GEOSYNTHETICS RESEARCH AND APPLICATIONS IN THE MINING AND MINERAL PROCESSING ENVIRONMENT

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ABSTRACT

This paper presents research conducted under the 2003 North American Geosynthetics Society Award of Excellence. The objective of the research was to investigate the use of geosynthetics in the mining and processing sector and to summarize field performance results related to geomembrane (GM), geosynthetic clay liners (GCLs) and geogrid applications. The paper commences with a summary of challenges in environmental mine management and formulates key questions for determining the suitability of geosynthetics for a particular application. Examples of case studies are then reviewed, including: 1) GCLs covered with shallow soil covers to limit infiltration and possibly acid rock drainage (ARD); 2) GCLs installed below GMs; 3) estimation of the longevity of high density polyethylene (HDPE) exposed to ARD; 4) use of geogrid to cover a ponded area on a tailings impoundment; and 5) use of HDPE to cover tailings. Technical considerations for GCL and GM installations are presented and polymer degradation mechanisms are summarized to put current practice in the mining industry in perspective. Areas requiring further research are identified.

It was found that the mining and mineral processing industry is moving more and more towards the use of geosynthetics for civil, geotechnical and environmental engineering applications. Geosynthetic liners and collection pipes for heap leach operations are widely used and ever higher target heap heights are fostering the development of new design, laboratory testing, and construction methods. The duration of the service life of geosynthetics and their cost-effectiveness compared to other available alternatives are the main concerns facing the mining and mineral processing industry, especially for their use in long-term geotechnical and environmental control.

Keywords: geomembrane, GM, GCL, mining, waste containment

1. INTRODUCTION

The geosynthetics industry has been growing rapidly in the past 25 years and geosynthetic materials have become common features in many modern civil, geotechnical and environmental engineering applications. At mine sites, geomembranes (GMs) have been primarily used for liquid containment (drainage waters, process solutions, treatment ponds), as basal liners for heap leach facilities or other solid waste facilities, and to some extent, for tailings impoundments. Reclaimed fill structures may also include relatively impervious GM liner caps to prevent precipitation from infiltrating into the underlying fill materials to achieve full containment or diversion of liquids. Geogrids have been used to stabilize soft soils for road construction and mine tailings for soil cover placement. Geopipes are used for conveyance of runoff, drainage, process waters, or for leak detection around mine sites. Table 1 summarizes common types of geosynthetics and their application in the mining industry.

Table 1. Common Geosynthetic Materials and Applications in the Mining Industry

Geosynthetic Material	Polymer Type	Principal Application
Geomembranes	HDPE, LLDPE, Plasticized PVC, PP	heap leach liner, surge pond containment, settling ponds waste containment, water and solutions impoundments, engineered covers
Geonets	HDPE	drainage
Geogrids	HDPE, Polyesters (PET), PP	stabilization of soft soils, base for road construction
Geopipes	HDPE, LLDPE, PVC	conveyance of clean, drainage and process waters
Geotextiles	PP, PET	cushion layers, filter cloths

Note: HDPE = high density polyethylene; PVC = polyvinyl chloride
LLDPE = linear low density polyethylene; PP = polypropylene

The suitability of geosynthetics for long-term applications for waste containment in the mining industry is still being scructinized. Although laboratory tests predict lifespans of up to several hundred years for materials such as HDPE (Koerner, 2004), manufacturers are willing to warranty their products (materials and their replacement) for up to 20-30 years (e.g. Colorado Lining International, 2005). While short and medium term (up to ~ 30 years) geosynthetics performance data is available, long-term field performance data is non-existent and available predictions have been based on a variety of laboratory tests and modeling to date. In addition, unsatisfactory field performance results have been reported and have prompted the geosynthetics industry to improve their products and respective user guidelines (Melchior, 2002; Rollin, 2004; Koerner, 2004; Koerner and Koerner, 2005). These factors may be contributing reasons for the limited use of geosynthetics to address long-term issues such as the control of Metal Leaching (ML) and acid rock drainage (ARD).

1.1 Objectives and Scope

This paper presents research conducted under the 2003 North American Geosynthetics Award of Excellence awarded by The North American Geosynthetics Society (NAGS). The objective of the research was to investigate the use of geosynthetics in the mining and processing sector and to summarize field performance results and technical considerations related to geomembranes (GMs), geosynthetic clay liners (GCLs) and geogrid applications. The study methodology included but was not limited to a questionnaire sent to the mining industry, individual industry contacts, personal communication with consultants and colleagues, and literature review. To meet the objectives, challenges in environmental mine management were reviewed, pertinent case studies of geosynthetic use were identified, technical considerations were summarized, and key issues regarding the use of geosythetics to meet those challenges were raised.

