THE USE OF LOW SULPHIDE TAILINGS AS THE MOISTURE RETAINING LAYER IN ENGINEERED COVER SYSTEMS TO PREVENT AMD[1]

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ABSTRACT: The production of acid mine drainage (AMD) is one of the primary problems of the mining industry. One way to reduce the formation of AMD is to place over the acid generating materials a cover that shields them from oxygen by limiting gas flux by diffusion. Such engineered cover system usually involves layering various types of soils to create capillary barrier effects. In most cases, natural materials, like till and clay, are used as the fine material layer in a composite system. This study evaluates the use of low sulphide tailings in the cover, rather than a fine grained soil. The results of laboratory and *in situ* experiments, conducted over the last 8 years, have demonstrated that the use of non-acid generating tailings as the moisture retaining layer is an effective method to limit the oxygen flux and the ensuing generation of AMD. The paper presents the main findings of this extensive investigation, and also discusses the main concepts behind the analysis and design of efficient covers with capillary barrier effects (CCBE) to prevent AMD.

1. INTRODUCTION

The environment can be affected by mining operations in differing interactive ways. The generation of acid mine drainage (AMD) caused by the oxidation of sulphide minerals in the presence of water is probably the main threat to various natural ecosystems located near to existing mines. AMD is recognized as a multi-factor pollutant, the main factors being acidity, metal toxicity, suspended solids and salinization (Gray 1997). The overall impact of AMD is also influenced by the buffering capacity of the receiving water and available dilution. Contamination by AMD can be categorized as chemical, physical, biological and ecological. It can result in the direct elimination of various plants and animal species, which damages the food chain and significantly reduces ecological stability. (Gray 1997).

Over the last few years different approaches have been proposed to limit the generation of AMD from sulphidic waste rock or mine tailings. Usually, these techniques try to eliminate one (or more) of the three main components of the oxidation reactions: oxygen, water and sulphide minerals. Creating an oxygen barrier is considered to be the best option in many cases.

There are different types of oxygen barriers that can be used. For example, a water cover is often used to limit the availability of oxygen to the reactive materials (e.g. Li et *al.* 1997). One can also use oxygen consuming materials in covers to reduce the flux of oxygen to materials underneath (e.g. Tassé et *al.* 1997; Cabral et *al.* 1997). Covers made of

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different types of soils using capillary barrier effects constitute another alternative. In many cases, a cover with capillary barrier effects (CCBE) may be the only viable option, despite the relatively high cost involved for their construction.

To reduce the construction costs of such a CCBE cover, Aubertin and Chapuis (1991) have proposed using non reactive tailings (i.e. tailings with very low sulphide content that do not generate AMD) as the fine material layer in the CCBE. This type of material is often found in abundance in mining areas (the Abitibi-Témiscamingue, in the province of Québec, is one example), close to problematic sites. About 8 years ago, an extensive laboratory program was undertaken in order to evaluate the hydro-geotechnical properties of low sulphide tailings for use in CCBE. The results, presented in various reports and publications (Aubertin et *al.* 1995, 1996, 1998), demonstrate that this type of particulate material can have advantageous characteristics for use as the fine grained moisture retaining layer in a cover with capillary barrier effects. Nevertheless, before using the material in a real large scale CCBE placed over reactive tailings, additional laboratory tests, numerical modeling, and *in situ* studies were necessary to confirm the initial laboratory results.

This paper briefly presents the capillary barrier effects phenomena. The results of laboratory and field tests performed to evaluate the efficiency of low sulphide tailings as a moisture retaining layer follow. Finally, the main conclusions about the performance of tailings as a cover material for limiting the generation of acid mine drainage are summarized.

2. COVERS WITH CAPILLARY BARRIER EFFECTS

The main role of a cover with capillary barrier effects (CCBE), constructed to reduce the production of AMD in a humid climate, is to limit the diffusion of oxygen. To do so, the cover must maintain a high degree of saturation in one (or more) of its layers. Indeed, 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. Nicholson et *al.* 1989; Rasmuson and Erikson 1986; Aachib et *al.* 1993).

