Development and Application of Mine Site Reclamation Methods to Control Acid Generation in Canada

Bruno Bussière[1] and Michel Aubertin[2]

[1]RIME – Research Institute on Mines and the Environment, Université du Québec en Abitibi-Témiscamingue (UQAT), 445 Boul. De l'Université, Rouyn-Noranda, Canada, Bruno.Bussiere@uqat.ca

[2]RIME – Research Institute on Mines and the Environment, Polytechnique Montréal, 2900 boul. Édouard-Montpetit, Montréal, QC H3T 1J4, Canada, Michel.Aubertin@polymtl.ca

1. Introduction

The mining industry is an important asset for the economy of many regions throughout Canada, especially with respect to exports and employment, but also through numerous technological developments. Nevertheless, mining operations generate various types of wastes that can be harmful to the environment, particularly when they have the potential to generate acid mine drainage (AMD). In this case, appropriate control and remediation measures must be applied at the mine waste storage facility. Over the last few years, various techniques have been developed and implemented in Canada to limit the production of AMD and mitigate its environmental impacts. Usually, these techniques aim at eliminating one (or more) of the three main reactants in the oxidation reactions that lead to acid production: oxygen, water, and sulphide minerals. Some typical examples are summarized here.

2. Principal AMD control methods used in Canada

Sulphide separation and reuse of desulphurized tailings

The presence of sulphide minerals is essential to generate AMD; by extracting (separating) a sufficient portion of these minerals, the quantity of AMD generated can be effectively limited. The necessary recovery of sulphide minerals will depend on the amount of neutralizing minerals. Various techniques, such as flotation and gravimetric separation, can be used to separate the sulphides from the tailings (e.g. McLaughlin and Stuparyk 1994; Benzaazoua et al. 2000). This control method is mainly applicable for actively operating sites (e.g. Derycke, 2012), but the recycling (sulphide extraction combined with metal recovery) of abandoned mine wastes can also be considered in some cases.

This relatively new approach is at the planning stage at the Doyon-Westwood mine in Québec, Canada. Around 20% of the tailings produced at the Westwood mine would be desulphurized and the resulting non-acid generating tailings will be recycled to construct a monolayer cover over the reactive tailings of the neighboring Doyon's site (Rey et al. 2016). In association with the elevated water table (EWT) technique, this type of cover is designed to prevent AMD through the control of oxygen flux (this approach is described below). The same principle has already been used at the Detour Lake gold mine in Ontario, where a 1 to 1.5 m monolayer cover of desulphurized tailings was deposited in 1998-1999. The installation has been monitored since 2001-2002 and has shown a reduction of the oxygen fluxes where the EWT was maintained at a sufficiently high level. Nevertheless, due to the use of coarser cover materials than was originally planned, the efficiency of the design was found to be insufficient in some areas (Dobchuk et al. 2013). Desulphurized tailings have been used at the Kemess mine in British Columbia, in an innovative manner, to reduce the construction cost of a tailings storage facility. Tailings have undergone flotation for desulphurization and cycloning in order to remove the finer portion and thus obtain a more uniformly graded non acid-generating tailings sand. This material was then recycled as filling for the dam structure (Ramussen et al. 2004).

Oxygen barriers

Limiting oxygen availability for the reactive mine wastes is one of the most practical and effective approaches to control AMD, especially under humid climatic conditions (e.g. SRK 1989; MEND 2001). Various approaches can be used to create an oxygen barrier such as placing a water cover; elevating the water table and adding a single-layer cover; placing a layered cover with capillary barrier effects (CCBE) over the reactive wastes; or installing an oxygen-consuming barrier; these techniques (except the latter) are briefly described below.

Water cover and elevated water table techniques

The water cover technique consists of completely covering the reactive mine wastes with water by submerging the mine wastes in a lake or by building dykes to hold both the mine waste and the water that submerges them. Because the solubility of oxygen is much lower in water (8.6 mg/L) than in air (285 mg/L) and the oxygen diffusion coefficient is about 10,000 times smaller in water (2×10^{-9} m^2/s at 25°C) than in air (1.8×10^{-5} m^2/s at 25°C) (e.g. Romano et al. 2003; Awoh et al. 2013), the flux of oxygen reaching the mine wastes can be sufficiently low to prevent significant AMD generation. However, a water cover is a complex, dynamic system that is subjected to several phenomena that influence its capacity to control AMD generation. These include tailings erosion and resuspension, oxygen migration, oxidation of sulphidic tailings by dissolved oxygen (DO), release of dissolved metals, and water exchange with the surrounding environment (see Figure 1) (e.g. Rescan 1996; Adu-Wusu et al. 2001; Vigneault et al. 2001; Catalan and Yanful 2002).

