USE OF GEOSYNTHETICS IN THE MITIGATION OF ACID ROCK DRAINAGE
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ABSTRACT
This paper summarizes case studies of geosynthetic installations for the mitigation of acid rock drainage (ARD). Acid rock drainage (ARD) may be generated when sulphide-bearing materials are exposed to oxidizing conditions in the presence of water and if the sulphidic materials contain insufficient alkaline minerals such as calcite. ARD generation from sulphide-bearing mine waste is a significant environmental and financial problem in the mining industry, because it usually has high metal and sulphate concentrations, high acidity and a low pH, which contaminate receiving environs, if not properly managed. Reviewed case studies include: field installations of polyethylene (PE) and geosynthetic clay liner (GCL) capping systems for waste rock and tailings; PE geomembrane use in heap leaching; and testing and performance evaluations of PE and polypropylene geosynthetics and GCLs. On the basis of the reviewed case studies, geomembranes such as HDPE or LLDPE may be suitable in composite liner or cover systems to augment the hydraulic barrier and potentially the oxygen diffusion characteristics of a soil-based liner or cover system to mitigate ARD. Based on the case studies and a literature review, GCLs may be suitable as hydraulic barrier, but likely not as oxygen diffusion barrier in cover systems intended to mitigate ARD.

RÉSUMÉ
Ce papier résume les études de cas d'installations de geosynthetic pour la réduction le drainage rocheux acide (DRA). Le DRA peut être produit quand les matériaux de sulphure-maintien sont exposés à oxyder de conditions dans la présence d'eau et si les matériaux de sulphidic contiennent des minéraux alcalins insuffisants tels que calcite. La génération de DRA est un problème significatif, écologique et financier. Les études réexaminées incluent: les installations de polyéthylène (PE) et de membrane argile-géosynthétique (MAG) pour la réduction de DRA; l'usage de polyéthylène dans heap leach; les investigations et évaluations d'exécution de geosynthetics de PE, de polypropylène et de MAG. En se basant sur le cas réexaminé étudie, les geomembranes tel que HDPE ou LLDPE peut être convainVenable dans le paquebot composé ou les systèmes de couverture pour accroître la barrière hydraulique et potentiellement les caractéristiques de diffusion d'oxygène d'un paquebot système de couverture pour adoucir DRA. A basé les études de cas et une revue de literature, les MAGs peut être une barrière hydraulique convenable, mais probablement pas comme une barrière de diffusion d'oxygène.

1. INTRODUCTION
One of the most long-term and potentially detrimental impacts of mining may be the generation of acid rock drainage (ARD). ARD is generated during oxidation of sulphidic materials that are commonly co-deposited with the mineral(s) of interest. ARD may form naturally, if sulphidic materials contain insufficient alkaline minerals such as calcite or dolomite. ARD, characterized by low pH levels, high acidity, and high sulphate and metal concentrations, can contaminate receiving environs, if not properly managed.

The prevention and/or mitigation of ARD is challenging due to the long-term nature of the ARD and the associated metal leaching (ML) problem. ARD continues to be generated until available sulphides have been oxidized, which may take decades, unless mitigative measures are implemented.

1.1 Objectives
This paper summarizes key aspects of ARD generation and common capping technologies to mitigate ARD. Subsequently, several case studies are summarized in which geosynthetics have been installed in the field or investigated for their suitability to reduce ARD generation.

2. ARD GENERATION AND MITIGATION
2.1 ARD Generation
In sulphidic materials with insufficient alkaline materials, ARD develops naturally in three stages in which the pH drops progressively from near neutral levels in Stage I to very low pH levels (< 3.0) in Stage III. Sulphide oxidation reactions in the first stage are primarily abiotic and relatively slow, reactions in the third stage are primarily biotic (biologically mediated) and rapid, and reactions in the second, transitional stage are a mixture. Key ingredients for sulphide oxidation are water and oxygen.

Bacteria most commonly isolated from ARD generating environments include Thiobacillus ferrooxidans, Leptospirillum ferrooxidans, and T. thiooxidans (Rawlings 1997). These bacteria are all gram-negative and obligately autotrophic. Autotrophic bacteria use carbon dioxide or other carbonate species as carbon source and do not depend on organic matter for growth.
T. ferrooxidans grow optimally at pH levels of 1.8 to 2.5 at a temperature ranging from 30 to 35°C, but some strains of T. ferrooxidans are also adapted to growth in lower temperatures (Rawlings 1997). L. ferrooxidans are able to grow at pH levels as low as 1.2 at a temperature ranging from 20 to 45°C. T. thiooxidans grow in association with T. ferrooxidans and L. ferrooxidans are able to grow at pH levels as low as 0.8 at a temperature ranging from 30 to 35°C (Rawlings 1997).