1.2 Challenges in Environmental Mine Management

Environmental protection challenges in the mineral sector include:

1) Mines, unlike other facilities such as dedicated landfill sites, usually have a much larger footprint (typically hundreds of hectares). Therefore, environmental protection measures have to be practical, robust, economical, acceptable to regulatory bodies, sustainable and environmentally sound.
2) Duration of responsibility and/or the post closure period for the site may extend over several decades and even centuries especially for sites with acid generating or radioactive wastes; hence waste containment and environmental control systems need to be functioning in the long-term and be economically feasible. Most ML/ARD mitigation and control measures must be designed, constructed, and operated in a manner that allows them to perform indefinitely under normal and extreme climatic conditions.
3) Management of mine waste does not generate revenue for environmental controls - no tipping fees can be charged as in the case of dedicated landfill sites, because mine waste is generated and remains on site, to a large extent. Thus, engineering controls for waste management have to be technically and economically feasible.
4) Waste management is normally considered a major liability to the industry. However, the industry recognizes the extent of this liability and diligent control measures are implemented such aspects as design for closure to minimize long-term liabilities. Small studies have been carried out to investigate possible recycling of mine waste, but no favourable, economically viable results have been reported.
5) Mines are often located in remote areas, which might make transportation of construction materials to the site difficult and expensive. In most cases, local materials are preferably used for construction and remediation purposes if available and suitable.
6) The environment is often harsh, especially for those sites with ML/ARD or that are located at high elevations. Therefore, measures to mitigate and control ML/ARD or other problems must be compatible with site-specific conditions and implemented according to defined specifications required to meet performance objectives.
7) For logistical reasons, most existing mine and mineral processing waste storage facilities are located in topographic depressions or at the bottom of slopes. These areas are often zones of ground water discharge with high rates of flow during some periods of the year. Under such conditions, leaching will continue even if an engineered cover effectively limits surface infiltration.
8) Limited resources tend to be dedicated for maintenance, inspection, monitoring and surveillance programs during closure and long-term care and maintenance. Therefore, control systems have to be robust and relatively maintenance free.
9) During the post closure stage, major inspections of waste containment systems by qualified personnel are typically only done on bi-annual or annual basis in Canada or even less frequent in other parts of the world. Infrequent inspections by a competent person may lead to structural failure that could have been prevented through a more frequent structured monitoring program.

10) Suitable, local materials to serve as geosynthetic interface materials, such as clay, gravel, sand and silt, may be lacking at some sites, especially those located in northern climes.

Since mine site management concerns, such as dam and slope stability and ML/ARD mitigation and control, are long-term, it is critical to ensure that materials used for environmental and geotechnical controls require minimal maintenance and monitoring, perform as designed, have a long service life, and are economically feasible. For the benefit of readers unfamiliar with ARD, pertinent aspects are briefly reviewed in the next paragraph.

ARD is a serious environmental and economic concern facing the mining industry today. ARD, characterized by low pH levels, high acidity, and high sulphate and metal concentrations and can contaminate receiving environs, if not properly managed. ARD forms naturally in three stages, if sulphidic materials are insufficiently buffered with alkaline minerals such as calcite. As ARD develops, the pH drops progressively from near neutral to slightly acidic levels and then to very low pH levels (< 3.0). 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 stage (transition stage) are both abiotic and slow and biotic and fast. Bacteria most commonly isolated from ARD generating environments include Thiobacillus *ferrooxidans,* Leptospirillum *ferrooxidans*, and T. *thiooxidans* (Rawlings, 1997). T. *ferrooxidans* are purely autotrophic and 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). To mitigate ARD, physical barriers have been used to minimize infiltration of precipitation, oxygen diffusion, and oxygen flux to the sulphidic material.

Key questions in the assessment of the suitability of geosynthetics for a particular application include:

1) Do they work to address the challenge (e.g. compatibility with the mine and environment, containment, collection, conveyance, isolation, etc.) in the mining environment?
2) What is the projected service life and how does that service life compare to the required service life of the facility?
3) What are the costs and requirements for initial geosynthetic installation, subsequent maintenance, and eventual replacement, recycling or abandonment?
4) What are the competing alternatives to geosynthetics and is the use of geosynthetics cost-effective compared to other options (e.g. natural soils, engineered soil-based systems for containment, pump and treat)?

This paper addresses the first two questions for GCL and polyethylene (PE) and polypropylene (PP) products. Answers to the third question may vary greatly depending on the required products (type, polymer formulation, thickness or weight, etc.), the manufacturer, shipping, installation environment, and therefore, are site- and/or waste-type specific. Budget estimates for material costs may be in the range of US$0.34 to US$0.60/ft^2 (CDN$5-10/m^2) for GCLs, US$0.22 toUS$0.60/ft^2 (CDN$3.50-8.00/m^2) for linear low density polyethylene

(LLDPE) GMs, US$0.22 to US$0.60/ft^2 (CDN$4-8/m^2) for HDPE GMs, and approximately US$0.16/ft^2 (CDN$1.70/m^2) for heavy (e.g. 16 oz) geotextile cushion layers.

