An evaluation of the elevated water table concept using laboratory columns with sulphidic tailings
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ABSTRACT
The elevated water table concept is a potentially effective means of reducing acid mine drainage from reactive tailings impoundments. The effectiveness of the technique, based on a controlled phreatic surface position, depends on many factors including the capillary retention properties of the waste material, climatic conditions, water balance of the impoundment, as well as the tailings mineralogy and buffering capacity. In this study, an investigation was undertaken to evaluate the effectiveness of an elevated water table for controlling acid mine drainage from mine tailings. The laboratory experiments used columns of tailings from the Louvicourt Mine in Quebec, Canada. The columns had different water table elevations and were subjected to transient recharge. Oxygen consumption and aqueous chemistry of the drainage water were monitored at regular intervals. The results of this study showed that an elevated water table can be very effective in reducing acid mine drainage.

RESUME
La technique de la nappe surélevée est considérée comme un moyen efficace pour réduire le drainage minier acide de résidus miniers réactifs. L'efficacité de la technique, qui est basée sur un contrôle de la position de la surface phréatique, dépend de plusieurs facteurs incluant les propriétés capillaires des résidus, les conditions climatiques et le bilan d'eau du parc, ainsi que de la minéralogie et de la capacité tampon des résidus. Dans cette étude, des essais en colonne sur des résidus réactifs de la mine Louvicourt située au nord de la province du Québec (Canada) ont été réalisés en laboratoire pour évaluer l'efficacité de la méthode de la nappe surélevée dans le but d'empêcher la production de drainage minier acide. La position de la nappe a été fixée à différents niveaux dans les colonnes en tenant compte de la courbe de rétention en eau des résidus miniers. Les résultats obtenus montrent que l'application de la méthode de la nappe surélevée peut être très efficace dans la réduction du drainage minier acide.

1. INTRODUCTION
Over the past several years, the concept of an elevated water table has been considered as a possible option for management and closure of mine tailings impoundments. The interest in this new technology is related to its physical and economic advantages. For example, with an elevated phreatic surface in the tailings, the sulphide oxidation rate could be reduced to that of a full water cover, while improving the geotechnical stability of the engineered works. According to MEND (1996), various studies have suggested that important cost savings can also be realized with this technology. However, since this is a relatively recent tailings management concept, data are scarce with regard to its effectiveness and optimal design conditions are not well defined. The present research project has been motivated by these and other important questions.

The principle of an elevated water table is based on maintaining a sufficiently high degree of capillary saturation within the tailings above the water table in order to inhibit sulphide oxidation. A conceptual model of an elevated water table in reactive tailings is shown in Figure 1 for the case of a peripheral dam with an impermeable core or in the case of hillside deposition. Previous research on existing reactive tailings sites has shown a correlation between the depth of the water table and the flux of oxygen (Elberling and Nicholson 1996; Tibble, 1997; Tibble 1997; Nicholson and Tibble 1997; Elberling and Damgaard 2001; Dagenais, 2005). Laboratory experiments have also shown the influence of the degree of saturation within the tailings on the rates of sulphide oxidation (Elberling and Nicholson 1996; Tibble 1997; Hollings et al. 2000; Mbonimpa et al. 2003; Dagenais, 2005).
Reactive tailings

2. MATERIALS AND METHODS

To evaluate the effectiveness of the elevated water table concept as a management and reclamation method for acid-generating mine tailings, column tests were performed with sulphidic tailings from the Louvicourt Mine, Quebec, Canada. The tailings were characterized according to their mineralogical and chemical properties, acid generating potential and hydro-geotechnical properties. The results are presented in the following sections.

2.1. Sample characterization

The Louvicourt tailings are fresh, unoxidized, and sulfur rich (34-40 wt % of pyrite). They were collected directly at the concentrator. To prevent pre-oxidation, the samples were preserved under water until the start of the laboratory experiments.