2.2 Common ARD mitigation measures

To achieve economically feasible long-term ARD mitigation is difficult. Also, what may be the best option at one mine site may not be suitable at another.

Mitigative measures for Stage I ARD waste are typically focused on preventing ARD generation by minimizing sulphide oxidation. The majority of ARD capping technologies for Stage I ARD waste are aimed at curtailing oxygen and/or water transport to the sulphidic material in order to disrupt the natural oxidation process. Low water infiltration and low oxygen diffusion into the sulphidic material may be achieved by installing a low permeability soil-based cover system consisting of bentonite mixtures or clayey and silty soils. For example, a till cover was installed at the Equity Silver mine in B.C., Canada (Aziz and Ferguson 1997). Tailings with a low sulphur content have also been used as a fine-grained cover material and oxygen diffusion barrier for potentially acid generating (PAG) materials (Ricard et al. 1997). Minimal diffusion of oxygen into tailings has also been achieved by flooding the tailings with water, because the rate of oxygen diffusion through water is approximately 10,000 times slower than the oxygen diffusion through air ($D_a = 1.78 \times 10^{-5}$ m$^2$/s at 25°C; $D_w = 2.0 \times 10^{-9}$ m$^2$/s at 25°C). This type of cover is often referred to as ‘water cover’. In the case of a water cover, only the exposure of the tailings to oxygen is minimized (limited to the dissolved oxygen concentration in water) whereas the exposure to water is high. It should be noted that whatever cover or capping option is selected, there is typically some requirement to collect and treat drainage waters prior to their release to the receiving environment.

Practiced mitigative measures for Stage III ARD waste usually reduce the quantity of leachate generation by diversion of clean run-on and runoff and/or capping and subsequent treatment of the collected leachate (often referred to as ‘collect and treat’ option). Common chemical treatment technologies involve raising the pH of the acidic drainage in water treatment plants so that dissolved metals precipitate and subsequent pH adjustments to levels that are suitable for release to the receiving environment (usually pH 6-9). Other treatment methods involve bacterial sulfate reduction.

 Arresting or reversal of sulphide oxidations in Stage III ARD waste is difficult. Establishment of anaerobic conditions would be a good start. Bacterial sulphate reduction is possible, if environmental conditions are suitably modified. Organic cover systems that contain materials such as biosolids (recyclable solid residues generated during municipal waste water treatment) have been used for this purpose. For example, Elliot et al. (1996) found that lime stabilized sewage sludge (LSSS) used as a tailings cover actively changed the underlying tailings environment by reversing the ARD process. They measured an increased pH, decreased dissolved metal concentration, and observed the formation of a reducing environment at the cover-tailings interface.

Reclamation specialists differ in their views regarding the use of natural and man-made products in engineering works intended to mitigate ARD. Although most soil-based cover systems are susceptible to dessication and potentially to freeze-thaw effects, which may reduce their effectiveness in mitigating ARD, soils are perceived to be ‘stable’ and functioning in the long-term. Geosynthetics on the other hand are man-made and are known to be prone to degradation and oxidation. Laboratory tests predict lifespans of up to several hundred years for materials such as high density polyethylene (HDPE) geomembranes (Koerner 2004). However, geosynthetics manufacturers are willing to warranty their products (materials and their replacement) for up to 20-30 years (e.g. Colorado Lining International, 2005). Also, short to medium term (up to ~ 30 years) geosynthetics performance data is available, but long-term field performance data is non-existent and available predictions have been based on a variety of laboratory tests and modeling to date.

Regulatory authorities also tend to regard the use of geosynthetics as a temporary measure to mitigate and control ML/ARD, as suppliers of geosynthetics currently warranty their products for up to 20-30 years. Regulators in some countries and jurisdictions (for example, Canada) require financial security to cover unexpected poor cover performance and replacement costs. For example in Canada, ML/ARD sites are required to be kept under long-term care and maintenance for at least 100 years.

The use of geosynthetics to mitigate ARD generation from tailings and mine waste rock competes with methods such as the use of natural soils (e.g. clayey soils) or modified soils (e.g. sand-bentonite barriers), water covers, store and release covers, rigid covers (e.g. shotcrete), and conventional and paste backfill (reduces the quantity of tailings impounded).

