not new. Work at the United States Bureau of Mines in the 1970's and the Australian CSIRO in the 1980's demonstrated its potential use in dewatering mine tailings. However, these studies all used metal electrodes, which suffered from very high rates of corrosion, and presented difficulties in collecting and managing the decant water. The recent development of conductive polymers and their use in the manufacture of geosynthetics products such as tubular meshes (see Hamir et al., 2001) has opened up the possibility of using electrokinetic geosynthetics (EKGs) for large scale dewatering of mine tailings, either in-situ, or even in-plant, where electrokinetic belts have been fitted to conventional filter belt machines, providing greatly enhanced dewatering rates and improved final solids content values. These experiments are described in Fourie et al (2007) and Lockhart and Stickland (1984) and illustrate that dewatering of mine tailings is feasible for unit energy consumption rates of between about 1 and 5 kW/hour (per dry tonne of tailings treated). As this cost is based on dry tonnes, the energy consumption rates are extremely low, and once logistical problems are adequately addressed, use of EKGs in mine tailings dewatering might become a viable treatment technology.

3.7.3 *Stabilisation of high-risk tailings storage facilities.*

Ewert et al. (2008) describe the procedures used to cap and stabilise old uranium TSFs that remained from the time of the German Democratic Republic. These facilities posed significant risk to the population and the new, unified German government spent a considerable amount of money stabilising and covering them. This project used significant amounts of geosynthetic products, with the area exceeding 500 hectares being covered by a nonwoven geotextile overlain by a high-strength geogrid, prior to installation of prefabricated vertical drains to depths of 5 to 8m, at 1.5m centres. The project was completed satisfactorily, but the cost was very significant, with a total of over 6 billion Euros being spent on the entire remedial works (which included backfilling of old pits and reworking of rock dumps). Clearly this kind of project would in all likelihood be a one-off, but it does illustrate the use of geosynthetics in dealing with an otherwise intractable problem.

3.7.4 *Reinforcement of TSF slopes*

An unusual application is described by Wei et al. (2009), in which the outer perimeter of a copper tailings facility was reinforced over an 80m long stretch of the TSF using geogrids placed at 2m vertical centres. The grids, which were 466 g/m^2 products having a tensile strength of 50kN/m, were placed from the outer perimeter, back into the TSF over a distance of 110m. Reportedly, this allowed increased slope angles to be achieved, but the financial justification of this approach was not described. Based on current unit costs of placing tailings in most existing mining operations, it is difficult to understand how such a procedure can be cost-effective, but it does represent an interesting application of geogrid reinforcing.

3.7.5 *Containment dike raising with reinforced earth walls*

There are some examples in Brazilian mining projects of raising the crest of tailings dams or dikes, using reinforced earthen walls. In these examples, raises of 2 to 4 m high dikes have been used to prolong the life of existing TSF. In these types of works, layers of geotextiles are applied, embracing compacted soil layers, about 20 to 40 cm (one or two compacted layers). After construction, the geotextile face is covered by a geomembrane, to avoid exposure to UV that could degrade the geotextiles.

4 THE NEED FOR EDUCATION OF THE END USER

During preparation of this paper, discussions with a number of engineers involved in production aspects of mining engineering revealed a distinct lack of understanding of the potential role of geosynthetics in mining. A predominant approach appears to be to leave technical decisions in the hands of general engineering consultants, many of whom may have little or no expertise in the field of geosynthetics. It is suggested that there is an excellent opportunity for the IGS to become involved in awareness programmes and providing, or at least facilitating, training of both mining personnel currently in the workforce, as well as undergraduate mining engineers. As is well recognised, undergraduate students are potentially receptive to new ideas and technologies, and given the enormous potential for the application of geosynthetics in mining, this could be a valuable investment of time and effort.

