ABSTRACT

Acid Mine Drainage (AMD) from mine wastes is one of the most environmental challenges currently facing the mining industry. AMD is the result of the natural oxidation of sulphides exposed to air and water. When mining wastes have the potential to produce AMD, these reactive wastes have to be managed to meet existing environmental regulations. The LTA site (property of Barrick Gold Corp.) contains sulphide tailings that have the potential to generate AMD. The closure option Barrick selected was to construct a multilayered cover with capillary barrier effects (CCBE). The main objective of this CCBE is to prevent the production of Acid Mine Drainage (AMD) from the tailings stack covering an area of approximately 60 ha. Since its construction in 1996, the cover has been monitored to evaluate its performance. Two of the measured parameters are volumetric water content and matrix suction. This paper presents some of the main results from the monitoring program that started seven years ago. The results show that the cover is largely able to maintain a high degree of saturation (greater than 85%) in the moisture-retaining layer. The actual performance of the CCBE on the flat surface of the 60 ha site is even better than expected at the design stage. The area that requires more specific attention with the LTA cover is the influence of slopes that can reduce the performance of the CCBE during dry periods. However, these effects seem to be local and do not significantly affect the overall performance of the CCBE to mitigate the production of AMD at the LTA site.

1. INTRODUCTION

The mining sector is vital to the Canadian economy and includes mines for base, precious metals, gemstones, and industrial minerals. However, mining operations produce large amounts of waste, which must be properly managed to protect the environment. These wastes include overburden (both soil and rock) and fine-grained mill tailings produced by the ore processing plant, mine dewatering and sediments produced by water clarification from different units of operation, and sludge produced from water treatment of various sources. Some of these waste materials have the potential to adversely impact the environment, if not properly managed. More attention is required when they contain sulphides. In this case, the oxidation of sulphides by atmospheric oxygen tends to acidify meteoric water which are then more prone to mobilise some of the metals contained in the rock. This phenomena lead to the formation of acid mine drainage (AMD) that has to be controlled to prevent environmental impacts (e.g. Ritcey, 1989; SRK, 1988; Aubertin et al., 2002).

A number of closure schemes have been proposed to control the formation of AMD from acid producing tailings. Many of the proposed options aim at preventing oxygen ingress through the use of oxygen barriers to limit sulphide oxidation. In that regard, it is possible to use a water cover to reduce the availability of oxygen to the underlying acid generating mine waste (e.g. Fraser and Robertson, 1994; Amyot and Vézina, 1997; Simms et al. 2001). An oxygen barrier can also be created by placing a cover
made of oxygen consuming materials such as wood waste, straw mulch or other organic residues (e.g. Tremblay, 1994; Tassé et al., 1997; Cabral et al., 2000). Another effective way to limit oxygen migration is based on the use of a cover with capillary barrier effects (CCBE). This type of barrier relies on high moisture-retention in one of its multiple layers to prevent oxygen migration (e.g. Nicholson et al., 1989; Aubertin et al., 1993, 1995; Ricard et al., 1997).

The LTA site tailings impoundment contains sulphides and is categorised as potentially acid generating. To identify the best closure option for this site, extensive technico-economical analysis and hydgeochemical studies were performed once the operations curtailed (SENES, 1995; McMullen et al., 1997; Ricard et al., 1997). Based on these studies, the owner (Barrick Gold Corp.) selected the construction of a CCBE as the rehabilitation approach for the LTA site. The geochemical study (SENES, 1995) stipulates that a degree of saturation ($S_r$) in the moisture-retaining layer of 85 % should sufficiently reduce the migration of oxygen to properly control the production AMD from the sulphide tailings. More details on the selection of the best cost-effective closure plan can be found in McMullen et al. (1997) and Ricard et al. (1997).