ARD mitigation costs tend to vary from site to site depending on the site logistics and design objectives. Excluding long-term maintenance costs of the water cover and appurtenances, the initial construction cost may be significantly lower for water covers than for engineered soil-based (earthen) cover systems. Hall (1999) reported a cost of $29,000 per hectare (ha) for a 90 ha facility for the relocation of some tailings, and research, design and construction of a water cover at the Falconbridge “New” Tailings area, following shut-down of the Falconbridge Mill. In comparison, installation costs for engineered earthen covers typically range from $200,000 to $450,000 per ha. However, lower cover construction costs of $65,000 per ha for a 60 ha Tailings Storage Facility have been reported by Ricard et al.
(1997). That cover system consisted of 0.5 m sand, 0.8 m tailings with a low sulfur content, and 0.5 m sand (Ricard et al. 1997). Aziz and Ferguson (1997) reported cover construction costs of $35,000 per ha for a till cover system for waste rock that consisted of 0.5 m compacted till and 0.3 m of uncompacted till. However, the latter two cover systems did not always produce anticipated assessment results and initial project objectives have not always been met.

3. CASE STUDIES

In the spirit of exploring the use of polyethylene (PE), polypropylene (PP), and geosynthetic clay liners (GCLs) in the mitigation of ARD, a variety of case studies were compiled. Section 3.1 summarizes key characteristics of polymers, PE, and PP. Section 3.2 introduces GCLs. Field installations of geosynthetics to mitigate ARD are presented in Section 3.3 and studies on testing and performance evaluation are given in Section 3.4.

3.1 Characteristics of Polymers and Polyethylene (PE) and Polypropylene (PP) Geosynthetics

Polymers in geosynthetics are subject to degradation and, therefore, their service life depends on their constituent resins and additives and the environmental conditions they come in contact with. Polymers are long-chain molecules built through addition (polymerization) of small repetitive molecules called monomers. Polymer chains are linked together by weak inter-chain interaction and stay intact as long as the applied chemical or physical stresses are lower than the inter-chain interaction. The chemistry of polymers is governed by the laws of organic chemistry and is directly related to the types of molecular groups along its chains (Kay et al. 2004).

Polymer degradation is caused by mechanisms such as oxidation, temperature and temperature stresses, UV radiation, chemical attack, mechanical stress, and microbiological activity (Kay et al. 2004). In general, the service life becomes shorter the higher the exposure of oxidizing agents, the higher the temperature, and the higher the exposure to UV radiation. The service life due to chemical solvent attack depends on the type of solvent. The service life of geosynthetics is usually extended by adding antioxidants, UV stabilizers, or pigments to the polymer formulations.

The long-term oxidation-induced aging of geosynthetics such as PEs and PPs occurs in three discrete time horizons: Stage A) antioxidant depletion time, Stage B) induction time, and Stage C) time to reach reduction in the desired engineering property (Bonaparte et al. 2002). Typically, Stage A is the longest and is projected to range from several to hundreds of years based on laboratory testing (e.g. for HDPE; Koerner 2004) during which the desired engineering properties remain essentially the same. Stage B is a transition stage that is much shorter than Stage A. In Stage B, a measurable amount of oxidation induced chain scission (breaking C-C bonds in polymer chain) occurs. The time to reach reduction in the desired engineering property in Stage C varies, but may be quite brief. Embrittlement is a physical manifestation of the degradation process. Oxidation is accelerated by the catalytic effects of transition metal ions in a chemically activated state. Of these, ferric iron (Fe$^{3+}$) is the most common but copper and manganese have also been shown to be important (Rollin 2004). High ferric iron concentrations are associated with ARD generation.

PE geosynthetics are very resistant to chemical substances and do not easily deteriorate when exposed to alkaline and acid agents (except oxidizing acids), salt solutions, or microbes, because they are non-polar in nature (Kay et al. 2004). Due to their resistance to chemical attack and low glass transition temperature of $-50^\circ$C, PE geosynthetics have been the most widely used in the mining and mineral processing industries. Since a polymer becomes brittle and loses its impact resistance when the temperature is below its glass transition, PE may be more appropriate in cold climates than PP (Kay et al. 2004). The glass transition temperature of PPs is typically around $-10^\circ$C. A drawback of HDPE is that it is sensitive to environmental stress cracking in the presence of a sensitizing agent. Compared to HDPE, linear low density polyethylene (LLDPE) is less susceptible to stress cracking and has higher interface friction values, is easier to install in cold climates, and is able to sustain more strain (Lupo and Morrison 2005). Another difference between LLDPE and HDPE is that large panels of LLDPE (e.g. up to $\sim 1.800$ kg) can be manufactured at the factory, which may eliminate field seaming. In contrast, HDPE panels require field seaming. Since precipitation in any form, whether rain, snow, dew, or fog can bring an HDPE installation to a halt (Layfield 2006), LLDPE geomembranes may be easier to install in humid climates or at remote locations. PE geomembranes usually consist of 96-97.5% polyethylene resin, 2-3% carbon black, and 0.5-1.0% antioxidants and other additives (Koerner 2004).