On the other hand, the increase in use of geosynthetics by the mining industry indicates confidence in the effectiveness of these products for solving some of their problems, whether it is linings, transitions, filtering media, etc. Future growth in confidence, and thus rates of use in mining applications, depends on both the quality of the products offered by the industry and on the installation procedures (QA/QC), aspects that also deserve ongoing input and commitment from the IGS. Bad installation conditions or bad products will result in poor solutions and consequently create or increase the mining industry's scepticism in regard to the use of geosynthetics. Most of the large mining corporations have very well developed risk management and risk minimisation strategies as part of their corporate culture. Uncertainty in product performance and product durability are both issues that will restrict wider implementation of geosynthetics in the mining industry due to this risk-averse culture.

5 FUTURE OPPORTUNITIES

In mining, the acceptance of any new technology is ultimately evaluated in terms of how it affects the unit cost of producing a unit of a particular commodity, be it an ounce (or a gram) of gold or a pound (kilogram) of copper. It is therefore likely that in the short term, the greatest market potential for geosynthetics will continue to be in areas where production aspects dominate. An obvious example of this is heap leach pads. A problem with this application is the relative dearth of good quality research and field investigations. Recently, Rollin et al. (2010) have provided some much-needed field information on relative leakage rates through a range of different geomembranes used in pond liner applications, such as those discussed in Section 3.4. Although these are not heap leach pads, the information will provide mining industry personnel with some confidence that the geosynthetics industry is active in self-evaluation projects. More data of this sort from operational heap leach operations would be invaluable, although clearly not easy to obtain.

There also appears to be some ongoing confusion and debate about the relative merits of various polymer types for use in heap leach applications. For example, Denis and Marcotte (2009), discuss eleven issues that they suggest illustrates the inherent engineering advantages of PVC over other geomembranes materials. Given the earlier discussion in this paper, which suggested that HDPE and LLDPE are the preferred options, it is little wonder that mining personnel are not only confused by these differences in opinion, but frankly sceptical of an industry that cannot provide standardised tests to prove conclusively which is the preferred material in particular applications. At the moment there appears to be a plethora of tests used for certain indicator properties, such as the truncated cone test for measuring the puncture resistance of geomembranes. Standardised tests that address the particular aspects of heap leach applications, such as very high normal loads, and intermittent exposure to high strength chemicals (and perhaps the combination of these) would help to address the concerns of potential end-users.

6 CONCLUSIONS

The potential market for geosynthetics within the mining industry is not fully developed. In applications where production considerations dominate, such as heap leach pads, evaporation ponds and underground backfilling using hydraulic fill, the benefits of geosynthetics are well accepted. However, in some of these applications there continues to be differences of opinion regarding the applicability of various polymer types and various geomembranes products. It is in the interests of the wider geosynthetics community that these differences are resolved and that standardised and accepted test methods are developed for screening geosynthetic products for use in these applications. Failure to do this could be detrimental to attempts to consolidate the use of geosynthetics in these production applications.

In applications where production is perhaps a secondary issue and issues such as environmental protection are more important, the market penetration of geosynthetics is less impressive. It is suggested that this is partly due to the lack of enforceable legislation dictating particular performance criteria for waste storage areas, e.g. requiring that leakage rates from tailings storage facilities are no more than a certain quantum, and placing the onus on the owners of these facilities to prove conclusively that these leakage rates are not being exceeded. The mining industry is very good at addressing performance criteria, and this approach is more likely to succeed than a prescriptive approach, in which companies are forced to install a particular lining system. It is also important to realise that mining companies are usually international in nature, often working in both developed and developing countries. Discrepancies in required performance criteria in different parts of the world in otherwise identical applications is unacceptable and will lead to potentially polluting operations simply moving to countries where expensive performance criteria are not enforced. The geosynthetics industry could contribute by assisting with the development of universally acceptable guidelines for the performance of tailings storage facilities in particular, but also waste rock dumps.

Finally, it is suggested that the temptation to exaggerate the potential benefits of geosynthetics within mining applications, and particularly the inappropriate use of products, be avoided at all costs. It can only lead to negative perceptions of the industry as a whole, and to ongoing scepticism of the potential benefits of geosynthetics products. A particular example of this would be the use of geosynthetics in cover design systems, where the environmentalists are attempting to facilitate the evolution of natural and sustainable covers, incorporation of a synthetic material could be seen to be completely counter-productive and an example of engineers enforcing technical solutions in applications where they are inappropriate.

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