Answers to the fourth question will also be site-, ore-, and/or waste-specific. The use of geosynthetics to mitigate and control ARD from tailings and waste rock competes with methods such as the use of natural soils or modified soils, collection and treatment (with or without any cover), water covers, store and release covers, rigid covers (e.g. shotcrete), conventional and paste backfill (reduces the quantity of tailings impounded), and desulphurization of tailings. For example, depending on the site-specific factors, the overall cost of material procurement, engineering and installation may be upward of $250,000 per hectare or $25 per square meter for an engineered cover to mitigate ARD while a store and release cover has been estimated to cost $84,000 per hectare (Mchaina, 1995, 2003). Depending on site and waste characteristics, options such as collection and treatment have proven to be the economical and practical approach to dealing with ARD problems. Whatever cover or capping option is selected, there is typically some requirement to collect and treat drainage waters. As such, 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. As discussed earlier, suppliers of geosynthetics warranty their products for up to 20-30 years, consequently, regulatory authorities tend to regard the use of geosynthetics as a temporary measure to mitigate and control ML/ARD.

2. GEOSYNTHETICS

The review of key technical considerations and examples of case studies for the use of geosynthetics in the mining and mineral processing industries commences with GCLs, followed by polyethylene (PE) and polypropylene (PP) products. GCLs have been used extensively in landfill design and construction as hydraulic barriers and secondary hydraulic barriers below GMs. GCLs have been used by the mining industry for capping and waste containment (Ecosystem Restoration, 1995; Crouse et al., 1999 and 2000), but not as widely used as in the municipal waste management industry. Presented case studies include GCLs covered with shallow soil covers to limit infiltration and possibly acid rock drainage, and GCLs installed below GMs.

2.1 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 (Stewart and von Maubeuge, 1997).

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 1.0×10^{-11} to 5.0×10^{-11} m/s at the factory (Koerner and Daniel, 1997; Petrov and Rowe, 1997). GCLs are generally more resistant to cracking due to freeze-thaw cycles and desiccation than compacted clay liners (Koerner and Daniel, 1997).

2.1.1 Technical Considerations for Design and Construction with GCLs

Key considerations for design and construction with GCLs are listed below prior to detailing case studies to emphasize some of the technical considerations and to present recent research.

1) **Shipping, handling, and storage practices need to address the fragileness of the GCLs to prevent damage, punctures and/or premature hydration**. If a GCL hydrates prematurely and is subsequently loaded, for example by walking or placing soil on it, the hydrated bentonite may be squeezed out from underneath the confined area towards the less confined GCL resulting in high hydraulic conductivity zones.

2) **Proper construction techniques need to be followed.** Basic installation guidelines are typically provided by GCL manufacturers. Additional, more stringent guidelines may have to be adopted to address site-specific or waste-specific issues. In all installations, it is crucial 1) to prevent premature hydration of GCLs, 2) to prevent puncturing or ripping of the GCL, 3) to apply a confining pressure equivalent to at least 300 mm of soil cover on top of the GCLs as soon as possible after placement (at least on the same day and prior to any precipitation on that day), 4) to provide adequate seam overlap (25 to 45 cm) to accommodate GCL shrinkage due to temperature changes, 5) to add sufficient bentonite in the seam areas, and 6) to prevent wrinkles during GCL installation. Improper installation can result in significant decreases in performance. Unsatisfactory performance is often due to improper site preparation, for example, by placing GCLs on top of or below soils that are so coarse or angular that the GCL is punctured. Wrinkles may result in localized redistribution of hydrated bentonite (squeezing of bentonite to less confined zones) in the GCL resulting in higher hydraulic conductivity in affected areas. Insufficient bentonite in seam areas may lead to significant leakage, especially when GCL is installed to contain liquids (Chamberlain et al., 1997).

3) **GCL liquid permeability and flux vary with confining stress**. For low confining stresses (< 420 kPa), the higher the confining stress, the lower the permeability and the flux (Trauger, 2005).

4) **The GCL (bentonite and geotextiles) needs to be chemically compatible with the liquid or gas that it will come in contact with** (e.g. regarding pH levels, acidity, chemical compound(s)). For example, bentonite tends to maintain its swelling capacity in the pH range of 2 to 13 (Olsta, 2005). Therefore, GCLs are not compatible with strong acids (pH < 2) nor with strong bases (pH >13).