PPs are generally more resistant to creep and relaxation fatigue at higher temperatures than PEs. Chemical resistance of PPs is similar to or higher than that of PEs (Kay et al. 2004). However, PPs are more sensitive to oxidation than PEs (Kay et al. 2004). PP typically consists of 98% polypropylene resin, 2-3% carbon black, and 1-2% other additives (Koerner 2004).

3.2 Characteristics Geosynthetic Clay Liners (GCLs)

Geosynthetic clay liners (GCLs) have become popular as hydraulic barriers in composite soil/geosynthetic cover and liner systems for landfills or as replacements for compacted clay liners. Compared to natural clay liners, GCLs are quicker to install, require less on-site QC/QA, occupy less volume, and use lighter weight construction equipment.

GCLs consist of a layer of bentonite clay supported by geotextiles and/or GMs and held together by needling, stitching, or chemical adhesion. Most currently manufactured GCLs are needle-punched. GCLs are
usually classified based on their bentonite content, the type and weight class of top and bottom geotextiles (such as woven (W), nonwoven (NW), or scrim-reinforced), type of internal support (e.g. needle-punched or stitch-bonded), and extra features (manufacturer specific). In scrim-reinforced geotextiles, a woven geotextile and a non-woven geotextile are needle-punched together. The hydraulic conductivity of most sodium bentonite GCLs ranges from $1.0 \times 10^{-11}$ to $5.0 \times 10^{-11}$ m/s at the factory (Koerner and Daniel 1997). GCLs are generally more resistant to cracking due to freeze-thaw cycles and desiccation than compacted clay liners (Koerner and Daniel 1997).

3.3 Case Studies of Field Installations of Geosynthetics to Mitigate ARD

3.3.1 LLDPE Capping of ARD waste rock (Frobel et al. 2003)

A soil cover system incorporating a LLDPE geomembrane as barrier layer was installed above an area of approximately 26 ha (65 acres) to minimize ARD generation from Stage III ARD waste. ARD originated from approximately 15.3 million m$^3$ of sulfidic waste rock and spent heap leach ore that had been deposited in a valley fill known as Ruby Gulch (Frobel et al. 2003).

Prior to the installation of the cover system, the 550 m long waste rock slopes were regraded to 3.5H:1V (16°) to enhance slope stability of the cover system that incorporated a LLDPE geomembrane. In total, nine slope breaks (8 m wide benches) were created to ensure that the maximum vertical height of the sloped areas was 12 m.

The installed cover system consisted of:

1) 150 mm (6 in) thick topsoil seeded with native grasses
2) 900 mm (36 in) thick soil and rock
3) 450 mm (18 in) thick processed, crushed Minus 25.4 mm (1 in) rock as free draining layer. This layer was installed at the geomembrane/soil interface to minimize seepage forces during high rainfall events and spring thaw in order to prevent slope failure.
4) LLDPE barrier:
   a) Slopes and benches:
      - 2 mm (80 mil) thick LLDPE structured geomembrane with integral drain structure on top and spike grip texture on the bottom surface & 335 g/m$^2$ nonwoven polypropylene geotextile
   b) Terraced areas:
      - 2 mm (80 mil) thick LLDPE smooth geomembrane & 335 g/m$^2$ nonwoven polypropylene geotextile
   c) Perimeter ditches:
      - 1.0 mm (40 mil) thick LLDPE geomembrane/geotextile composite with 670 g/m$^2$ geotextile bonded to both sides of the LLDPE
5) 300 mm (12 in) thick roller compacted processed Minus 25.4 mm ore base layer.
6) Waste rock dump working surface.

To ensure adequate drainage from the benched areas, 3,800 m (12,500 ft) long subsurface drains (300 mm (12 in) and 450 mm (18 in) geopipe) were also installed.

The installed LLDPE geomembrane met the Geosynthetic Institute Standard GRI GM-17 with the exception of asperity height, which was increased to 0.38 mm (15 mils) to ensure a rough surface. In addition, a minimum interface friction angle of $\delta = 28^\circ$ with the compacted ore base layer was specified. During installation, the nonwoven geotextile was positioned and thermally welded at all overlaps after the placement of the geomembrane.

Resloping the waste rock piles to 3.5H:1V and installation of the geomembrane cover system were completed in 2002 at an estimated cost of US$17.5 million. Estimated costs for placement of the final soil cover and revegetation were US$3.5 million. Thus, overall costs for the cover system and surface water drainage ditches was approximately US$21 million for 26 ha or US$807,500/ha. No performance data was provided for this installation.

