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The impact of mining solutions/liquors on geosynthetics

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ABSTRACT

Mine owners and operators are presented today with a diverse range of geosynthetic products which all appear to provide similar benefits. Key factors in selecting geosynthetics for use in the mining industry include construction and operational durability issues such as slope stability, puncture resistance and resistance to weathering; but also their chemical resistance when they come into contact with the extreme liquors present on many mining operations and processes. The long-term performance of the geosynthetic depends largely on the type of polymer used in the manufacture, or in the case of geosynthetic clay liners (GCLs), also on the mineralogy and chemical make of the bentonite present in the GCL. This paper provides a guide to the characteristics of the leachates/liquors likely to be generated for a given mining process and the likely effect it will have on the performance of a given geosynthetic.

1. Introduction

The use of geosynthetics in various mining operations is now widespread. While they have not been accepted as readily as in the general construction market, growth in the mining industry is occurring as operators begin to understand the advantages associated with the use of these materials. For many of the applications such as load support and retaining structures the design and application is easily transferred to the mining field, albeit normally with far higher loading criteria. Examples of these types of applications are reported in Bouazza et al. (1995), Lupo and Morrison (2007), and Ozcelik (2008).

When it comes to containment and mine site remediation however, it is not a simple matter of transferring the technology from the tried and tested geosynthetics applications common to waste containment facilities such as landfills, where the information is widely available and well established (Bouazza and VanImpe, 1998; Rowe, 1998; Bouazza, 2002; Bouazza et al., 2002, 2006a, 2007, 2008a; Jeon et al., 2007; Rowe et al., 2004, 2009; Rowe, 2005; Touze-Foltz et al., 2008; Guyonnet et al., 2009) to the mining industry. This is primarily due to the extreme ranges in leachate properties generated from the various ore extraction processes and the harsh environment to which geosynthetic materials are therefore exposed. Nevertheless, the rapid growth seen in the past decade in mining exploration and operation has led to a sharp increase in the use of a wide range of geosynthetic materials by the mining industry for all type of applications. Smith (2008) reported that from 1987 to 2008 more than 60 square kilometers of geomembrane liners were installed in leach pads alone. In addition to geomembranes which are extensively used in evaporation ponds, heap leaching and disposal of tailings (Breitenbach and Smith, 2006; Thiel and Smith, 2004), other major applications include geosynthetic clay liners (Aubertin et al., 2000; Kim and Benson, 2004; Lange et al., 2007, 2009; Bouazza and Rahman, 2007; Benson et al., 2008), geosynthetic capillary breaks in cover systems (Park and Fleming, 2006; Bouazza et al., 2006c), geotextile tubes and electrokinetic geosynthetics to dewater tailings and minewater sludges (Newman et al., 2004; Fourie et al., 2007), and filtration and drainage (Gilbert and James, 2004; Lupo and Morrison, 2007, Majdi et al., 2007).

This paper will concentrate on the containment and remediation aspects of geosynthetics in mining due to the paucity of information available on this particular topic. It will focus in particular on the following mining operations: Coal (Table 1),

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Table 1
Coal mining and stockpile leachates (note mitigation strategy shown in parenthesis).

Geosynthetics	Acid and metalliferous drainage (pH down to 2)	Elevated sulfate salinity (up to 5000 mg/L SO_4)	Elevated sulfate and chloride concentrations in arid environments	Acid and metalliferous drainage pH <2–3	Alkaline water, metalliferous with elevated chloride and sulfate concentrations
Polyester geotextile	Strength & strain loss at temperatures >90 °C (maintain low temperatures)	Strength & strain loss at temperatures >90 °C (maintain low temperatures)	No known effects	Strength & strain loss at temperatures <70 °C, due to acid hydrolysis (maintain low temperatures)	Strength & strain loss at temperatures >50 °C @ pH = 10, due to alkali hydrolysis (maintain low temperatures)
Polypropylene geotextile	Strength unaffected at temperatures <95 °C	Strength unaffected at temperatures <95 °C	No known effects	Strength unaffected at temperatures <95 °C	Strength unaffected at temperatures <95 °C
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (Use methylated HALS that are resistant to acid attack)	No known effects	No known effects	Strong acidic solutions can deactivate hindered amine stabilizers (Use methylated HALS that are resistant to acid attack)	No known effects
Sodium bentonite geosynthetic clay liner (GCL)	Dissolution of clay minerals and increased permeability (buffer to pH > 4 to promote precipitation of metals) Loss of sodium due to exchange with metals	Loss of clay gel and increased permeability (maintain GCL hydration[a] prior to and during contact with leachate) Loss of sodium due to exchange with metals	Potential loss of clay gel and increased permeability (maintain GCL hydration[a] prior to and during contact with leachate)	Loss of sodium due to exchange with metals (buffer to pH > 4 to promote precipitation of metals)	Loss of sodium due to exchange with metals Potential loss of clay gel and increased permeability (maintain GCL hydration prior to and during contact with leachate)

