LARGE SCALE APPLICATIONS OF COVERS WITH CAPILLARY BARRIER EFFECTS TO CONTROL THE PRODUCTION OF ACID MINE DRAINAGE

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ABSTRACT: Covers with capillary barrier effects (CCBE) have been used in recent years as part of the closure plan for mines having an acid mine drainage (AMD) problem. These covers can be used to limit oxygen and/or water migration. Different evaluation methods were used as part of a monitoring program to evaluate the efficiency of CCBE built at mining sites in Quebec, Canada and Nevada, USA. Results obtained from the monitoring program indicate these covers can, when properly designed and constructed, effectively reduce water infiltration in the case of a semi-arid climate, and limit oxygen migration in the case of more humid climatic conditions.

KEYWORDS: Covers, Acid mine drainage, Monitoring, Modelling, Behaviour and performance.

RÉSUMÉ : Des couvertures à effets de barrière capillaire (CEBC) ont récemment été utilisées pour la restauration de sites miniers ayant un problème de drainage minier acide (DMA). Ce type de recouvrement aide à contrôler la formation de DMA en limitant l’infiltration d’eau et/ou l’apport d’oxygène vers les résidus miniers réactifs. Différentes techniques d’auscultation ont été mises en place pour comprendre et évaluer le comportement de recouvrements construits sur différents sites miniers au Québec, Canada, et au Nevada, USA. Les résultats obtenus indiquent que des CEBC adéquatement conçues et construites peuvent effectivement réduire l’infiltration d’eau en climat semi-continental, alors qu’elles limitent efficacement la migration de l’oxygène en climat plus humide.

MOTS-CLEFS : Couverture, drainage minier acide, auscultation, modélisation, comportement et performance.

1. Introduction

Acid mine drainage (AMD) ensuing from the oxidation of sulphide minerals contained in mining wastes remains one of the critical environmental challenges for the mining industry. The oxidation reaction can cause acidification and heavy metal release in surface and ground water. To inhibit the acid formation, one must exert control on the constitutive elements (i.e. sulphide, water, or oxygen) of the oxidation reactions. Over the last decade or so, construction of cover with capillary barrier effects (CCBE), used to limit oxygen and/or water migration, has been a part of the closure plans for various mines with an AMD problem.

In a humid environment, studies have shown that preventing oxygen from reaching the sulphiocic minerals is a practical approach for controlling AMD generation (e.g. SRK 1989; MEND 2001). A CCBE built for a humid environment can reduce oxygen ingress toward the underlying reactive waste rock or tailings, by maintaining one of its layers close to full saturation (e.g. Nicholson et al., 1989; Collin and Rasmuson, 1990). In arid and semi-arid climates, it is difficult to build a cover
system which maintains a layer close to saturation. Under these climatic conditions, the cover is subjected to extended dry periods, and the effect of evaporation (and evapotranspiration) would render it ineffective as an oxygen barrier (MEND, 2001). A CCBE built in a relatively dry climate should rather aim at controlling the influx of water to the reactive waste rock or tailings by diverting it or storing it for later evaporation. This type of cover is sometimes referred to as a “Store, divert and release” (SDR) cover (i.e. Zhan et al. 2001; Martin et al. 2005).

The optimization of the CCBE design (either for humid or arid climates) requires work involving simultaneous laboratory and field experiments combined with the application of numerical tools. This paper presents the advances made in this area through the authors’ work using various experiments and tools, and referring also to recent cases where covers have been constructed on tailings impoundments and a spent leach pad (equivalent to a waste rock pile). First, a brief review of the fundamental principles governing the behaviour of CCBE is presented. It is followed by the description of laboratory and field work that lead to the construction of a full-scale CCBE. Applications of full-scale CCBE on actual mine sites are then presented. Finally, the conclusion sums up the challenges and the knowledge gained from the application of these covered systems.

