HYDROGEOTECHNICAL BEHAVIOR OF FIELD EXPERIMENTAL CELLS USED TO SIMULATE CCBEs

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ABSTRACT

Field experimental cells were constructed in 2007 to assess the performance of different cover scenarios for the reclamation of the Parc 1 tailings disposal facility at the Westwood-Doyon Mine site (Abitibi, Quebec). Three configurations of cover with capillary barrier effects (CCBEs) with different thicknesses and material types for the moisture retention layer (MRL) were studied. MRL with 80 cm till, 40 cm till, and 40 cm clayey silt were used for cell nos. 2, 3, and 5, respectively. The capillary barrier layer (CBL) and drainage and protection layer (DPL) of the CCBE consisted of 30 cm gravel. A reference cell without cover was also constructed to compare the geochemical performance of the CCBEs. Due to an unexpected flooding in the leachate exit area of the cells in spring 2008, the cell instrumentation for hydrogeotechnical monitoring was postponed to spring 2009. Changes with time in volumetric water content, suction, soil oxygen concentration, and temperature were measured at different depths. This paper presents and discusses preliminary results obtained from spring 2009 to autumn 2010. In all cases, the degree of saturation S_r is lower in the CBL than in the MRL, indicating the presence of capillary barrier effects at the interface of these layers. Cell nos. 2 and 5 showed hydrogeotechnical behavior typical of an effective CCBE, with S_r maintained above 85% in the MRL and lower than 30–50% in the DPL and CBL. Based on the obtained results, and as expected, MRL thickness and the type of construction material used appear to affect the hydrogeotechnical behavior of the CCBE. Oxygen concentration profiles through the CCBEs were used to estimate the oxygen flux, and results indicate that cell nos. 2 and 3 performed better than cell no. 3. CCBE performance is currently being investigated using the geochemical monitoring data.

KEYWORDS

Tailings disposal facility, Covers with capillary barrier effects (CCBE), Experimental cells, Hydrogeotechnical behavior, Oxygen flux

INTRODUCTION

The mining industry generates significant amounts of solid waste materials, including mill tailings, which are generally stored in tailings impoundments. When tailings contain sulfide minerals that can be naturally oxidized in the presence of water and oxygen, highly acidic sulfate- and metal-rich drainage can be generated. The processes involved in the generation of acid mine drainage (AMD) from sulfide-rich minerals have been extensively described in the literature (e.g., Jambor and Blowes 1994; Perkins et al., 1995; Aubertin et al., 2002). AMD is the main environmental challenge facing the mining industry around the world, and when not well controlled, it can wield a considerable impact on ecosystems. Some methods have been developed to control AMD production from tailings. In humid climates such as in the province of Quebec, Canada, oxygen barriers are the most appropriate methods to reclaim mine waste disposal areas containing AMD-generating tailings. Water covers, mono-or multilayered dry covers (e.g., covers with capillary barrier effects – CCBEs), and elevated water tables (EWTs) can be used as oxygen barriers (Aubertin et al., 2002). In order to select the most appropriate rehabilitation method for a given tailings impoundment, various factors must be taken into account, including the site topography and management, the waste properties, and cover materials availability.

Physical models (in the laboratory and in the field) and numerical models are used to assess the short- and long-term behavior of rehabilitation techniques.

This study focuses on the Parc 1 tailings impoundment at the Doyon-Westwood Mine site located 30 km east of Rouyn-Noranda (Abitibi, Quebec) operated by IAMGOLD. Approximately 3 Mt of potentially acid-generating tailings are stored on a 75 ha area, with confining dykes built partly with potentially acid-generating waste rocks. Based on the depth of the water table, three zones can be distinguished: (1) a flooded zone, (2) a zone with a shallow water table, and (3) a zone with a deeper water table. The site rehabilitation strategy investigated here is the use of a combination of techniques according to water depth into the tailings: a water cover for zone 1, an EWT for zone 2, and a CCBE (quasi-horizontal) for zone 3. In addition, an inclined CEBC could be placed on the dyke slopes. The combination of three rehabilitation techniques allows reducing reclamation costs and improving overall performance. Details on the three rehabilitation techniques can be found in the literature. Below, the focus is on the CCBE technique, which would be applied to the portion of Parc I with low water table.