[a] Hydration with high purity water (EC < 1000 mS/cm) with low Ca and Mg concentration.

Uranium (Tables 2, 3), Aluminium (Table 4), Copper (Tables 5, 6), Gold (Tables 7, 8), Nickel (Table 9), Tin (Table 10) and Iron (Table 11). It should be stressed that the information provided in these tables is largely based on available literature.

Each mining process creates different leachates, each of which could possibly affect the long-term performance of the various polymers which make up the geosynthetic material. The aim of this paper is to define each mining process, the characteristic leachate/liquor associated with the mining process and what effect it might have on the generic polymer of the geosynthetic, as well as on the clay component of GCLs. It should be noted that while a generic polymer or mineral type may be better suited than others to a particular application, the chemical constituents may vary within a given polymer or clay type i.e. for example not all HDPE's will perform exactly the same way, which could have a marked effect on relative long-term performance of two HDPE's when compared to each other.

2. Unique aspects of the application of geosynthetics in mining

2.1. Geomembranes and geotextiles

Geomembranes have become critical components in mining facilities where their performance in containment of process solutions has been proven. These include base liners for heap leaching pads, liners to concrete basins and tank liners and in some cases control and mitigation of acid mine drainage (AMD) from tailings or waste rock dumps. Geotextiles are typically used, not as widely as geomembranes, in separation and filtration systems for waste rock dumps or tailings or for erosion control.

Heap leach pads are generally constructed utilizing as much as possible the natural topography of the site. The pad area is cut and filled as required, and trimmed to achieve a desired slope of 0.5–1%. HDPE or LLDPE are normally used for the base of the pad with the liner being between 1 and 1.5 mm thick over the pad and between 2 and 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 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 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 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

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Table 2
Uranium ore waste rock pile or ROM ore stockpile.

Geosynthetics	Acid and metalliferous drainage (pH down to 2)	Elevated sulfate salinity (up to 10,000 mg/L SO^4)	Elevated radioactivity
Polyester geotextile	Strength & strain unaffected at temperatures <70 °C (Maintain low temperatures)	Strength & strain unaffected at temperatures <70 °C (Maintain low temperatures)	Radionulcides can promote free radical oxidation (Use gamma stable stabilization packages)
Polypropylene geotextile	Strain reduction at temperatures 20 °C to 95 °C (Allow for increased elongation in design)	Strain reduction at temperatures 20 °C to 95 °C (Allow for increased elongation in design)	Radionulcides can promote free radical oxidation (Use gamma stable stabilization packages)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	HDPE can be swelled due to kerosenes use in SX solutions above 40 °C (Maintain low temperatures or use PVDF or vinyl esters)	No known effects	Radionulcides can promote free radical oxidation (Use gamma stable stabilization packages)
Sodium bentonite geosynthetic clay liner (GCL)	Dissolution of clay minerals and increased permeability (Buffer to pH > 4 to promote precipitation of metals) Loss of sodium due to exchange with metals	Loss of clay gel and increased permeability (Gelling agents needed)	No known adverse performance issue of radiation, otherwise as for elevated salinity and metalliferous leachates (Maintain GCL hydration[a] prior to and during contact with leachate)

PVDF = polyvinylidene fluoride.
[a] Hydration with high purity water (EC < 1000 mS/cm) with low Ca and Mg concentration.