The effectiveness of this type of cover is dependant upon a phenomenon called the capillary barrier effect. This effect is present when a fine grained material is placed over a coarser one. The two materials have different hydrogeological properties because of their different textures. In the initial desaturation stage, the fine grained material layer will retain water more easily then the coarse layer because it has smaller interstitial pores. As the coarse material drains, the presence of gas in its pore space reduces the interconnectivity of the voids which reduces its hydraulic conductivity (k). This reduction of k in the coarse layer reduces the vertical water flow from the fine material and the latter layer can remain almost fully saturated at all times. More details about capillary barrier effects and CCBE can be found in the literature (e.g. Rasmuson and Erikson 1986; Nicholson et *al.* 1989; Akindunni et *al.* 1991; Morel-Seytoux 1992; Aachib et *al.* 1993; Aubertin et *al.* 1995; Aachib 1997; Bussière 1999).

Covers with capillary barrier effects (CCBE) usually contain three to five layers made of different materials. Each layer has to play one (or more) specific role(s). Figure 1 is a schematic illustration of a CCBE. The bottom layer is made of a fairly coarse material which functions as both a mechanical support and a capillary break. The fine grained material (low sulphur tailings in this study), utilized as the moisture retaining layer, is placed upon the first layer to create the capillary barrier effect. Another coarse material is placed upon the fine grained material layer to prevent water loss by evaporation and help lateral drainage. The other two layers (protection and surface layers) are protective layers against erosion and bio-intrusion for the CCBE; these are not discussed further in this paper.

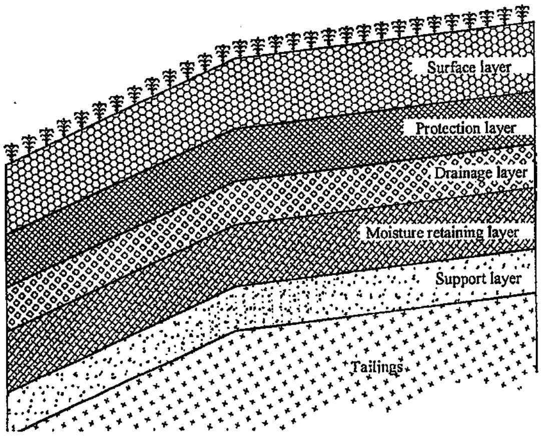

Figure 1. Typical configuration of a CCBE used to limit the production of AMD (Aubertin et *al.* 1995)

3. COLUMN TESTS INVESTIGATION

The laboratory testing of the hydro-geotechnical characteristics of low sulphur tailings has demonstrated that these materials have relatively low hydraulic conductivity ($10^{-6}<k_{sat}<10^{-4}$ cm/s), good water retention characteristics (1.5<AEV<3.5 m of water) and a good resistance to cracking from freeze-thaw cycles (Aubertin et *al.* 1995, 1996, 1997, 1998). Because of these promising characteristics, it was decided to further investigate the potential use of low sulphide tailings as the moisture retaining layer in a CCBE by performing column tests.

3.1 Column test description

A series of ten columns were constructed in 1993 to be used for a testing period of two years. These columns were made of plexiglas, and eight of them were 1.7 meters height. A schematic illustration of the columns is presented in Figure 2. The cover layers, which are placed over a layer of acid generating tailings, include a layer of sand (30 cm in thickness), a low sulphur tailings layer (50 cm in thickness), and a final layer of sand (20 cm in thickness). Two smaller columns were also built with reactive tailings to act as controls. TDR probes were placed at different locations in the columns to measure volumetric water content in the different layers of the covers. These measurements allow to estimate the efficiency of the cover in limiting gas infiltration by using the relationship between volumetric water content (or degree of saturation) and the effective diffusion coefficient of the soil or tailing (see equation 1).