A typical CCBE cover is constructed of at least three layers (multilayered cover – see Figure 1). A fine-grained layer called the moisture retention layer (MRL) is placed between two coarse-grained layers: a top drainage and protective layer (DPL) to prevent erosion, evaporation, and bio-intrusions; and a bottom capillary break layer (CBL), which also supports the MRL. When a fine-grained material (MRL) overlies a coarser-grained material (CBL), the difference in water retention between the two materials creates capillary barrier effects, which limit the vertical flow of water at the interface. The capillary barrier effects therefore help maintain the fine-grained material at near saturation. Due to the low gas diffusion through soil with high moisture content, a highly saturated layer is created, reducing the availability of oxygen at the bottom of the cover. By limiting the oxygen diffusion, the cover reduces AMD production.

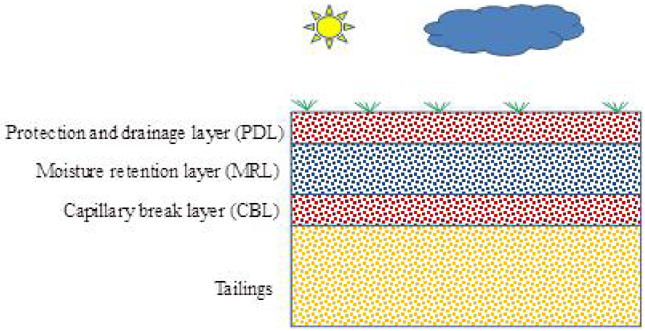

Figure 1 – Schematic configuration of a CCBE

CCBE performance has been studied using physical models at the laboratory scale with column tests (e.g., Aubertin et al., 1999; Bussière et al., 2004), at intermediate scale using experimental cell tests (e.g., Bussière et al., 2007), and at real scale on existing tailings impoundments (e.g., Bussière et al., 2006, 2009; Maqsoud et al., 2009; Dagenais et al., 2012). Most of these studies focused on hydrogeotechnical behavior and oxygen flux through the cover to the underlying reactive tailings. However, some studies have directly monitored oxygen concentration profiles in the laboratory (e.g., Nengovhela et al., 2007; Demers et al., 2009) or at intermediate- and large-scale in the field (e.g., Yanful 1993; Renken et al., 2005; Patterson et al., 2006; Mbonimpa et al., 2008a). Although CCBEs have been extensively studied, and their behavior is now fairly well understood, the final (optimal) CCBE configuration and its subsequent performance may be affected by various factors, including the construction materials and layer thicknesses. Therefore, the Doyon Mine decided to investigate the influence of these parameters in order to determine the optimal CCBE design to reclaim the Parc 1 tailings impoundment. For that purpose, three field experimental cells were constructed at Parc I to assess the impact of material type (till and clayey silt) and thickness (40 and 80 cm) of the

MRL on CCBE effectiveness. A reference cell without cover was also investigated.

This paper presents the construction and instrumentation of the cells and the materials characterization. Preliminary results of the hydrogeotechnical monitoring performed from May 2009 to August 2010 are presented and discussed.

CELL CONSTRUCTION AND INSTRUMENTATION

Parc I at the Doyon-Westwood Mine site can be divided into two parts, separated by a dyke in the east-west direction and with a level difference of about 1–2 m. The water pond is located in the west zone of the north part. The four cells were constructed in the east zone of the south part of the tailings impoundment, close to the separation dyke. The cells were constructed based on the design of Bussière et al. (2007). Essentially, they were inverted pyramid-shaped reservoirs (see Figure 2) lined with a geomembrane to prevent outside water from flowing into the cell. At the surface, the cells were square-shaped, with a side length of about 10 m. A slightly sloped drainage pipe was connected to the bottom of each cell to allow pore water to exit from the cell. The leachate exit was located at the toe of the separation dyke in the north part of the tailings impoundment. A flooded U-tube placed at the end of the pipe prevented oxygen from penetrating into the pipe. The tightness of the connection between the drainage pipe and the geomembrane was verified by filling the cell with water and then monitoring the water level over 24 hours with the cell drainage pipe open. No change in water level was observed in any cell. The cells were then filled with tailings from Parc I over a thickness of about 2.3 m. The tailings were excavated from the impoundments at depths where the tailings were considered unoxidized.