The water cover technique has been applied to control AMD at many sites throughout Canada, and the efficiency of this technique has been well demonstrated. For instance, at the Don Rouyn site, located 4 km west of Rouyn-Noranda (Québec, Canada), an old quarry filled with sulphide-rich tailings (83% pyrite) from the Gallen mine was flooded with water to control AMD (Awoh et al. 2013). The old AMD tailings pond, Solbec-Cupra, was flooded by building two small impervious dams. The water cover since its construction is able to control AMD generation. An artificial reservoir was built using 2.5 km impervious dykes to create a water cover at the Louvicourt mine site located 25 km east of Val d'Or (Québec, Canada). These tailings (30 to 50% pyrite) were deposited directly underwater to prevent interactions between atmospheric oxygen and sulphide minerals (Vigneault et al. 2001). Since the construction, no significant AMD generation has been observed at the site. At the Equity Silver mine in British Columbia (Canada), tailings containing pyrite (5 to 10%), arsenopyrite, and pyrrhotite were submerged under a 4-m water cover to limit oxidation (Rescan 1996). Also, at the Quirke cell 14 tailings site, located 16 km north of the city of Elliot Lake (Ontario, Canada), pre-oxidized uranium mine tailings were flooded under a 1-m water cover over an area of 192 ha to reduce the long-term generation and mobility of contaminants (Peacy et al. 2002).

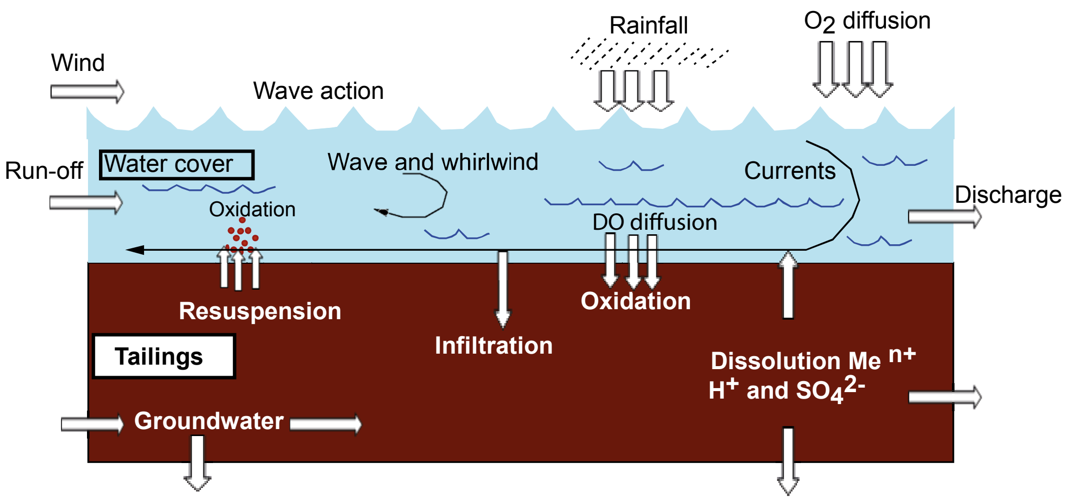

Figure 1: Conceptual model of a water cover (adapted from Li et al. 1997 and Aubertin et al. 2002)

Water covers can, however, raise serious concerns about physical stability, and can be difficult to maintain over the long term (Aubertin et al. 1997). To reduce the geotechnical risks associated with a water cover, an alternative approach for tailings was proposed relatively recently: the EWT technique (Orava et al. 1997; Ouangrawa et al. 2010). The EWT technique consists of maintaining a high degree of saturation in the tailings by raising the water table, in order to reduce the oxygen diffusion rate and prevent sulphide oxidation (see Figure 2). A high degree of saturation is maintained by limiting water losses by seepage and evaporation, while favoring capillary rise. As for a water cover, the EWT relies on the low effective diffusion coefficient of oxygen in nearly saturated media (Mbonimpa et al. 2003). This reclamation approach was recently applied at two abandoned mine sites in Québec: the Aldermac site and the Manitou site. Detailed monitoring programs have been implemented at both sites to assess the performance of this relatively new approach (Maqsoud et al. 2013; Ethier et al. 2013).

