Use of Geomembranes in Reclamation Covers for Reactive Mining Waste Disposal Sites

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ABSTRACT
Geomembranes are among the alternatives for materials used in cover systems to control acid mine drainage (AMD) upon closure of mining waste disposal sites. An ongoing investigation has highlighted the paucity of information in the literature on covers with geomembrane components for mining waste applications (i.e., tailings and waste rock). The main outcomes from this investigation have been aggregated to identify factors that control the performance of geomembranes in mining waste cover applications and to generate a summary of recommended practices in terms of geomembrane installation, mechanical and thermal stability, transport characteristics (primarily water and air/oxygen), degradation, and overall long-term performance. This article presents and discusses the main results from this evaluation and addresses the main concerns for the closure and reclamation of reactive mining waste disposal sites in particular using geomembranes.

RÉSUMÉ
Les géomembranes sont parmi les matériaux employés dans les systèmes de recouvrement afin de contrôler la génération de drainage minier acide (DMA) à la fermeture des aires d'entreposage. Une étude actuellement en cours a montré qu'il y a peu d'informations disponibles dans la littérature quant à l'utilisation des géomembranes dans les couvertures pour la restauration des parcs à résidus et des haldes à stériles. Les principaux résultats de cette étude ont été utilisés afin d'identifier les facteurs contrôlant la performance des géomembranes dans les recouvrements et proposer une synthèse des meilleures pratiques en termes d'installation, de stabilité mécanique et thermique, de transport de l'oxygène et de l'eau, de dégradation et de performance à long terme. Cet article présente et discute les principaux résultats de cette étude et aborde les principaux défis liés à la fermeture et à la restauration des aires d'entreposage de rejets miniers.

1 INTRODUCTION

The depletion of ore reserves progressively brings all mines near their closure stage when the site must be reclaimed. The main goals of mining sites reclamation include eliminating the health and safety risks, controlling the production and migration of contaminants, and creating field conditions that minimize long term monitoring, maintenance and risks (Aubertin et al., 2002; MERN, 2017).

Applying effective closure measures to reactive mine waste disposal sites (i.e., tailings impoundments and waste rock piles) that produce acid mine drainage (AMD) typically raises various challenges (SRK, 1989; INAP, 2012; Aubertin et al., 2015; 2016). AMD can be generated when sulfidic minerals (pyrite, pyrrhotite, and others) are in contact with water and oxygen (e.g., Blowes et al., 2014; Nordstrom et al., 2015). The oxidation reactions reduce the leachate pH and increase concentration of soluble elements (including metals). Discharge of acid mine drainage may lead to significant adverse environmental impacts, and thus contaminated effluents must be treated before release. Active chemical treatment is commonly used during mine operation; however, this is not a long-term solution for mine closure (Robertson, 2011; Aubertin et al., 2016).

Prevention and control of AMD at the source is the preferred approach for reclamation of reactive waste disposal sites. Careful planning and analysis of the reclamation works should provide integration of reclamation into the mine operations, following the guiding principles of "Designing for Closure" (SRK, 1989; Aubertin et al., 2002; 2015).

One of the major challenges regarding closure and reclamation of mine sites producing AMD is the extended lifetime of required engineered works, which is generally indefinite (Vick, 2001). This aspect raises various concerns regarding the long term geotechnical and geochemical stability of the sites (Aubertin et al., 1997; 2002; 2011).

Cover systems made of different materials (layers) are often part of the reclamation works. Such covers mainly aim to control water infiltration or oxygen migration into the reactive wastes (SRK, 1989; Aubertin et al., 1995; 2002; 2015; MEND, 2004). The cover can be constructed with natural soils or synthetic materials including geomembranes. The behavior of covers constructed with geological materials has been extensively investigated. However, the use of geomembranes in covers constructed to reclaim mine sites is poorly documented and understood. An assessment of the use of geomembranes for mine waste sites is presented herein including coverage of examples available in literature, main considerations, and a suggested framework for the selection and potential use of geomembranes.

2 COVERS TO PREVENT AMD

The reactions leading to AMD can be summarized with the following chemical formulation:

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4 \quad [1]$$

This relationship indicates that sulfuric acid is produced by the reaction between sulfides (pyrite in this case), water, and oxygen (Kleinmann et al., 1981; SRK, 1989; INAP, 2012). Other components, such as ferric iron and bacteria, may also play a role in the process (Blowes et al., 2014).

Control measures applied upon mine site closure typically aim at limiting the availability of at least one of the three reactive components in reaction [1]. For example, sulfidic minerals in tailings can be separated using desulfurization processes at the mill (Benzaazoua et al., 2008), or these can be sorted and managed separately for waste rocks (Aubertin, 2013).

Different types of covers can be constructed over reactive wastes to limit water inflow or oxygen ingress. Layered cover systems have been commonly applied on the nearly horizontal surfaces of tailings impoundments and waste rock piles, and these systems also can be used, with some adjustments, for inclined areas such as the external face of tailings dikes and the slope of waste rock piles (e.g., Bussière et al., 2003; Aubertin et al., 2009). Covers typically include at least one layer acting as a hydrogeological barrier. This layer can be made of one or a combination of fine-grained earthen materials, a geosynthetic clay liner (GCL), or a geomembrane (GM); the latter is the focus of this article.