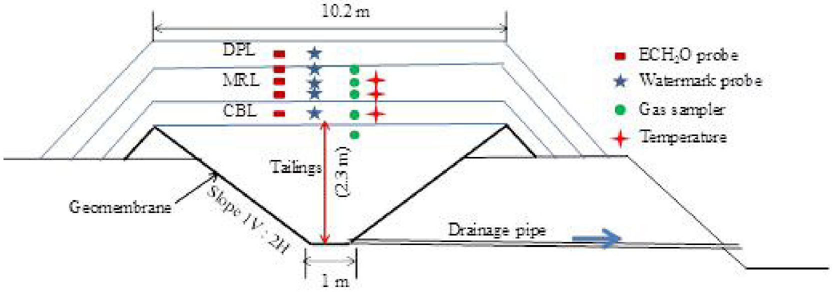

Figure 2 – Schematic section of a typical experimental CCBE (not at scale) and the installed monitoring equipment

Figure 3 shows the different cover scenarios studied. For cell nos. 2, 3, and 5 (Cell no. 1 modeled the EWT technique, and is not presented here), tailings were covered with a CCBE with 30 cm CBL and DPL constructed of gravel, and an MRL with various thicknesses and materials (till, clayey silt). MRLs with 80 cm till, 40 cm till, and 40 cm clayey silt were used for cell nos. 2, 3, and 5, respectively.

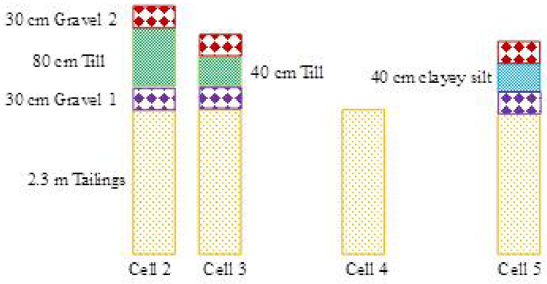

Figure 3 – Schematic configuration of the cells (Cell no. 4 without cover is a control cell)

Originally, the same gravel (from the same borrow pit) was to be used for the DPL and CBL. However, grain-size distribution analyses performed on the collected samples during construction indicated that the gravel used in the CPL (gravel 1) was different from the gravel used later in the DPL (gravel 2) (see Table 1). Cell no. 4, without a cover, was used as a control cell. The materials used for constructing the different CCBE layers were compacted using a vibrating plate compactor. Dry density and water content were measured at several points with a nuclear moisture-density apparatus. These parameters were used to estimate the porosity n. Porosity in the MRL was also determined after construction by sampling materials with known volume at different depths and determining the water content and relative density.

Table 1 summarizes the main physical properties of CCBE and tailings materials: the relative density of solid grains D_r (or G_S), the effective diameter D_{10} (diameter corresponding to 10% passing on the cumulative grain-size distribution curve), the % passing through sieve no. 200 (or 0.075 mm), the coefficient of uniformity C_U, the average porosity n, and the air entry value obtained from water retention curves estimated with the MK model (Aubertin et al., 2003). The average porosity was 0.28 and 0.30 for the CBL and DPL, respectively. The porosity of the MRL was 0.22 in cell nos. 2 and 3 and 0.38 in Cell no. 5. The clayey silt with $D_{10} = 2.7\times10^{-3}$ mm was slightly finer than the till (with $D_{10}=5.1\times10^{-3}$ mm). The mineralogical composition of the tailings was determined by X-ray diffraction on three samples, indicating that the tailings contained about 46% quartz, 25% muscovite, 14% albite, 6% chlorite, 4 % pyrite, 3 % calcite, and 2% gypsum. Chemical analysis with ICP-AES indicated that the tailings placed in the cells contained about 2.2% Ca, 1.5% Mg, 0.1% Mn, 5.9% Fe, and 3.7% S.

Table 1 – Physical characteristics of cover and tailings materials

Parameter	Gravel 1-CBL	Gravel 2-DPL	Till	Silt	Tailings
Specific gravity G_s (–)	2.76	2.76	2.73	2.71	2.83
Effective diameter D_{10} (mm)	17	0.22	5.1×10^{-3}	2.7×10^{-3}	4×10^{-3}
Passing no. 200 (%)	5	0	45	65	96
Coefficient of uniformity C_U (–)	65	11	36	18	6
Average porosity n (-)	0.28	0.30	0.22	0.38	-
Air entry value AEV (kPa)	0.5	1	20	25	-