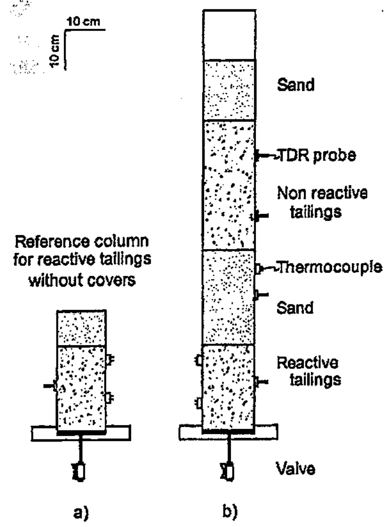

Figure 2. Schematic diagram of the column: a) control column, b) covered column.

The sand used in the columns is a typical concrete sand with an air entry value (AEV or ψ_a) of about 25 cm of water and a saturated hydraulic conductivity k_{sat} of 2.1×10^{-2} cm/s. The different low sulphide tailings used as the moisture retaining layer in the column tests were similar to those studied in the preliminary investigation program; their ψ_a was typically between 200 and 300 cm of water and k_{sat} between 10^{-4} and 10^{-6} cm/s.

In all columns, which were initially saturated before the bottom valve was opened, water was added from the top periodically (approximately 10 cm of water per month). The water percolating down was recovered at the bottom of the columns and analyzed for electric conductivity, pH, sulfate and metal contents. The volumetric water content of the different layers was also measured regularly. This information provided indications of the possible reactions occurring in the columns and allowed an estimate of the performance of the covers in limiting the generation of AMD.

3.2 Results

3.2.1 Degree of saturation profiles

The degree of saturation (S_r) was determined from the volumetric water content (θ) measurements with TDR probes ($S_r=\theta/n$, where n is the porosity). Typical S_r for three different drainage periods are presented in Figure 3. The figure also presents degree of saturation profiles predicted with the numerical model HYDRUS (Kool and van Genuchten 1991); more information on these calculations are given in Aachib (1997).

It can be observed that the two layers of sand drained rapidly, as expected for such type of cover with capillary barrier effects. Because of that, the hydraulic conductivity of the sand drops and the water is retained in the moisture retaining layer made of low sulphide tailings. The degree of saturation of the moisture retaining layer remained above 90% at all time, even after a drainage period of 28 days.

These degree of saturation can be used to estimate the effective diffusion coefficient D_e of each soil. To do so, one can utilize the Eberling et *al.* (1994) equation :

$$[1]\quad D_e = \tau D_a^0\left(1-S_r\right)^{\alpha} + \tau S_r D_w^0/H$$

where D_a^0 is the diffusion coefficient for a pure air phase (1.8×10^{-5} m^2/s at 25°C), D_w^0 is the diffusion coefficient for a pure water phase (2.2×10^{-9} m^2/s), H is the dimensionless modified Henry's law constant (33.9 @ 25°C), α and τ are fitting parameters (typically: $\tau = 0.273$ and $\alpha = 3.28$ as proposed by Eberling et *al.* 1994). The validity of this equation was confirmed with various experimental results (Aubertin et *al.* 1995; Aachib 1997).

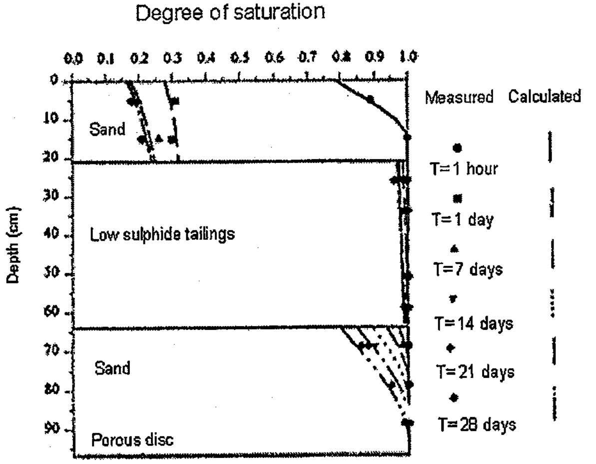

Figure 3. Typical volumetric water content profiles measured at different times in the columns.