Geomembranes have been used in civil engineering applications for decades (e.g., van Santvoort, 1994; Rollin et al., 2002; Müller, 2007; Koerner, 2012). The use of geomembranes in mining is more recent and somewhat more limited, yet it is rapidly progressing (e.g., Breitenbach and Smith, 2006; Renken et al., 2007; Lupo and Morrison, 2007; Fourie et al., 2010). Currently, the main use of geomembranes at mine sites is to create impervious liners below heap leach pads, pregnant solution basins and, lately, under tailings impoundments and waste rock piles. Recently, geomembranes have been suggested and used to a limited extent as cover material.

3 USE OF GEOMEMBRANES FOR MINE WASTE COVERS

Geomembranes are thin polymeric sheet materials used in various containment applications. Polyolefins (polyethylene and polypropylene) are the most commonly used geomembrane polymers. For example, the relative amounts of geomembrane use in the U.S. are approximately 35% high density polyethylene (HDPE), 25% linear low-density polyethylene (LLDPE), 25% polyvinyl chloride (PVC), 10% flexible polypropylene (fPP), 3% ethylene propylene diene terpolymer (EPDM), and 2% chlorosulphonated polyethylene (CSPE) (Koerner, 2012). Additional polymers used in geomembrane manufacture are ethylene interpolymer alloy (EIA), very low-density polyethylene (VLDPE), flexible very low-density polyethylene (fVLDPE), thermoplastic polyolefin (TPO), thermoplastic polyurethane (TPU), ethylene vinyl alcohol (EVOH) as part of layered systems, and others (Geosynthetics, 2018). Reinforced geomembranes also are available with the main classes including LLDPE-R, fPP-R, EPDM-R, CSPE-R, and EIA-R (Koerner, 2012). Geotextiles impregnated with asphalt or polymers and multilayer bitumen geocomposites also are considered geomembrane products (e.g., bituminous geomembranes) due to the main barrier function of these fabricated materials. Of baseline polymer characteristics, crystallinity (that varies from amorphous to semicrystalline to crystalline) has significant influence on geomembrane properties and behavior. The majority of geomembranes are either semicrystalline or amorphous, with HDPE representing the high end of semicrystallinity and PVC representing highly amorphous geomembranes. Increasing crystallinity generally results in increased chemical resistance and tensile properties, and decreased flexibility, strain at failure, impact and puncture resistance, and stress crack resistance (Koerner, 2012; Narejo, 2016).

Data and analysis on geomembranes in the literature as a function of application category mainly relate to the use of these materials in bottom liner systems for municipal solid waste landfills and also to the use for ponds, reservoirs, and canals, that hold various types of liquids ranging from water to hazardous chemicals. Data and analysis on geomembranes reported in the literature as a function of polymer type is primarily for HDPE geomembranes as these are the most common type of geomembrane used for bottom liner systems. Significantly less data is available for geomembranes in cover system applications, in particular for geomembranes used in layered systems with overlying and underlying soil and/or geosynthetics layers (i.e., more data is available for exposed geomembranes). Also, less data is available for non-HDPE geomembranes used for containment applications. The main reasons for more information on HDPE and limited information on cover system geomembranes and non-HDPE geomembranes include:

i) the need for extensive assessment of low stress crack resistance and low impact and puncture resistance of HDPE for use in high chemical resistance environments as well as under high stresses.
ii) the perceived simplicity and less rigorous requirements and service environments associated with cover systems compared to bottom liner systems due to less demanding chemical environments, low mechanical stresses, and less critical containment constraints including limited direct contamination of surrounding subgrade soils and groundwater in case of leaks.
iii) the perceived less stringent requirements and service environments for non-HDPE geomembranes as these materials typically are used for containment of water and less aggressive/non-hazardous liquids as well as low availability of non-HDPE geomembranes in practice.

For mine waste sites, the main objectives for use of geomembranes in cover systems are in line with use of dry covers and aim to minimize generation of AMD (as described above). These objectives are attained through minimizing ingress of water and oxygen into the mine wastes. The use of geomembranes described herein applies to multi-layer covers where geomembranes are not directly exposed to atmospheric conditions and rather placed between over and underlying layers of materials. Typical mine waste covers with geomembranes (Aubertin et al., 1995; 2002) have the same main design principles and are similar in configuration to conventional covers for landfills (Yesiller and Shackelford, 2011). The basic configuration consists of from top to bottom: a vegetative soil layer, a protective soil layer, a blanket filter/drainage layer, and a barrier system (individual geomembrane or composite with geomembrane-compacted clay or geomembrane-GCL). A protective/foundation layer is used below the barrier layer. A schematic of a cover system configuration for mining waste sites is presented in Figure 1, which identifies the different layers according to their main function. In practice, cover systems on mine wastes generally include fewer layers than the five shown in Figure 1, as some of these can be combined (for instance B and C, made of coarse grained materials; Aubertin et al., 2002; 2009; Bussière, 2007). A geomembrane can be used in Layer D in Figure 1.