Initially planned for spring 2008, the instrumentation of the cells was postponed to spring 2009 due to partial flooding of the cells in spring 2008, attributable to an unprecedented water management problem at the Doyon Mine. It was decided to connect the drainage pipes (see Figure 2) to vertical pipes and to use peristaltic pumps controlled with switch levels installed at the bottom of the pipes to allow regular emptying and to prevent water stagnation in the vertical pipes. It became necessary to provide a power supply to the site, which further delayed cell instrumentation. A water level probe was placed at the bottom of the vertical pipe to monitor changes in water level in the tubes in order to estimate leachate flow rates. Cell nos. 2, 3, and 5 (with CCBE) were instrumented to monitor the volumetric water content and suction using ECH_2O probes (DECAGON Inc.) and Watermark probes (IRROMETER Inc.), respectively (see Figure 2 for sensor locations). This monitoring technique and the main properties of the probes have been described in Maqsoud et al. (2007). Probes were installed in the middle of each CCBE layer. Additional probes were placed in the MRL close (about 5 cm) to the interfaces with the DPL and CBL. For each soil type, a calibration curve was previously established for the ECH_2O probes. Soil temperature was also monitored with temperature probes (IRROMETER Inc.). All probes were connected to dataloggers to allow continuous data monitoring with 12-hour frequency. In addition, dedicated gas sampler tips connected to tubings running from the tips to the surface were installed within the CCBE and the tailings beneath to determine vertical oxygen concentration profiles. Soil gas was pumped with a peristaltic pump and the oxygen concentration was measured on site using an optical oxygen sensor. The oxygen measurement procedure is described in detail in Mbonimpa et al. (2008a). Only interstitial gas samplers were installed every 20 cm from depths of 30–110 cm from the surface in reference Cell no. 4 (volumetric water content and suction were not monitored). A climatic station was also installed at Parc I to monitor various climatic parameters, including air pressure and temperature, precipitations, air relative humidity, wind speed and direction, and net solar radiation.

PRELIMINARY MONITORING RESULTS

Results of hydrogeotechnical measurements performed from May 2009 to August 2010 and of oxygen measurements performed in September 2010 are presented and discussed in this paper.

Change in degree of saturation with time

Figures 4–6 show the changes in the degree of saturation S_r with time for cell nos. 2, 3, and 5, respectively, with daily precipitations recorded at Parc I (precipitation data from June 22 to October 07, 2010 are not available). S_r was obtained from the volumetric water content measured with the ECH_2O probes installed at different depths through the CCBE and from the average porosity n of each CCBE layer.

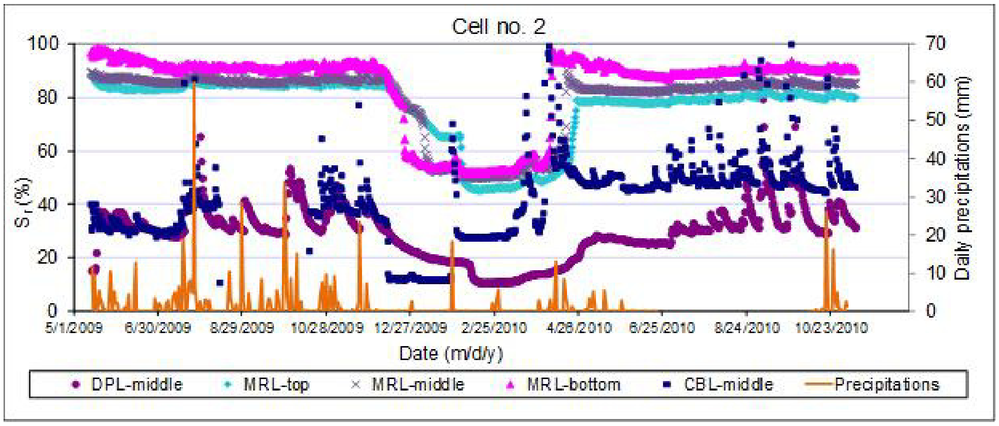

Figure 4 – Change in S_r at different depths in the CCBE of Cell no. 2 with time and daily precipitations recorded at the Doyon Mine site (precipitation data from June 22 to October 07, 2010 not available)

