Oxygen monitoring in a cover with capillary barrier effects

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ABSTRACT

Covers with capillary barrier effects (CCBEs) are increasingly popular in the mining industry. CCBEs are used to inhibit the production of acid mine drainage (AMD) resulting from the oxidation of sulphide minerals in waste rocks and mill tailings. Under humid climatic conditions, CCBEs installed on tailings are generally designed to limit oxygen migration into the disposal site. This type of oxygen barrier relies on the high moisture content in one of the cover layers to prevent oxygen migration. Such CCBEs have been used to rehabilitate various tailings sites in the Abitibi-Témiscamingue region of Quebec. Following these projects, the hydraulic behaviour of CCBEs is now well understood as these have been monitored for more than a decade. However, their performance in terms of controlling oxygen concentration has not been as extensively assessed. A preliminarily investigation was conducted in 2006 and 2007 to evaluated the vertical oxygen profiles at different locations in a CCBE. Oxygen concentrations were monitored using two types of gas probe kits: “retract-a-tip” and “dedicated tip.” During the field measurements, interstitial gas samples were collected at different depths in the cover and underlying tailings, and then transported to the laboratory for gas analyses by chromatography. On-site analyses of oxygen concentrations in pumped interstitial gas were also performed using an optical oxygen sensor. The results tend to confirm that the oxygen concentration at the base of the CCBE are low, indicating that the cover is effectively acting as an oxygen barrier.

RÉSUMÉ

Les couvertures avec effet de barrière capillaire (CEBC) sont de plus en plus utilisées dans l’industrie minière, comme moyen efficace pour réduire la production du drainage minier acide provenant de l’oxydation des minéraux sulfureux des roches stériles et des rejets du concentrateur. En climat humide, les CEBC mises en place au-dessus des résidus visent généralement à limiter le flux d’oxygène dans les sites d’entreposage des rejets miniers. Ce type de barrière à l’’oxygène est lié au maintien d’un haut degré de saturation dans la couche de rétention d’eau pour empêcher la migration d’oxygène. Cette technique de CCBE a été appliquée pour la réhabilitation de quelques sites miniers situés dans la région d’Abitibi-Témiscamingue du Québec. À la suite de ces projets, le comportement hydrique de ces CEBC est actuellement bien compris pour avoir été suivi depuis plus d’une dizaine d’années. Néanmoins, leur performance en termes du contrôle de la concentration d’oxygène n’a pas été évaluée profondément. Une telle investigation a été réalisée en 2006 et 2007. À cet égard, les profils verticaux d’oxygène ont été mesurés dans différentes stations avec un système d’échantillonnage de gaz interstitiel à pointe rétractable et à pointes dédiées. Au cours de ces mesures de terrain, le gaz interstitiel a été échantillonné à différentes profondeurs de la couverture et dans les résidus sous-jacents, et transporté au laboratoire pour être analysé par chromatographie en phase gazeuse. La concentration d’oxygène dans le gaz interstitiel pompé a aussi été analysée sur place à l’aide d’un senseur optique d’oxygène. Les résultats montrent que la concentration d’oxygène à la base de la CCBE est faible, ce qui indique que le recouvrement joue efficacement le rôle de barrière à l’oxygène.

1 INTRODUCTION

Mining activities in several Canadian provinces generate a large amount of wastes, including tailings and waste rock. Some of these mine wastes have the potential to adversely impact the environment if not properly managed. In this regard, special attention is required when they contain iron sulphide minerals, such as pyrite and pyrrhotite. The oxidation of sulphides by atmospheric oxygen tends to acidify meteoric waters; this phenomenon is known as Acid Mine Drainage (AMD) or Acid Rock Drainage (ARD) (SRK, 1989; Ripley et al. 1996; Morin and Hutt 1997). Equations describing the chemical reactions have been presented by Kleinman et al. (1981), Evangelou (1995), and Aubertin et al. (2002). If the mine wastes also contain carbonate minerals, a partial or complete neutralization of the acidic water is possible. Simply stated, when the acid neutralization potential is not sufficient or has been exhausted, AMD occurs. The acidic water can then mobilize some of the elements contained in the wastes due to their increased solubility at low pH. In these situations, actions must be taken at the mine site to prevent environmental impacts caused by AMD.