The coefficient D_e can then be put in the Fick's first law which calculate the flux of gas (oxygen in this case) :

$$[2]\quad F(t) = D_e \frac{\partial C(t)}{\partial z}$$

Using analytical or numerical solutions for this equation allows a calculation of the oxygen flux. For example, when the degree of saturation is 10% in the upper sand layer, 94% in the moisture retaining layer and 30% in the lower sand layer, the flux of oxygen through the cover is estimated to be about 0.07 kg of $O_2/m^2/yr$, compared to typical value of between 9 and 32 kg of $O_2/m^2/yr$ for uncovered sulphidic tailings (e.g. Tibble and Nicholson 1997). Thus, the placement of the CCBE would reduce the amount of oxygen available for the oxidation of sulphide minerals by a factor of between 130 to 450. These results confirm the high efficiency (above 99% reduction) of the CCBE for limiting the infiltration of oxygen and AMD generation.

3.2.2 Water quality

The results in terms of water quality can be interesting to evaluate the performance of a CCBE. Figure 4 (taken from Aachib 1997) shows the evolution of pH, conductivity, iron and sulfates for one typical column with a CCBE. It demonstrates that the pH remained near 6 (the water added at the top had a pH of 5.5 to 6), the conductivity near 5 mS/cm, the iron concentration near zero (after the first 100 day period, when residual oxidation byproducts were leached) and the sulfate concentration near 0.4 g/l (also after the first 100 days). The higher values in conductivity, iron concentration and sulfate concentration for the first 100 days were mainly due to the oxidation that occurred prior to the placement of the materials in the column.

The effectiveness of the CCBE can be evaluated by comparing the water quality results of the covered tailings with those of the control columns. The results for one of the control column are shown in figure 6. The pH of the control column droped from approximately 6 to less than 3 during the experiment. The conductivity of the water percolating through the control column increased rapidly to values between 10 and 35 mS/cm. The concentration of iron varied from 5 to 20 g/l and sulfate content increased during the experiment from 10 to 90 g/l. The water quality of the leachate percolating through the control columns was significantly affected by the oxidation of the sulfide minerals contained in the reactive tailings. However, from this study, it is clear that the CCBE placed over the reactive tailings effectively limited the generation of acid mine drainage. More details on these columns experiments are given in Aubertin et *al.* (1995, 1997) and in Aachib (1997).

4. *IN SITU* TEST PLOTS

Following these laboratory studies, *in situ* cells were constructed to evaluate, on a larger scale and under more realistic conditions, the performance of CCBE built with low sulphide tailings.

4.1 Description of the *in situ* cells

Three cells with covers made of low sulphide tailings were built during the summer 1995 on ITEC Mineral Inc.'s site, near Val d'Or, Québec, Canada. The configuration of the cells is shown in Figure 5. Each of the three CCBE covers had 3 layers placed on top of reactive tailings. The top layer was made from 0.3 m sand and the bottom is 0.4 m made from the same concrete sand. The fine material layer, placed between the two sand layers, was made of low sulphide tailings with a different thickness for each cell: 0.3 m for cell #3, 0.6 m for cell #1 and 0.9 m for cell #5. A control cell was also built to evaluate the performance of the CCBE in limiting the generation of AMD. The sulphidic tailings contain about 5% pyrite and are considered acid generating, with a Net Neutralization Potential (NNP) of -88 kg $CaCO_3$/tm (Bernier 1997). The basic characteristics of the different materials are presented in Table 1; these are very similar of those of the materials used for the above mentioned column test investigation.