5) **Need to consider internal shear strength of hydrated GCL (ASTM D 6496) and interface shear strength of GCL with the materials above and below it (ASTM D 6243).**

GCLs are typically internally reinforced with needle-punching or other methods, because the angle of internal friction for unreinforced bentonite is low (approximately 4-9^o corresponding to a slope of 14H:1V to 6H:1V) (Thiel, 2005). Interface strength of GCLs is material specific and depends on the geotextile (woven or nonwoven) and whether hydrated bentonite extruded through the fabric. Slope stability should be evaluated on a case by case basis for in situ soils and the combinations of geosynthetics and other materials added to the slope assuming average and worst-case conditions. Long-term reinforced GCLs on 3H:1V slopes (33% or 18.3^o) should be no problem for soil cover systems (Thiel, 2005). However, Bonaparte et al. (2002) cited numerous 2H:1V cover systems containing GCLs that failed. On slopes steeper than 3H:1V, it is recommended to use needle-punched GCLs with a non-woven geotextile on top and a scrim-reinforced non-woven geotextile on the bottom.

6) **Need to minimize ion exchange of monovalent Na^+ for divalent cations such as Ca^{2+} or Mg^{2+}.** The exchange of monovalent Na^+ for divalent cations such as Ca^{2+} or Mg^{2+}, can lead to significant increases in GCL hydraulic conductivity, because the divalent ion decreases the swelling capacity of the bentonite which in turn results in higher porosity (Melchior, 1997; James et al., 1997). It is important to note that ML/ARD phenomena are in part characterized by the release of divalent cations even before acid is generated. Sometimes this is due to liming during milling. To illustrate increased hydraulic conductivity after ion exchange, Lin and Benson (2000) conducted a series of swell test on GCL specimens using deionized water (DI) and 0.0125 M $CaCl_2$. The hydraulic conductivity of samples subjected to four wet-dry cycles using 0.0125 M $CaCl_2$ was 4,000 times as high as the hydraulic conductivity of samples subjected to wet-dry cycles using distilled water.

   To prevent exchange of monovalent Na^+ for divalent cations, GCLs have been placed directly beneath GMs (Benson, 1999). However, although placement of GCLs below GMs may address the problem of ion exchange, it might create a GCL desiccation problem (see GCL case studies by Southen (2005), Koerner and Koerner (2005)).

7) **Need to protect GCLs from tearing and cracking due to differential settlement.** This requirement can be achieved by good site preparation and following appropriate QA/QC protocols during construction/installation.

2.1.2 GCL Case Studies

2.1.2.1 Field performance of 45 cm soil cover systems containing GCLs in temperateclimate (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^{o}20'N, 10^{o}20'E; mean annual precipitation of 750-1,000 mm). Two 100 m^2 lysimeters were integrated into the landfill cover to measure the percolation rate through a needle-punched and a stitch-bounded GCLs under a cover consisting of 30 cm topsoil (sandy loam) and 15 cm drainage layer (gravel) (Melchior, 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 (Melchior, 2002):

- 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.
- A network of cracks, up to 2 mm wide, that did not 'heal' after rewetting of the GCLs developed during the summer of 1995.
- 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.
- 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.
- The estimated percolation through the needle-punched and stitch-bounded GCLs was 1.7×10^{-7} $m^3/m^2/s$, or approximately 3,400 times the original permeability.
- 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, Melchior (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-bounded GCLs was 1.7×10^{-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).

2.1.2.2 Field performance of 45 cm soil cover systems containing GCLs in humid climate (Renken et al., 2003a, 2003b, 2003c, 2005)

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 > 2,200 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 (bottom to top) 0.75 m potential acid generating tailings, 0.1-0.15 m fine sand, a needle-punched GCL (Bentomat® ST), 0.1-0.15 m fine sand, 0.25-0.35 m of coarse sand and gravel, and 0.05-0.10 m top soil seeded with a grass and legume mixture.

Renken et al. (2005) 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 1×10^{-10} to 2×10^{-10} m/s in 2004.

2.1.2.3 Laboratory Study: GCL desiccation below a geomembrane

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 12.1 to 13% resulted in increased final water contents in all four GCL specimens tested (increase from initial water content of 70 to 82% to final water content of 90 to 112%) under a temperature gradient of 25.5 to 29 (^{o}C/m). In contrast, 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 (decrease 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 (^{o}C/m) (Southen, 2005). Desiccation cracks were numerous and relatively uniformly spaced in a honeycomb pattern. Based on Southen's (2005) results, one may conclude 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.

2.1.2.4 Panel Separation of GCLs below textured Geomembranes that were left uncovered (Koerner and Koerner, 2005)

Koerner and Koerner (2005) investigated GCL panel separations that occurred in landfill cover systems at five locations. Separation of the adjacent GCL panel edges ranged from 0 to 300 mm for most cases and up to 1,200 mm in the worst case. At one landfill, just about every adjacent GCL panel along the upper southerly facing slope separated. Koerner and Koerner (2005) investigated the effects of longitudinal steep slope tensioning of the GCL, GCL shrinkage (e.g. due to cyclic wetting and drying), and GCL contraction on relatively flat slopes for these cases. In all five cases, the GCLs had been installed below textured GMs (with the textured side facing the GCL) that had been left exposed from two months to five years with no covering of any type. GCLs with non-woven geotextiles on both sides with no internal scrim reinforcement were found to be a major cause for GCL panel separations (Koerner and Koerner, 2005). It should be noted that Koerner and Koerner (2005) did not investigate the effect of ion exchange on the shrinkage behavior of the GCLs. Ion exchange could have occurred with the subsoil as was reported by Melchior (2002).