This paper presents first a brief description of the LTA cover and its instrumentation. Then, the authors discussed how the hydraulic behavior of the CCBE was evaluated from measurements of the volumetric water content ($\theta$) and suction ($\psi$) at strategic locations. This is followed by conclusions on the performance of the CCBE to limit AMD production at the LTA site after seven years of monitoring,

2. LTA COVER: LOCATION, CONFIGURATION AND INSTRUMENTATION

The LTA tailings pond is located in Fournière and Dubuisson Townships, approximately 8.5 km southeast of Malartic, Québec. The LTA tailings site covers an area of approximately 60 ha, is delimited by four dams, and contains about 12 m of sulfide tailings placed over 5 m of non acid generating tailings (McMullen et al., 1997; Ricard et al., 1997). The site was rehabilitated during 1995-1996 period. The rehabilitation scenario consisted in the construction of a multilayered cover with capillary barrier effects (CCBE). The objective of the CCBE is to reduce water infiltration and oxygen flux to the reactive tailings and, consequently, the production of acid mining drainage from the sulphide tailings.

The main role of a CCBE constructed in a humid climate is to limit the diffusion of oxygen to the reactive mine wastes, to reduce the production of AMD. To do this, the cover must maintain a high degree of saturation in one (or more) of its layers. The diffusion of gas through a nearly saturated soil can be low enough to limit the influx of oxygen from the atmosphere to the reactive wastes (e.g. Rasmuson and Erikson 1986; Nicholson et al., 1989; Aachib et al. 1993; Yanful, 1993). The effectiveness of this type of cover depends upon a phenomenon known as the capillary barrier effect. This effect is present when a fine-grained material is placed over a coarser one in unsaturated conditions (above the water table). The two materials have different hydrogeological properties because of their different particle size distribution. During a drainage stage following an important water inflow (ex. snow melt), the fine grained material layer tends to retain water more easily then the coarse layer because it has smaller interstitial pores (and higher capacity to retain water by capillary forces). As the coarse material drains, the presence of gas in its pore space reduces the interconnectivity of the water filled voids, which reduces its hydraulic conductivity ($k$). This reduction of $k$ in the coarse material layer further reduces the vertical water flow from the fine-grained material and the latter material can remain almost fully saturated at all times if protected from drying by evaporation (Bussière et al., 2001).

The LTA cover is made of three layers. From the bottom to top (see Figure 1):

- a 0.5 m layer of sand used as support and a capillary break layer;
- a moisture-retaining layer with a thickness of 0.8 m. This layer is made of a non reactive tailings (called MRN tailings) taken from the nearby Malartic Goldfield property (a site which belongs to the Quebec Natural Resources Ministry). The goal of the moisture-retaining layer is to reduce water infiltration and oxygen diffusion to the reactive tailings;
- A 0.3 m sand and gravel top layer that acts as the capillary break, and protective layer against erosion, evaporation and bio-intrusion.
Figure 1: Schematic section of the CCBE installed on the LTA site

The main geotechnical properties of the MRN tailings and the sand used in the covers are summarized in Table 1 (Golder Ass., 1996; Firlotte, 1996). Properties of the sand and gravel are taken as similar to those of the sand (Ricard et al., 1997). The MRN tailings have a grain-size distribution typical of hard rock tailings (Aubertin et al., 1995) with a percentage passing 0.08 mm between 65 and 90% and a D10 (diameter of particles at 10% passing) of about 0.005 mm. The sand has a low percentage of fine particles (less than 5% smaller than 0.08 mm) and cobbles (no particles with a diameter greater than 15 cm). The saturated hydraulic conductivities of these materials are: 5x10^-5 cm/s for the MRN tailings and 1.2x10^-1 cm/s for the sand. The porosity of the moisture retaining layer (MRN tailings) measured in the field was between 0.36 and 0.50. The air entry values ψa of the materials measured in the lab is between 200 to 275 cm of water for MRN tailings (about 20 to 27 kPa), depending on the porosity and the grain size (McMullen et al., 1997; Ricard et al., 1997). The ψa values of the sand measured in the lab is between 20 to 40 cm of water (Ricard et al., 1997). The MRN tailings contain a small quantity of sulphur (on average 1.82%) but are not acid generating because of its high neutralization potential (SENES, 1995). Finally, it is important to mention that a natural silt with higher water retention properties was used as moisture-retaining layer in the slope of the West Dam. In this paper, only the results obtained on areas covered with the MRN tailings are presented and discussed. For more details about the materials properties, the design and the construction of the CCBE, the reader is referred to McMullen et al. (1997), Ricard et al. (1997, 1999), Golder Associates (1999), and Aubertin et al. (2002, Chapter 13).