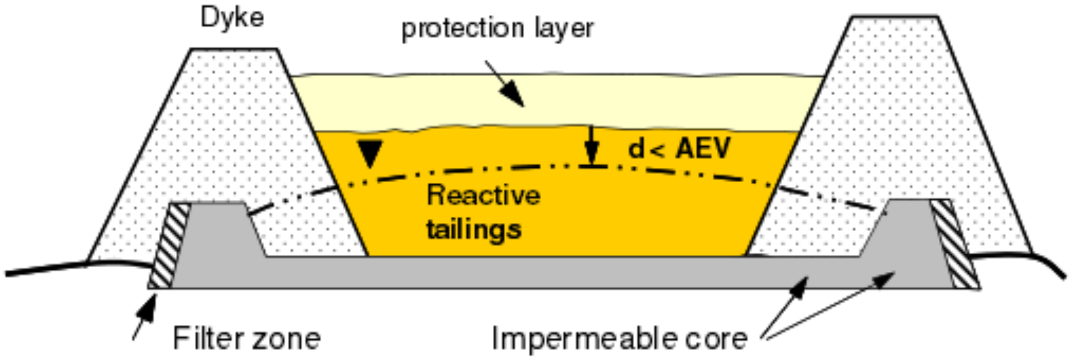

Figure 2: Conceptual model of an elevated water table within reactive tailings for reducing acid mine drainage (adapted from Ouangrawa et al. 2010)

Cover with capillary barrier effects

A multi-layered CCBE uses unsaturated soil properties to create the capillary barrier effects that maintain one of the layers at a high degree of saturation S_r at all times. The high value of S_r in the moisture-retaining layer creates an efficient barrier against oxygen ingress by impeding gas advection and diffusion (Mbonimpa et al. 2003). Such types of cover can thus limit AMD generation by limiting sulphide oxidation reactions.

The effectiveness of this type of cover is dependent upon a phenomenon called the capillary barrier effect. This effect can be induced when a fine-grained material layer is placed over a coarser one. The two materials have different hydrogeological properties because of their different textures. In the initial desaturation stage, the fine-grained material retains water more easily than the coarse material due to its smaller pores that increases its air entry value (AEV). As the coarse material drains, the presence of gas in its pore space reduces the interconnectivity of the voids and the related hydraulic conductivity (k). This reduction of k in the coarser material layer reduces the vertical water flow from the finer material above; the latter layer can remain thus almost fully saturated at all times, creating an oxygen barrier. More details about capillary barrier effects and CCBEs can be found in various publications including Nicholson et al. (1989), Aubertin et al. (1995, 2002, 2006), and Bussière et al. (2003).

CCBEs usually contain three to five layers of distinctive materials; each layer has a specific purpose. Figure 3 is a schematic illustration of a CCBE. The bottom layer is made of a fairly coarse material which functions as both a mechanical support and a capillary break. The fine-grained material that forms the moisture retaining layer is placed on top of the support layer to create the capillary barrier effect. Another coarse material is placed over the fine-grained material layer to prevent water loss by evaporation and aid lateral drainage. The other two layers (protection and surface) protect the CCBE against erosion and bio-intrusion.

The acid-generating Les Terrains Aurifères (LTA) site, located in Abitibi, Québec, Canada, was reclaimed with a CCBE to control AMD. This CCBE was constructed nearly 20 years ago and it has been monitored since then, demonstrating that such a cover can be efficient as an oxygen barrier (Bussière et al. 2006). A somewhat similar layered cover has also been successfully applied at the Lorraine mine site, near Latulippe, Québec, Canada (Aubertin et al. 2006). Another example of CCBE is the Equity Silver site, situated in the humid, alpine climate of north central British Columbia, Canada. The ability of this soil cover system to limit oxygen flux and water flow to underlying reactive waste rock was evaluated using a detailed instrumentation program. The field data indicated that the lower, compacted layer maintained a high degree of saturation (i.e. ≥ 90%), which controlled the oxygen flux (Weeks and Wilson 2005).