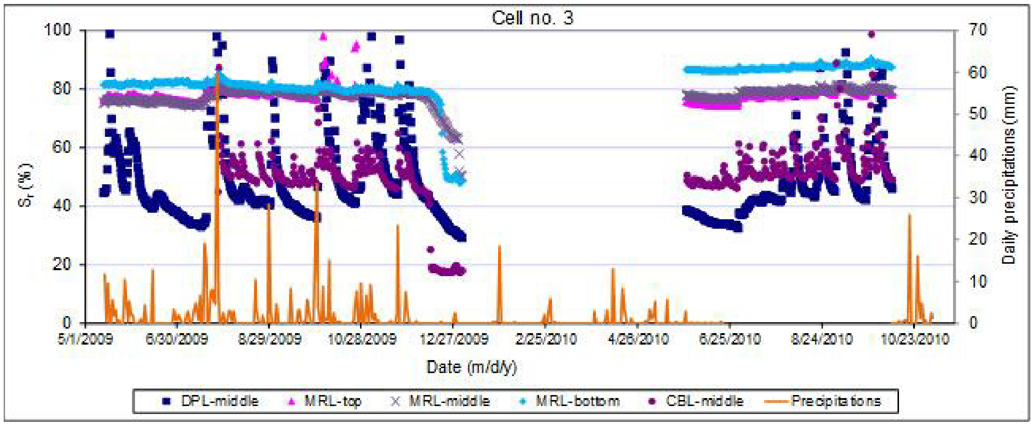

Figure 5 – Change in S_r at different depths in the CCBE of Cell no. 3 with time and daily precipitations recorded at the Doyon Mine site (precipitation data from June 22 to October 07, 2010 not available)

S_r decreased during the winter because part of the water was frozen. The sensor provides only the unfrozen water content. As expected, S_r increased from top to bottom of the MRL. Furthermore, S_r in the MRL was lower in Cell no. 3 than in cell nos. 2 and 5, particularly in 2009. The degree of saturation in the MRL of Cell no. 3 tended to increase during 2010. S_r was also lower in the CBL than the MRL (80–100%). The difference in S_r between the CBL and the MRL indicates the presence of capillary barrier effects. A comparison between the changes in S_r and in precipitation shows that the peak variations in S_r in the gravel of the DPL outside winter are attributed to rainfall events. Nevertheless, one peak was observed in the winter (see Figures 4 and 6) due to an atmospheric temperature rise to 3 °C on January 27, 2010. Thawing began slowly in early March, with positive maximum temperature (up to 12 °C), for a consequent increase in the degree of saturation S_r in the DPL. This was followed by a period of negative maximum temperature (up to -8 °C) from March 20 to 28, causing S_r to decrease once more. However, S_r in the MRL and CBL was less sensitive than in the top layer to precipitations.

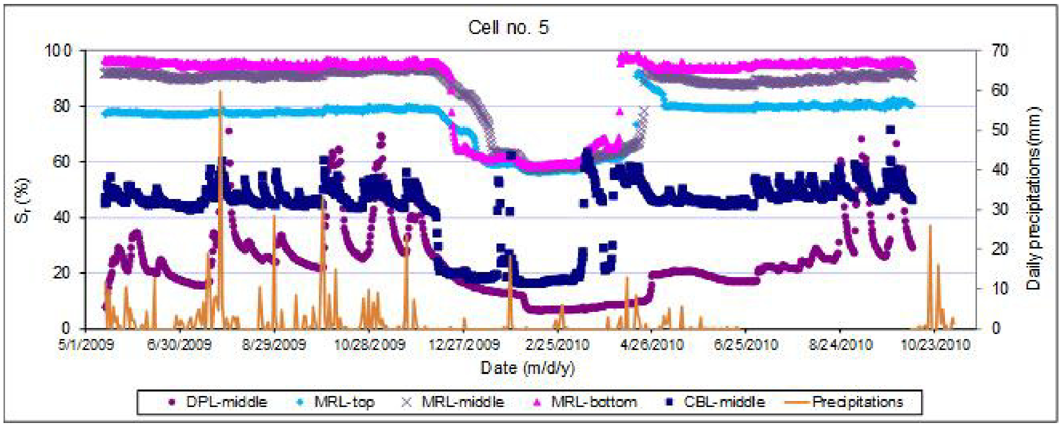

Figure 6 – Change in S_r at different depths in the CCBE of Cell no. 5 with time and daily precipitations recorded at the Doyon Mine site (precipitation data from June 22 to October 07, 2010 not available)

Figures 7a–c show the saturation profiles through the CCBE in cell nos. 2, 3, and 5 for the data collected in summer 2009, where depth 0 corresponds to the CCBE surface. No substantial variation in S_r was observed in the MRL. The hydrogeotechnical behavior, which is typical of an effective CCBE, indicated that the degree of saturation S_r in the MRL should be maintained at above 85%, whereas the S_r in the DPL and CBL were generally lower than 30–50% (Bussière et al., 2007). The target value of 85% was attained in Cell no. 2 on the whole thickness of the MRL and in Cell no. 5 from the middle to the bottom of the MRL.