2. Fundamentals of a CCBE

Capillary barrier effects appear when unsaturated flow occurs in layered soils of different hydraulic properties (Rasmuson and Erikson, 1986; Nicholson et al., 1989; 1991; Aubertin et al., 1995, 1996, 1999). Under unsaturated conditions, the coarse-grained soil placed under a fine-grained material tends to drain easily, hence reaching a low volumetric water content $\theta$. At low $\theta$ values, such coarse-grained soils (sand or gravel) have a low unsaturated hydraulic conductivity that limits downward movement of water which can be present in the fine-grained soil layer above. The fine textured soil then acts as a reservoir where water is stored by capillary forces. A more detailed description of capillary barrier effects can be found in Nicholson et al. (1989), Collin and Rasmuson (1990), Morel-Seytoux (1992), Aubertin et al. (1995, 1996), Khire et al. (1999), and Bussière et al. (2003a).

Figure 1 is a schematic illustration of a CCBE used in a humid climate. These covers usually contain three to five layers made of different materials. Each layer has to play one (or more) specific role(s). In Figure 1, the coarse-grained soil (support layer or capillary break layer) placed underneath the fine-grained soil (moisture-retaining layer) limits downward movement of water and prevents desaturation of the moisture-retaining layer. The top coarse-grained material placed over the fine-grained soil layer acts as a drainage layer and also limits loss of water by evaporation from the surface. The other two layers (protection and surface layer) are protective layers against erosion and biointrusion (Aubertin et al., 1995). In the system, the water retention layer is designed to maintain a high degree of saturation at all time. The diffusion of gas (oxygen) through this nearly saturated layer is low enough to prevent the significant production of AMD (Nicholson et al., 1989; Collin and Rasmuson, 1990; Yanful, 1993; Aubertin et al., 1995, 1999; Mbonimpa et al., 2003). Example of such CCBE applications can be found in Yanful et al. (1993, 1999), Aubertin et al. (1997a, 1999), Ricard et al. (1997, 1999), Khire et al. (1999), Lundgren (2001), Bussière et al. (2003a), and Dagenais et al. (2001, 2005). Some of these cases are described in the following.
Under arid or semi-arid climatic conditions, SDR covers use the capillary barrier effect created by the superposition of materials of different hydraulic properties to limit the downward flow of water at their interface. Again here, downward infiltration is limited by the placement of a fine-grained material layer over a coarser material. During a storm event on a flat area, the infiltrating water is stored in the fine grained layer for later evaporation release (e.g. Wilson et al. 1995; Williams et al. 1997). For an inclined cover, the water can also be diverted down the slope along the interface in the layered system (Ross, 1990; Stormont, 1995, 1996; Harries et al. 1997; Zhan et al., 2001; Bussière et al., 2003b; Martin et al., 2005; Aubertin et al. 2006).

Different techniques can be used to evaluate the efficiency of a CCBE. Monitoring the cover’ hydrogeological behaviour is done with sensors measuring the volumetric water content $\theta$ and suction $\psi$, placed in the different layers of the cover (Yanful et al., 1993; Wilson et al., 1995; Aubertin et al., 1995, 1997a, 1999; Khire et al., 1999; Zhan et al., 2001). For a cover built in a humid climate, field measurements are expected to show low $\theta$ in the capillary break layer and a high $\theta$ in the moisture-retaining layer. The suction (negative pressure) $\psi$ in the moisture-retaining layer should not exceed the material air entry value (i.e. suction at which the largest pores start to desaturate). For a SDR cover, the water content $\theta$ should remain low in the coarse grained material serving as a capillary break, while it can vary in the storage layer. Other monitoring techniques can involve the measurement of water infiltration and water quality. Also, for a CCBE used as an oxygen barrier, the measurement of the oxygen gradient or flux through the cover can provide valuable information on its actual efficiency (e.g. Elberling et al. 1994; Aubertin et al. 1995, 1999; Bews et al., 1997; Bussière et al., 2002, Mbonimpa et al., 2002, 2003).