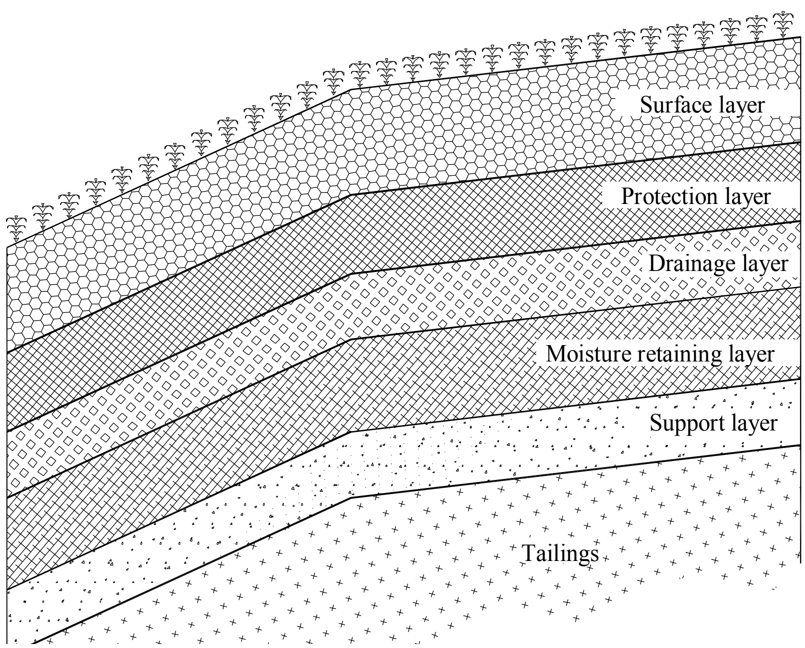

Figure 3: Typical configuration of a CCBE used to limit the production of AMD (Aubertin et al. 1995, 2016)

Water infiltration barriers

As mentioned earlier, water is one of the essential components for the generation of AMD. Hence, one can control the production of acid by limiting water flow though the reactive mine wastes. To do so, a water infiltration barrier may be built on top of the mine waste disposal area. Covers made of low hydraulic conductivity soils and/or synthetic materials, such as geomembranes or bentonite geocomposites, can be used. The configuration of these covers can be similar to designs developed for the isolation of domestic and hazardous wastes (e.g. Aubertin et al. 1995). There are however many concerns regarding the use impervious materials (soils or geosynthetics) in covers (Aubertin et al. 2016). For instance, in the case of a geomembrane included in the cover placed over an acid-generating mine sites, the critical issues include: (i) their limited lifetimes, which are usually on the order of decades, while the reclamation of mine sites is required for centuries (at least); (ii) the presence of defects and wrinkles that may significantly diminish their efficiency; (iii) the effects of settlement and risk of sliding along the slopes (Aubertin et al. 2016). A few mine sites in the province of Québec have been covered with a geomembrane and/or natural fine-grained soils, including the Normetal, Poirier, Aldermac, and Barvue sites; however, very little information is available to assess the actual performance of the covers with respect to controlling AMD.

Another option to limit water infiltration in arid and semi-arid conditions is the use of store-and-release (SR) covers (also known as alternative, water balance, or evapotranspirative covers). Such engineered systems are attracting considerable interest as they may represent an advantageous alternative to more traditional covers that rely on materials having a low saturated hydraulic conductivity (e.g. Morris and Stormont 1997; Zhan et al. 2001). Some indications also suggest that this approach could be used in the cold, semi-arid climate of the Canadian Arctic.

Insulation covers for cold climate

A reclamation technique specific to arctic (cold) regions is the insulation cover, which aims to incorporate tailings into the natural permafrost. Low temperatures in the reactive tailings will slow down the oxidation reactions and reduce the generation and migration of pollutants (Dawson and Morin 1996; Holubec 1993). A typical insulation cover consists of adding, over reactive tailings, one or many layers of non-reactive material having a thickness greater than the active layer depth (i.e. the depth of ground that is subject to annual thawing and freezing in areas underlain by permafrost; e.g. Kyhn and Elberling 2001; IPA 2015; see Figure 4). An insulation cover, as a reclamation technique, has been used to reclaim tailings storage facilities at some sites in Canada (Holubec 2004; Rykaart and Hockley 2009).