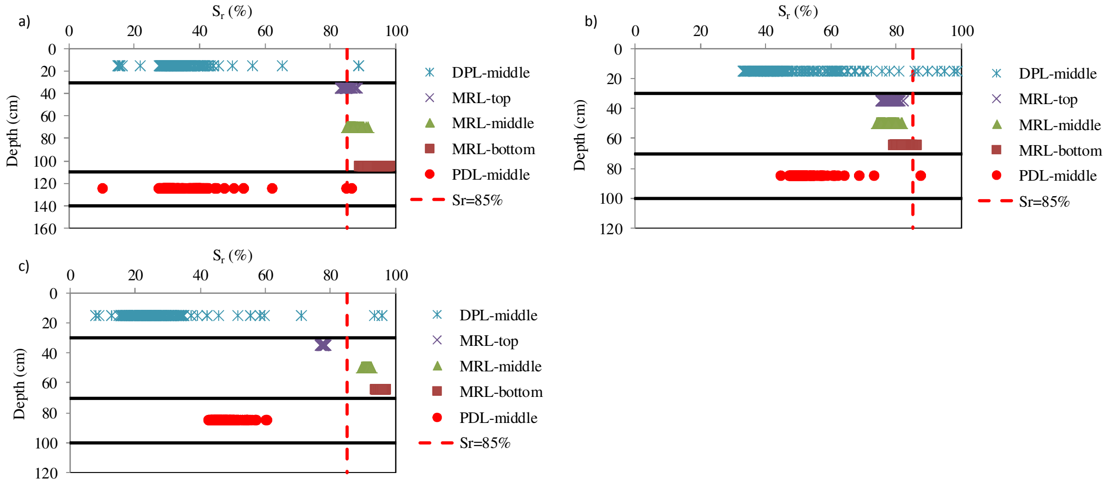

Figure 7 – Saturation profiles in a) Cell no. 2, b) 3, and c) 5 using data from May–September, 2009

Typical changes in suction and soil temperature with time

Figures 8 and 9 show typical changes in suction and soil temperature measured every 12 hours in Cell no. 5. Soil temperature was measured in the middle and at the bottom of the MRL and in the middle of the CBL. Fluctuations in air temperature measured every 30 min are also shown. The Watermark probes used for suction monitoring are not appropriate in winter, due to water freezing. Outside the winter period, suctions in the MRL remained lower than about 14 kPa. Suctions were higher at the top than in the middle and at the bottom of the MRL, which is in good accordance with the S_r profiles. Figure 9 indicates that the lowest temperature measured at the different depths in the CCBE is 0 °C (the same observation was made for the other cells) even if air temperature decreased up to -30°C. This could be a limitation of the temperature probes used. Surprisingly, the results presented in Figure 6 indicate that part of the soil water remained unfrozen in all CCBE layers during winter (up to 60% unfrozen S_r in the MRL), even though the temperature was at least 0 °C in these layers.