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.

Swell-induced waves/wrinkles/blisters can lead to problems in HDPE liners in concrete basins such as in solvent extraction tanks and mixers in the mining industry. In such applications, cast-in HDPE liner (i.e. stud liner or anchor sheet) is used to protect the walls and floor of concrete tanks. 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).

Acid leachate or AMD from waste rock dumps and tailings is characterised by low pH and high concentration of metals which can be detrimental to the quality of groundwater or surface water around mine sites. Geomembranes and geotextiles have been considered for use as part of containment systems for AMD (Gulec et al., 2004). Both materials were found to be resistant to short term degradation when in contact with AMD liquids. Gulec et al. (2004) compared the antioxidant depletion rates of HDPE geomembranes after immersion, in synthetic AMD 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. 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 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, 420–560 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

Table 3
Uranium ore processing process pond water.

Geosynthetics	Sulfuric acid solutions pH < 1, very high Sulfate (SO_4) concentrations	Hypersalinity due to evaporative elevation in concentrations of chloride and sulfate	Elevated radioactivity
Polyester geotextile	Strength unaffected at temperatures <70 °C (maintain low temperatures)	No known effects	Radionulcides can promote free radical oxidation (use gamma stable stabilization packages)
Polypropylene geotextile	Strength affected by high concentrations at temperatures >60 °C (maintain low temperatures and low acid concentrations)	No known effects	Radionulcides can promote free radical oxidation (use gamma stable stabilization packages)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effects	Radionulcides can promote free radical oxidation (use gamma stable stabilization packages)
Sodium bentonite geosynthetic clay liner (GCL)	Loss of clay gel and increased permeability. Dissolution of clay minerals and increased permeability (design for periodic barrier replacement)	Loss of clay gel and increased permeability (gelling agents needed.[a] Design for periodic barrier replacement)	(No known effects)

[a] Synthetic and bio-polymers or other organic additives may enhance resistance of bentonite to adverse affects of high salinity.

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Table 4
Bauxite refining alumina production.

Geosynthetics	Highly alkaline pH leachate (pH > 10)	High Na concentrations (also High salinity due to use of seawater (pH neutral, EC50,000 mS/cm)	Elevated temperature of cooling water (>60 °C)
Polyester geotextile	High pH can catalyze hydrolysis of the polyester at high temperatures (>60 °C) (maintain low temperatures)	No known effects	No known effects
Polypropylene geotextile	High pH can degrade the phenolic antioxidants (supplement that stabilization package with additional HALS stabilizers)	No known effects	Slightly elevated risk of oxidation (ensure adequate stabilization package is present)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	As above	No known effects	As above
Sodium bentonite geosynthetic clay liner (GCL)	Dissolution of clay mineral and potential loss of barrier component (design with high pH resistant clays[a] or buffer pH to promote precipitation of metal hydroxides)	Loss of clay gel and increased permeability (maintain GCL hydration[b] prior to and during contact with leachate)	Loss of bentonite swelling and increased consolidation at elevated temperature (design for barrier cooling)

[a] Testing by Benson et al. (2009) and Gates and Bouazza (2009) indicates some bentonites can resist the impact of high pH solutions.
[b] Hydration with high purity water (EC < 1000 mS cm) with low Ca and Mg concentration.

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.

2.2. Geosynthetic clay liners

Interest in the use of GCLs as the secondary liners for leach pads has increased markedly in the past decade. Just as for geomembranes, the application of GCLs in mining generally pushes the performance beyond recommended limits typical for other environmental and engineering applications. Exposure of the GCL to high overburden and traffic stresses and excessive temperatures as well as high salinity and extreme pH of the leachates and liquors not only affect the geosynthetic components as described above, but also can impact negatively on the performance of the bentonite component. It must be stressed however, that these affects also will be apparent, often in amplified fashion, on compacted clay soils and other traditional barriers. Rigorous testing is recommended to ensure components will meet or exceed design criteria.