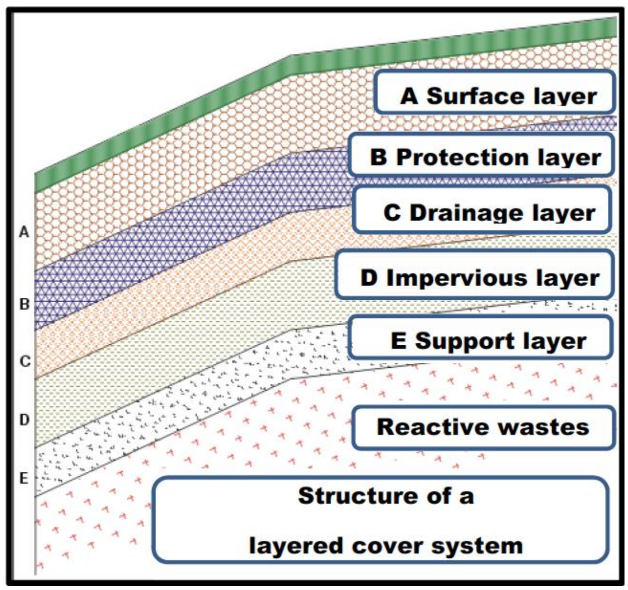

Fig. 1. Multi-Layered Cover System (Aubertin et al., 2002; 2015; 2016).

Material selection in cover designs is affected by relative location of the specific materials in the containment system. Soil filter/drainage materials can be used along the top of a mine waste site and geosynthetics can be used alongside slopes. Geosynthetics also can be used along the top deck. Similarly, protection layers (i.e., support layers) underneath the barrier layers can be soil along top deck and geosynthetics along top deck and side slopes.

As intact geomembranes are very effective to prevent fluid migration, they are sometimes considered impervious. In practice, the amount of liquid or gas that go through a geomembrane can be much larger than the intact value due to the presence of various types of defects in the geomembrane and along seams subsequent to their placement, installation and protection, even when good quality control measures are applied (e.g., McQuade and Needham, 1999; Koerner, 2012; Beck, 2013; Bauters, 2015). The integrity of geomembranes can also be affected by the presence of wrinkles, which may significantly diminish their efficiency (Rowe, 2005; Chappel et al., 2012; Koerner, 2012). These concerns and a few others (see below) have influenced regulators who now often require double-layer protection in covers. Such increased protection can be provided by combining a geomembrane with a compacted clay layer or with a geosynthetic clay liner in composite barriers.

The timelines associated with the use of geomembranes in mine waste covers are immediate, short term, and long term. The immediate timeline refers to the construction period of the cover systems, whereas short term describes service timelines of months to years and long term describes service timelines of decades and beyond. The main consideration for the use of geomembranes in mine waste covers in the immediate term is installation survivability. The two main issues in installation survivability are formation of defects and wrinkles during construction. Defects are generated during placement, seaming, and backfilling and lead to uncontrolled transfer of fluids through the geomembranes in the short and long terms. Wrinkles are generated during placement and can lead to defects during the installation stage and create stress concentrations and associated defects (e.g., cracks) in the short and long term.

For both short and long term, prevention of stress concentrations and permanent stresses is critical. Stress concentrations may directly lead to formation of tears or holes in geomembranes. In addition, stress concentrations and permanent stresses can indirectly lead to defects for example, in HDPE geomembranes through the progressive stress cracking mechanism. Reduced thickness of geomembranes under stress can lead to increased transfer of water and oxygen (Koerner, 2012).

In general, expansion, compression, or differential settlement in the short and long term in waste rock piles are relatively low because of their favorable engineering properties (high saturated hydraulic conductivity, low water retention properties and high friction angle). However, differential settlement and flexural or tensile stresses typically are present in covers at the surface of tailings impoundments due to their high compressibility and low strength (typical values presented in Bussière (2007)).

Slope stability under quasi-static and dynamic conditions is another aspect to be addressed, taking into account the potential effect of pore water pressures along the interfaces and the relatively low friction angle with adjacent soils or other geosynthetics (particularly in the long term due to the viscous behavior of geomembranes) (Negussey et al., 1989; Duncan and Wright, 2005).

Thermal stresses also may develop in geomembranes used in mine waste covers due to diurnal, seasonal, annual, and long-term temperature variations. Increased temperatures further promote polymer degradation mechanisms and accelerate aging. Decreased temperatures decrease flexibility and render geomembranes brittle (Koerner, 2012).

Best practices for proper installation of geomembranes to reduce formation of defects and wrinkles and to prevent stress concentrations and high stresses during use are included for example in Giroud and Morel (1992), Scheirs (2009), Koerner (2012), Koerner and Koerner (2013), and Narejo (2016). Similarly, design calculations for mechanical stability are presented by Scheirs (2009) and Koerner (2012), for example.