Table 1: Main properties of the materials used in the LTA cover

<table>
<thead>
<tr>
<th></th>
<th>n</th>
<th>D_{10} (mm)</th>
<th>D_{50} (mm)</th>
<th>D_{50} (mm)</th>
<th>ψa (cm of water)</th>
<th>k_{sat} (cm/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>MRN tailings</td>
<td>0.36 to 0.5</td>
<td>0.003 to 0.0075</td>
<td>0.037 to 0.085</td>
<td>0.030 to 0.065</td>
<td>200 to 275</td>
<td>5.0x10^-5 (n = 0.44)</td>
</tr>
<tr>
<td>Sand</td>
<td>0.34 to 0.36</td>
<td>0.120 to 0.600</td>
<td>1 to 15</td>
<td>0.7 to 8</td>
<td>20 to 40</td>
<td>1.2x10^-1 (n = 0.35)</td>
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</table>

The first instruments were installed in the cover in 1996 (Stations CS and PS in Figure 2). Other monitoring stations were installed in 1997 (Stations PS and TA) to better follow the hydraulic behaviour in the sloping areas. The main hydraulic parameters monitored at these stations are volumetric water content θ and matrix suction ψ. The analysis of these two parameters allows to correlate the hydraulic behaviour with the CCBE performance in reducing oxygen diffusion through the moisture-retaining layer.

The time domain reflectometry (TDR) technique (e.g. Topp et al., 1980) was used to measure the volumetric water content for the different stations. This equipment has been used successfully by the authors for laboratory measurements (e.g. Aubertin et al., 1995; Maqsoud et al., 2002) and has also been used in the field by other researchers to evaluate cover performance (e.g. Yanful and St-Arnaud, 1991;
Zhan et al., 2001). The measurement error given by the manufacturer (Soilmoisture Equipment Corp.) is ± 2.5%. The CS 96 and the PS 96 stations are also equipped with Watermark sensors to measure the matrix suction in the moisture-retaining layer. The WATERMARK sensor (granular matrix sensor) is an indirect, calibrated method of measuring soil water suction. It is an electrical resistance sensor, read by a hand-held meter which converts the electric resistance reading to a calibrated reading of soil water suction. The main advantages of this sensor include: no periodic maintenance; not subject to damage by freezing temperatures; matrix not dissolve in the soil water (like gypsum block). Previous studies (e.g. Shock et al., 1999, 2002) showed that WATERMARK sensors give reliable results for suction between 80 to 800 cm of water (or 8 to 80 kPa). The location of the equipment in Stations PS 96 and CS 96 is presented in Figure 3. The Watermark sensor W2 and the TDR probe T3 are located at the same elevation (15 cm from the bottom of the moisture retaining layer), while the Watermark sensor W4 and the TDR probe T5 are installed at 15 cm from the interface between the moisture retaining and the top layers. More details about the instrumentation can be found in Golder Associates (1999).
3. Monitoring Results

This section presents representative results of the CCBE hydraulic behaviour at the LTA site. First shown are results that illustrate the capillary barrier effects, which are necessary for maintaining a high degree of saturation in the moisture-retaining layer. Secondly, evolution of volumetric water content measurements in the moisture-retaining layer, for representative stations, and \textit{in situ} water retention curves for these stations are presented to evaluate the capacity of the cover to maintain a high degree of saturation. These results are shown for stations located on both the flat and sloping areas of the site.

3.1 Presence of the capillary barrier effects

The aim of the cover is to use capillary barrier effects to maintain a high degree of saturation in the moisture-retaining layer. A typical volumetric water content profile in an effective CCBE corresponds to low values of $\theta$ in the two coarse-grained materials and high $\theta$ values in the moisture retaining layer (e.g. Aubertin et al., 1995, 1996; Bussière and Aubertin, 1999). With the exception of the CCBE south section where the phreatic surface is located in the cover, the volumetric water content values measured at the different stations since 1996 are typical of those expected for an effective CCBE. As an example, Figure 4 shows the evolution of volumetric water content measurements since 1996 at Station CS 96-1 (see Figure 2 for the location). In this figure, CS 96-1-T1 corresponds to the volumetric water content in the bottom sand layer (capillary break layer) while CS 96-1-T3 and CS 96-1-T5 correspond to volumetric water content measured at the bottom and at the top of the moisture-retaining layer respectively. The $\theta$ values measured by TDR probes CS 96-1-T3 and CS 96-1-T5 are usually greater than 37% (correspond to S, values greater than 84% for a porosity n of 0.44) while the ones measured by CS 96-1-T1 is usually between 12% and 18% (correspond to S, values between 34 and 51% for a porosity n of 0.35). The fact that the volumetric water content in the bottom sand layer (CS 96-1-T1) are much lower than the ones measured by the probes in the moisture-retaining layer clearly indicates the creation of the desired capillary barrier effects.
3.2 Results obtained on the flat area