Different management options and rehabilitation strategies are available to inhibit acid production. Under the relatively humid climate prevailing in many of the mining regions of Canada, oxygen barriers are considered to be the most viable option for tailings impoundments (e.g. SRK 1989; MEND 2001). Covers with capillary barrier effects (CCBEs) can be used for this purpose. This type of oxygen barrier relies on a high moisture content in one (or more) of the multiple layers in the cover to control oxygen migration (e.g. Nicholson et al. 1989; Collin and Rasmusson 1990; Yanful 1993; Aachib et al. 1993; Bussière et al. 2003).

Gas migration in a CCBE placed on AMD-generating tailings is mainly controlled by molecular diffusion (Collin, 1987, 1998; Collin and Rasmuson 1988; Nicholson et al. 1989; Kim and Benson 2004). The molecular diffusion flux is related to the moisture content of the cover layer which directly affects the effective oxygen diffusion coefficient (D_e) appearing in Fick's first law. This effect is illustrated in Figure 1, which shows that the degree of saturation (S_r) has a significant influence on the value of D_e; the more than 4-orders of magnitude decrease seen in this figure, when going from a dry to a saturated state, is due to the presence of pore water that impedes oxygen transport. Because the oxygen flux available for sulphide oxidation is proportional to D_e, the CCBE efficiency in limiting oxygen migration directly depends on the value S_r .

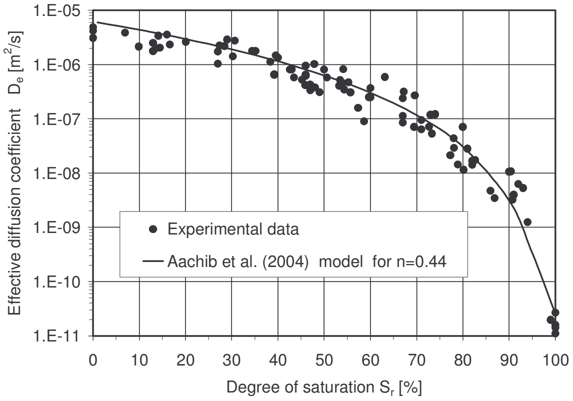

Figure 1. Effective oxygen diffusion coefficients D_e measured in laboratory tests and estimated with a semi-empirical relation proposed by Aachib et al. (2004) for different materials

Well developed design tools are available for engineered CCBEs. Assessment monitoring must nonetheless be planned for short-, medium- and long-term to verify if the performance meets the design criteria. In practice, CCBEs are generally instrumented to assess their hydraulic behaviour, by monitoring climatic conditions as well as water infiltration and evaporation response in terms of suction and volumetric water content (or degree of saturation S_r,) in the different layers. Based on the relationship between D_e and S_r, (see Figure 1), and using Fick's first and second laws (e.g. Collin and Rasmusson 1988; Nicholson et al. 1989; Mbonimpa et al. 2003), the oxygen barrier performance in terms of oxygen flux control can be indirectly determined using numerical or analytical models (e.g. Yanful 1993; Aubertin et al. 1997, 1999; Bussière 1999; Bussière et al. 2003; Dagenais et al. 2005; Mbonimpa et al. 2008, this conference). Simplified assumptions are then used to calculate the oxygen flux, such as a zero oxygen concentration at the CCBE-tailings interface and absence of oxygen in the CCBE at the beginning of the diffusion process.