Use of geomembranes in mining waste cover systems has been reported. HDPE geomembranes were installed at the closed Poirier and Normétal mines (Lewis and Gallinger, 1999; Maurice, 2002; 2012); a portion of the Aldermac mine site (Cyr et al., 2011); at the Barvue site (Zetchi and Fouquet, 2017); a portion of the Eustis site (Cyr, 2011, personal communication); and also on experimental cells (10 m $\times$ 50 m) under Nordic conditions at the Raglan mine (Raglan Mine 2017, personal communication) in Québec Canada. In all these cases, 1.5 mm-thick (smooth or textured) HDPE was used. HDPE geomembranes also have been used at other mine sites elsewhere in Canada and other countries (e.g., Patterson et al., 2006; Meiers et al., 2012; Bradley et al., 2015; Power et al., 2017). A summary of full-scale and trial installations of geomembranes for waste rock piles and tailings in cold regions in North America and Europe was provided in MEND (2009). The geomembranes included HDPE and bituminous geomembranes. Use of a single PVC geomembrane cover was reported for coal mining wastes in Allen (1994).

The geomembranes selected have typically been HDPE with a few cases reported for the use of bituminous geomembranes and a PVC liner. Detailed descriptions generally have not been provided for the selection of the specific geomembrane types used in the reported field cases. Monitoring of the performance of the cover systems has been provided in a limited number of studies and typically included short timeframes of months to years (e.g., Allen, 1994; Hofton and Schwenger, 2010; Meiers and Bradley, 2017). Monitoring of the condition of the installed geomembranes during service has not been reported to the authors' knowledge. There is a scarcity of data for providing good assessment of the long-term performance of geomembranes in mining waste covers.

4 FRAMEWORK FOR GEOMEMBRANE USE

The main issue for mining waste sites is the exceedingly long duration of service life for these systems. Mine sites that produce AMD need to be constructed and maintained for timeframes extending from many decades to centuries. Such works need to be designed to resist long term conditions that may affect the material properties and loading conditions, and hence require high factors (and margins) of safety (Aubertin et al., 2011). In addition, use of geomembranes at mine waste sites is mainly applicable to cases with relatively shallow slopes including use for tailings impoundments and relatively flat top areas of waste rock piles. In most cases, geomembrane characteristics prevent their use on steep slopes (>15 to 20°) (Briançon et al., 2002), such as on the side of waste rock piles that could have slopes of 26° and greater at the closure stage (Aubertin et al., 2015). Specific considerations are provided in this section for effective use of geomembranes at mine waste sites based on an extensive literature review, main examples of which are provided in preceding sections, as well as mine waste and containment system expertise of the co-authors.

Formation of wrinkles during construction can be reduced by using reinforced geomembranes that have lower thermal coefficients than unreinforced geomembranes. Reinforced geomembranes also provide resistance to development of stresses due to differential settlement in the long term. Flexible geomembranes and light-colored geomembranes also assist with reducing formation of wrinkles. Use of prefabricated seams with low requirement for field seams reduces installation time, particularly beneficial in regions with extreme climates, and on the whole reduces potential for development of defects in geomembranes during field installation. Flexible geomembranes can be factory seamed to cover large areas. Flexible geomembranes also conform to underlying subgrade in case of differential settlement providing further benefits in the long term. Overall, flexible geomembranes, geomembranes with low thermal coefficients, reinforced materials, and geomembranes with high interface friction, and high resistance to transport of water and oxygen are recommended over materials that are stiff, slippery, prone to undergoing significant thermal expansion and contraction, and with low transport resistance.

Integrity of geomembranes after installation can be verified using electrical leak location surveys (ASTM, 2015; 2016). Upon installation, prior to placement of overlying layers, various methods can be used on uncovered geomembranes: water puddle, water lance, spark tester (only for conductive-backed materials), and arc tester. Dipole method can be used on soil-covered geomembranes subsequent to placement of overlying layers, during service life. In addition, a permanent monitoring system can be installed in the cover system above or below the geomembrane for monitoring over time. For long-term monitoring, several factors need to be considered during the design of the cover system including total depth of layers above the geomembrane, presence of geosynthetics above or below the geomembrane, conductivity/water saturation of overlying layers, contact with and conductivity/water saturation of underlying layers, perimeter electrical isolation, and protruding features (piping, instrumentation, etc.).

The filter/drainage layer above the single or composite geomembrane barrier layer can provide lateral drainage and reduce the reliance on the geomembrane in the system as the sole barrier against leakage. Adequate lateral drainage prevents ponding of water in the layers above the geomembrane in the short and long term. This allows for both preventing high heads above defects in the geomembrane layer to minimize leakage through the geomembrane and for maintaining low porewater pressure to ensure slope stability. Similarly, overlying layers designed as store-release materials can reduce water infiltration in relatively dry regions. These water management layers need to be designed considering fluctuations in percolation with respect to climatic variations in a given year (e.g., Bossé et al., 2015) as well as include critical (extreme) events (e.g., Zhan et al., 2001; Aubertin et al., 2009). While average historic climatic parameters can be used for near term conditions, potential effects of climate change need to be considered in design and analysis for estimating long-term behavior, including evolution of volumetric water content and development of water heads. Potential variations in the slope angle also need to be evaluated for maintaining long-term effectiveness of the drainage system. Measurements can be used to monitor water content of the layers above the geomembrane and assess effectiveness of the drainage or the store-release layers.

