Review of reclamation techniques
for acid generating mine wastes upon closure of disposal sites

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ABSTRACT: Acid mine drainage (AMD) remains a major environmental challenge for the mining industry. The preferred options for effectively limiting the environmental impact of AMD consist in controlling the reactions through the use of preventative techniques. Their principal objective is to exclude at least one of the constitutive elements of the chemical reactions, i.e. water, oxygen, or sulfidic minerals. The article recalls the basic principles and reviews different approaches for the prevention and control of AMD upon mine closure. The main methods include multi-layer covers, water covers, and an elevated water table (with a mono-layer cover). Their main advantages, limitations and uncertainties are addressed. Alternative approaches, such as environmental desulphurization and co-disposal of waste rock and tailings, are also discussed.

INTRODUCTION

The mining industry contributes significantly to the economy of many regions around the globe. However, there are also some drawbacks associated with mining operations. One of these is the challenge associated with the large amount of wastes produced which need to be managed safely and economically.

As ore reserves are depleted, all mines will reach the closure stage beyond which the site must be reclaimed. The general goal is then to return the mine site to a satisfactory state by eliminating the risks to health and safety, controlling contaminant production and migration, and establishing conditions that require a minimum of monitoring and maintenance in the long term (Aubertin et al. 2002).

Although apparently straightforward, effective closure measures are not easily applied to disposal sites where the mine wastes (tailings and waste rock) contain reactive minerals that can produce acid mine drainage (AMD). The generation of acidic effluents is a well-known phenomenon that has been studied for decades (e.g.

Singer and Stumm 1970; SRK 1989). AMD is typically produced when sulfidic minerals (such as pyrite and pyrrhotite) are exposed to atmospheric conditions. The reactions between the iron sulfides, oxygen and water then reduce the leachate pH (often to around 2), favoring the solubilisation of various elements (including metals) present in the rock. As acid mine (or rock) drainage can be a major threat to local ecosystems, the effluent must be treated before discharge. However, active chemical treatment, often employed during mining operations, is not a viable (nor acceptable) option upon closure due to the long term costs involved, infrastructure requirements and maintenance, and the large amount of sludge produced (Aubertin et al. 2002; Robertson 2011). The primary goal of mine site reclamation should be to prevent the production of AMD.

The vast amount of work performed and the experience gained over the last two to three decades clearly indicate that the reclamation of reactive wastes disposal sites is best achieved when it is planned in advance and integrated into the mining production cycle. This guiding principle of "Designing for Closure" has in fact been considered for many years (SRK 1989; Aubertin et al. 2002), but it must be admitted that it is seldom being applied diligently by the industry (Aubertin et al. 2015); this aspect will be addressed further below.

One of the major challenges regarding closure and reclamation of sites producing AMD is the required life time of the engineering works that must be constructed and maintained. This duration can be very long, and it is sometimes considered indefinite (Vick 2001). This has a major impact on the geotechnical (physical) and geo-environmental (chemical) design criteria for various works such as the dikes surrounding tailings impoundments and the external slopes of the waste rock piles (Aubertin et al. 1997, 2002, 2011).

This article summarizes the main techniques available for the reclamation of AMD generating sites, with an emphasis on those that are more commonly applied under relatively wet (and cold) climatic conditions (such as those in the eastern provinces of Canada). The presentation is largely based on previous work conducted by the authors and their industrial and academic collaborators on tailings sites, with some additional information on waste rock.

GLOBAL REACTION AND MAIN PREVENTION METHODS

Pyrite (FeS_2) is usually the most abundant iron sulfide mineral in mine wastes so it is often used to express the reactions leading to the production of sulfuric acid. These reactions can be simplified into a single global expression:

$$FeS_2 + 15/4O_2 + 7/2H_2O \rightarrow Fe(OH)_3 + 2H_2SO_4 \qquad [1]$$
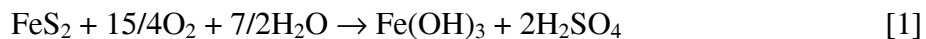
This equation confirms that sulfidic minerals, water and oxygen are required to produce AMD. The detailed reactions include various steps that may also involve contributions from other oxidizing agents (e.g. ferric iron) and bacteria (Kleinman et al. 1981; SRK 1989; Aubertin et al. 2002; INAP 2012; Anawar 2015).

Prevention and control methods target the three components on the left hand site of Eq. 1. In the case of tailings, the sulfidic minerals can be separated (and managed

separately) by using desulfurization techniques (Benzaazoua et al. 2008); this approach can be very advantageous, as will be discussed further below. The availability of water and oxygen can be controlled using different types of barriers placed on top and around the reactive wastes, as will be described in the following. It is also possible to use complementary mitigation methods to reduce the reaction rate, such as temperature control (in cold climate), surface passivation and anti-bacterial agents, but most of these techniques suffer from a number of disadvantages and they are usually considered less reliable; they will not be discussed here.

MULTILAYERED COVERS

Covers made of a few layers of different materials, each playing a distinct role, are commonly used to control water infiltration and/or oxygen ingress at disposal sites (Aubertin et al. 1995, 2002; MEND 2004); they also play various other roles with respect to surface stability and future use (and esthetic) of the sites.

This type of cover is now commonly applied on the nearly horizontal surfaces of tailings impoundments, but they can also be used, with some adjustments, for inclined areas such as the external face of dikes and the slope of waste rock piles (Bussière et al. 2003; Aubertin et al. 2009). In all cases, the characteristics of the cover must be adapted to the local conditions in terms of climate, hydro(geo)logical site characteristics, available materials, and reactive wastes properties.