Only a few studies have been conducted on the direct monitoring of oxygen distribution in CCBEs and underlying tailings to validate the above-mentioned hypothesis. Oxygen concentration profiles were measured, for example, by Yanful (1993) in instrumented laboratory columns with covered and uncovered tailings and in field test plots at the Waite Amulet site located near Rouyn-Noranda, Quebec. Lundgren (2001) measured oxygen concentrations beneath covers overlying two waste rock dumps using a diffusion cell connected to a flushing and measurement valve. Renken et al. (2005) measured the change in oxygen concentrations with depth on test plots constructed at the Premier Gold Project located near Stewart, British Columbia. Patterson et al. (2006) monitored oxygen concentrations in the unsaturated zone of a composite cover overlying a sulphidic tailings facility using online oxygen probes. Nengovhela et al. (2007) determined the oxygen content in six tailings dams around the Witwatersrand Basin (South Africa) over a 2-month period using a multi-level gas sampling device in an attempt to understand oxygen diffusion in acid generating tailings dams. Gosselin et al. (2007) reported on a study of oxygen migration in exposed tailings during laboratory column tests. Demers et al. (2007) measured oxygen concentration profiles in instrumented columns to evaluate the efficiency of a single layer low sulphide tailings cover placed over acid-generating tailings to reduce the oxygen flux reaching the reactive tailing. The results obtained in these investigations tend to confirm the validity of Fick's laws, with a reaction term, to estimate the oxygen flux in reactive tailings (exposed or covered). However, there is still a need more precisely evaluate the oxygen concentration gradients inside and just below layered covers.

Field investigations were performed by the authors in 2006 and 2007 to determine vertical oxygen concentration profiles in a CCBE and underlying tailings at a site located in Abitibi-Témiscamingue, Quebec. This investigation is described in this paper. More specifically, the interstitial gas sampling techniques are presented followed by a description of the gas analysis methods (gas chromatography and direct on-site measurements using an optical oxygen sensor). Preliminary results are also presented. Some of the difficulties encountered with the measurement techniques are briefly discussed.

2 OXYGEN CONCENTRATION MONITORING

Various techniques exist to sample and analyse gas in soils and other porous media (e.g. Dane and Topp, 2002). In this study, the sampling probe kits consisted of a probe tip through which the soil gas sample was collected at different depths in the CCBE layers and underlying tailings using a probe tube that extended from the tip to the ground surface. A reusable tip and permanent probes were used, both manufactured by AMS Inc.. Before gas sampling, a purge was performed to ensure that there was no stagnant air in the sampling system and that the collected sample is representative of interstitial soil gas conditions. Also, an equilibration time following probe installation and purge was allowed before pumping the soil gas. The purge volume was estimated based on the internal volume of the tubing (considering atmospheric pressure conditions).

The soil gas samples were collected and analyzed using two techniques to determine oxygen concentration in the samples. These techniques are described below.

2.1 Soil gas probe with a reusable tip

The gas vapour probe with a reusable tip (or retract-a-tip) was developed by AMS Inc. as a survey tool for the collection of discrete soil gas samples using a temporary casing. The probe tip is connected to a fluoropolymer tubing that runs into the gas probe extension. Figure 2 illustrates the probe tip during driving. The tip is screwed into the extension and the tip part, covered with fine screen mesh, is inside the extension. The hardened stainless steel tip opens when the extension is pulled back a few cm for gas sample collection (see Figure 3). Soil gas can then be collected using a manual or peristaltic pump. The collected gas can be analyzed on site, or stored in airtight Tedlar bags that have been previously purged with nitrogen and then sent to the laboratory for analysis.

Figure 2. Tip and extension during driving

Figure 3. Extension pulled back to open the sampling section which is covered with fine screen mesh.

When gas sampling at a given depth is completed, the device can be subsequently driven further to predetermined deeper sampling points. Once sampling is completed, the probe can be removed from the soil without damage to the tip using a removing jack. The tip can be washed and reused for further gas sampling.

2.2 Permanent soil gas probes

This procedure sets a permanent point that can be used for repeated gas samplings at the same location. The tip, which is connected to a fluoropolymer tube, is driven into the subsurface by hand using a slide hammer or by an electric hammer drill. The tubing is introduced into the gas probe extensions that insert the tip into the soil. The tip contains recessed gas inlet holes that are protected by the extension during probe installation (see Figure 4). When the desired depth is reached, the extensions are removed using a special jack that leaves the dedicated tip imbedded at the desired location. The fluoropolymer tubing that runs from the tip to the surface allows gas sampling by manual pumping or with a peristaltic pump. Collected gas samples can be analyzed directly on site or stored in airtight Tedlar bags for later analysis in the laboratory.