3. Laboratory and field experiments

A study, spanning over more than ten years, was conducted by the authors on the hydrogeological behaviour of CCBE aiming at a reduction of AMD generation (Aubertin et al., 1995, 1997b, 1999; Bussière et al. 2003a, 2005). The initial phase of the project started with the hydro-geotechnical properties characterisation of various tailings. The favorable hydraulic properties (water-retention properties and hydraulic conductivity) of non acid generating tailings make them a very effective material to be used in a CCBE, as the moisture retaining layer, to limit oxygen migration (e.g. Aubertin et al. 1995, 1997a; Aachib et al. 1998).
3.1. Laboratory testing

Column tests combined with 1D numerical simulation were used to study the hydrogeological and geochemical behaviour of layered systems, in which the capillary layer was made of clean (non acid generating) tailings. The efficiency of these systems to limit AMD generation has been evaluated by comparing control columns where reactive tailings were covered by a layered system to a reference column containing only reactive tailings (Aubertin et al., 1995, 1997b; Aachib et al., 1998). Figure 2a presents the laboratory experimental set-up.

The column tests results show that the tailings layer, placed between two sand layers, stayed close to saturation, even during dry periods lasting up to 60 days. This high water content reduced the oxygen flux to the tailings underneath. The column tests also helped validating the numerical calculations on water distribution, as shown in Figure 2b. Leachate collected from the columns confirmed the efficiency of the CCBE as pH remained high and sulphates values remained low for the control column (with cover) compared to the reference column, as can be seen in Figure 3.

Figure 2. a) Experimental set-up for the column tests, and b) results from monitoring (symbols) and simulation (lines) (adapted from Aubertin et al., 1997b; Aachib et al. 1998).

Figure 3. a) pH and sulphate from control column b) pH and sulphate from reference columns (Aubertin et al., 1997b).
3.2. Field testing

To complement the previous laboratory studies, experimental cells were constructed in 1995 to evaluate, on a larger scale and under more realistic conditions, the performance of CCBE using silty materials as the moisture-retaining layer (Aubertin et al., 1999; Bussière, 1999). Figure 4a presents a view of the cells at the end of the construction phase; the site is located on the Manitou mine site, near Val-d’Or, Québec.

The results showed the capillary barrier effects necessary to maintain a high degree of saturation in the moisture-retaining layer were present in all cells for the four years of monitoring. Figure 4b presents the low $\theta$ of the sand layer creating the capillary effects and the high $\theta$ in the moisture-retaining layer for the year 1998. In figure 5, water quality of the leachate confirmed the efficiency of the CCBE to limit acid mine drainage production: the pH was between 6 and 7 for the covered cells compared to a pH lower than 3 for the control cell. Sulphates and metals loading were reduced by more than two orders of magnitude in the covered cells. The information gathered from these field plots over 4 years confirmed the efficiency of CCBE to control AMD production.

Figure 4. a) Experimental cells constructed at the Manitou mine site; b) value of $\theta$ measured in 1998 in the CCBE of one of the experimental cell (after Aubertin et al. 1999 and Bussière, 1999; see also Bussière et al., 2005).

Figure 5. Water quality collected at the bottom of cells a) pH b) Sulphates concentration (Bussière et al., 2005).
4. Large scale applications of CCBE

As mentioned above, CCBE have been shown, through laboratory column tests and in situ test cells, to be a practical means of preventing AMD generation. These experimental evaluations have lead to the application of large scale covers at various locations over the past years. Three cases are described here.

4.1. LTA mine site

The cover constructed at the LTA site is one of the first large scale covers with capillary barrier effects constructed in a humid climate on an acid generating tailings impoundment. The LTA site is located near Malartic, in the Abitibi region (Québec). This 60-hectare cover is made of three layers: a capillary break layer 0.5 m thick, a moisture-retaining layer of 0.8 m thick made of non acid-generating tailings and a 0.3 m thick protection layer put on top. The design objective was to reduce oxygen migration through the CCBE. The design objective was to obtain a degree of saturation $S_r \geq 85\%$ (for a porosity $n$ of 0.44, this corresponds to $\theta$ of about 37%) in the moisture-retaining layer (Ricard et al., 1997, 1999; Bussière et al, 2003c). After its construction in 1996-1997, instruments were installed in the CCBE to monitor its response over time.