As stated above, covers must be able to perform adequately for a very long time. This creates many challenges for their design, construction, and maintenance.

Fig. 1 illustrates a typical multi-layered cover system that contains five layers; the actual number of layers (from two to more than five) depends on a number of factors related to site specific conditions and design criteria. In Fig. 1, the superficial Layer A serves to integrate the surface of the site to the local environment. It is usually made of organic soils that facilitates the controlled establishment of vegetation; care must be taken (with some maintenance) to avoid the potentially negative effects of roots on the cover performance. Layer B is a protection layer that helps stabilize the site and prevents bio-intrusions; it is made of coarse grained materials with a high content of cobbles. Layer C is a drainage layer of granular (sand and/or gravel) material that controls water inflow laterally and vertically. In many cases, layers B and C can be combined into a single one. This coarse-grained layer may also play the role of a capillary break, to prevent moisture loss by evaporation. Layer D is the actual hydrogeological barrier in the cover. It is made of a relatively impervious material such as a fine grained soil, a geomembrane (GM), a geosynthetic clay liner (GCL) or a combination of these; considering its key role, characteristics of layer D will be discussed more extensively below. Layer E is the support layer placed on the reactive waste; the granular material used here may also act as a capillary break that prevents upward or downward moisture movement.

The thickness of the different layers may vary, from a few mm (in the case of a GM) to more than one meter (Aubertin et al. 2002, 2015). The different layers thicknesses must be optimized as these significantly affect the efficiency and cost of the cover.

Infiltration barrier

As stated above, a multilayered cover can be designed to prevent water inflow. In this case, Layer D would typically be made of a fine grained soil (such as a compacted clay layer, CCL), a geomembrane (GM), a geosynthetic clay liner (GCL), or a combination of two of these.
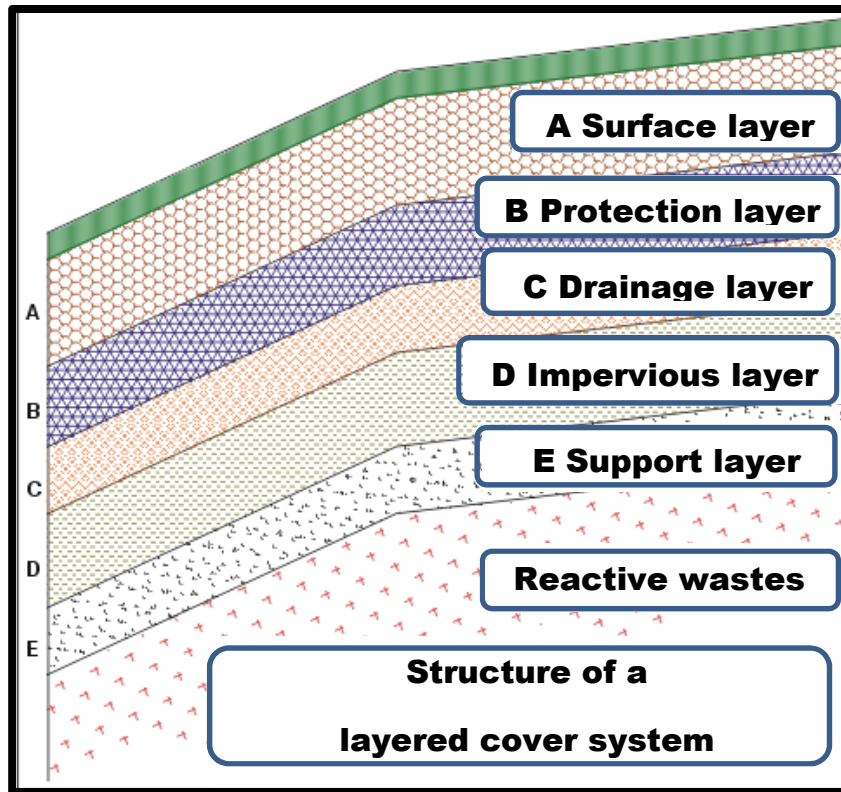

FIG. 1. Configuration of a cover with five layers made of different materials (adapted from Aubertin et al. 1995, 2002)

In the case of soils, care must be taken to select one that is not prone to permanent cracking when exposed to wetting-drying or freezing-thawing cycles. Many plastic clays are susceptible to these problems, so they should be avoided as much as possible when the climatic conditions are critical (Aubertin and Chapuis 1991; Aubertin et al. 1995, 2002). Low plasticity silts may be preferable in many cases (even if they are often somewhat more pervious) because cracks induced in these materials tend to heal upon rewetting. Along the same line, non-acid generating tailings can constitute a good alternative as they often have the required properties to perform well (Aubertin et al. 1995; Bussière 2007); they may also be cheaper and easier to put in place than clays.

Geomembranes are sometimes used as an impervious layer, but many concerns have been raised regarding their use in covers, particularly regarding the presence of defects and wrinkles which may significantly diminish their efficiency (Rowe et al. 2012; Aubertin et al. 2015). The effect of settlements and risk of sliding along the

slopes are other major concerns (Aubertin et al. 1995, 2002). These issues and others have influenced regulators who now often require double-layer protection with a GM.