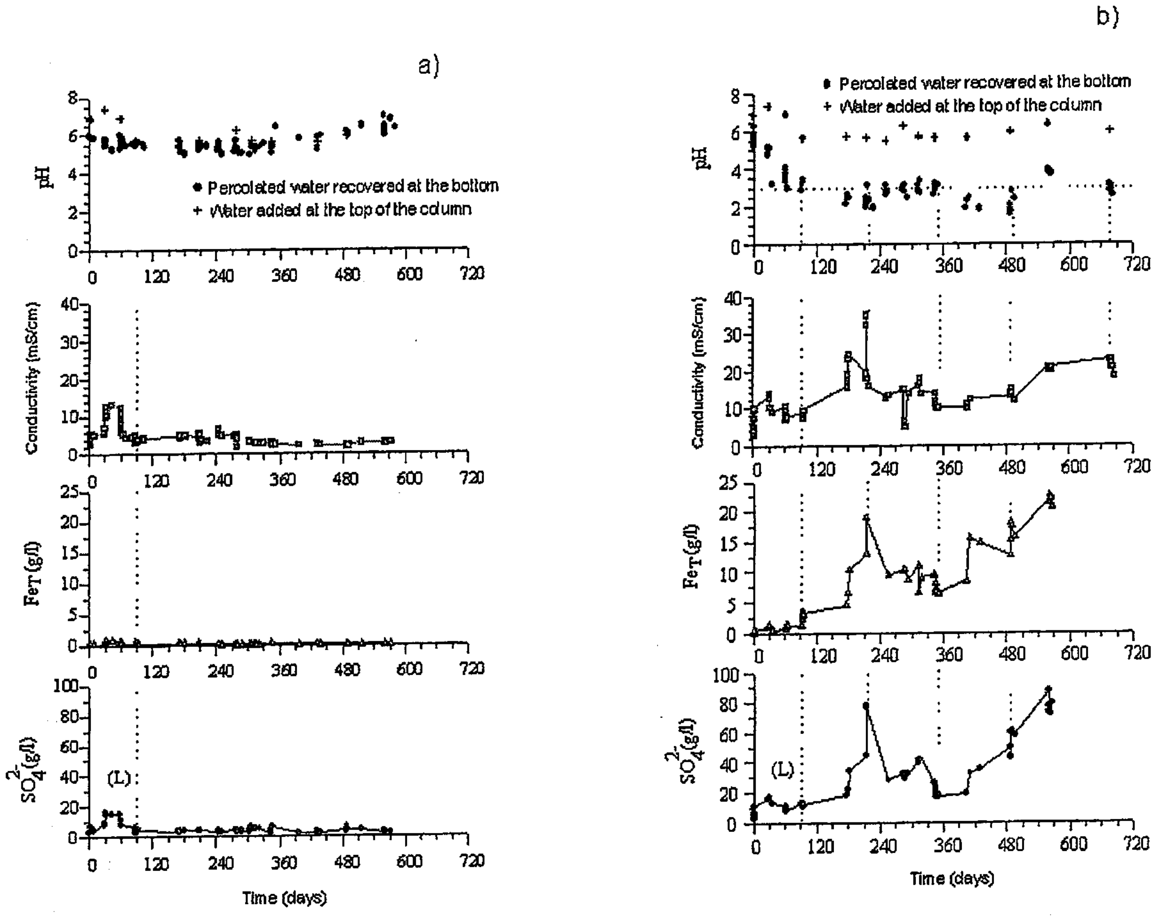

Figure 4. Water quality results for a) a covered column and b) for a control column.

4.2 Instrumentation and monitoring

The covers built for the experimental cells were instrumented and monitored between August 1995 and November 1998. The main parameters monitored included volumetric water content θ, matric suction ψ, and chemical composition of the leachate. A time domain reflectometry (TDR) technique (e.g. Zegelin et *al.* 1992; Aachib et *al.* 1993) was used to measure the volumetric water content. The matric suction was also measured in each of the three layers of the different covers, using Watermark sensors and Jet Fill Tensiometers (model 2725). Each of the sensors was located close to a TDR probe allowing a comparison between the θ-ψ relationships obtained in the laboratory and *in situ*.

As shown in Figure 5, the cell design also allowed for the collection of the percolated water in the underground reservoirs. During and after sampling, the chemical water characteristics were analyzed for pH, conductivity and, occasionally, sulfate and metal contents.

4.3 Results

During the field project, a number of measurements were made. All the results were included in the preliminary reports submitted to MEND and were also presented in a concise format within the final report (Aubertin et *al.* 1999).

Table 1. Some properties of the materials used in the experimental cells.