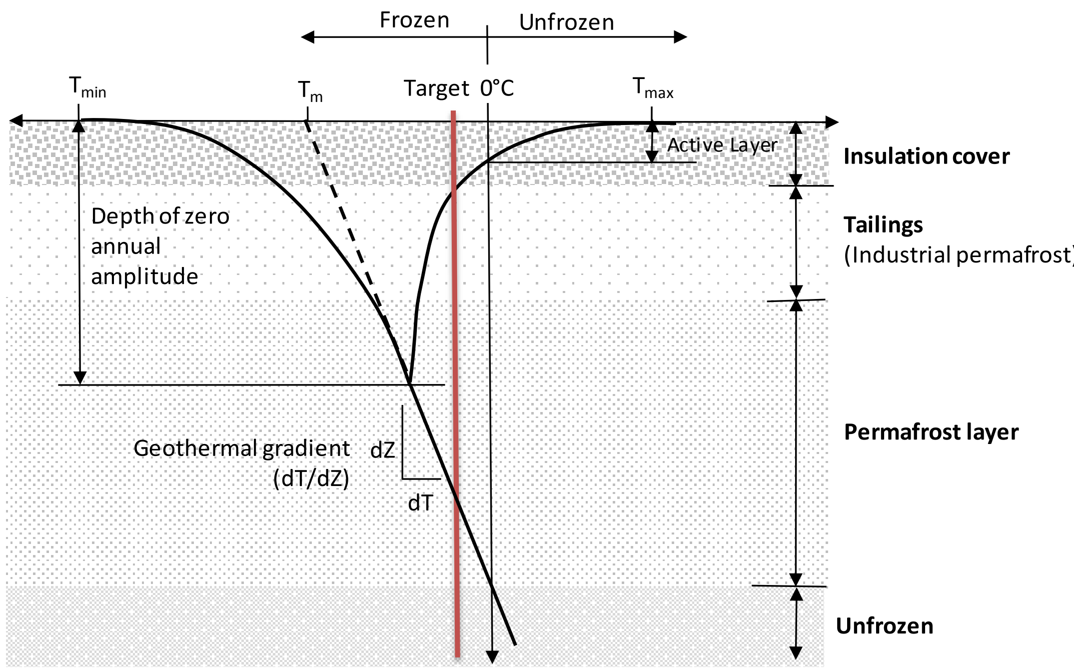

Figure 4: Schematic temperature profile representing the active zone for a tailings storage facility with an insulation cover in a continuous permafrost zone (modified from Andersland and Ladanyi 2004)

3. Final remarks

Reclamation of AMD generating sites requires careful planning, rigorous design, and sound construction methods. The reclamation program also involves many other aspects to complement the main elements of the closure plan. For example, the establishment of vegetation on the surface of the disposal site is often needed to control erosion, and is sometimes a requirement included in the regulations. In this case, the effect of the vegetation on the engineered systems must be carefully assessed. Also, engineered systems and their surroundings must be instrumented and monitored closely. In the case of AMD generating wastes, monitoring must last for an extremely long time, and should be attached to a well- controlled maintenance program. An emergency plan is also required during the mine operation and upon its closure. It must identify all of the potential problems (even the least likely) and the actions needed to resolve them; these actions must be planned and prepared in advance by identifying the responsibilities and required resources. More information on the challenges related to AMD mine site reclamation are provided in Aubertin et al. (2002, 2016).

4. References

Adu-Wusu, C., Yanful, E.K., Mian, M.H. (2001). Field evidence of resuspension in a mine tailings pond. Canadian Geotechnical, Journal, 38: 796-808.

Amyot, G., Vézina, S. (1997). Flooding as a reclamation solution to an acidic tailings pond – the Solbec-Cupra case. Proc, 4th ICARD conference, Vancouver, BC, Canada, Vol. 2, 681-696.