Figure 4. Tip (with gas inlet holes) linked to a fluoropolymer tube that runs through the driving extension

2.3 Oxygen concentration measurements

Two different types of measurements were performed to determine the oxygen concentration in the gas samples. The first one was used in 2006 and the second one in 2007.

For the measurements performed during the summer of 2006, gas samples were collected in airtight (nitrogen-purged) Tedlar bags. The bags were transported to the laboratory where gas analysis was performed within 24 hours with an Agilent MicroGC gas chromatograph equipped with O_2 / N_2 and CO_2 detection coils. The MicroGC is a portable gas chromatograph with an injection loop that ensures consistent sample injection. Calibration was performed prior to each analysis session using ambient air. Additional regular calibrations were performed using standard samples containing 5%, 10%, 15% and 20.8% O_2 and 100ppm, 500ppm, 1% and 9.73% CO_2.

In the summer of 2007, *in situ* oxygen measurements were performed using a PSt3 oxygen sensor and an OXY-10 reader (PreSens GmbH). The sensor consists of a polymer optical fibre (POF) with a polished distal tip coated with a planar oxygen-sensitive foil. The end of the polymer optical fibre is covered with a high-grade steel tube (OD 4 mm) to protect both the sensor material and the POF. These sensors are highly accurate (+ 0.1% oxygen M/M) and can measure oxygen concentration in the gas phase or dissolved in water. They provide a reading in less than 10 seconds in the gas phase and in less than 60 seconds for soluble oxygen. They must be calibrated prior to each test. The oxygen concentration measurement is based on quenching the luminescence caused by collisions between oxygen and luminescent dye molecules in an excited state (Wolfbeis 1991; Klimant et al. 1995, 1997; Holst et al. 1997). The detection of the luminescence lifetime as an oxygen-dependent parameter makes this oxygen meter superior to those based on luminescence intensity measurements, because oxygen measurements are not affected by the light source or detector stability. Intensity fluctuations caused by fibre bending or changes in the sample's optical properties (coloration, turbidity, refractive index, etc.) do not interfere with oxygen measurements. The technology is also immune to interference caused by pH, ion (e.g. sulphide) or salinity changes or changes in viscosity. Furthermore, no oxygen is consumed during the experiment.

Figure 5 illustrates the measurement technique. Oxygen is pumped from the fluoropolymer tubing. An oxygen probe inserted in the pump discharge tube and connected to the OXY-10 meter measures the oxygen concentration during pumping. The OXY-10 meter is connected to a PC that displays the data. Because the sampling tube contains an initial gas volume, it is generally observed that the oxygen concentration decreases and then stabilizes. Once the reading has been taken, the end of the pumping tubing must be hermetically sealed to avoid any gas exchange with the atmosphere.

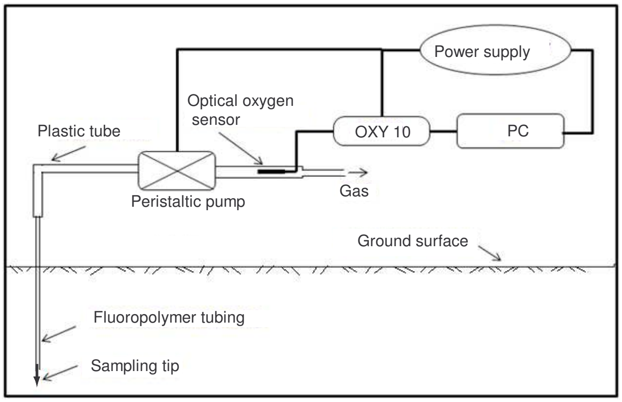

Figure 5. Measurement of O_2 in the interstitial gas pumped from the ground, using optical oxygen sensors

3 SAMPLING STATIONS, DEPTHS AND DATES.

The experimental site with the CCBE presents two distinct areas: a flat area where the slope is about 0.5% and inclined area where the slope is around 3H:1V. The three-layer CCBE was made of (from the bottom to top - see Figure 6):

- a 0.5 m thicklayer of sand and gravel used as support and a capillary break layer;
- a 0.8 m thick moisture-retaining layer made of non acid-generating tailings; and
- 0.3 m of sand and gravel placed on the top which serves as drainage and protective layer against evaporation and erosion.