Properties	Sand	Low sulphur tailings	Sulphidic tailings
Grain size			
% gravel fraction	8-10	0	0
% sand fraction	85-88	15-25	70-77
% silt fraction	2-7	70-80	23-28
% clay fraction	0	4-5	0-2
Hydraulic conductivity (cm/s)	$3x10^{-2}$ to $5x10^{-2}$ for $0.30 < n < 0.32$	$2x10^{-4}$ to $5x10^{-5}$ for $0.4 < n < 0.46$	$2x10^{-3}$ to $3x10^{-4}$ for $0.36 < n < 0.44$
Air Entry Value (kPa*)	2 to 4 n=0.33	20 to 40 for $0.39 < n < 0.43$	7 to 11 for $0.38 < n < 0.42$

* 9.8 kPa = 1 m of water

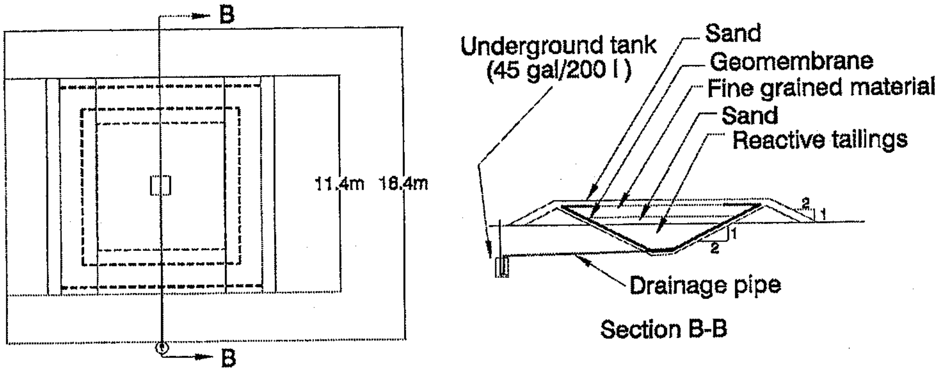

Figure 5. Typical configuration of test plots with CCBE placed on reactive tailings

4.3.1 Degree of saturation profiles

Figure 6 shows typical volumetric water content measurements (θ vs depth) for one of the five covered cells at different times. As expected, the value of θ was low in the two sand layers (usually between 0.05 to 0.15) and high in the fine layer (usually above 0.33). For cells #1, #3 and #5 (cells with low sulphur tailings as moisture retaining layer), the degree of saturation, corresponding to the measured volumetric water content, was usually above 85% to 90%. These saturation ratios are usually considered sufficient for limiting the generation of AMD from acid generating tailings (e.g. Ricard et *al.* 1997).

4.3.2 Water quality

Some water quality monitoring results are shown in Figures 7, 8 and 9. Figure 7 demonstrates that the pH of the percolated water from the covered cells #1, #3 and #5 remained above 6 for the entire experiment. On the other hand, the pH from the control cell leachates confirmed that the sulphidic tailings were acid generating, with drops in pH from approximately 6 for the first year to values of about 2 by the end of the experiment. The conductivity measurements were consistent with the measured pH values; high values were obtained for the percolated water from the control cell (from ≈ 10 to 50 mS/cm) while much lower values were measured in the water from the covered cells (between 2 to 3 mS/cm).

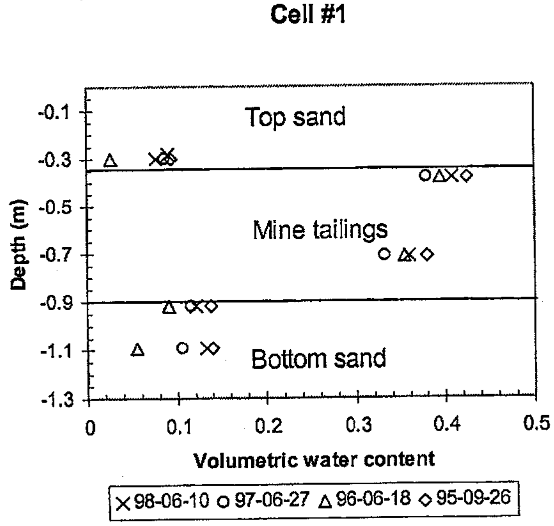

Figure 6. Typical volumetric water content profiles measured at different times during the *in situ* experiment.