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 °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., 2006b; Gates 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 inter-particle pores (Bouazza et al., 2008b). 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 (e.g. 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).

3. Coal

Coal is extracted from coal seams, the method of extraction i.e. open pit or underground, depends on the depth below ground level, geology and environmental factors. The majority of the

Table 5
Copper ore waste rock pile or ROM ore stockpile.

Geosynthetics	Acid and metalliferous drainage (pH down to 1)	Elevated sulfate salinity (up to 7000 mg/L SO_4)	High copper concentrations
Polyester geotextile	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain lower temperatures)	No known effect	No known effect
Polypropylene geotextile	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect	No known effect
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	As above	No known effect	No known effect
Sodium bentonite geosynthetic clay liner (GCL)	Dissolution of clay minerals and increased permeability loss of sodium due to exchange with metals (design for periodic barrier replacement)	Loss of clay gel and increased permeability (gelling agents needed)	Loss of clay gel and increased permeability (gelling agents needed)

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Table 6
Copper ore heap leach process liquors & process water neutralisation pond leachates.

Geosynthetics	Sulfuric acid solution used for leaching. Low pH (<1)	Sulfuric acid-rich water (pH = 1–2)	Sulfate concentrations up to 20,000 mg/L SO_4
Polyester geotextile	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain low temperatures)	No known effect	No known effect
Polypropylene geotextile	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect
Sodium bentonite geosynthetic clay	Dissolution of clay minerals and increased permeability (design for periodic barrier replacement)	Dissolution of clay minerals and increased permeability (design for periodic barrier replacement)	Loss of clay gel and increased permeability (gelling agents needed)

Table 7
Gold ore waste rock pile or ROM ore stockpile leachates, heap leach process (Cyanide) liquors & TSF/tailings dam leachates (during operations).

Geosynthetics	Acid and metalliferous drainage (pH down to 2)	Elevated sulfate salinity (up to 5000 mg/L SO_4)	Acid and metalliferous water (pH < 1)
Polyester geotextile	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain low temperatures)	No known effect	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain low temperatures)
Polypropylene geotextile	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Sodium bentonite geosynthetic clay Liner (GCL)	Loss of sodium due to exchange with metals. Dissolution of clay minerals and increased permeability (design for periodic replacement of barrier)	Loss of clay gel and increased permeability (gelling agents needed. Maintain hydrated state of GCL)	Dissolution of clay minerals, loss of barrier component and increased permeability. Loss of sodium due to exchange with metals. (design for periodic replacement of barrier)

world's coal reserves are recoverable by underground mining. Currently, almost two-thirds of worldwide hard coal production comes from underground mines. In Australia however, this proportion is significantly lower. Major Coal producing countries include China, USA, India, Australia and South Africa. Two types of coal are mined in black or brown varieties, resulting in similar leachate generation. Table 1 shows the effects that various leachates from coal processing might have on geosynthetics.

4. Uranium

Traces of uranium occur almost everywhere on Earth, the ore is mostly present at relatively low concentrations. Most uranium mining is very volume-intensive, and thus tends to be undertaken as open pit mining. It is also undertaken in only a small number of countries worldwide, as the resource is relatively rare. Ores with as little as 0.1% uranium are mined, crushed in mills and processed by chemical methods including leaching and solvent extraction. Tables 2, 3 show the effects that various leachates from uranium processing might have on geosynthetics.

5. Aluminium (bauxite)

Bauxite is the naturally occurring form of aluminium ore and is the third most abundant element in the Earth's crust. It is typically mined in open-pits and normally processed into alumina near the mining operation. Major bauxite producing countries include Australia, Guinea, Brazil, Jamaica, and the former Soviet Union. On a worldwide average, 4–5 tonnes of bauxite are needed to produce two tonnes of alumina, from which one tonne of aluminium can be produced. Table 4 shows the effects that various leachates from Aluminium processing might have on geosynthetics.

Table 8
Effects of various leachates from gold processing.