3.3.2 HDPE Cover System over Tailings (Maurice and Wiber 2004)

One of the most notable geosynthetic installations in Canada was done at the Poirier Mine located in northwestern Quebec, some 150 kilometers northeast of Rouyn-Noranda. The mine operated from 1965 to 1975 and rehabilitation works started in 1998 to 2000. The remediation work involved installation of a HDPE GM cover system over approximately 5,000,000 tons of tailings (Maurice and Wiber 2004). The rehabilitated tailings area was 46 ha. The cost-effectiveness of a very low permeability HDPE cover system consisting of a HDPE GM and a protective soil layer was evaluated against a compacted clay cover. The HDPE GM was deemed to be better suited than the compacted clay to maintain structural integrity when subjected to abnormal differential settlement. The HDPE cover system also proved to be cheaper than compacted clay because the latter required a much thicker frost-protection soil layer.

Some of the challenges experienced during construction included the following: tailings were flowing up to the surface after placement of the protective soil layer; the HDPE GM was punctured by a tree stump and underlying liquefied tailings escaped to the surface through the puncture; and liquefaction of tailings caused a significant subsidence (Maurice and Wiber 2004). The HDPE cover system was evaluated four years after installation and it was concluded that the facility performed as intended. As this is one of the major liner installations in Canada, it will be critical to monitor its performance in the long-term and beyond the manufacturer’s guaranteed service life.

3.3.3 Use of PE in Heap Leaching (Ossa Defilippis 2005)

The use of heap leach pads started in the 1980s with gold recovery operations. The heap leaching process may be used to extract gold and/or silver or copper from
low grade deposits. For example, copper may be extracted with the SX-EW (oxide leaching and solvent extraction-electrowinning) process. In the heap leach process, the ore is piled onto a liner and an extractant solution is applied to the surface, which dissolved the metal in the ore. The metal bearing leachate (pregnant solution) is collected above the liner and pumped to a solvent extraction plant to remove and concentrate the mineral. Gold is typically extracted with an alkaline extractant and copper with a weak acid solution.

The heap leach industry has been using geosynthetic materials such as geomembranes, geopipes, geotextiles, geonets and studded concrete liners extensively with good success (Ossa Defilippis 2005). Millions of square meters have been placed on heap leaching of oxide and sulphide ores. For example, the base layer of a heap leach pad is usually a HDPE or LLDPE geomembrane with a thickness of ranging from 1.0 mm to 1.5 mm. Conveyor channels are commonly lined by a thicker HDPE geomembrane. They discharge into intermediate and pregnant solution ponds, which are often lined with a double HDPE liner (1.5 mm thick) that has a HDPE geonet drainage layer in the middle (Ossa Defilippis 2005).

During the heap leaching of sulphide ores, air is forced through the pile and leach solution is applied to stimulate bioleaching of the ores. Continuous irrigation leaches the ore, but also the antioxidants of the geomembrane. The service life of the liner is a function of the polymer resin, the geomembrane thickness, and the installation practices. The quality of the geomembrane depends geomembrane density, thickness, carbon black content, carbon black dispersion, resistance to stress cracking, oxidative induction time (OIT), oven aging, UV aging, tensile strength, and tear and puncture resistance (Ossa Defilippis 2005).

3.3.4 GCL Cover on Apache Tailings (Olsta and Friedman 2002)

The Apache tailings impoundment is located in Leadville, Colo within the California Gulch Superfund site. This site was placed on the American National Priorities List in 1983 because of ARD impact on surface waters in the California Gulch and the heavy metals loading in the Arkansas River.

A 7 ha multi-layer cover system was installed on top of a tailings impoundment. The cover system consisted of a GCL, a geocomposite drainage layer, and a 45 cm (18 in) soil cover. The minimum recommended soil cover above a GCL is typically 0.3 m.

A double-nonwoven needlepunched GCL was used on the slopes, which ranged from 3H:1V and 5H:1V and a woven-nonwoven needlepunched GCL was used on the relatively flat top of the impoundment. A triplanar drainage geocomposite was chosen for the drainage layer. The soil cover was seeded with a native seed mixture and protected with a single-sided biodegradable straw erosion control blanket. Surface water run-on and runoff ditches were also lined with GCL. No performance or cost data was provided in the article.

3.3.5 GCL Cover on Zortman Landusky Surprise Pit (Olsta and Friedman 2002)

The Zortman Landusky Surprise Pit cap is located in Landusky, Montana. To minimize ARD generation from the Surprise Pit, the Pit floor was backfilled with PAG waste rock to establish positive drainage and some clean material was placed on the top of the backfill and graded to a 3% slope. Subsequently, a 5 cm (2 in) layer of bentonite was spread over the backfill and compacted. This bentonite layer was then covered with a membrane-laminated unreinforced GCL. The lamination consisted of a thin polyethylene membrane. No performance or cost data was provided in the article.