To prevent similar problems with GM/GCL cover systems, Koerner and Koerner (2005) recommended the following:

- To cover GM/GCL composite liners in a timely manner (site specific) to minimize exposure to cyclic temperature extremes;
- To only use scrim reinforced GCLs (at least one of the geotextiles in the GCL should be scrim-reinforced);
- To have a minimum GCL overlap of 25 to 45 cm (10 to 18 in);
- To use GCLs with a low as-manufactured moisture content to minimize shrinkage;
- To protect GM/GCL composite liners or covers from thermal stress when left exposed by using thermal blankets, geofoam, or other insulation techniques.

2.1.3 Potential for GCL use in ML/ARD Mitigation

GCLs, and especially GCLs installed below GMs, have been used extensively as hydraulic barriers in the municipal waste industry (Koerner, 1998). Based on this extensive use, GCLs installed below GMs used as **hydraulic barrier in cover systems** to mitigate and control ARD are 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 Cu^{2+}, Zn^{2+}, and Pb^{2+}. Thus, the performance of GCLs as hydraulic barriers in liner systems to mitigate ARD appears questionable, 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 GCL's suitability to act as a 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 (which could increase the porosity and probably the effective oxygen diffusion coefficient) 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.

Future field performance research focused on the oxygen diffusion aspects of GM/GCL and GM/GCL/GM cover systems would be needed to assess the utility of cover systems containing GCLs to mitigate ARD. Further laboratory and field performance research of GM/GCL, GM/clay, GM/GCL/GM, GM/clay/GM liner systems would be essential to assess the utility of liner systems containing geosynthetics to mitigate and control ARD/ML problems. Field performance should also be investigated at subzero climes that are typical in the mining industry.

2.2 Other Geosynthetics

The summary of other geosynthetics commences with a description of common formulations and mechanisms of degradation. This is followed by technical considerations for GM installations and examples of case studies. Presented case studies include: 1) estimation of longevity of HDPE (high density polyethylene) coupons after exposure to synthetic ARD; 2) considerations for heap leaching; 3) soft tailings stabilization; and 4) use of a HDPE cover system for tailings.

2.2.1 Common formulations of geosynthetics and mechanisms of degradation

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). Common formulations of geosynthetics are presented in Table 2. 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 (GSE, 2002). The service life of geosynthetics is usually extended by adding antioxidants, UV stabilizers, or pigments to the polymer formulations.

Table 2. Approximate Formulations of Common Geosynthetics (Koerner, 2004)

Polymer Type	Resin	Various Additives	Carbon Black / Pigment	Filler	Plasticizer
Polyethylene / Polyester / Polystyrene	97%	0.5-1.0%	2-3%	0	0
Polypropylene	96%	1-2%	2-3%	0	0
Polyvinyl Chloride (unplasticed)	80%	2-3%	5-10%	10%	0
Polyvinyl Chloride (plasticed)	35%	2-3%	5-10%	25%	30%

The long-term oxidation-induced aging of geosynthetics occurs in three discrete stages: 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 (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.

When exposed to heat, internally stressed polymer chain segments tend to reorganize themselves to achieve a more stable, crystalline state. Increased crystallinity affects the material properties and results in increased stiffness and reduction of the geosynthetics' permeability and elasticity (Kay et al., 2004). In HDPE geosynthetics, a higher crystallinity increases its susceptibility to stress-cracking (environmental stress cracking or ESC) which is a serious concern. ESC refers to the brittle failure of a stressed sample in the presence of a sensitizing agent. The ESC deformation tends to occur within thin sections even if the stress is applied over a relatively large area and ultimately leads to a complete rupture of the material. Studies have shown that the stress level involved in ESC failure is typically less than one half of the short-term yield stress (Kay et al., 2004). A notch, a scratch, or some other type of stress concentrator accelerates the stress-cracking process.

Polymers can resist deterioration upon exposure to solvents, if the inter-chains links are stronger than the interaction of the solvent with the polymer. Amorphous phases are typically more vulnerable to solvent penetration than crystalline phases and therefore resistance of a particular polymer increases with its crystallinity (Kay et al., 2004). Due to this fact, HDPEs are more resistant to solvent attack than LLDPEs (linear low density polyethylenes). For PE (polyethylene) and PP (polypropylene), swelling of the amorphous phase due to solvent penetrations can create a stressed zone at the interface between amorphous and crystalline phases, resulting in chain ruptures (Kay et al., 2004).

2.2.1.1 Characteristics of Polyethylene and Polypropylene Geosynthetics

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 $-50^{o}C$, 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 $-10^{o}C$. A drawback of HDPE is that it is sensitive to environmental stress cracking in the presence of a sensitizing agent. Compared to HDPE, 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). 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).