Two different types of hydraulic behaviour have been observed on the nearly flat area of the LTA site: capillary barrier effects are active in the cover where the water table is deep, and the cover is nearly saturated by capillary rise when the phreatic surface is close to or in the CCBE. For instance, Figure 6 shows $\theta$ values obtained at the monitoring station CS96-1 where the water table is deep, and at station CS96-5 where the water table is high. One can see that $\theta$ of the sand layer for this last station is large compared to the one measured in the sand layer at station CS96-1. In both situations, the degree of saturation in the moisture-retaining layer remains above 85% (Bussière et al., 2003c).

A small aerial portion of the cover constructed on the LTA site is located on the sloping side of the tailings dams. CCBE on an inclined slope are affected by both horizontal and vertical flow. It is more difficult to maintain the desired $\theta$ in the moisture-retaining layer along the upper parts of a slope, and this possible desaturation can influence the performance of the cover (Aubertin et al. 1997b). To study this subject further, a laboratory model was constructed and 2D simulations were conducted. Results showed a significant effect of the geometry on pressure and water distribution. This effect is illustrated in Figure 7, which shows $\theta$ values measured at the base and at the top of a sloping two layer system (obtained from measurements during inclined box tests ; Bussière, 1999; Bussière et al., 2000, 2003a). A numerical study based on the LTA site was also performed to quantify the effects of geometry on the performance of the CCBE. The results showed the possible...
desaturation that may sometimes occur near the upper part of the cover along the slope. These results have led to the concept of suction breaks aimed at reducing the possible decrease in the degree of saturation in the cover (Aubertin et al. 1997b). This approach was tested following the construction of test areas on the sloping cover, where hydraulic breaks have been added. Part of this work is still ongoing. Results obtained to date on the LTA site, combined with numerical calculations, have confirmed the positive contribution of such suction breaks on the moisture distribution and on the ability of the cover to control the oxygen flux (Bussière et al. 2000; Maqsoud et al. 2005).

Figure 7. Measured (symbols) and calculated (lines) values of θ taken at a) top of the slope b) bottom of the slope in an inclined layered system tested in the laboratory (Bussière, 1999; Bussière et al., 2003a).

4.2. Lorraine mine site

A cover fairly similar to the one constructed on the LTA site was used at the Lorraine site, located in the Témiscamingue area, Québec. The 12-hectare CCBE built on this site is composed of three layers: a 0.3 m thick capillary break layer; a 0.5 m thick moisture-retaining layer; a protection layer 0.3 m thick. The targeted oxygen diffusion flux value was set at 20 to 40 g/m²/year, which is comparable to that of a stagnant water cover. For steady state conditions using Fick’s first law, this corresponds to an effective diffusion coefficient $D_e$ of $1.1 \times 10^{-9}$ to $2.2 \times 10^{-9}$ m²/s, which translates into a degree of saturation of about 88% for the fine grained soil (porosity of 0.38) in the water retention layer serving as the oxygen barrier (Nastev and Aubertin, 2000; Dagenais et al., 2001, 2005).

The layered cover was also instrumented after its construction. The volumetric water content and suction measurements, made between 1999 and 2003, show that the capillary barrier effects are effective where needed on the site (i.e., where the water table is below the tailings surface). For instance, Figure 8 shows that for a representative monitoring station (B-5), measured suctions in the lower sand layer ranged from 2 to 12 kPa, draining this coarse material to a degree of saturation as low as 20%. Suctions measured in the silt typically vary from 0 to 25 kPa, which is below its air entry value; the degree of saturation measured in situ is typically above 88%, although it can vary from 80 to 100% at different locations (Dagenais et al., 2001, 2005; Dagenais, 2005).