But the main objection regarding the use of a geomembrane in covers for acid generating mine sites is their limited lifetimes, which is usually expressed in decades (Koerner et al. 2011; Rowe et al. 2014; Rowe and Ewais 2015). Such fairly short lifetimes are not compatible with the very long term requirements for such cover.

Geocomposite clay liners (GCL), made with bentonite and geotextiles, constitute another alternative for the impervious layer. In this case, attention must be paid to potential problems with the GCL uniformity and integrity, low friction angle, limited efficiency against oxygen diffusion, and the risk of in-situ alteration of their physicochemical properties (Aubertin et al. 2000, 2015; Benson and Scaliar 2008; Liu et al. 2013).

In addition to non-acid-generating tailings, other alternative materials have also been considered (and used) in covers, including pulp and paper or deinking residues, and other types of industrial waste. Documented cases are however relatively scarce and many of these raise serious questions. Each material must thus be assessed in details to meet robust design criteria.

Water retention covers

Under relatively dry climatic conditions, it is possible to design the cover so infiltration water would be stored in the layer close to the surface, and then released during dry spells by evaporation. Such so-called store-and-release (SR, or alternate) covers have been shown to be quite efficient at reducing the quantity of water reaching the underlying waste, provided that the right materials are used to create the required capillary barrier effect (described below) and storage capacity. This type of cover has been constructed at the Barrick Goldstrike operation in Nevada, USA (Zhan et al. 2000), and also applied within experimental cells at the Kettara mine, Morocco (Bossé et al. 2015).

The amount of precipitation (recharge) that can be handled by this type of cover is however limited, so it is usually not appropriate for horizontal covers under humid climates.

For inclined surfaces, moisture retaining covers can be designed to divert part of the infiltrating water toward the side and base of the slope. Such Store-Divert-Release (SDR) covers also take advantage of the unsaturated materials properties to accumulate water in a retention layer, and then force it to flow along the slope until discharge and evaporation reduces the water content. A SDR cover has been constructed on the slope of a heap leach pad at the Barrick Goldstrike operation (Zhan et al. 2001, 2014). The main design criterion in this case is the diversion length (LD), which is illustrated on Fig. 2. This length is associated with the down dip limit (DDL; Ross 1990; Stormont 1996; Zhan et al. 2001; Aubertin et al. 2009). It depends on the different materials hydrogeological properties (i.e. water retention curves and hydraulic functions; see Fig. 3 discussed below), the amount of water (precipitation) to be handled, the thickness (and available porosity) of the layers, and the inclination angle of the surface (Aubertin et al. 2009). The cover design must be adapted to the local conditions, which may require some innovative configuration. It may not be an appropriate solution for all situations; again, specific analyses must be

conducted to ensure the satisfactory cover performance to control the production of AMD.
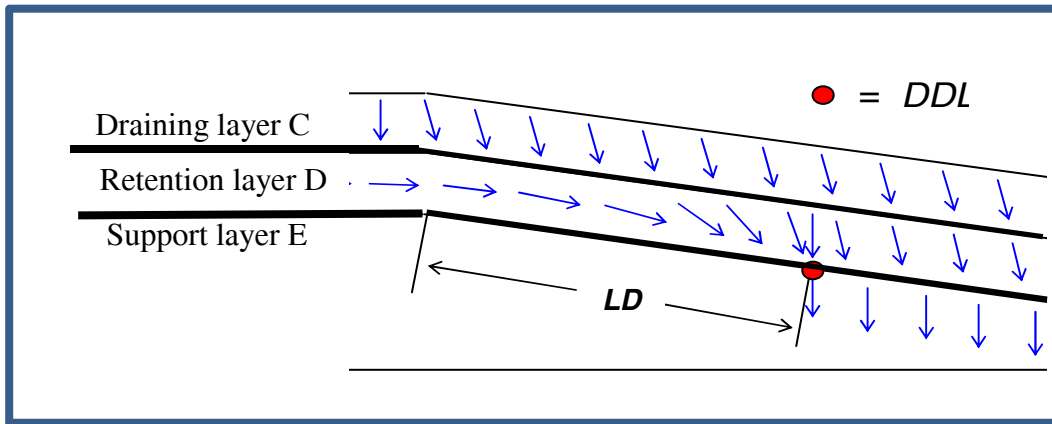

FIG. 2. Schematic representation of the water flow along an inclined SDR cover made of a coarse draining layer (C) placed on a moisture retention layer (D) and a coarser material layer (E) (adapted from Bussière 1999 and Aubertin et al. 2009).

Oxygen barrier

For regions having a relatively humid climate (with a highly positive annual water budget), it is often more efficient and economical to design the layered cover system to create a barrier against oxygen ingress (Aubertin et al. 2002, 2006).

GM and GCL can, in principle, prevent oxygen migration, but the limitations mentioned above makes these materials less attractive than other alternatives. In practice it is usually preferable to use thick layers made of more durable geomaterials to create an oxygen barrier. The most efficient and practical means is to use a water retention layer that maintains a high degree of saturation at all time, so it can efficiently limit the oxygen flux (by advection and diffusion). To do so, it is usually required to select a material that will be able to create a capillary barrier in the cover above the water table (under unsaturated conditions).

A cover with capillary barrier effects (CCBE) is typically made of layers of materials with distinct hydrogeological properties (Aubertin et al. 1995, 2002, 2006; Bussière et al. 2003). Water retention in a CCBE is mainly associated with capillary and adhesion forces which are typically more pronounced in unsaturated soils with a finer pore structure.