2.2.2 Technical Considerations for Design and Construction with GMs

Key technical considerations for the successful installation of GMs follow.

1) **Need to consider the environmental stress cracking or ESC degradation process when HDPE geosynthetics are exposed to chemical substances and mechanical stresses**. Material specifications including a resistance to stress cracking higher or equal that proposed in the GRI GM13 (2003) specification for GMs (based on ASTM D5397) should be considered. Stress on PE materials should be minimized (Kay et al., 2004).

2) **Need to ensure that candidate geosynthetics meet appropriate tensile strength, puncture resistance, and tear strength requirements for the desired application.** Typical protocols to assess material properties are ASTM D 4885 for tensile strength, ASTM D 4833 for puncture resistance, and ASTM D 1004 and D5884 for tear strength.

3) **Need to ensure that interface properties are compatible with adjacent materials and anticipated loadings.** The interface of any two materials can cause problems (e.g. old / new GM or prefabricated penetration structure / GM; GCL / GM; GM / geotextile). Thermally induced failures need to be considered, especially if the materials will be directly exposed to thermal fluctuations on a long-term basis (e.g. in cover systems). One of the key items to be considered is the coefficient of thermal expansion of adjacent materials (Kay et al., 2004). Load testing and interface shear testing (ASTM D5321) and slope stability analysis should be conducted based on anticipated field conditions and candidate liner/cover materials. Field test pads are also recommended by some practitioners to confirm modeling results.

   Analyses of past slope failures on GM lined fill structures, such as solid waste landfills and heap leach pads, have shown that liner induced failures tended to occur at the planar GM liner interface with weaker under- or overlying materials (Breitenbach, 2004). Slope failures from weak foundation conditions were found to be due to one or more of the following: reactivation of a previous landslide, thawing of frozen subgrade soils, overly wet subgrade, subgrade subsidence (e.g. due to compressible soils), and excavations into toe areas of the fill (Breitenbach, 2004).

4) **Shipping, handling, and storage practices need to prevent damage of GMs.** Geosynthetics delivered to an installation site need to be inspected for damages. Damaged goods should be discarded.

5) **The geosynthetic has to be chemically compatible with the liquid or gas that it will come in contact with (e.g. ASTM D 5322, D 5747).** The response to solvent exposure(s) and other chemical or mechanical stresses should be evaluated for candidate materials, especially if exposure is frequent and if no relevant performance data exists (for example, if geosynthetics will be exposed to a cocktail of chemical compounds). General information and guideline tables regarding the chemical compatibility of geosynthetics are available from geosynthetic manufacturers or in the literature. For example, HDPE usually performs satisfactorily up to 60°C when exposed to 10% HCl, 35% HCl, 10% H_2SO_4, 50% H_2SO_4, and sodium cyanide (GSE, 2002). However, halogen hydrocarbons can severely affect the properties of PE.

6) **Proper construction techniques need to be followed.** Geomembranes are typically installed by specialized firms. The site has to be prepared to prevent punctures or other

damage to the GM and it has to be protected from natural hazards. The intactness of installed GMs can be checked by pressure testing the seams and with electrical methods on the width of the panels. Wrinkles in installed GMs have to be minimized (best prevented), because wrinkles induce internal stresses that can reduce the GMs service life. Wrinkles in GMs located above a GCL may induce a vertical stress on the GCL, which tends to cause redistribution of hydrated bentonite inside the GCL (Dickinson and Brachman, 2003). Nonuniform distribution of bentonite may lower the overall hydraulic performance of the GCL by creating hydraulic 'holes' (i.e. zones with higher hydraulic conductivity). To avoid waves or wrinkles in GMs, light-colored (e.g. white) GMs could be used, GMs could be deployed and seamed without intentional slack, GMs could be covered with an overlying light colored temporary geotextile until backfilling with cover soils occurs, and backfilling could be performed only in the coolest part of the day or even at night (Bonaparte at al., 2002).

7) **Need to protect GMs from tearing and cracking due to differential settlement.** This may be achieved by ensuring firm and uniformly graded foundations for the GMs.

2.2.3 Polyethylene and Polypropylene Case Studies

2.2.3.1 Laboratory Study: Exposure of geosynthetics to synthetic ARD (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 (2003) standard, were kept in the ARD solutions at 20^{o}C, 40^{o}C, and 60^{o}C for 21 months and several others were immersed in synthetic ARD for 10 weeks at 80^{o}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/m^2), and a drainage composite consisting of a HDPE geonet with a needle-punched, non-woven PP geotextile (200 g/m^2) heat bonded to each side. The synthetic ARD was prepared with deionized water (DI) using $FeSO_4 \cdot H_2O$, $ZnSO_4 \cdot 7H_2O$, $CuSO_4$, $CaSO_4$, and H_2SO_4 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 SO_4^{2-}, and 200 mg/L Ca (Gulec et al., 2005).