The CCBE performance at the Lorraine site was also examined in term of reducing the oxygen flux diffusing to the reactive tailings. Oxygen fluxes were calculated, with Fick’s laws, using the effective diffusion coefficient $D_e$ determined from modified oxygen consumption tests done at 7 different locations on the cover in 2000 (Dagenais, 2005). Some of these results are presented in Table 1; these show that the oxygen flux through the CCBE varies from 0.2 to 39 g/m²/year. The
flux calculated from the $\theta$ measured at the test stations are also presented in Table 1. Both estimation methods give results that are fairly close to each other, with fluxes that are almost always inferior (or very close) to the targeted flux adopted for the cover design (see details in Dagenais, 2005).

![Figure 8. Measured values for suction and degree of saturation in the Lorraine mine site cover (station B-5).](image)

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<th>Table 1. Oxygen flux (g/m²/year) calculated from the modified oxygen consumption tests and from volumetric water content measurements (Dagenais, 2005).</th>
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4.3. **Goldstrike mine site**

A simple cover was installed on the AA heap leach pad of the Barrick Goldstrike mine, located near Elko, Nevada. This SDR cover uses the capillary barrier effects to limit the downward flow of water into the leached ore (a material similar to waste rock). Following a series of laboratory tests and of numerical analyses, the cover was built on the leach pad. Instruments were added to examine the cover performance under natural and irrigated conditions. The SDR cover is made a 0.6 m thick monolayer of fine grained material (name Carlin silt). Figure 9 shows $\theta$ measurements in the cover (at 15 cm, 45 cm) and in the leach pad (at 75 cm, 120 cm) for one of the test cells; the amount of water added (large amount, in this case) during the irrigation test is also shown. The infiltration tests performed indicate that the cover can hold significant moisture during a wetting period; for most cases, there was little change in the moisture in the leach pad despite the increase water content in the cover (Zhan et al., 2001). However, for very larger water inflow, the diversion capacity can be exceeded, as illustrated in Figure 9 (i.e. after le large addition of water early in the test).
Numerical simulations in 2D have shown that the SDR cover response is sensitive to many factors, such as variations in the material properties, dump slope angle and length, potential evaporation over the area, and precipitation duration and intensity (e.g. Bussière et al., 2003b; Martin et al., 2005; Aubertin et al. 2006). These analyses have also shown that the diversion capacity of the monolayer cover can be exceeded following very large precipitation events, in accordance with the data obtained in situ (as shown in Figure 9). To handle such extremely wet conditions, a multilayered SDR cover can be more suited as it can divert larger volumes of water on a longer diversion length. Examples of such alternate design for SDR covers are presented in Martin et al., (2005) and Aubertin et al. (2006).

5. Conclusion

The application of covers with capillary barrier effects (CCBE) to mine sites having an acid mine drainage problem was developed in recent years. It was shown that well designed CCBE can be effective in controlling the water and/or oxygen flux to the reactive tailings and waste rocks underneath. The process leading to an optimum design is an iterative one which includes laboratory material characterisation, physical modelling, validated numerical calculations for parametric study, and field test plots. Various materials and configurations can be used in covers. The key element is the difference in the hydraulic properties of the chosen materials, which is required to create the capillary barrier effects at the interface between materials with different texture.

Once constructed, monitoring programs are required for a CCBE to assess its hydrogeological response and to evaluate its effectiveness in limiting downward water flow and/or oxygen flux. Monitoring results form the LTA and Lorraine sites, located in Québec, indicate that capillary barrier effects are well developed in these covers, which can thus maintain the moisture-retaining layer close to saturation ($S_r$ generally superior to 85 %). This is required to reduce the oxygen flux at acceptable levels through a cover built for a wet climate. The oxygen fluxes estimated from volumetric water content or from the modified oxygen consumption tests have been shown to be lower than 40 g/m²/year, a flux comparable to that of a water cover. The field and modelling data obtained on the inclined portion of the LTA cover also illustrate the important role of the slope angle and length on the water distribution in such layered systems. On the other hand, the measurements made on the sloping cover at the semi-arid Barrick Goldstrike mine site showed that it is effective in diverting water along the sloping area. The results shown here, and in other referenced work, thus indicate that many factors, such as cover configuration, material properties, layer thickness, slope length and angle, and climatic conditions may influence the efficiency of the cover. These must be taken into account when assessing the reclamation option.
6. References