This is illustrated with the schematic representation of the water retention curves and hydraulic functions shown in Fig. 3 for a coarse grained soil (sand) and a finer grained soil (silt). Fig. 3a shows that the silt has a greater volumetric water content θ (and thus a larger water retention capacity) compared with the sand, at a given suction; this translates into a larger air entry value (AEV or ψ_a) and water entry value (WEV or ψ_r) for the silt. The higher moisture content, at a given suction, means that the unsaturated hydraulic conductivity of the silt is also larger (Fig. 3b).

In a CCBE, the upper fine-grained soil (i.e. layer D in Fig. 1 and 2), located above a coarser material (layer E) that easily desaturates, tends to store moisture

coming from the surface as water does not easily move downward into the underlying material due to its low hydraulic conductivity at the reduced volumetric water content (or degree of saturation). Water then tends to accumulate in the moisture retaining layer (MRL) until the negative pressure (suction) at the interface approaches the water entry value WEV (or ψ_r) of the coarse-grained material. The WEV corresponds, on the water retention curve (WRC), to the suction ψ at which water starts to penetrate significantly into the material on a wetting path; this suction is reached at the residual water content θ_r of the coarse grained material (Fig. 3a). Once water moves across the interface, it progressively increases the degree of saturation and hydraulic conductivity of the coarser material (Fig. 3b), hence dissipating the capillary barrier effect.
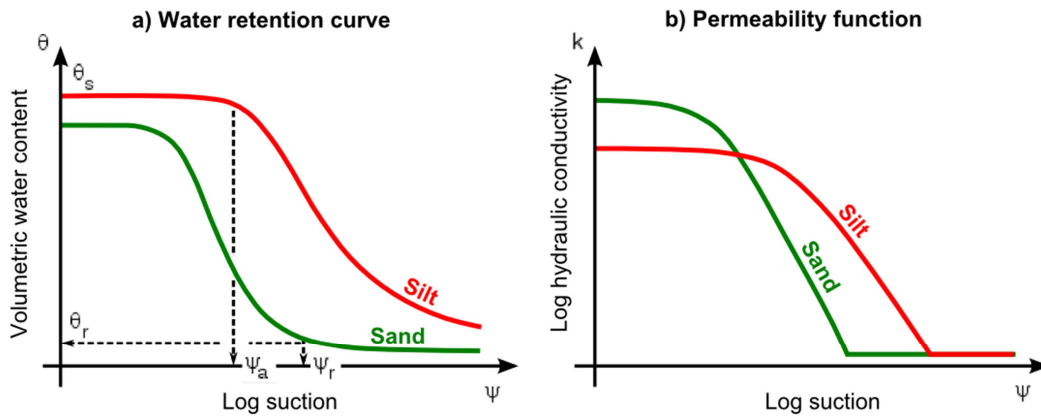

FIG. 3. Schematic hydraulic functions for a fine grained soil (silt) and a granular soil (sand).

An efficient CCBE constructed on a relatively flat surface will be able to maintain a high degree of saturation (> 85 to 90%) over time in the fine-grained, water retention layer (D). This greatly reduces the air permeability in this material (to almost zero) and it significantly diminishes the oxygen diffusion flux F_{O2} across the moisture retaining layer. Oxygen diffusion can be expressed using the first Fick's law (e.g. Mbonimpa et al. 2003):

$$F_{O2} = - D_e (\partial C_{O2}/\partial Z) \qquad [2]$$

where the term in parentheses represents the oxygen concentration (C_{O2}) gradient, over vertical distance (Z-axis), from the surface to below the cover. This diffusive flux depends directly on the value of the effective diffusion coefficient D_e, which in turn varies with the degree of saturation S_r, as illustrated in Fig. 4. The value of D_e is reduced by orders of magnitude when the material goes from a low to a high degree of saturation (Aubertin et al. 1995, 2000, 2006; Aachib et al. 2004). An oxygen barrier is effective when the moisture retaining layer is highly saturated. When the CCBE is well designed and constructed, it can reduce the oxygen flux by more than 99% (compared with exposed tailings), to values below 1 mole O_2/m^2/year

(Mbonimpa et al. 2003; Bussière et al. 2003, 2006). This is usually sufficient to effectively control the production of AMD.

Maintaining a high degree of saturation on the relatively flat (almost horizontal) surface of a tailings impoundment is fairly straightforward, but the situation can be quite different along sloping areas such as on tailings dikes and waste rock piles. In this case, care must be taken to assess the possible desaturation of the moisture retaining layer uphill, due to the movement of water induced by the downhill hydraulic gradient (Aubertin et al. 1999; Bussière et al. 2003).