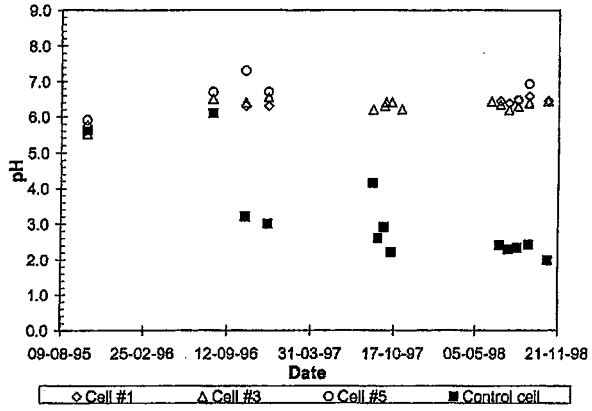

Figure 7. Evolution of the percolated water pH

Because sulphates are produced by the oxidation of sulphide minerals, the cover performance can also be evaluated from the sulphate concentration of the percolated water. Results presented in Figure 8 show that there is an approximate difference of two orders of magnitude in the sulphate concentrations between the control cell and covered cells. This means that the oxidation is reduced by approximately two orders of magnitude, even if the precipitation of secondary minerals (like gypsum and jarosite) in the control cell is ignored (nevertheless, these minerals were observed). The relative performance of the covers can equally be evaluated by comparing metals concentration in the water from the control cell and the water from the covered cells. For cells #1, 3 and 5, Figure 9 indicates an approximate reduction in zinc concentration of 3 to 4 orders of magnitude. Similar results were observed for copper and iron.

It can therefore be said that the covers, were efficiently designed and constructed, although the individual efficiency varied according to the specific configuration and material characteristics; more details on these experiments are given in the final MEND report (Aubertin et *al.* 1999)

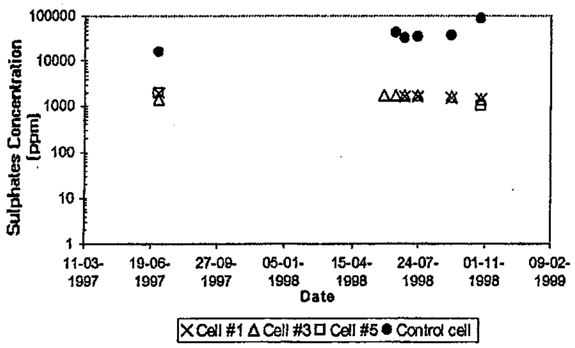

Figure 8. Concentrations measured in the cells leachate for sulphates

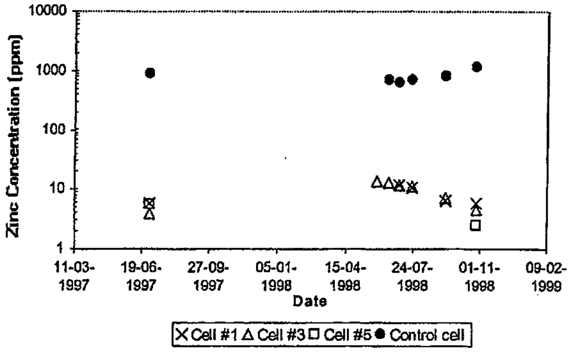

Figure 9. Concentrations measured in the cells leachate for zinc

5. CONCLUSION

This paper presents the results of a detailed study on the behavior of CCBE acting as oxygen barriers to reduce the generation of AMD. A key feature of the studied cover systems was that one of the layers was made of low sulphide tailings. The laboratory and field studies demonstrate the good performance of the covers in which the low sulphide tailings acted as a moisture retaining layer. For the duration of the test periods, both the field and laboratory results indicate that there was little or no oxidation generated from the reactive tailings protected by the covers.

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