For multi-layer cover designs with geomembranes for mine waste sites, two modifications can be considered to extend effectiveness of the cover system. First, an insulation layer beneath surface layers may be used to maintain the temperature of the geomembrane at a selected level and/or to minimize diurnal or seasonal temperature fluctuations. Avoiding temperature extremes, maintaining moderate temperatures, and reducing thermal variations reduce/prevent development of thermal stresses and direct (thermal) and indirect (e.g., chemical, oxidation, creep) degradation mechanisms as well as provides service temperature conditions more in line with temperatures associated with determination of material properties and response. Tire chips, encapsulated fiberglass, extruded polystyrene, and polyurea foam were indicated to be effective for landfill liners against frost protection (Benson et al., 1996) and can potentially be adapted for use at mine waste sites in cold regions as well as in hot/desert regions. Additional waste, byproduct, and virgin materials can be adapted for use in mine waste sites at different climatic regions (Andersland and Ladanyi, 2003; Hanson et al., 2016). This approach needs to be adjusted appropriately with regard to placement of insulation layers near the geomembrane in cold regions, while permafrost is left unaltered in surface/near-surface layers to provide a barrier to moisture and oxygen ingress into the mine waste mass. Use of insulation needs to be evaluated with respect to potential thermal degradation of geomembranes against benefits of frozen ground in regions undergoing cyclic freezing and thawing.

Second, a filter/drainage layer can be used between the barrier layer and the foundation layer. Alternatively, the foundation layer may be designed to provide this function. This lower filter/drainage layer in the cover system is adapted from the gas collection layer in a conventional landfill cover and is used to detect leakage and remove the infiltrating water prior to entry into the mine wastes to maintain barrier function. The drainage layer is designed using estimates of leakage through defects in the geomembrane for worst-case scenario leakage conditions (i.e., maximum water head above the geomembrane and lowest slope angle).

Specifications for mining waste cover geomembranes including guidance for test methods for baseline index properties and performance properties and testing frequencies need to be developed. Similarly, guidance for geomembrane quality control and quality assurance during manufacturing and installation including test methods and testing frequencies also need to be developed specifically for mine waste covers with consideration of very long service lifetimes. Varying levels of requirements (e.g., Zanzinger, 2012) can be developed for different timelines and level of containment requirements with respect to proximity to ground and surface water sources and potential for contamination. Probability based quality practices can be implemented for management of risk at varying levels (e.g., Foye et al., 2016).

Direct use of lifetime predictions based on analysis conducted on specific geomembranes subjected to specific aging/degradation mechanisms and stress conditions are not recommended. The response of the geomembranes is highly dependent on material characteristics and testing conditions and not directly applicable to other materials and service conditions. Such analyses are useful for providing generalized trends and broad-based material and application comparisons.

A summary of boundary conditions and relevant testing and analysis methods is presented in Table 1, based on the information and data gathered in this study. Guidance is provided for implications associated with design and service conditions for geomembranes in mining waste covers.

5 FINAL REMARKS

Many factors influence the success of the reclamation work performed on AMD generating sites. Geomembranes inherently have shorter lifetimes than earthen materials and thus their use may not be compatible with the long-term closure requirements for sites that contain AMD generating wastes (e.g., Robertson, 2011; Aubertin et al. 2002; 2015; 2016). Hence, use of geomembranes need to be evaluated with consideration to improved performance of cover systems with geomembranes in comparison to cover designs without these materials. Periodic replacement of geomembranes can be warranted in case of significant technical and financial benefits. Prior use of specific types of geomembranes (e.g., HDPE) in mine waste covers should not be considered precedent, and detailed analyses should be conducted for specific requirements and constraints of individual projects.

Table 1. Testing and analysis for use of geomembranes in cover systems for AMD generating mine waste disposal sites.

Boundary Conditions Design Feature	Relevant Testing and Analysis Parameter	Notes
Installation stresses	Mechanical stresses, protrusions, placement of overlying layers	Specialized construction procedures needed to prevent excessive damage
Service stresses	Thermal cycles, stress relaxation, creep, differential settlement	Wrinkling of geomembranes produces stress concentrations and produces conduits for fluid transport Timely cover of geomembranes is important to prevent wrinkle formation Long-term deformation characteristics are a function of creep, which is temperature dependent
Defects in geomembranes	Leak location testing after installation/over time Estimating defect generation / material degradation over time	Defects influence mechanical, hydraulic, and durability behavior
Slope stability	Long slope lengths, steep slopes, porewater pressure development in slopes, interface shear strength Potential variation in slope angles over time in long term	Significant difference between peak and large-displacement shearing resistance Surface texture characteristics of geomembranes control mechanisms of interface shear Interface shear strength for composite cover systems is temperature dependent
Climate	Near term: Cyclic variations in temperature and precipitation Long-term: Variations due to climate change	Covering with bulk insulation material can limit amplitude of thermal cycles Average meteorological parameters affected by climate change Intensity of extreme meteorological events influenced by climate change
Thermal response of geomembranes	Ductility of geomembranes is highly temperature dependent	Brittle behavior of geomembranes specifically problematic in cold regions Large diurnal temperature changes problematic during installation
Water and oxygen transport	Variations between material types, variations due to water content of overlying layers, variations due to temperature cycles Variations in diffusion characteristics due to changes in GM thickness and GM formulations	Hydraulic conductivity for intact geomembranes generally low and testing not required Extent of installation damage relevant Diffusion may control transport
Geomembrane aging and degradation	Determination of material properties under the effects of degradation mechanisms Accelerated testing to evaluate long-term properties and lifetimes	Long-term effectiveness dependent on maintaining material properties over time