Geosynthetics	Elevated chloride and sulfate salinity	Elevated CN- and possibly NH4OH	Moderate to strongly alkaline solutions (pH = 9–11) containing highly elevated CN- (up to 500 mg/L) and possibly NH4OH
Polyester geotextile	No known effect	No known effect	High pH can catalyze hydrolysis of the polyester at high temperatures >60 °C (maintain low temperatures)
Polypropylene geotextile	No known effect	No known effect	High pH can degrade the phenolic antioxidants (supplement that stabilization package with additional HALS stabilizers)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	No known effect	No known effect	High pH can degrade the phenolic antioxidants (supplement that stabilization package with additional HALS stabilizers)
Sodium bentonite geosynthetic clay liner (GCL)	Loss of clay gel and increased permeability	Loss of clay gel and increased permeability	Dissolution of clay mineral and possible loss of barrier component (design with high pH resistant bentonites[a] or buffer pH to promote precipitation of metal hydroxides)

[a] Testing by Benson et al. (2009) and Gates and Bouazza (2009) indicates some clays can resist the impact of high pH solutions.

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Table 9
Nickel waste rock pile or ROM ore stockpile leachates, heap leach process liquors.

Geosynthetics	Elevated sulfate salinity Sulfate concentrations up to 20,000 mg/L SO_4	Acid or near neutral and metalliferous drainage	Sulfuric acid used for leaching. Highly acid (pH < 1) and nickel-rich drainage. Sulfuric acid used for leaching. Acid (pH = 2–4)
Polyester geotextile	No known effect	No known effect	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain low temperatures)
Polypropylene geotextile	No known effect	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	No known effect	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Sodium bentonite geosynthetic clay liner (GCL)	Loss of clay gel and increased permeability (gelling agents needed. Maintain hydrated state of GCL)	Loss of exchange capacity; possible dissolution of clay minerals and increased permeability (maintain GCL hydration prior to and during contact with leachate)	Dissolution of clay minerals, loss of barrier component and increased permeability (design for periodic replacement of barrier)

Table 10
Tin waste rock pile or ROM ore stockpile leachates.

Geosynthetics	Acid and metalliferous water (pH = 2–3)	Elevated sulfate salinity (up to 5000 mg/L SO_4)	Acid and metalliferous water (pH down to 2)
Polyester geotextile	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain low temperatures)	No known effect	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 deg.C (maintain lower temperatures)
Polypropylene geotextile	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)
Sodium bentonite geosynthetic clay liner (GCL)	Loss of sodium due to exchange with metals. Dissolution of clay minerals. (design for periodic replacement of barrier)	Loss of clay gel and increased permeability (gelling agents needed. Maintain hydrated state of GCL)	Dissolution of clay minerals. Loss of sodium due to exchange with metals. (design for periodic replacement of barrier)

6. Copper

Sulfide and oxide ores are mined and processed to form copper. Copper ores are extracted (leached) with sulfuric acid, usually using the heap leach process. The ore rich solution is then transferred to tanks containing scrap iron and agitating the solution to precipitate the copper. Major copper producing countries include USA, Chile, Peru and Canada. Tables 5, 6 show the effects that various leachates from copper processing might have on geosynthetics.

7. Gold

Gold is mined either using underground hard rock mining techniques which extract the ore through shafts or tunnels or from open cut mines. Once the ore is mined the gold is extracted by means of cyanide leaching. Major gold producing countries include South Africa, the United States and Australia. Tables 7, 8 show the effects that various leachates from gold processing might have on geosynthetics.

Table 11
Iron ore waste rock pile or ROM ore stockpile leachates.

Geosynthetics	Acid and metalliferous drainage (pH = 2–3)	Magnetite ore, acid and metalliferous drainage (pH down to 2)	Elevated sulfate salinity (up to 7000 mg/L SO_4) Acid and metalliferous drainage (pH < 2)
Polyester geotextile	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain lower temperatures)	Acid-catalyzed hydrolysis of PET can occur at temperatures greater than 60 °C (maintain lower temperatures)	No known effect
Polypropylene geotextile	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect
Polyolefin geomembranes (e.g. HDPE, LLDPE, fPP, etc.)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	Strong acidic solutions can deactivate hindered amine stabilizers (use methylated HALS that are resistant to acid attack)	No known effect
Sodium bentonite geosynthetic clay liner (GCL)	Dissolution of clay minerals. Loss of sodium due to exchange with metals. (design for periodic replacement of barrier)	Loss of clay gel and increased permeability (gelling agents needed. Maintain hydrated state of GCL)	Dissolution of clay minerals. Loss of sodium due to exchange with metals. Potential loss of clay gel and increased permeability.