Three locations on the flat surface were selected for gas sampling (Stations F), and three stations were located near the top of the slope (Stations S). At each station, interstitial gas was sampled at a minimum of five different depths, as shown in Figure 6. Sampling near the surface in the protective layer was abandoned because (as expected for a coarse-grained material exposed to climatic conditions) the initial measurements indicated oxygen concentrations of about 20.9%.

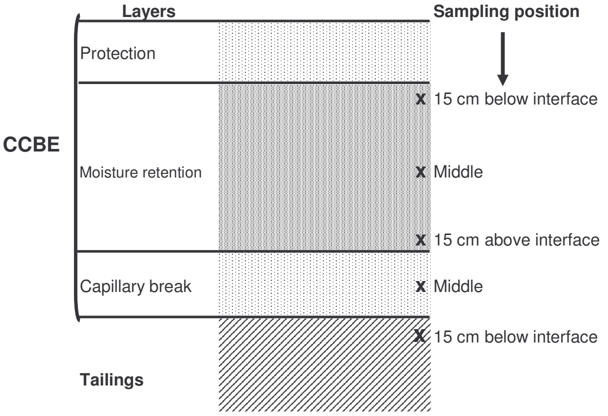

Figure 6. Sampling positions for a given station

During the summer of 2006, trenches were excavated at 25 stations and devices were installed in the moisture-retention layer to monitor the CCBE's hydraulic behaviour. These devices include time-domain reflectometers (TDR with a buriable waveguide and 2 meter cable form SOILMOISTURE EQUIPMENT CORP.), Echo probes (EC 5 model from DECAGON DEVICES, Inc.) to measure volumetric water content, and Watermark sensors (IRROMETER Co.) to measure suction. The thicknesses of the CCBE layers were determined at the different stations during excavation of trenches. As the soil gas sampling stations were placed close to the hydraulic monitoring stations; these layer thicknesses were used to determine the location of the sampling depths, as indicated in Fig. 6. Some soil gas sampling tips were installed at the same depths as the probes used for hydraulic measurements for comparison purposes.

Under a relatively humid climate, a CCBE on tailings acts as an oxygen barrier, and can remain effective even after a long period without precipitation (e.g. Bussière et al. 2003, 2007). Its performance should be monitored over time under the various site conditions, including unfavourable situations. In this investigation, it was decided to set the sampling days according to the weather forecast. In fact, after a significant precipitation event, the cover layers could be highly water-saturated, which made the gas sampling difficult. Soil gas sampling was also difficult in May and early June, as the cover materials were still water-soaked after the snow and soil had melted. Only the period from early July to late October were appropriate for sampling. However, at least 3 days without heavy precipitation was required before sampling could be performed.

Sampling dates and methods are given in Tables 1 and 2 for the different stations, classified as stations on the flat surface (F) and sloping cover area (S). In 2006, sampling with reusable retract-a-tips (RT) and dedicated tips (DT) was performed. In 2007, only sampling with dedicated tips (DT) was done.

The OXY-10 reading system broke down on July 27 due to generator surcharge. No further measurements could be conducted in 2007.