3.4 Case Studies regarding the Performance Evaluation of Geosynthetics to Mitigate ARD

3.4.1 Effects of synthetic ARD on Polymer Properties (Gulec et al. 2004, 2005)

Gulec et al. (2004, 2005) estimated the antioxidant depletion rates in 1.5 mm thick HDPE GM coupons after their immersion in synthetic ARD at various temperatures. HDPE coupons, which met the GRI GM13 standard, were kept in the ARD solutions at 20°C, 40°C, and 60°C for 21 months and several others were immersed in synthetic ARD for 10 weeks at 80°C. Gulec et al. (2004, 2005) also evaluated mechanical and hydraulic properties of HDPE coupons and of a needle-punched, non-woven PP geotextile (200 g/m²), and a drainage composite consisting of a HDPE geonet with a needle-punched, non-woven PP geotextile (200 g/m²) heat bonded to each side. The synthetic ARD was prepared with deionized water (DI) using FeSO₄·7H₂O, ZnSO₄·7H₂O, CuSO₄, CaSO₄, and H₂SO₄ and had an average pH of 2.4. It contained approximately 1,500 mg/L Fe, 350 mg/L Zn, 35 mg/L Cu, 4,500 mg/L SO₄²⁻, and 200 mg/L Ca (Gulec et al. 2005).

In the laboratory, Gulec et al. (2004) established antioxidant depletion rate ranging from 0.0051 to 1.2056 1/month for coupons totally immersed in the synthetic ARD (Table 1). The antioxidant depletion rate was very temperature dependent. The estimated antioxidant depletion time for immersed HDPE coupons ranged from 67.3 to 83.3 years for synthetic ARD at 20°C, compared to 3.7 to 4.5 years for synthetic ARD at 60°C (Table 1).

Gulec et al. (2004) presented estimates for one-sided ARD exposure inferred from estimates that had been obtained for geosynthetics exposure to water and air by others. Based on this inference, Gulec et al. (2004) estimated an antioxidant depletion time for immersed HDPE coupons of 210 years assuming an initial OIT of 100 min and of 238 years assuming an initial OIT of 200 min at a temperature of 20°C.

Gulec et al. (2005) did not observe any statistically significant changes in the hydraulic and mechanical...
properties of the tested materials, based on an analysis of variance (ANOVA) and linear regression. In the opinion of the authors of the present paper, no significant deterioration of engineering properties should be expected within 21 or 22 months, because 22 months corresponds to approximately 2.9 half-lives of the anti-oxidation depletion rate S (t_{1/2} = ln2/S) measured for HDPE at 60°C; i.e. the duration of the test period chosen by Gulec at al. (2004, 2005; Table 1). Also, based on previously reported research (Kay et al. 2004), PP was expected to show similar chemical resistance compared to PE, at least, in the temperature range of 20-60°C.

### 3.4.2 Performance of a Soil Cover Systems containing GCLs in a temperate climate (Melchoir 2002)

The following case study demonstrates the importance of safeguarding GCLs in shallow soil cover systems (0.4 - 1.0 m) against desiccation and ion exchange.

In 1994, a large lysimeter study commenced on the Hamburg-Georgswerder landfill to test the field performance of GCLs. The landfill is located near Hamburg in northern Germany (~ 53°20’N, 10°20’E; mean annual precipitation of 750-1,000 mm). Two 100 m² lysimeters were integrated into the landfill cover to measure the percolation rate through a needle-punched and a stitch-bounded GCL under a cover consisting of 30 cm topsoil (sandy loam) and 15 cm drainage layer (gravel) (Melchoir 2002). Three other products, including a Grundseal® GM, were tested under similar conditions in smaller control plots. Grundseal® is a composite product consisting of the thin HDPE liner with granular bentonite adhesively glued to one side. The following key results were reported (Melchoir 2002):

1) The needle-punched and stitch-bonded GCLs, except for the GM-bentonite GCL, were penetrated by fine roots starting in 1994. Only a few roots grew in the overlaps of the GM-bentonite GCL.

2) A network of cracks, up to 2 mm wide, that did not ‘heal’ after rewetting of the GCLs developed during the summer of 1995.

3) In the needle-punched and stitch-bounded GCLs, sodium bentonite had become calcium bentonite within two years after installation due to ion exchange with the cover soils. As a result, the swelling capacity of the bentonite in the needle-punched and stitch-bounded GCLs was less than half of its original capacity in 1996 and 1998.

4) In the composite GM/GCL, the calcium content of the bentonite increased as well (from 20 to 28%), but not as dramatically as for the other GCLs. (Ion exchange in the composite GM/GCL may have occurred with the subsoil.) The swelling capacity of the composite GM/GCL decreased from 20 mL/2g to 12 mL/2g from 1994 to 1999.