The grain size distribution was determined with a Mastersizer laser granulometer (Malvern Inc.), and also with standard sieving procedures. The results, consistent with previous studies by Li and St-Arnaud (2000) and Vigneault (2001), showed that the Louvicourt mine tailings are mainly composed of particles in the silt and fine sand fractions with a percentage passing 80 µm of about 90 % (and 80 % passing 40 µm). The effective diameters, corresponding to 10 % (D10) and 60 % (D60) passing on the cumulative grain size distribution curve are 2.06×10⁻⁴ cm and 2.38×10⁻³ cm respectively. The solid relative density Ds (or specific gravity Gs) is 3.513, determined by a procedure based on the ASTMD854-91 standard. For mineralogical analyses, an X-Ray diffractometer (PHILLIPS model, CuKα 1,542 Ångströms) and an optical microscope were used. The results showed that the Louvicourt tailings consist of silicates such as quartz (21 wt.%), chlorite (11%), muscovite (7%), and paragonite (6%). The primary sulphide mineral is pyrite (up to 40wt.%), while chalcopyrite, sphalerite and galena exist in trace amounts. Carbonates are represented by dolomite (4wt.%), magnesite (4%) and ankerite (<1%). The primary oxide mineral is magnetite (4%).

The saturated hydraulic conductivity of the tailings (ksat,G) was evaluated using rigid and flexible wall permeameter tests and with the modified Kozeny-Cambrin relation (eq.1) (Aubertin et al., 1996; Mbonimpa et al., 2002), written as:

\[ k_{sat,G} = C_G \frac{\gamma_w e^{(3+x)}}{\mu_w (1+e)} C_u^{1/3} D_{10}^{-2} \]  \[ \text{(1)} \]

where \( e \) is the void ratio, \( \gamma_w [ML^{-2}T^{-2}] \) is the unit weight of water (9.81 kN/m³), \( \mu_w [ML^{-1}T^{-1}] \) is the dynamic viscosity (10⁻⁵ Pa.s), \( x = 2 \) is a parameter introduced in the void ratio function to account for the effect of tortuosity, \( C_G \) is a constant used in the general equation proposed for granular materials (=0.1), and \( C_u \) is the uniformity coefficient (D60/D10).

The results show that the ksat of the Louvicourt mine tailings is in the range 10⁻⁶ - 10⁻⁵ cm/s for a void ratio of 0.5 - 0.7.

The water retention curves of the materials were determined in Tempe cells using a procedure based on the ASTM D3152-72 standard; nitrogen is used to induce gas pressure in the cell, to avoid oxidation during the tests. The water retention curves were also predicted with the modified Kovacs (MK) model equations (eq.2 to 6) (Aubertin et al., 2003):
\[
S_r = \frac{\theta}{n} = S_c + S_a^* (1 - S_a)
\]  
[2]

with

\[
S_a^* = 1 - (1 - S_a)
\]  
[3]

\[
S_a = a_c C_\psi \left( \frac{h_{co}}{\psi_n} \right)^{2/3} e^{1/3} \left( \frac{\psi}{\psi_n} \right)^{1/6}
\]  
[4]

\[
S_c = 1 - \left[ (h_{co} / \psi)^2 + 1 \right]^{-m} \cdot \exp\left[ -m (h_{co} / \psi)^2 \right]
\]  
[5]

\[
C_\psi = 1 - \frac{\ln(1 + \psi / \psi_r)}{\ln(1 + \psi_0 / \psi_r)}
\]  
[6]

where \( h_{co} \) [L] is the equivalent capillary rise in the porous medium, \( m [-] \) is the pore size distribution parameter in the MK model (\( m = 1/C_u \)), \( C_u [-] \) is the uniformity coefficient, \( a_c [-] \) is the adhesion coefficient (\( a_c = 0.01 \)), \( e [-] \) is the void ratio, \( \psi [L] \) is the water suction (head), \( \psi_n [L] \) is the normalised suction (\( \psi_n = 1 \) cm when \( h_{co} \) and \( \psi \) are expressed in cm), \( \psi_0 [L] \) is the suction at complete dryness, (\( \psi_0 = 10^3 \) cm; e.g. Lu and Likos, 2004), \( \psi_r [L] \) is the residual suction, and \( C_\psi [-] \) is a correction factor for full dryness introduced by Fredlund and Xing (1994).

The results in Figure 2 show that the Air Entry Value (AEV) of the Louvicourt mine tailings obtained by experiment is around 400 cm, which is in the same range as the AEV obtained from the WRC calculated with MK model (also shown in Fig. 2).