Estimates of the antioxidant depletion rates in the HDPE material were based on the first-order (exponential) degradation equation for the Oxidation Induction Time (OIT). Based on the antioxidant depletion rates, S, listed in Table 3 for synthetic ARD with an average pH of 2.4, the corresponding half-lives of the antioxidant depletion for the HDPE coupons were 135.9 months (11.3 years) at 20^{o}C, 14.4 months (1.2 years) at 40^{o}C, 7.65 months (0.63 years) at 60^{o}C, and 0.57 months (0.05 years) at 80^{o}C. The estimated lifetime of the HDPE depended primarily on temperature, the type of liquid, and the initial OIT. At 20^{o}C, the HDPE lifetime (for immersed specimens) ranged from 67.3 to 83.3 years for synthetic ARD (Table 3). At 40^{o}C, the HDPE lifetime ranged from 14.3 to 17.7 years for synthetic ARD (Table 3). At 60^{o}C, the lifetime ranged from 3.7 to 4.5 years for synthetic ARD and from 7.8 to 9.7 years for deionized water (Table 3).

Table 3. Estimated Lifetime for a 1.5 mm GRI MR13 HDPE geomembrane immersed in synthetic Acid Rock Drainage and Deionized Water

Immersion Medium	Temperature	Measured Anti-Oxidant Depletion Rate S (Gulec et al., 2004) (1/month)	Anti-oxidant Half-life based on measured S (= ln(2)/S) (year)	Anti-Oxidant Depletion Rate S based on regression [1] (1/month)	Estimated Lifetime (years) based on S values and Arrhenius Plot [2] Initial OIT 80.5 min	Initial OIT 100 min	Initial OIT 270 min
Synthetic Acid Rock Drainage	20°C (293°K)	0.0051	11.3 years	0.0063	67.3	70.2	83.3
	40°C (313°K)	0.0480	1.2 years	0.0296	14.3	14.9	17.7
	60°C (333°K)	0.0906	7.65 months	0.1155	3.7	3.8	4.5
	80°C (353°K)	1.2056	0.58 months		1.1	1.1	1.4
DI Water	60°C (333°K)	0.0514	13.48 months	0.0543	7.8	8.1	9.7

Notes: 1 a) The regression equation 'ln S = 19.16 - 7099(1/T)' for synthetic acid rock drainage was based on an Arrhenius plot obtained for T = 293°K, 313°K, and 333°K (Gulec et al., 2004).

b) The regression equation 'ln S = 15.79 - 6228(1/T)' for deionized water (DI) was based on an Arrhenius plot obtained for T = 333°K and data presented by others (Gulec et al., 2004).

2 The estimated lifetime was calculated by assuming a final OIT of 0.5 min and an initial OIT as indicated.

$$Estimated\_Lifetime = \frac{\ln(inital\_OIT) - \ln(final\_OIT)}{S}$$

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 measured for HDPE at 60°C; i.e. the duration of the test period chosen by Gulec at al. (2004, 2005) was well within the expected ‘safe’ timeframe in which deterioration of engineering properties would not be expected. 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.

2.2.3.2 Case Study: Considerations for Heap Leaching

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, typically a 1.5 mm or 2.0 mm HDPE or LLDPE 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 metal. Gold is typically extracted with an alkaline extractant and copper with a weak acid solution. Most of the current heap leach facilities are single-lined (Thiel and Smith, 2004).

Heap leaching presents several engineering challenges for the construction, operation and the decommissioning. A typical ultimate target height for current heap leach facilities is 50 m, but some operations have target heights of 150-200 m. In addition, GMs are typically not protected from overlying coarse granular soils with heavy geotextile cushion layers to save costs and to increase slope stability. Thus, the exerted pressure on the basal liner and leachate collection system of a typical heap leach facility is or will be very high, because ore density ranges from 1,500 to 1,800 kg/m^3 (Thiel and Smith, 2004; Lupo and Morrison, 2005). Detailed laboratory testing is required to evaluate whether potential liners are physically and chemically compatible with the high anticipated loading and the environmental and operating conditions.

A potential problem with the use of polyethylene (PE) GMs as heap leach liners is that irrigation with extractant solutions may induce exothermic reactions and the growth of meso- and thermophilic bacteria in the ore. Elevated temperatures in the heap would result in earlier degradation of the PE membrane. Soil temperatures of up to 50^{o}C have been observed in field heap leach operations (Thiel and Smith, 2004). Thiel and Smith (2004) also reported the use of concentrated sulphuric acid (H_2SO_4) at some operations to extract copper from leach piles. This practice led to compatibility problems with the GM liner; one installation in Chile experienced significant softening of the HDPE GM (Thiel and Smith, 2004). HDPE has been found to be incompatible with concentrated H_2SO_4 at high temperature (GSE, 2002; Smith, 2003).