Table 1. Dates and sampling methods in 2006

Date	Station F10	Station F14	Station F16	Station S17
July 17	RT	-	-	-
August 21	RT	RT	RT	RT
August 31	RT+DT	RT+DT	-	-
October 6	RT+DT	RT+DT	-	-

Table 2. Dates and sampling methods in 2007

Date	Station F10	Station F14	Station S13	Station S12
June 21	DT	DT	-	-
July 6	DT	DT	DT	DT
July 23	DT	DT	DT	DT

4 RESULTS

4.1 Gas chromatography (2006)

As mentioned above, O_2, N_2 and CO_2 concentrations were determined by gas sample analysis using gas chromatography (GC). Figure 7 shows results obtained at Station F10 using RT sampling. One sees that the oxygen concentration decreased from 20.9% at the surface to 8.7% at 15 cm above the interface between the capillary break layer and moisture-retention layer, and to 2% at the CCBE-tailings interface (depth of 160 cm). Carbon dioxide increased with depth, rising from 0.04% at the surface to 6.2% at the bottom of the CCBE. This CO_2 increase indicates that there was some neutralization of the sulphide mineral oxidation products by carbonates. It should be noted that the tailings and the materials used as the moisture-retention layer were oxygen-reactive, although the latter were not acid-generating. Only the oxygen profiles are presented in the following.

Figures 8 and 9 show typical O_2 concentration profiles for soil gas sampled on July 31, 2006, using RT and DT sampling methods at stations F10 and F14, respectively. The results are representative of those obtained at other stations and on other sampling dates (see Table 1). It can be seen that some profiles show the expected O_2 decrease with depth. However, other profiles are less conclusive. Subsequent investigations showed that the less conclusive measurements were mainly due to the use of less airtight bags for gas transport to the laboratory. Two models of sampling bags were used: 10 of an old model and 30 of the new model Tedlar bags. Although the sampling bags used were supposed to be airtight, the bags in the newer batch were found to have leaked during the investigation conducted in 2007. On site oxygen concentration measurements using the optical oxygen sensor in the newer bags were therefore systematically lower than those measured with the CG and the same optical sensor after transporting the sample to the laboratory. However, the same values were measured on site and in the laboratory for the older bag model. It was therefore decided in 2007 to measure oxygen concentration directly on site without transporting the gas to the laboratory.

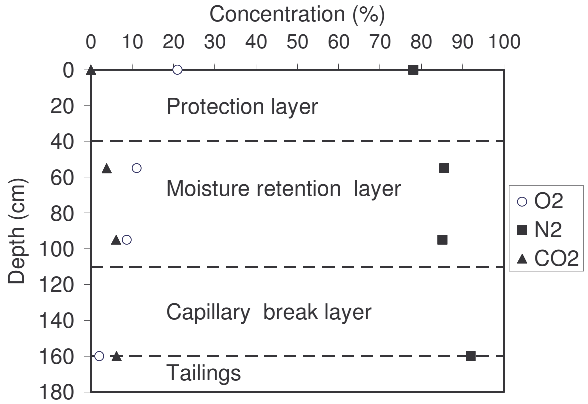

Figure 7. Measured (with GC) O_2, N_2 and CO_2 concentration profiles obtained from soil gas sampled using RT at Station F10 (July 17, 2006).

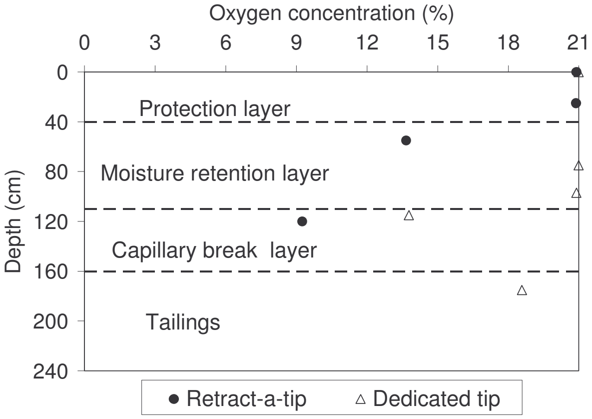

Figure 8. Measured (with GC) O_2 concentration profiles for soil gas sampled using RT and DT at Station F10 (July 31, 2006).