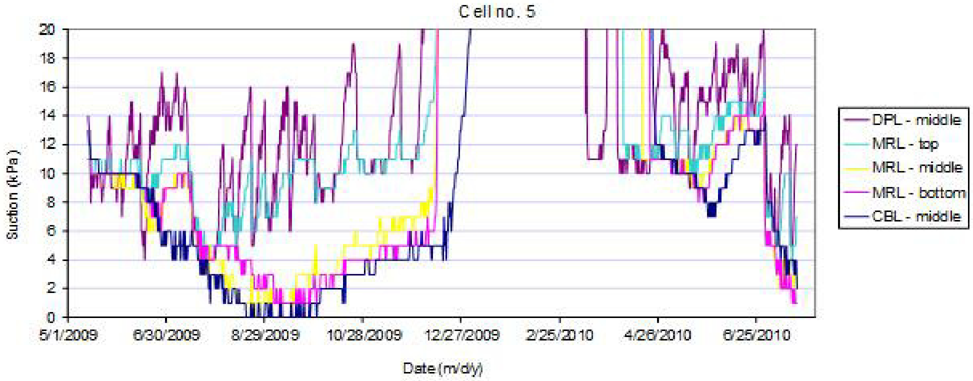

Figure 8 – Change in suction at different depths in the CCBE of Cell no. 5

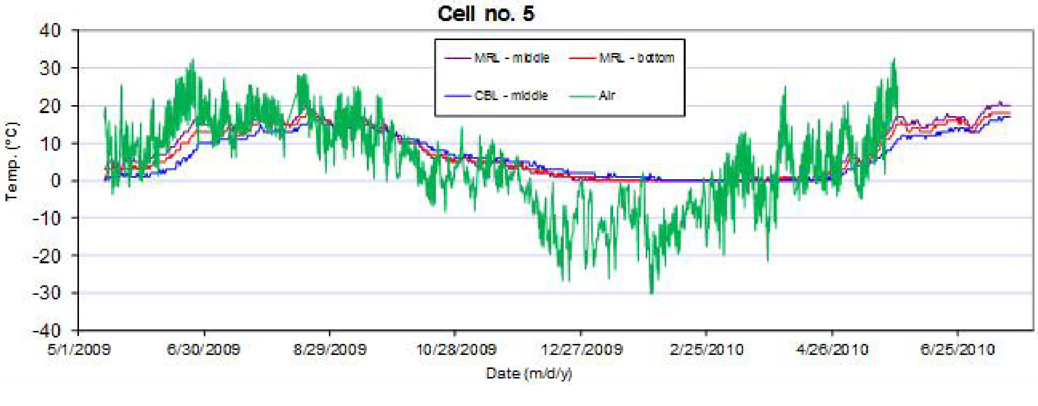

Figure 9 – Change in soil temperature at different depths in the CCBE of Cell no. 5 (z = 0 cm at the surface of the CCBE

Oxygen concentration profiles

Oxygen concentration profiles were determined through the CCBE. Typical measurement results obtained on September 1, 2010 are given in Figure 10. Field measurements were performed after a period of 3 days with no precipitation, which is thought to provide favorable conditions for oxygen migration. The atmospheric oxygen concentration was 20.9% or 276.7 mg/L. The oxygen concentration profiles shown in Figure 10 are almost linear within each cover layer because oxygen is not consumed within the cover materials (when the potential microbial oxygen consumption is assumed to be negligible). The oxygen concentrations remained high in these CCBEs, even though the MRLs were nearly saturated. The oxygen concentration in the middle of the CBL (or at 20 cm above the tailings–CCBE interface) was approximately 245 mg/L (or 18.5%), 261 mg/L (or 19.7%), and 254 mg/L (or 19.2%) for cell nos. 2, 3, and 5, respectively. Moreover, oxygen consumption by tailings beneath a CCBE was shown to have a significant impact on the oxygen distribution in the CCBE (Mbonimpa et al., 2008b). In the present study, the tailings were probably close to saturation, such that reactivity was low. This hypothesis is supported by the amount of the pumped interstitial water when sampling soil gas from the sampler tips installed in the tailings beneath the CCBEs. Further support is provided by the limited oxygen penetration into the tailings beneath the CCBE. In fact, despite the relatively high oxygen concentration in the CBL, oxygen was almost completely depleted at a depth of about 5 cm. This oxygen penetration is very low compared to that observed in the tailings exposed to atmosphere in reference Cell no. 4 (more than 1m; see Figure 10).

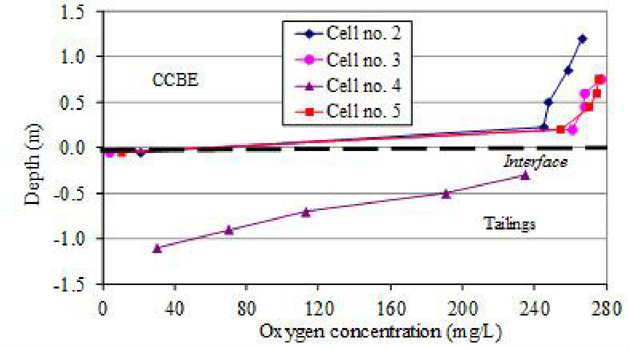

Figure 10 – Oxygen concentration profiles through the cells (depth 0 corresponds to the CCBE-tailings interface)