Formulations of geomembranes, design and installation practices, and monitoring methods evolve and improve and therefore, it can be expected that their serviceable durability will increase over time. Nonetheless, cost of use with potential replacements/repairs and cost of monitoring of cover designs with geomembrane components also need to be considered in comparison to designs solely with earthen materials. Additional research is required to provide guidance on material selection and specific properties and configurations for mining waste cover applications with a geomembrane.

Determination of long-term mechanical and hydraulic performance characteristics under representative conditions is needed including assessment of in situ performance. Environmental and mechanical stresses in mining waste cover applications also should be better defined to establish ultra-long-term durability evaluations. Coupled mechanical-hydraulic-thermal response of geomembranes in these applications is critical for performance and requires further investigation

6 REFERENCES

Allen, S.R., (1994), "Evaluation and standardization of rolled erosion control products," *Geotextiles and Geomembranes*, 14(3-4), p. 207-221.

Andersland, O.B. and Ladanyi, B., (2003), *Frozen Ground Engineering* (2nd edition), Wiley, NY.

ASTM D6747, (2015), "Standard guide for selection of techniques for electrical leak location of leaks in geomembranes," *ASTM International*, West Conshohocken, PA.

ASTM D7007, (2016), "Standard practices for electrical methods for locating leaks in geomembranes covered with water or earthen materials," *ASTM International*, West Conshohocken, PA.

Aubertin, M., Chapuis, R.P., Aachib, M., Bussière, B., Ricard, J.F., and Tremblay, L., (1995), *Évaluation en Laboratoire de Barrières Sèches Construites à Partir de Résidus Miniers*, *École Polytechnique de Montréal*, MEND Report 2.22.2a.

Aubertin, M., Dionne, J., Marcoux, L., (1997), "Design guidelines and stability criteria of engineering works for water covers," *Proc. 4th International Conference on Acid Rock Drainage (ICARD),* Vancouver, Vol. IV, p. 1851-1866.

Aubertin, M., Bussière, B., and Bernier, L., (2002), *Environnement et Gestion des Rejets Miniers*, Manual on CD-Rom, Presses Int. Polytechnique Montreal, Quebec, Canada.

Aubertin, M., Cifuentes, E., Apithy, S., Bussière, B., Molson, J., and Chapuis, R.P., (2009), "Analyses of water diversion along inclined covers with capillary barrier effects," *Canadian Geotechnical Journal*, 46(10), p. 1146-1164.

Aubertin, M., Bussière, B., James, M., Mbonimpa, M., and Chapuis, R.P., (2011), "Vers une mise à jour des critères de stabilité géotechnique pour la conception des ouvrages de retenue de résidus miniers," *Proc. Symp. Mines and Environment*, Rouyn-Noranda, Quebec, CIM (CD Rom), 38 p.

Aubertin, M., (2013), "Waste rock disposal to improve the geotechnical and geochemical stability of piles," *Proc. 23rd World Mining Congress*, Montreal, 8 p.

Aubertin, M., Pabst, T., Bussière, B., James, M., Mbonimpa, M., Benzaazoua, M., and Maqsoud, A., (2015), "Revue des meilleures pratiques de restauration des sites d'entreposage de rejets miniers générateurs de DMA," *Proc. Symp. Mines and Environnement*, Rouyn-Noranda, Quebec, CIM (CD Rom), 67 p.

Aubertin, M., Bussière, B, Pabst, T., James, M., and Mbonimpa, M., (2016), "Review of reclamation techniques for acid-generating mine wastes upon closure of disposal sites," *Geotechnics for sustainable energy, GSP 270*, A. Farid, A. De, K. R. Reddy, N. Yesiller, and D. Zekkos, (Eds.), ASCE, p. 343-358.

Bauters, T., (2015), "Possible to achieve zero leaks in geomembrane-lined containment systems using geoelectric leak location surveys," *GWRI Geoenvironmental Engineering Symposium*, California Polytechnic State University, San Luis Opisbo (also personal communication with M. Aubertin).

Beck, A., (2013), "Synopsis of panel discussion on liner integrity surveys," *Geosynthetics*, geosyntheticsmagazine.com.

Benson, C.H., Olson, M.A., and Bergstrom, W.R., (1996), "Temperatures of insulated landfill liner," *Transportation Research Record*, 1534, p. 24–31.

Benzaazoua, M., Bussière, B., Demers, I., Aubertin, M., Fried, E., and Blier, A., (2008), "Integrated mine tailings management by combining environmental desulphurization and cemented paste backfill: Application to mine Doyon, Quebec, Canada," *Minerals Engineering*, 21, p. 330–340.