All the CS 96 stations are located on the flat areas of the LTA cover. These stations are mainly located in the northern portion of the site. Two different situations were observed on this plateau: i) the phreatic surface is close to or in the CCBE, or ii) capillary barrier effects are present in the cover and the volumetric water content measurements are close to those at saturation.

Results from Stations CS 96-10, CS 96-8, CS 96-7, CS 96-6, and CS 96-5 showed high $\theta$ values in the moisture-retaining layer and in the capillary break layer since the construction of the cover in 1996. An example of results ($\theta$ vs time) for these stations (Station CS 96-5; see Figure 2 for the exact location) is presented in Figure 5. In this figure, CS 96-5-T1 corresponds to the measurement in the capillary break layer and CS 96-5-T3 is associated to $\theta$ measurements at the bottom of the moisture-retaining layer. Figure 5 shows a slight reduction of $\theta$ during the first year but the measurements stay near 40% (for a porosity $n$ of 0.44, this $\theta$ value corresponds to a degree of saturation $S_r$ of 90%). The slight reduction of $\theta$ during the first year can be attributed to a possible evolution of geotechnical properties of the moisture-retaining layer during the first season. The stations located near the North Dam usually showed a hydraulic behaviour typical of CCBE (see Figure 4), with $\theta$ values between 0.4 and 0.44 (which correspond to a degree of saturation higher than 90%). Hence, from these results, it can be said that the oxygen flux towards the reactive tailings is reduced significantly due to the high degree of saturation in the sulphide tailings and in the two first layers of the cover.

At Station CS 96-5, a Watermark sensor is located near the probe CS 96-5-T3 to measure suction ($\psi$) in the moisture-retaining layer. The $\psi$ values measured, since 1996, were between 0 and 130 cm of water (or 0 to 13 kPa). These suction values are well under the Air Entry Value ($\psi_a$ between 200 and 275 cm of water; see Table 1) of the MRN tailings. This explains the high $\theta$ values measured in this material. The portion of the in situ water retention curve (WRC) obtained by plotting simultaneous measurements of $\psi$ and $\theta$ also confirmed that there is no drainage evidence of the moisture-retaining layer (see Figure 6).

Results from Station CS 96-3 (not presented here because of space constraints) show a water distribution similar to the one at Station CS 96-1 presented in Figure 4 (again typical of a CCBE). Since 1996, the $\theta$ measurements in the capillary break layer usually vary between 0.15 and 0.25, while measurements in the moisture-retaining layer vary between 0.37 and 0.47 for the bottom portion of the layer (TDR probe CS 96-3-T3) and between 0.33 and 0.39 in the upper portion of the layer (TDR probe CS 96-3-T5). In this case, the capillary barrier effects maintain a high degree of saturation in the moisture-retaining layer, which efficiently limits the diffusion of gas through the cover. Results for Stations CS 96-2, CS 96-4, and CS 96-9 are not presented because of reading problems with the TDR probes.
3.3 Results obtained on the slope

A small portion of the cover on the LTA site was constructed on the sloping sides of the tailings dams. Previous study showed that slope influences the hydraulic behaviour of CCEB (e.g. Ross, 1990; Stormont, 1996; Miyazaki, 1993; Aubertin et al., 1997; Bussière, 1999). To evaluate the impact of the slope on the performance of the LTA cover, monitoring stations were installed on the inclined areas of the site (see Figure 2). To illustrate how slope influences this behavior, two stations are chosen in this study: the first one is located near the top of the slope (PS 96-1) and the second is located near the bottom of the same slope (PS 96-3). More details on slope effect at the LTA site can be found in Golder Associates (1999), Bussière (1999), Bussière et al. (2001, 2003).