Figure 5 shows a picture of the LTA site located in Abitibi, Québec, Canada, during cover construction. This CCBE was constructed about 20 years ago and it has been monitored, demonstrating that such a cover can be efficient as an oxygen barrier (Bussière et al. 2006). Another somewhat similar layered cover has been successfully applied at the Lorraine mine site, near Latulippe, Québec, Canada (Aubertin et al. 2006).
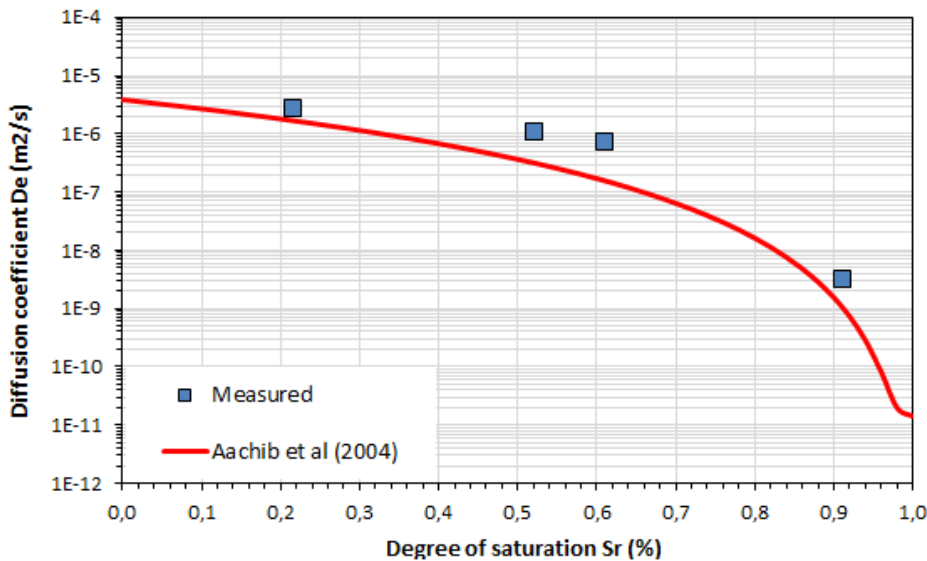

FIG. 4. Value of the effective diffusion coefficient of oxygen D_e based on diffusion tests on silty tailings and on the predictive model of Aachib et al. (2004) (adapted from Pabst 2011).

In addition to the various types of materials and cover configurations mentioned above, it is also possible to use oxygen consuming materials (such as wood chips or low sulfide tailings) to build (part of) a cover. Although these can perform well in the short term, the efficiency of such type of cover tends to diminish over time with the depletion of the oxygen consumption potential.

WATER COVERS AND ELEVATED WATER TABLE

Covering reactive mine wastes with water has long been used to control the production of AMD. The low solubility of oxygen combined with its low diffusion coefficient in water make this a potentially very efficient technique. In practice, this technique has mainly been applied to tailings, such as at the Louvicourt and Solbec-

Cupra mine sites in Québec, Canada (Aubertin et al. 2002). It may require the addition of impervious material along the base (liner) and sides (dikes) of the impoundment. It can also be applied to waste rock under specific circumstances.
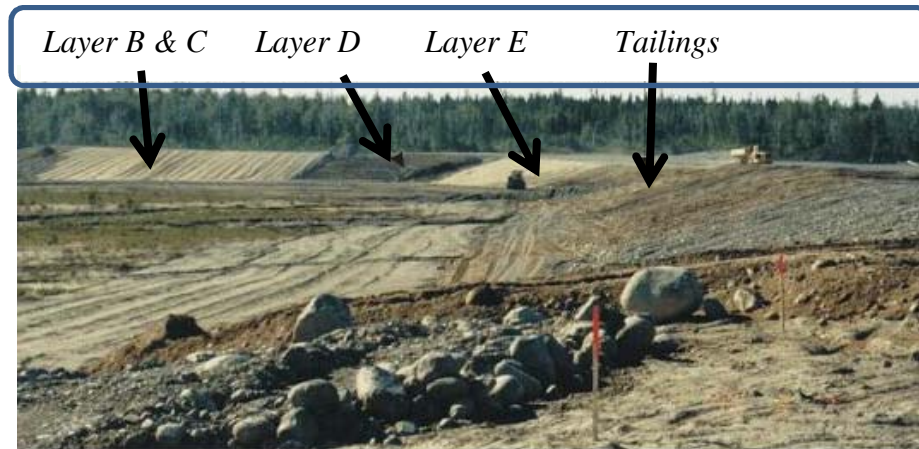

FIG. 5. The LTA tailings disposal site during the construction of a CCBE made of three layers (adapted from Aubertin et al., 2002)

Reactive mine wastes can be deposited immediately under water, thus preventing oxidation from the start, or they can be flooded at a later time during the mine life. Using existing lakes and rivers is tempting, but this practice if often regulated (prevented) by governmental agencies. Hence, engineered structures must usually be constructed to retain the aqueous cover, which must be thick enough to prevent resuspension of the fine grained particles (Li et al. 1997; Yanful and Catalan 2002). The main challenge in this case is to ensure the long term physical (geotechnical) stability of the retaining structures, over an indefinite lifespan (Aubertin et al. 1997, 2002, 2011). As such long term conditions may induce unavoidably high risks for (catastrophic) failure, due to the increasing probability of exceeding the system capacity over time, regulators are now often reluctant to allow the application of this technique if it involves the construction and maintenance of man-made structures.

An alternative is to dispose of the reactive wastes in open pits with stable slopes. This technique has been applied with success at the Don Rouyn site in Abitibi (QC, Canada). In this case, the analysis and design must take into account contaminants migration in the fractured rock mass surrounding the wastes (Aubertin et al. 2015).

Like for all the other types of covers, water (aqueous) covers require extensive monitoring and site surveillance.

A somewhat similar but often more advantageous alternative to water covers is to use an elevated water table (EWT) to prevent tailings oxidation. This technique consists of raising the phreatic surface to a depth less than the height of the saturated capillary fringe in the tailings, i.e. $h < AEV$, as illustrated in Fig. 6 (Aubertin et al. 1999; Ouangrawa et al. 2010; Pabst 2011). Raising the water table is easier when the impoundment was designed to prevent exfiltration. For other cases, it can be done by modifying the water balance of the site, by increasing the water retention capacity of the tailings, or by decreasing the lateral flow of groundwater (Orava et al. 1997).