Comparison of oxygen fluxes

For MRL materials with a relatively high degree of saturation, it is generally assumed that oxygen transport occurs mainly by molecular diffusion, and that other transport mechanisms such as advection and infiltration can be neglected. The measured oxygen profiles through the MRLs can be used to estimate the oxygen flux passing through the cover and reaching the acid-generating tailings placed beneath using the oxygen gradient method (e.g., Elberling et al., 1993; Demers et al., 2009) based on Equation (1):

$$F = -D_e \times \frac{\partial C}{\partial z} \qquad (1)$$

where C, D_e, and F are the oxygen concentration [ML^{-3}], effective diffusion coefficient [L^2T^{-1}], and flux [$ML^{-2}T^{-1}$] and z is the diffusion depth [L]. The oxygen gradient $\partial C/\partial z$ [ML^{-4}] corresponds to the slope of the oxygen profile, and can be obtained from Figure 8. The coefficient D_e can be estimated from the porosity n and the degree of saturation S_r in the MRL using the model proposed by Aachib et al. (2004) (see also Gosselin et al., 2007).

Table 2 shows the average degrees of saturation at the bottom, middle, and top of the MRL on the day of oxygen monitoring (Sept. 01, 2010), estimated D_e, oxygen concentration gradients derived from the slopes of the oxygen concentration profiles within the MRL, and daily oxygen fluxes calculated with Eq. (1). The oxygen fluxes are similar for cell nos. 2 and 5 and slightly lower than the flux in Cell no. 3.

Table 2 – Parameters used to estimate the oxygen flux using the gradient method

Parameters	Cell no. 2	Cell no. 3	Cell no. 4	Cell no. 5
Average porosity n (–)	0.22	0.22	–	0.38
Average degree of saturation S_r (%)	85	81	–	88
Estimated oxygen diffusion coeff. D_e (m^2/d)	6.9×10^{-4}	14.2×10^{-4}	–	6.2×10^{-4}
Oxygen concentration gradient $\partial C/\partial z$ (g/m^4)	26.6	30.9	255.2	17.7
Daily oxygen flux F from O_2 profile (g/m^2d)	1.8×10^{-2}	4.4×10^{-2}	–	1.1×10^{-2}
Conservative daily oxygen flux F (g/m^2d)	24.0×10^{-2}	98.4×10^{-2}	–	43.1×10^{-2}

For a conservative CCBE design, oxygen concentrations at the top and bottom of the MRL are assumed to be 276.7 mg/L or 20.9% and 0 mg/L or 0% (which occur for highly reactive tailings), with a linear distribution from top to bottom. Using the values of D_e given in Table 2, daily oxygen fluxes of 24.0×10^{-2}, 98.4×10^{-2}, and 43.1×10^{-2} g O_2/m^2d would be obtained for cell nos. 2, 3, and 5, respectively (see Table 2). This conservative approach overestimates the daily oxygen flux by at least one order of magnitude in these cases. Oxygen profile monitoring through experimental cells can allow better designs of the CCBE configuration.

CONCLUDING REMARKS

Experimental cell nos. 2, 3, and 5 were constructed in 2007 at Parc I of the Westwood-Doyon Mine site to assess the effectiveness of cover with capillary barrier effects (CCBE) to act as an oxygen barrier and control AMD generation. A reference cell (Cell no. 4) without CCBE was also constructed. The hydrogeotechnical behavior of the cells was monitored from spring 2009. The results showed that high degrees of saturation S_r (> 85%) were maintained in the moisture retention layer (MRL) of the CCBEs in cell nos. 2 and 5. Although the MRLs in cell nos. 2 and 3 were constructed of the same material (till), the degree of saturation was higher in Cell no. 2 (with MRL thickness of 80 cm) than in Cell no. 3 (with MRL thickness of 40 cm). A comparison of cell nos. 3 and 5 (with MRL of equal thickness at 40 cm) but constructed with a till and a clayey silt, respectively, showed slightly higher degrees of saturation in Cell no. 5 than in Cell no. 3. Water retention curves measured on samples collected during the cell dismantling will allow improve the interpretation of the hydrogeotechnical behavior of the CCBEs. The oxygen flux estimated from oxygen concentration profiles through the CCBEs indicated that Cell no. 3 was less effective than cell nos. 2 and 5. CCBE performance is currently being investigated using the geochemical monitoring data.

ACKNOWLEDGMENTS

The authors thank IAMGOLD, Division Doyon, for funding this project. Technical support by Nil Gaudet, Yvan Poirier, and David Bouchard (at URSTM, UQAT) and Mario Gagnon and Danis Janvier (at IAMGOLD) is gratefully acknowledged.

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