3.3.1 Station PS 96-1 located near the top

Station PS 96-1 is located near the top of the South-East dam (see Figure 2). The PS 96-1-T3 TDR probe was defective and only the results from the PS 96-1-T5 probe located in the moisture-retaining layer, near the top interface with the sand and gravel layer, is shown here. As can be seen in Figure 7, the $\theta$ values remained usually above 30 % since 1996, except for the measurements done during August and at the beginning of September 2002 when $\theta$ dropped to approximately 24.5 %. This low $\theta$ value is attributed to the long drought period observed in the Abitibi-Témiscamingue region during the Summer of 2002. However, this situation quickly normalized after it rained in September and the $\theta$ measurements reached approximately 30 % before the winter. Noted that somewhat similar hydraulic behaviour was observed at Stations PS 96-6 and PS 96-7.

The hydraulic behavior of the cover at the Station PS 96-1 can also be represented by the in situ WRC. Figure 8 shows that the drop of $\theta$ is caused by the increase in suction in the moisture-retaining layer. The higher suctions measured exceeded 300 cm of water (values greater than the laboratory $\psi_a$ for the MRN Tailings). As shown in Figure 8, such suctions can induce a partial drainage of the moisture-retaining layer. According to this curve, the in situ $\psi_a$ is close to about 100 and 150 cm of water (lower than the laboratory $\psi_a$). These results confirm that slope influences the moisture-retaining layer hydraulic behavior.

3.3.2 Station PS 96-3 located near the bottom of the slope

Station PS 96-3 is located at the bottom of the South-East dam (see Figure 2) and on the same line as the previous station (PS 96-1). The evolution of $\theta$ measurements since 1996 from the TDR probes located near the bottom of the moisture-retaining layer is presented in Figure 9. The volumetric water content is usually above 0.40, which corresponds to a $S_\theta$ value of more than 90% (greater than the design criteria: 85%). Even the dry period observed in 2002 did not seem to affect the $\theta$ values measured in the moisture-retaining layer at this location.

Contrarily to Station PS 96-1, the in situ WRC (see Figure 10) does not show any significant drainage of the moisture-retaining layer. This is largely due to the lower suctions measured in the MRN tailings, which were usually lower than 100 cm of water. These values are below the $\psi_a$ of the MRN tailings.
Figure 5: Evolution of volumetric water content measurements at Station CS 96-5

Figure 6: In situ Water Retention Curve of the MRN Tailings at CS 96-5 station

Figure 7: Evolution of volumetric water content measurements at the PS 96-1 station
4. SUMMARY AND CONCLUSION

The LTA site is one of the first mine tailings impoundment sites that has been rehabilitated with a cover with capillary barrier effects (CCBE). The site has been continuously monitored since its construction in 1996. One of the key feature of the program is the evaluation of the CCBE hydraulic behavior, by measuring the volumetric water content and soil matrix suction. The main results from the seven year monitoring program are:
• Overall, the cover is performing above design where the degree of saturation in the moisture-retaining layer is well above the design criteria of 85%.

• It has been demonstrated that it is more difficult to maintain on the slopes the desired volumetric water content in the moisture-retaining layer which can influence the performance of the cover. The upper part of the slopes are more affected by the desaturation process than the lower part, especially during prolonged dry periods; however recharge occurs when precipitations occur. While we now understand how to mitigate such effects, it is not considered required to modify the cover as its overall performance to achieve the original objectives are met.

• In the south section of the site, the phreatic surface is located in the cover, which explains the high $\theta$ values in the capillary break layer and moisture-retaining layer.

• In the areas where the phreatic surface is well below the cover, the capillary barrier effects are active.

Even if the upper part of the slope may, under specific situations (prolonged dry periods), not meet temporarily the design criteria of a $S_r \geq 85\%$, the overall performance of the CCBE on the 60 ha site exceeds expectations from the design stage. More work is presently being done to evaluate the performance of the LTA cover by integrating the slight reactivity of the MRN tailings which may have a positive impact on its ability to limit gas diffusion (Bussière et al., 2002; Mbonimpa et al., 2003), and by performing other tests such as long-term oxygen consumption tests (Mbonimpa et al., 2002).

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6. REFERENCES