A monolayer cover made of coarse-grained material is placed above the tailings to increase water infiltration, reduce run-off, and limit water loss by evaporation; such is the case at the Aldermac mine site, Québec, Canada. For sufficiently humid conditions, a fine-grained material (such as tailings that don't produce AMD) can alternatively be used to form the cover, as shown at the Manitou-Goldex mine site, Québec, Canada (Ethier et al. 2013).

A well designed EWT with a monolayer cover has many advantages over a full water cover, including lower pore water pressures in the dikes and foundations, reduced downward and lateral seepage flow, absence of water movement due to the wind (which tends to increase oxygen availability in a water cover), and the strength gain of tailings submitted to suction (negative pore water pressure) in the vadose zone. The free board is also increased (by up to a few meters) by avoiding free water on the surface. Maintenance of the site can also be simpler and less costly than for other types of covers.
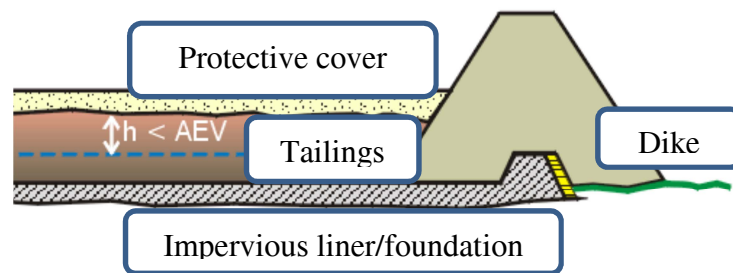

FIG. 6. Schematic view of an elevated water table in a tailings impoundment, with a protection layer made of coarse grained material (adapted from Aubertin et al. 1999).

OTHER COMPONENTS OF THE RECLAMATION PROGRAM

Closure and reclamation of AMD generating sites requires careful planning, rigorous design, and good construction methods. The program also involves many other aspects to complement the main elements of the reclamation works described above. For instance, the establishment of vegetation on the surface of the disposal site is often needed to control erosion, and it is sometimes a requirement included in the regulations. In this case, the effect of the vegetation on the engineered works must be carefully assessed. For example, deep rooting systems may be detrimental for the efficiency of a CCBE acting as an oxygen or water infiltration barrier. Interaction between deep roots and underground water with the EWT must also be considered. A positive contribution of the vegetation to evapotranspiration may be beneficial for store-and-release covers, and also for improving slope stability, but these need to be assessed on a case by case basis (e.g. Cooke and Johnson 2002). Again, this is easier to do when planned in advance.

During the operation and upon closure of mine wastes disposal sites, engineered works and their surroundings must be instrumented and monitored closely. In the case of AMD generating wastes, monitoring must last for a very long time. The

efficiency of the various techniques described above usually requires that specific characteristics be measured on the site, including the depth of the water table (or the pore water pressures near the base of the site), the quality of the surface and underground water, and the settlements and displacements of the various components. The efficiency of the reclamation works also requires specific measurements that should involve the volumetric water content and (negative) pore water pressures near the surface; oxygen concentrations and fluxes also need to be assessed to evaluate the cover efficiency (Aubertin et al. 1999; 2002, 2015; Bussière et al. 2006; Dagenais et al. 2012). The various instruments developed for these types of measurements must be properly installed and maintained so that they can provide reliable information.

Monitoring goes hand in hand with a regular inspection program. All the main components must be targeted during visits from the (independent) specialists involved in evaluating the site conditions and the performance of the reclamation (and related) works. The information gathered from field observations and instrumentation, and comparisons with initial design considerations (assumptions), must be well documented and permanently filed in several places. Corrective measures, when needed, must be applied swiftly, and rigorously.

An emergency plan is also required during the mine operation and upon closure. It must identify all the possible (potential) problems (even the least likely) and the actions to be taken; these must be planned and prepared in advance, by identifying the responsibilities and the resources required (Aubertin et al. 2002, 2011, 2015).

INTERGRATED MINE WASTES MANAGEMENT AND RECLAMATION

Mining is a rapidly evolving industry, and mine waste management practices are expected to progress at the same pace as other technological components. Although much work has been conducted in recent years, some components still lag behind. This is particularly the case with applications of the general principle of "Designing for closure". As discussed in more details elsewhere (Aubertin et al. 2015), there is often a large gap between the overall objectives of mining companies and the actual measures taken to improve mine wastes management. This is particularly the case when it comes to taking preventive measures to control AMD from the initial stages of the operation.

Many tools and techniques now exist to help with the management of such reactive wastes. Some take advantage of recent developments that favor the integration with other components of the mining operation (Bussière 2007; Benzaazoua et al. 2008). In this regard, environmental desulfurization of the tailings at the mill is a very promising avenue that allows the separation of the reactive fraction, which can then be managed separately from the (often larger) non-acid generating fraction. The former can for example be returned in underground stopes as cemented paste backfill, while the latter can be used to construct single or multi-layer covers (Benzaazoua et al. 2008).

Backfilling with tailings (as hydraulic or paste fill) or waste rock (as rock fill or to construct barricades) is another option that reduces the amount of waste on the surface, while improving ground stability and ore dilution in underground operations (Aubertin et al. 2002, 2011; Benzaazoua et al. 2008). Placing the reactive wastes in

open pits is another option, but care must then be taken to prevent contaminants migration in the surrounding fractured rock mass and groundwater.