The design, construction, and continued operation of leachate collection systems under high loading are challenging. Promotion of arching of the gravel or ore placed above leachate collection pipes is considered to be critical for distributing the load. Lupo and Morrison (2005) presented some design guidelines for those pipes. Advanced Drainage Systems (ADS, 2002) also presented a case study for a 60.96 mm (24") HDPE pipe (N12®) installed at the Morenci Mine, Arizona, USA. This pipe, joined by split couplers, was installed with loose backfill in a narrow trench carved in bedrock.

2.2.3.3 Case Study: Soft Tailings Stabilization (Neukirchner and Lord, 1998)

Neukirchner and Lord (1998) reported that a biaxial PP geogrid (Tensar BX-2000) was successfully used to cover a historically ponded (HP) area of the Consolidated Tailings Pile at the Eagle Mine Superfund site, located near Minturn, Colorado. The covered tailings and wastewater treatment sludge had extremely high moisture contents (41-737%) and low shear strengths (undrained shear strength 1.4 kPa – 8.6 kPa).

To cover the ponded area, two causeways were first constructed across the soft HP area using large rock (up to 1.8 m in diameter) available from an onsite borrow area. The causeways facilitated the movement of materials during construction and provided a 'firm starting base' for the geogrid (Neukirchner and Lord, 1998).

The geogrid material and a 45 cm (18 in) drainage layer were successfully placed on the HP area in the winter using the frozen surface as support. The drainage layer consisted of pit run (< 15 cm (6") cobbles and sandy gravel). Neukirchner and Lord (1998) found that the placement of the drainage layer was necessary (1) to drain water from the consolidation of the underlying materials, (2) to prevent the overlying fill from becoming saturated, and (3) to provide a solid base for the fill on top. A drainage water collection system was installed and was essential in removing spring snowmelt and water of consolidation. Operation of the system during freezing days and/or night presented a significant challenge (Neukirchner and Lord, 1998). Placement of the drainage layer occasionally caused large upward movement of the material being covered. Formation of these waves was addressed by moving to other work areas until some of the rise dissipated, by approaching the soft area from a different direction and by pushing material slowly onto the rise.

2.2.3.4 Case Study Poirier Mine: 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, it will be critical to monitor its performance in the long-term over and beyond the GM manufacturer's guaranteed service life.

3. SUMMARY

This paper summarized key considerations for the use of geosynthetics in mining related applications. Pertinent case studies were presented. It was found that the mining and mineral processing industry is moving more and more towards the use of geosynthetics for civil, geotechnical and environmental engineering applications. Geosynthetic liners and collection pipes for heap leach operations are widely used and ever higher target heap heights are fostering the development of new design, laboratory testing, and construction methods. The duration of the service life of geosynthetics and their cost-effectiveness compared to other alternatives are currently the main concerns in the mining industry, especially for their use in long-term geotechnical and environmental controls.

Due to their resistance to chemical attack and the low glass transition temperature of –50°C, polyethylene (PE) geosynthetics have been the most widely used in the mining and mineral processing industries. Primary concerns of their use are physical, mechanical, and chemical compatibility with site conditions and adjacent materials. Subjecting the materials to less stress, lower temperatures, and less oxidizing agents increases their service life and vice versa. The service life is very temperature dependent. For example, it was found that the HDPE lifetime ranged from 67.3 to 83.3 years for synthetic ARD at 20^{o}C, compared to 3.7 to 4.5 years for synthetic ARD at 60^{o}C (for fully immersed coupons) in one of the reviewed case studies. The technique of heap leaching with concentrated sulphuric acid has led to chemical compatibility problems with a GM liner in the field. The use of geogrids to stabilize soft soils has been well demonstrated.

Future field performance research focused on the oxygen diffusion aspects of GM, GM/GCL and GM/GCL/GM cover systems would be needed to assess the effectiveness of these systems to mitigate and control ARD. Further laboratory and field performance research for GM, GM/GCL, GM/clay, GM/GCL/GM, GM/clay/GM liner systems would be essential to assess the effectiveness of liner systems containing geosynthetics to mitigate and control ARD/ML problems.

ACKNOWLEDGEMENTS

The research for this paper was conducted under the 2003 North American Geosynthetics Society (NAGS) Grand Award of excellence. The NAGS Awards of Excellence Program was initiated in 1989 as an industry sponsored program to recognize excellence in the state-of-art and state-of-practice of geosynthetics in North America. The authors appreciate and thank all supporters and contributors to this study. Thank you for responding to our questionnaire. Special thanks go to Bruno Herlin of Terrafix Geosynthetics Inc., Dr. Tony Sperling of Sperling Hansen Associates, and Western Tank and Lining for sharing detailed factory, field and design information.

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ASTM D 5747. Standard test method for tests to evaluate the chemical resistance of geomembranes to liquids.

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