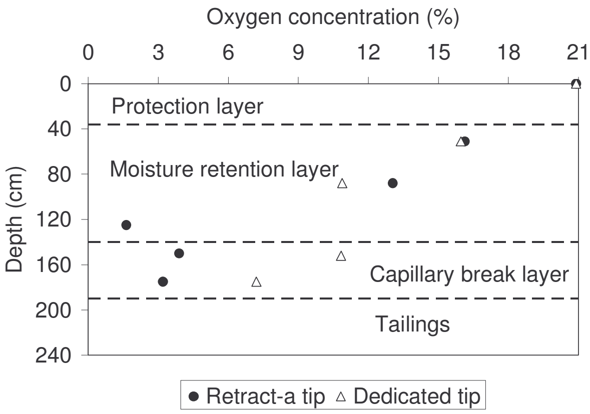

Figure 9. Measured (with GC) O_2 concentration profiles for soil gas sampled using RT and DT at Station F14 (July 31, 2006).

4.2 Optical sensor measurements (2007)

Typical results for the measurements made on the site in 2007 using optical oxygen sensors are shown in Figures 10 to 13. In all cases, the profiles obtained are consistent.

For stations F10 (Fig. 10) and F14 (Fig. 11), located on the cover flat surface, oxygen concentrations beneath the CCBE are almost zero. Figures 12 and 13 present the results obtained for stations S13 and S12 located on the slope near Station F14. These two figures indicate that the oxygen concentrations below the CCBE are high at Station S13 located near the top of the slope compared to stations S12 and F14. Indeed, oxygen concentration values vary from 2 to 6% at Station F13 and from 0 to 1% at Station S12. These results can be attributed to a desaturation near the top of the inclined CCBE compared to the rest of the slope as observed with laboratory tests on physical models (Bussière 1999), field measurement results (Maqsoud et al. 2005) and numerical modelling (Bussière 1999; Bussière et al. 2003; Mbonimpa et al. 2008, this conference). It should, however, be mentioned that the moisture retention layer at Station S13 is somewhat thinner than at stations S12 and P14.

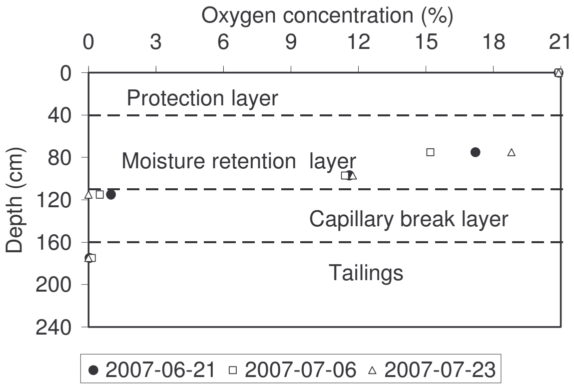

Figure 10. Measured (with an optical sensor) O_2 concentration profiles from soil gas sampled with a dedicated tip at Station F-10 (summer 2007).

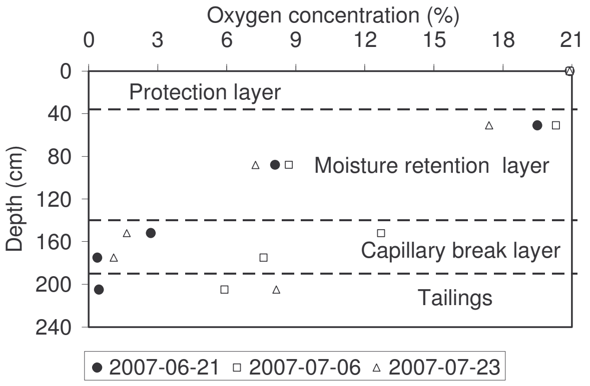

Figure 11. Measured (with an optical sensor) O_2 concentration profiles from soil gas sampled with a DT at Station F14 (summer 2007).

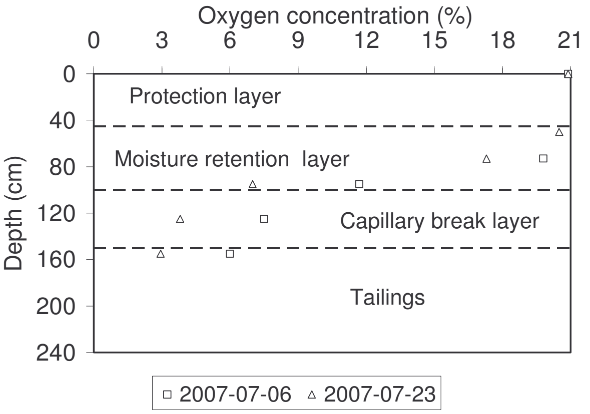

Figure 12. Measured (with an optical sensor) O_2 concentration profiles from soil gas sampled with a DT at Station S13 (summer 2007).