Andersland, O., Ladanyi, B. (2004). Frozen Groung Engineering (2nd Edition ed.). Hoboken, New Jersey, John Wiley & Sons, Inc.

Aubertin, M., Bussière, B., Pabst, T., James, M., Mbonimpa, M. (2016). Review of reclamation techniques for acid generating mine wastes upon closure of disposal sites. Geo-Chicago: Sustainabilty, Energy and the Geoenvironment. Chicago, August 14-18.

Aubertin, M., Molson, J., Bussière, B., Dagenais, A.M. (2006). Investigations of layered cover systems acting as oxygen barriers to limit acid mine drainage. Proc. Of the 5th Int. Conf. Environmental Geotechnics, Cardiff , UK., Vol. 2, 827-835.

Aubertin, M., Bussière, B., Bernier, L. (2002). Environnement et gestion des rejets miniers. CD-ROM, Les Presses Internationales Polytechnique, École Polytechnique de Montréal, Québec, Canada.

Aubertin, M., Dionne, J., Marcoux, L. (1997). Design guidelines and stability criteria of engineering works for water covers. Proc, 4th ICARD conference, Vancouver, BC, Canada, Vol. 4, 1851-1866.

Aubertin, M., Chapuis, R.P., Aachib, M., Bussière, B., Ricard, J.-F., Tremblay, L. (1995). Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. MEND Report 2.22.2a.

Awoh, S.A., Mbonimpa, M., Bussière, B. (2013). Field study of the chemical and physical stability of highly sulphide-rich tailings stored under a shallow water cover at the Don Rouyn site. Mine Water & the Environment, 32: 42-55.

Benzaazoua, M., Bussière, B., Kongolo, M., Mclaughlin, J., Marion, P. (2000). Environmental desulphurization of four Canadian mine tailings using froth flotation. International Journal of Mineral Processing, 6 : 57-74.

Bussière, B., Maqsoud, A., Aubertin, M., Martschuk, J., McMullen, J., Julien, M. (2006). Performance of the oxygen limiting cover at the LTA site, Malartic, Quebec. CIM Bulletin, 99(1096) : 1-11.

Bussière, B., Aubertin, M., Chapuis, R.P. (2003). The behaviour of inclined covers used as oxygen barriers. Canadian Geotechnical Journal, 40: 512-535.

Catalan, L.J.J., Yanful, E.K. (2002). Sediment-trap measurements of suspended mine tailings in shallow water cover. Journal of Environmental Engineering, 128: 19-30.

Dawson, R. F., Morin, K. A. (1996). Acid Mine Drainage in Permafrost Regions: Issues, Control Strategies and Research Requierements. MEND Report 1.61.2. Ottawa.

Derycke, V. (2012). Optimisation de la désulfuration de produits miniers en vue de la diminution de leur potentiel polluant : effet de la granulométrie, du type de sulfures, et évaluation de la qualité des eaux de drainage post-traitement. PhD Thesis in Environmental Sciences, UQAT.

Dobchuk, B., Nichol, C., Wilson, G. W., Aubertin, M. (2013). Evaluation of a single layer desulphurized tailings cover. Canadian Geotechnical Journal, 50(7): 777-792.

Ethier, M-P., Bussière, B., Aubertin, M., Maqsoud, A., Demers, I., Lacroix, R. (2013). In situ evaluation of the elevated water table technique combined with a monolayer cover on reactive tailings: monitoring strategy and preliminary results. 66th Canadian Geotechnical Conference and the 11th Joint CGS/IAH-CNC Groundwater Conference, GeoMontreal 2013, Geoscience for Sustainability, Paper 301.

Holubec, I. (2004). Covers For Reactive Tailings Located in Permafrost Regions Review. MEND Report 1.61.4. Ottawa.

Holubec, I. (1993). Preventing AMD by Disposing of Reactive Tailings in Permafrost. MEND Report 6.1. Ottawa: CANMET.

IPA (2015). International permafrost associaion. http://ipa.arcticportal.org/publications/occasional-publications/what-is-permafrost.

Kyhn, C., Elberling, B. (2001). Frozen cover actions limiting AMD from mine waste deposited on land in Arctic Canada. Cold Regions Science and Technology, 32(2-3), 133-142.