5) The estimated percolation through the needle-punched and stitch-bounded GCLs was 1.7×10^{-7} m³/m²/s, or approximately 3,400 times the original permeability.

6) By 1998 (after 4 years), all needle-punched and stitch-bounded GCLs had hydraulic conductivities several magnitudes larger compared to their initial values based on fixed wall hydraulic conductivity tests.

In summary, Melchoir (2002) found that desiccation, cation exchange, plant root penetration and shrinkage increased the hydraulic conductivity of needle-punched...
and stitch-bonded GCLs significantly under a shallow 45 cm soil cover. The estimated percolation through the needle-punched and stitch-bonded GCLs was $1.7 \times 10^{-7}$ m$^3$/m$^2$/s, or approximately 3400 times the original permeability. The composite GM/GCL performed better than the needle-punched and stitch-bonded GCL. During the performance evaluation, the GCLs were not exposed to freeze-thaw episodes, the pH was neutral, and soil and soil water were free of aggressive contaminants (Melchior 2002).

3.4.3 Performance of a soil cover systems containing a GCL in a humid climate (Renken 2006)

The authors of this paper conducted a field performance evaluation of a GCL soil cover system at the Premier Gold Project (PGP) located near Stewart, BC, Canada (~ 56°05'N, 130°00'W; Elevation 335 m; mean annual precipitation $> 1,500$ mm). The field performance evaluation commenced in 2002 for a GCL Plot, a Control Plot and two other treatment plots. The cover systems were evaluated for their ability to reduce infiltration and were evaluated for their ability to reduce infiltration and precipitation $> 1,500$ mm). The field performance of a GCL soil cover system at the Premier Gold Project (PGP) located near Stewart, BC, Canada (~ 56°05'N, 130°00'W; Elevation 335 m; mean annual precipitation $> 1,500$ mm). The field performance evaluation commenced in 2002 for a GCL Plot, a Control Plot and two other treatment plots. The cover systems were evaluated for their ability to reduce infiltration and permeability. The composite GM/GCL performed better than the needle-punched and stitch-bonded GCL. During the performance evaluation, the GCLs were not exposed to freeze-thaw episodes, the pH was neutral, and soil and soil water were free of aggressive contaminants (Melchior 2002).

3.4.3 Performance of a soil cover systems containing a GCL in a humid climate (Renken 2006)

The authors of this paper conducted a field performance evaluation of a GCL soil cover system at the Premier Gold Project (PGP) located near Stewart, BC, Canada (~ 56°05'N, 130°00'W; Elevation 335 m; mean annual precipitation $> 1,500$ mm). The field performance evaluation commenced in 2002 for a GCL Plot, a Control Plot and two other treatment plots. The cover systems were evaluated for their ability to reduce infiltration and oxygen flux into underlying, potentially acid generating tailings. The GCL cover system (~11.5 x 15 m) consisted of a grass and legume mixture.

Renken (2006) inferred that the GCL below the 45 cm soil cover in the humid climate appears to have, at least partially, desiccated during the second summer, because: 1) higher oxygen concentrations were observed in two out of three soil profiles in 2004 in the tailings; 2) GCL Plot runoff and interflow results were intermittent; and 3) some GCL specimens, exhumed in 2004, had air entry values (AEVs) of less than 10 kPa. These low AEVs would render the GCL susceptible to desiccation. The AEV is defined as the matric suction (sometimes also called soil suction) at which the first water filled soil pores drain. The GCL reduced oxygen concentrations in the covered tailings, but measured oxygen concentrations were still high enough to support sulphide oxidation (at least in the second summer), which was to be inhibited by the candidate cover system for the tailings. The inferred field hydraulic conductivity was $1 \times 10^{-10}$ to $2 \times 10^{-10}$ m/s in 2004.

3.4.4 GCL desiccation below a geomembrane (Southen 2005)

Southen (2005) found that GCL desiccation occurs under certain initial and boundary conditions when placed below a GM. Desiccation is primarily dependent on the initial water content of the subsoil beneath the GCL and the temperature gradient (Southen 2005). GCLs placed below a GM and on top of silty sand subsoil with an initial gravimetric water content ranging from 4.2 to 6.6% resulted in decreased final water contents in all four GCL specimens tested (increase from initial water content of 72 to 110% to final water content of 9.5 to 28.6%) under essentially the same temperature gradient of 24.8 to 27 °C/m (Southen 2005). Desiccation cracks were numerous and relatively uniformly spaced in a honeycomb pattern. Based on Southen’s (2005) results, it may be concluded that GCLs placed below a GM and on top of a drainage layer (which typically has a low gravimetric water content) are likely to desiccate unless they are recharged due to leaks in the GM.