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8. Nickel

Nickel mining has moved from traditional underground methods to large volume open pit operations. A sulfuric acid heap leaching process is used to recover the nickel from the nickel laterites. Major nickel producing countries include Russia, Canada, Australia, Indonesia and New Caledonia. Table 9 shows the effects that various leachates from nickel processing might have on geosynthetics. Table 10 is related to waste rock piles, stockpiles and the heap leach process.

9. Tin

Approximately 80% of the world's tin deposits occur as unconsolidated secondary or placer deposits in river beds and valleys or on the sea floor and as such are mined using open pit mining methods. The tin is removed from the ore by acid leaching. Major tin producing countries include Brazil China, Bolivia and Indonesia. Table 10 shows the effects that various leachates from tin processing might have on geosynthetics.

10. Iron

Most economic sources of iron ore consist of iron oxide minerals, the primary form which is used in industry being hematite. The mining involves removal of large quantities amounts of ore and waste in open cut operations. The ore is then ground to a suitable level and stockpiled, to allow transport and processing. Major iron producing countries include China, Brazil, Australia, and India. Table 11 shows the effects that various leachates from tin processing might have on geosynthetics.

11. Summary and conclusions

This paper has shown that a number of factors should be considered when incorporating geosynthetics into a modern mining operation, as contact with many of the leachates has the potential to reduce the performance of the material. One should not, however, lose sight of the fact that the natural materials they are replacing/complementing or augmenting, such as compacted clay liners, will be affected in similar ways. Therefore, rigorous analysis of each component of the design should be carried out to ensure the long-term performance of whatever material is used. The information provided in this paper is aimed at highlighting potential limitations of a given material and should not be used solely as a design tool as slight changes to leachates can have a significant effect of the performance of the geosynthetic material.

For geotextiles and geomembranes, the above tables indicate that regardless of the ore, process wastewaters and leachates having strongly alkaline or strongly acid pH, as well as elevated temperatures, are the greatest threats to their long-term performance. Excessive alkalinity and acidity promote polymer hydrolysis and ligand substitution reactions, resulting in loss of polymer strength. Degradation of antioxidants can be of concern for the long-term performance of geomembranes. Excessive temperature increases the rate at which these adverse reactions occur, but also directly affects geotextile and geomembrane strength and elongation. Design criteria must adequately assess and address the potential for chemical and thermal degradation. Swelling of 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. In this respect, vinyl ester type of liners, polyurea or polyvinylidene fluoride (PVDF) liners might be more suitable for this type of application.

For GCL materials, not only are the geotextiles affected, but the bentonite component also undergoes dissolution reactions at extreme pH, pore-structure and loss of gel at elevated salinity and shrinkage at elevated temperatures. All these reactions potentially adversely affect the hydraulic performance of the bentonite, but the available data is limited. For some bentonites (e.g. Gates and Bouazza, 2009) reactions at strongly alkaline pH appear to have minimal impact on hydraulic performance, but for others the effect can be catastrophic (Benson et al., 2008). The available evidence would suggest that reactions of strongly acid pH leachates (e.g. Jozefaciuk and Matyka-Sarzynska, 2006) adversely impact hydraulic performance of bentonite. Leachates of extreme pH from mineral ore processing are nearly universally coupled with very high ionic strength, and at least some of the adverse reactions of these leachates with bentonites are related to this hypersalinity. Recent developments (Kondo, 1997) toward improving bentonite resistance to high salinity show promise (Katsumi et al., 2008). It is expected that considerable research will be directed in the future toward improving bentonite performance to extreme pH, hypersalinity and temperature.

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