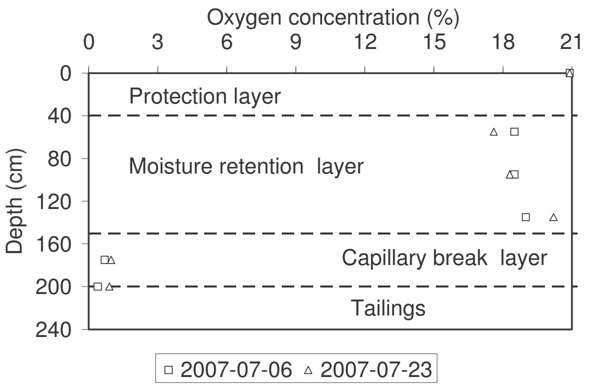

Figure 13. Measured (with optical sensor) O_2 concentration profiles from soil gas sampled with a DT at Station S12 (summer 2007).

5 DISCUSSION

The results of this study tend to indicate that the investigated CCBE is efficient at limiting the oxygen flux, based on the oxygen concentration distribution. However, oxygen profiles do not provide a complete picture to fully assess the flux through a cover. Numerical investigations of the effect of tailings' reactivity on the performance of the inclined CCBEs indicated that reactivity of both the CCBE materials and the underlying acid-generating tailings affects the oxygen concentration distribution. Details are provided in a companion paper also presented at this conference (Mbonimpa et al. 2008). As tailings reactivity increases, oxygen concentrations at the CCBE-tailings interface decrease (for other identical conditions). The reactivity of the tailings beneath the CCBE at the different gas monitoring stations was not evaluated so it is unknown. For a given tailings (with a given sulphide content), Gosselin et al. (2007) showed that the reactivity depends on the water content (or degree of saturation). The interpretation and comparison of the results presented above for different stations does not allow a complete evaluation of the cover preformance. Nevertheless, this type of data is quite valuable to complement other information to better undersand how a cover responds in the field.

It should be noted that the measured oxygen concentrations have not yet been validated by other methods. A preliminary investigation was performed to compare oxygen concentrations in gas sampled by pumping to concentrations obtained directly using 3 optical oxygen sensors installed in the CCBE layers at 3 sampling depths. Unfortunately, the sensors broke during the first measurements. A second validation study is planned for 2008.

Four additional sampling stations with dedicated tips were installed in the CCBE slopes in 2007 to study in more detail the effect of desaturation. Further measurements are planned. The measured oxygen concentration profiles will also be compared with profiles obtained by calculations based on hydraulic properties. Hydraulic data are being regularly collected at stations very close to those selected for gas monitoring.

6 CONCLUSION

This paper presents the results of a practical in-situ study on vertical oxygen profiles in a CCBE acting as an oxygen barrier to control acid mine drainage. Soil gas was sampled in 2006 and 2007 using retract-a-tip and dedicated tips. Oxygen concentrations in the samples were measured in the field with an optical oxygen probe and in the laboratory using gas chromatography. The typical results presented here indicate that there is a decrease in O_2 concentration with depth. The O_2 concentration is almost zero at the base of the CCBE at stations located on the flat surface tailings impoundment but the measured values can be higher near the top of inclined zones where the degree of saturation in the CCBE is less.

ACKNOWLEDGEMENTS

This investigation was enabled by the support of the Industrial NSERC Polytechnique-UQAT Research Chair in Environment and Mine Wastes Management (http://www.polymtl.ca/enviro-geremi/). The authors would like to acknowledge the support and participation of all their partners. The financial support of the UQAT-FIR 2006 is also acknowledged.

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