Non-reactive waste rock can also be used to construct one (or more) layer(s) in the cover system (i.e. infiltration layer with the EWT or capillary break layer(s) in a CCBE), in addition to their regular use to construct dikes around tailings impoundments.

Another promising avenue involves the construction of waste rock inclusions (WRI) in tailings impoundments to increase the rate of drainage and dissipation of excess pore water pressures and to improve the geotechnical stability of the dikes under static or dynamic (earthquake) loadings (James et al. 2013); this technique is illustrated in Fig. 7. When the waste rocks are reactive, it is also possible to prevent contact with atmospheric oxygen by maintaining an elevated water level in the tailings. A cover can added on the surface at the end of operations.
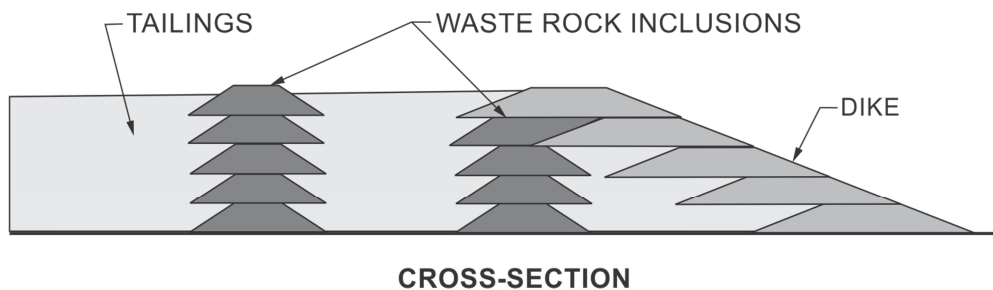

FIG. 7. Schematic illustration of waste rock inclusions in tailings (WRI); a cover can be added on top to control AMD (adapted from James et al. 2013)

When only a part of the waste rock can be placed as WRI in the impoundment (or returned underground as backfill), the remaining waste rock usually has to be placed in piles. In such cases, the waste rock pile should be designed and constructed to ensure the geotechnical and geochemical stability (Aubertin 2013). The construction a reactive waste rock piles must be well documented and monitored.

CONCLUDING REMARKS

Acid generating mine wastes raise many technical, operational and financial challenges for the industry. The costs and efficiency of the reclamation program can be optimised through early and careful planning, and by integrating into operations measures that will facilitate closure and maintenance of the site in the long term. Too often however, the reclamation program is initially limited to conceptual views, proposed in the early stages of the mine, but which are rarely updated sufficiently to establish a detailed reclamation program. This lack of detailed planning can have major economic and environmental consequences upon mine closure. There is also a tendency of idealizing (simplifying) the work to be done and to minimize the challenges and difficulties that will be encountered upon closure. Accounting practices, often based on a Net Present Value analysis (or a variant of it), may also create additional challenges as these often consider postponing investments (seen as

"expenses") as a way to increase the short term profits of the operation, while underestimating the negative effect that this may have in the long term.

The exceptionally long duration of the works that need to be constructed and maintained is a real challenge when the tailings or waste rocks are prone to produce AMD. Such works need to be designed to resist long term conditions that may affect the material strength and the loading conditions, and hence their factor (and margin) of safety (Aubertin et al. 2011). It can then be asked how will these disposal sites be maintained in the long term, and by whom? Like all corporations, mining companies have a limited operating life (of a few decades in most cases), while governmental agencies may not have the resources to take care of these sites (even when some funding is put aside for this purpose). This is an important issue that may greatly affect the social acceptability of future mining operations. A review of current practices seems to be required in this regard; the authors and their collaborators are directly involved in this process.

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REFERENCES

Aachib, M., Mbonimpa, M. and Aubertin, M. (2004). "Measurement and prediction of the oxygen diffusion coefficient in unsaturated media, with applications to silt covers". *Water, Air and Soil Polution.*, 156 : 163-193.

Anawar, H. Md. (2015). "Sustainable rehabilitation of mining waste and acid mine drainage using geochemistry, mine type, mineralogy, texture, ore extraction and climate knowledge." *J. Environmental Management*, 158:111-121.

Aubertin, M., and Chapuis, R.P. (1991). "Considérations hydro-géotechniques pour l'entreposage des résidus miniers dans le nord-ouest du Québec". *Proc. 2nd Int. Conf. On Reduction of Acid Rock Drainage*, Montreal, Canada, Vol. III, 1-22.

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., and Marcoux, L. (1997). "Design guidelines and stability criteria of engineering works for water covers." *Proc 4th Int. Conf. on Acid Rock Drainage,* Vancouver, BC, Canada, Vol. 4, 1851-1866.

Aubertin, M., Bussière, B., Monzon, M.,..., Chapuis, R.P., and Bernier, L. (1999). *Étude sur les barrières sèches construites à partir des résidus miniers. Phase II-Essais en place.* École Polytechnique de Montréal, MEND Report 2.22.2c.

Aubertin, M., Aachib, M., and Authier, K. (2000). "Evaluation of diffusive gas through covers with a GCL". *Geotextiles and Geomembranes*, Vol. 18 : 1-19.

Aubertin, M., Bussiere, B., and Bernier, L. (2002). *Environnement et gestion des rejets miniers*. Manual on CD-Rom, Presses Int. Polytechnique. Montreal., QC, Canada.