Blowes, D.W., Ptacek, C.J., Jambor, J.L., Weisener, C.G., Paktunc, D., Gould, W.D., and Johnson, D.B., (2014), "11.5 - The geochemistry of acid mine drainage," *Treatise on Geochemistry (Second Edition)*, H. Holland and K. Turekian, (Ed.), Elsevier, p. 131-190.

Bossé, B., Bussière, B., Hakkou, R., Maqsoud, A., and Benzaazoua, M. (2015), "Field experimental cells to assess the hydrogeological behaviour of store-and-release covers made with phosphate mine waste," *Canadian Geotechnical Journal*, 52(9), p. 1255-1269.

Bradley, C., Meiers, G., and Shea, J., (2015), "Closure of legacy waste rock piles: can we achieve passive treatment to manage residual seepage in the short term?," *Canadian Reclamation*, ISS.2, 15, p. 34-37.

Breitenbach, A.J. and Smith, M.E., (2006), "Overview of geomembrane history and design practices in the mining industry," *Proc. 8th International Conference on Geosynthetics*, Yokohama, Japan, 4 p.

Briançon, L., Girard, H., and Poulain, D., (2002), "Slope stability of lining systems–experimental modeling of friction at geosynthetics interfaces," *Geotextiles and Geomembranes*, 20(3), p. 147-172.

Bussière, B., Aubertin, M., and Chapuis, R.P., (2003), "The behavior of inclined covers used as oxygen barriers," *Canadian Geotechnical Journal,* 40(3), p. 512-535.

Bussière, B., (2007), "Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches," *Canadian Geotechnical Journal*, 44(9), p. 1019-1052.

Chappel, M.J., Brachman, R.W.I., Take, W.A., and Rowe, R.K., (2012), "Large-scale quantification of wrinkles in a smooth black HDPE geomembrane," *Journal of Geotechnical and Geoenvironmental Engineering*, 138(6), p. 671–679.

Cyr, J. (2011). Personal communication.

Cyr, J., Maurice, R. and Isabelle, D., (2011), "Restauration du site minier Aldermac," *Proc. C.R. Symposium 2011 sur l'Environnement et les Mines*, Rouyn-Noranda, QC.

Duncan, J.M. and Wright, S.G., (2005), *Soil Strength and Slope Stability,* Wiley, NY.

Fourie, A.B., Bouazza, A., Lupo, J., and Abrão, P., (2010), "Improving the performance of mining infrastructure through the judicious use of geosynthetics," *Proc. 9th International Conference on Geosynthetics*, Brazil, p. 193-219.

Foye, K.C., Toepfer, G.W., and Soong, T.-Y., (2016), "Evaluation of geomembrane destructive seam testing frequencies and risk management," *Geosynthetics, Forging a Path to Bona Fide Engineering Materials, GSP 275*, Y.G. Hsuan, S.K. Bhatia, and T.-Y. Soong, (Eds.), ASCE, p. 1-13.

Geosynthetics, (2018), *Specifier's Guide*, IFAI.

Giroud, J.P. and Morel, N., (1992), "Analysis of geomembrane wrinkles," *Geotextiles and Geomembranes*, 11(3), p. 255-276.

Hanson, J.L., Kopp, K.B., Yesiller, N., Cooledge, C.M., and Klee, E., (2016), "The use of recycled materials as thermal insulation in underground construction," *Geotechnics for Sustainable Energy, GSP 270*, A. Farid, A. De, K. R. Reddy, N. Yesiller, and D. Zekkos, (Eds.), ASCE, p. 94-103.

Hofton, T. and Schwenger, R., (2010), "Geomembrane cover on Normétal reactive tailings: A case study," *Proceedings of the 16th Annual BC-MEND ML/ARD Workshop*, Vancouver, British Columbia, W.A. Price and K. Bellefontaine (Eds.), December 2-3, 2009.

INAP (International Network for Acid Prevention), (2012), *Global Acid Rock Drainage (GARD) Guide*, http://www.gardguide.com.

Kleinmann, R.L.P., Crerar, D.A., and Pacelli, R.R., (1981), "Biogeochemistry of acid mine drainage and a method to control acid formation," *Mining Engineering*, March, p. 300-304.

Koerner, R.M., (2012), *Designing with Geosynthetics*, 6th Edition. Vol. 1 and 2, Xlibris Corporation.

Koerner, R.M. and Koerner, G.R., (2013), "The *intimate contact* issue of field placed geomembranes with respect to wave (or wrinkle) management," *GSI White Paper #27*, Geosynthetic Institute.

Lewis, B.A. and Gallinger, R.D., (1999), "Poirier site reclamation program," *Proc. Sudbury 99; Mining and the environment*, Ontario, Vol II, p. 439-448.

Lupo, J.F. and Morrison, K.F., (2007), "Geosynthetic design and construction approaches in the mining industry," *Geotextiles and Geomembranes*, 25, p. 96-108.

Maurice, R., (2002), "Restauration du site minier Poirier (Joutel) - Expériences acquises et suivi des travaux," *Proc. C.R. Symposium 2002 sur l'Environnement et les Mines*, Rouyn-Noranda, QC, p. 545-552.