Li, M. Aubé, B., St-Arnaud (1997). Considerations in the use of shallow water cover for decommissioning reactive tailings. Proc, 4th ICARD conference, Vancouver, BC, Canada, Vol. 1, 115-130.

Maqsoud, A., Mbonimpa, M., Bussière, B., Dionne, J. (2013). Réhabilitation du site minier abandonné Aldermac : résultats préliminaires du suivi de la nappe surélevée. 66th Canadian Geotechnical Conference and the 11th Joint CGS/IAH-CNC Groundwater Conference, GeoMontreal 2013, Geoscience for Sustainability, Paper 551.

Mbonimpa, M., Aubertin, M., Aachib, M., Bussière, B. (2003). Diffusion and consumption of oxygen in unsaturated cover materials. Canadian Geotechnical Journal 40: 916-932.

McLaughlin, J., Stuparyk, R. (1994). Evaluation of low sulphur rock tailings production at INCO's Clarabelle mill. Proc. of the Innovations in Mineral Processing Conference, Sudbury, 129-146.

MEND (2001). Manual report 5.4.2, Volume 1: Summary, Volume 2: Sampling and Analysis, Volume 3: Prediction, Volume 4: Prevention and Control, Volume 5: Treatment, Volume 6: Monitoring. Canada Centre for Mineral and Energy Technology, Ottawa, Canada.

Morris, C.E., Stormont, J.C. (1997). Capillary barriers and subtitle D covers: estimating equivalency. Journal of Enviromental Engineering, 123(1), 3-10.

Nicholson, R. V., Gillham, R. W., Cherry, J. A., Reardon, E. J. (1989). Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canadian Geotechnical Journal, 26: 1-8.

Ouangrawa, M., Aubertin, M., Molson, J., Bussière, B., Zagury, G.J. (2010). Preventing acid mine drainage with an elevated water table: Long-term column experiments and parameter analysis. Water, Air and Soil Pollution, 213: 437–458.

Orava, A.D., Tremblay, G.A., Tibble, A., Nichoslson, R. (1997). Prevention of acid rock drainage through application in-pit disposal and elevated water table concepts. Proc. of the 4th ICARD conference, Vancouver, Vol. 3, 973-983.

Peacy, V., Yanful, E.K., Payne, R. (2002). Field study of geochemistry and solute fluxes in flooded uranium tailings. Canadian Geotechnical, Journal, 39: 357-376.

Rasmussen, G., Hoffert, J., Tucker, G., Kinch, J., Colwell, D. (2004). The Kemess Mines Ltd. tailings dam construction using tailings construction sand. Proc. Of the 36th Annual Meeting of the Canadian Mineral Processors, Ottawa, Paper 4.

Rescan (1996). Geochemical assessment of Equity Silver tailings pond. MEND Project 2.11.5c, Vancouver, Canada, 123p.

Rey, N., Demers, I., Bussière, B., Mbonimpa, M., Lortie, S. (2016). Field experiments to test the elevated water table concept combined with a desulfurized tailings cover layer. Geo-Chicago: Sustainabilty, Energy and the Geoenvironment. Chicago, August 14-18.

Romano, C.G., Mayer, K.U., Jones, D.R., Ellerbroek, D.A., Blowes, D.W. (2003). Effectiveness of various cover scenarios on the rate of sulfide oxidation of mine tailings. Journal of Hydrology, 271: 171-187.

Rykaart, M., Hockley, D. (2009). Mine Waste Covers in Cold Regions. MEND Report 1.61.5a.

SRK (Steffen, Robertson and Kirsten) (1989). Draft Acid Rock Technical Guide. BC AMD Task Force, Vol. 1.

Vigneault, B., Campbell, P. G. C., Tessier, A., De Vitre, R. (2001). Geochemical changes in sulfidic mine tailings stored under a shallow water cover. Water Research, 35: 1066-1076.

Weeks, B., Wilson, G.W. (2005). Variations in moisture content for a soil cover over a 10 year period. Canadian Geotechnical Journal, 42: 1615-1630.

Zhan, G., Aubertin, M., Mayer, A., Burke, H., McMullen, J. (2001). Capillary cover design for leach pad closure. Proc. SME Annual Mtg., Denver, CO, USA, p 1-9.