3.4.5 Metal Migration in GCLs (Lange et al. 2004)

Lange et al. (2004) investigated metal migration in GCLs after their initial hydration with deaired, deionized water (DDW) and subsequent permeation with synthetic ARD. The synthetic ARD had a pH of 3.9 and contained the following ionic concentrations (in mg/L): Na$^+$ 460, K$^+$ 780, Cl$^-$ 43, SO$_4^{2-}$ 3540, Al$^{3+}$ 90, Cd$^{2+}$ 6, Cu$^{2+}$ 20, Fe$^{2+}$ 200, Mn$^{2+}$ 25, Zn$^{2+}$ 100, Ni$^{2+}$ 20. Once ARD was applied, the pH started to decline and the hydraulic conductivity increased. After the passage of 21-22 pore volumes (PVs), the pH was 4.6 and after the passage of 33 PVs, the pH was 3.9, and thereafter (33-44 PVs), the pH ranged from 3.8 to 4.9. The hydraulic conductivity was $2.8 \times 10^{-12}$ m/s at the start of the ARD permeation and $3.7 \times 10^{-11}$ m/s after the passage of 44 PVs (after 36 PVs of ARD permeation). The rate of increase in the hydraulic conductivity had not stabilized after the passage of 44 PVs. All metals with the exception of Al eventually reached their influent values. Effluent concentrations of some metals (Mn, Ni, Cd, Cu and Zn) were even higher than the influent values after the passage of 26 PVs (Lange et al. 2004). This was likely due to remobilization of initially precipitated metals in response to the drop in pore water pH.

4. DISCUSSION

The extensive use of HDPE and LLDPE geosynthetics in heap leach operations has proven that they are suitable for containment of corrosive ARD, at least in the short and medium term. Long-term performance data for the containment of ARD does not exist. The theoretical service life based on laboratory testing may be several decades to centuries. However, whether actual field performance will confirm these predictions is unknown at this time.

Cover systems that incorporate geosynthetics have been installed to reduce ARD generation. Again, long-term performance data does not exist. These cover systems will have the longest service life, if cover installations are designed and built by adhering to excellent QA/QC protocols and if chemical, physical, thermal stresses and UV exposure on the geomembranes are minimized. In addition, long-term slope stability of the soil cover system on top of the geomembrane has to be ensured to achieve a long service life.
GCLs, and especially GCLs installed below geomembranes (GMs), have been used extensively as hydraulic barriers in the municipal solid waste industry. Based on this extensive use, GCLs installed below GMs can be used as hydraulic barriers in cover systems to minimize ARD generation expected to perform well. Longevity of the GCL/GM system would be limited by the longevity of the GMs and the geotextiles of the GCLs, and the quality of installation.

The performance of GCLs in liner systems (GCLs alone or below GMs) would depend on the pH and acidity/alkalinity and the cation concentrations in the contained liquids. Since bentonite looses its swelling capacity below pH 2 (Olsta 2005), a GCL liner may fail when it is needed most to contain highly acidic solutions with a pH lower than 2. Ion exchange may also be an issue, because typical ARD has high concentrations of Cu²⁺, Zn²⁺, and Pb²⁺. Thus, the long-term performance of GCLs as hydraulic barriers in liner systems to mitigate ARD is uncertain, because if the GM would leak, the GCL would be exposed to a host of divalent cations at high concentrations which, in turn, would increase the hydraulic conductivity of the GCL (potentially beyond the liner performance specifications).

The suitability of GCLs to act as an oxygen diffusion barrier to mitigate ARD seems questionable based on the case studies reviewed. The main shortcomings of a GCL are its short oxygen diffusion path length and its susceptibility to desiccation. The likelihood of temporary partial or complete desiccation of GCLs under field conditions appears high due to the following factors:

1) GCLs under shallow soil covers are prone to desiccation and ion exchange;
2) GCLs under thick soil covers are also prone to ion exchange and potentially desiccation;
3) GCLs below GMs are prone to desiccation if installed above drainage layers (which is typical); and
4) GCLs installed between two GMs would remain ‘dry’ unless the GMs leak.

5. SUMMARY

This paper reviewed key aspects of ARD generation and common capping technologies to mitigate ARD. Case studies regarding the use and investigation of geosynthetic materials in the ARD mitigation were presented. On the basis of the results from the case studies geomembranes such as HDPE or LLDPE may be suitable in composite liner or cover systems to augment the hydraulic barrier and potentially the oxygen diffusion characteristics of a soil-based liner or cover system to mitigate ARD. Based on the literature review, GCLs may be suitable as hydraulic barrier, but likely not as oxygen diffusion barrier in cover systems intended to mitigate ARD.

REFERENCES