Maurice, R., (2012), "Normétal mine tailings storage facility HDPE cover: Design considerations and performance monitoring," *Proc. 9th International Conference on Acid Rock Drainage*, Ottawa, ON.

McQuade, S.J. and Needham, A.D., (1999), "Geomembrane liner defects-causes, frequency and avoidance," *Geotechnical Engineering*, 137(4), p. 203-213.

Meiers, G.P., O.Kane, M., and Mayich, D., (2012), "Field performance monitoring of a cover system with geosynthetics layers, case study - Franklin waste rock pile, Sydney. NS," *Proc. 9th International Conference on Acid Rock Drainage (ICARD)*, Ottawa, Ontario, Canada, 14 p.

Meiers, G. and Bradley, C., (2017), "The critical role of lateral drainage capacity in limiting leakage through a low permeability geomembrane cover," *Geotechnical Frontiers 2017: Waste Containment, Barriers, Remediation, and Sustainable Geoengineering, GSP 276*, T.L. Brandon and R.J. Valentine, (Eds.), ASCE, p. 127-138.

MEND, (2004), *Design, Construction, and Performance Monitoring of Cover System for Waste Rock and Tailings*, Report 2.21.4, Ottawa, Canada.

MEND, (2009), *Mine Waste Covers in Cold Regions*, Report 1.61.5a, Vancouver, Canada.

MERN, (2017), *Guide de Préparation du Plan de Réaménagement et de Restauration des Sites Miniers au Québec.* Ministère de l'Énergie et des Ressources naturelles, Québec.

Müller, W.W., (2007), *HDPE Geomembranes in Geotechnics*, Springer, 485 p.

Narejo, D., (2016), "17 - Geotextiles use for cushioning," *Geotextiles – from Design to*

Applications, R.M. Koerner, (Ed.), p. 395-411, http://dx.doi.org/10.1016/B978-0-08-100221-6.00017-6.

Negussey, D., Wijewickreme, W., and Vaid, Y., (1989), "Geomembrane interface friction," *Canadian Geotechnical Journal*, 26(1), 165-169.

Nordstrom, D.K., Blowes, D.W., and Ptacek, C.J., (2015), "Hydrogeochemistry and microbiology of mine drainage: An update," *Applied Geochemistry*, 57, p. 3-16.

Patterson, B.M., Robertson, B.S., Woodbury, R.J., Talbot, B., and Davis, G.B., (2006), "Long-term evaluation of a composite cover overlaying a sulfidic tailings facility," *Mine Water and the Environment*, 25, p. 137–145.

Power, C., Ramasamy, M., MacAskill, D., Shea, J., MacPhee, J., Mayich, D., Baechler, F., and Mkandawire, M., (2017), "Five-year performance monitoring of a high-density polyethylene (HDPE) cover system at a reclaimed mine waste rock pile in the Sydney Coalfield (Nova Scotia, Canada),". *Environ Sci Pollut Res Int*, 24(34), p. 26744-26762, DOI 10.1007/s11356-017-0288-4.

Raglan Mine (2017). Personal communication.

Renken, K., Mchaina, D., and Yanful, E.K., (2007), "Use of geosynthetics in the mining and mineral process industry," *Geosynthetics*, 25(4), p. 38-42.

Robertson, A.A., (2011), "Top 10 things that can go wrong with plans for mine closure," *Proc. Int. Conf. on Mine Closure*, Lake Louise.

Rollin, A.L., Pierson, P., and Lambert, S., (2002), *Géomembranes - Guide de Choix*. Presses Internationales Polytechnique.

Rowe, R.K., (2005), "Long-term performance of contaminant barrier systems," 45th Rankine Lecture, *Geotechnique*, 55(9), 631-678.

Scheirs, J., (2009), *A Guide to Polymeric Geomembranes*, Wiley, UK.

SRK, (1989), *Draft Acid Rock Drainage Technical Guide*, BCAMD Task Force.

van Santvoort, G.P.T.M., (1994), *Geotextiles and Geomembranes in Civil Engineering*. Revised edition, A.A. Balkema, Rotterdam.

Vick, S.G., (2001), "Stability aspects of long-term closure for sulphide tailings". *Proc. Safe Tailings Dams Constructions*, Gaellivare, Sweden, 12 p.

Yesiller, N. and Shackelford, C.D., (2011), "Chapter 13: Geoenvironmental Engineering," *Geotechnical Engineering Handbook*, B. M. Das Ed., J.Ross Publishing, p. 13.1-13.61.

Zanzinger, H., (2012), "Good-better-best HDPE geomembranes in engineered geoenvironmental applications," *Proc. One-Day Conference on Geosynthetic Lining Solutions and Related Issues*, S. Babu, K. Pradeep, and S. Sireesh, (Eds.), Indian Institute of Science, Bangalore, India, 11 p.

Zetchi, M. and Fouquet, G., (2017), "Restauration du site minierier abandonné Barvue," presented at *Québec Mines 2017*.

Zhan, G., Aubertin, M., Mayer, A., Burke, K., and McMullen, J., (2001), "Capillary cover design for leach pad closure," *Transaction SME*, 310, p. 104-111.