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

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 J.*, 46: 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 Environnement,* Rouyn-Noranda, QC, CIM (CD Rom), 38 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, QC, CIM (CD Rom), 67 p.

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

Benson, C.H., and Scaliar, J. (2008). "Field performance of GCLs used as hydraulic barriers in caps" *Proc. Symp. Mines and Environnement,* Rouyn-Noranda, QC, CIM (CD Rom), 12 p.

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 : 330–340.

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 J.*, 52 : 1-15.

Bussière, B (1999). "Étude du comportement hydrique de couvertures avec effets de barrière capillaire inclinées à l'aide de modélisations physiques et numériques." Ph.D. Thesis, École Polytechnique de Montréal, 354 p.

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

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

Bussière, B. (2007). "Colloquium 2004: Hydro-geotechnical properties of hard rock tailings from metal mines and emerging geo-environmental disposal approaches." *Canadian Geotechnical J.* 44(9): 1019-1052.

Cooke J.A., Johnson, M.S. (2002). Ecological restoration of land with particular reference to the mining of metals and industrial minerals: A review of theory and practice. *Environ. Rev.* 10: 41-71.

Dagenais, A.M., Mbonimpa, M., Bussière, B. and Aubertin, M. (2012). "The modified oxygen consumption test to evaluate gas flux through oxygen barrier covers*." Geotechnical Testing J.* ASTM, 35(1) : 150-158.

Ethier, M.P., Bussière, B., Aubertin, M., Maqsoud, A., Demers, I., and 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." *GeoMontreal 2013: Proc. 66th CGS Conference*, Montreal, Canada, 9 p.

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

James, M., Aubertin, M., and Bussière, B. (2013). "On the use of waste rock inclusions to improve the performance of tailings impoundments". *Proc. 18th Int. Conf. on Soil Mechanics and Geotechnical Engineering,* Paris, France, 735-738.

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 81:300-304.

Koerner, R.M, Hsuan, Y.G., and Koerner, G.R. (2011). "Geomembrane lifetime prediction: Unexposed and exposed conditions". *GRI White Paper #6, Geosynthetic Institute,* Updated, February 2011, 27 p.

Li, M., Aubé, B., St-Arnaud L. (1997). "Considerations in the use of shallow water covers for decommissioning reactive tailings." *Proc.4th Int. Conf. on Acid Rock Drainage,* Vancouver, Canada, Vol I: 117-130.

Liu, Y., Gates, W.P. and Bouazza, A. (2013). "Acid induced degradation of the bentonite component used in geosynthetic clay liners." *Geotextiles and Geomembranes*, 36:71-80.

Mbonimpa, M., Aubertin, M., Aachib, M., and Bussière, B. (2003). "Diffusion and consumption of oxygen in unsaturated cover materials". *Can. Geot. J.* 40: 916-932.

MEND (2004). *Design, construction and performance monitoring of cover system for waste rock and tailings*. Report 2.21.4. Ottawa, Canada.

Orava, A.D., Tremblay, G.A., Tibble, A., and Nichoslson, R. (1997). "Prevention of acid rock drainage through application in-pit disposal and elevated water table concepts.". *Proc. 4th Int. Conf. on Acid Rock Drainage,* Vancouver, Vol. 3, 973-983.

Ouangrawa, M., Aubertin, M., Molson, J., Bussière, B., and 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.

Pabst, T. (2011). "Étude expérimentale et numérique du comportement hydro-géochimique de recouvrements placés sur des résidus sulfureux partiellement oxydés." PhD Thesis, Ecole Polytechnique de Montréal, Canada, 582p.

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

Ross, B. (1990). "The diversion capacity of capillary barriers". *Water Resources Research,* 26: 2625-2629.

Rowe, R.K., Yang, P., Chappel, M.J., Brachman, R.W.I, and Take, W.A. (2012). "Wrinkling of a geomembrane on a compacted clay liner on a slope." *Geotechnical Engineering Journal,* SEAGS & AGSSEA, 43(3): 11-18.

Rowe, R.K. Abdelaal, F.B., Islam, Z. (2014). "Ageing of high-density polyethylene géomembranes of three different thicknesses." J. Geotechcnical and Geoenvironmental Engng, 11 p.

Rowe, R.K., and Ewais, A.M.R. (2015). "Ageing of exposed geomembranes at locations with different climatological conditions". Canadian Geotechnical J., 52: 326-343.

Singer, P.C., and Stumm, W. (1970). "Acid mine drainage: The rate determining step." *Science*, 167:1121-1123.

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

Stormont, J.C. (1996). "The effectiveness of two capillary barrier on a 10% slope". Geotechnical and Geological Engineering, 14:243-267.

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

Yanful, E.K., and Catalan, L.J.J. (2002). "Predicted and field measured resuspension of flooded mine tailings". J. Environmental Engineering, 128 : 341-351.

Zhan, G.S., Mayer, A., McMullen, J., and Aubertin, M. (2000). "Capillary cover design for a spent leach pad". Proc.Int. Symp. Hydrogeology and the Environment, Wuhan, China Environmental Science Press, Beijing, 144-150.

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

Zhan, G., Keller, J., Milczarek, M., Giraudo, J. (2014). 11 Years of evapotranspiration cover performance at the AA leach pad at Barrick Goldstrike Mines. Mine Water and the Environment. DOI 10.1007/s10230-014-0268-6.