The chemical composition of the tailings was determined by Inductively Coupled Plasma analysis (ICP-AES) after acid-Bromine digestion. Dilute HCl was used to extract sulfates and the resultant solution was analysed by ICP-AES. The silica content was determined by ICP-AES analysis following a Na\(_2\)O\(_2\)/NaOH fusion. The results show that the Louvicourt mine tailings are rich in Fe (27.3 wt%) and S (19.5 wt%) because of the presence of pyrite. Total sulphur and total inorganic carbon were obtained with the LECO CS-400 Carbon/Sulfur Series apparatus. The results were consistent with the ICP-AES analyses.

Acid-Base Accounting tests (ABA), were performed using the Sobek procedure (Sobek et al., 1978). The net neutralization potentials (NPN) were calculated by subtracting the acid generation potential (AP) from the neutralization potential (NP). The results gave an AP of 599.7 kg CaCO\(_3\)/t and a NNP of -558.3 kg CaCO\(_3\)/t. The PN/PA ratio is 0.07. These results show that the Louvicourt mine tailings can be interpreted as being highly acid generating with NNP values less than -20 kg of CaCO\(_3\)/t (e.g. SRK, 1989).

Figure 2. Water retention curves obtained from laboratory experiments (Exp.) and from the MK model (see text).

2.2 Column test equipment and methods

Figure 3 shows a typical experimental column. Each column was constructed from a Plexiglas cylinder with an inside diameter of about 0.1 m and a length of 0.50 m. The columns were equipped at the bottom with a ceramic plate to provide water table control. The ceramic plate has 0.5 bars of bubbling pressure, a saturated hydraulic conductivity of 3×10\(^{-5}\) cm/s and a thickness of 6.35 mm. A valve at the bottom of the column is connected to a bottle by a U-shape plastic pipe which permits application of suction (by controlling the position of the outlet) and sampling of leachate solutions. A removable TDR (Time Domain Reflectometry) electrode (Soilmoisture Trase 6050X1) with a length of 8 cm was used to measure the water content in the sand layer placed above the tailings; this layer serves as a capillary break to prevent excessive desiccation by evaporation. A temporary cap placed on the upper part of the column was equipped with an oxygen sensor to measure the oxygen consumption rate over short periods of time (2-5 hrs.) during the tests.

2.2.1 Tailings Consolidation

To reproduce their in situ depositional conditions, the tailings were consolidated within the column to a final height of 15 cm (Figure 3) and a void ratio of approximately 0.8. Before emplacing the tailings in the column, and to facilitate consolidation, some supernatant was extracted leaving an initial volumetric water content of approximately 0.50. The initial void ratio was approximately 1.2. Deformation due to load application was monitored directly with a comparator. Loading proceeded by successive increments of 8 to 16 kg every 24 to 48 hours, after dissipation of the pore water pressure. The final equivalent vertical stress was about 78 kPa. The water expelled on the surface of the tailings
in the column was collected and the 20 cm sand cover layer was then added.

2.2.2 Column test configuration and characteristics

Four columns were prepared for the experiments on the Louvicourt tailings (Table 1); other columns (not discussed here) were also mounted with other tailings mixtures. The mean experimental AEV is 425.0 cm while that predicted with the MK model is 299.3 cm. For sand, the estimated AEV is 17.5 cm whereas the experimental AEV is 15.3 cm. The columns were generally prepared as shown in Figure 3 except for column 12 (free draining control column), which contained only tailings and did not have a ceramic plate at the bottom nor sand on top.

Table 1. Experimental column characteristics

<table>
<thead>
<tr>
<th>No.</th>
<th>n</th>
<th>e</th>
<th>Wi(1) wt%</th>
<th>Sr wt%</th>
<th>k_sat (cm/s)</th>
<th>Ψ (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.45</td>
<td>0.78</td>
<td>42.4</td>
<td>97.1</td>
<td>1.60e-5</td>
<td>227.8</td>
</tr>
<tr>
<td>4</td>
<td>0.46</td>
<td>0.84</td>
<td>41.8</td>
<td>92.0</td>
<td>2.27e-5</td>
<td>150.4</td>
</tr>
<tr>
<td>6</td>
<td>0.44</td>
<td>0.80</td>
<td>42.6</td>
<td>95.8</td>
<td>1.86e-5</td>
<td>77.0</td>
</tr>
<tr>
<td>12</td>
<td>0.43</td>
<td>0.75</td>
<td>39.9</td>
<td>93.0</td>
<td>1.35e-5</td>
<td>0.0</td>
</tr>
<tr>
<td>Sand(2)</td>
<td>0.40</td>
<td>0.73</td>
<td>5.0</td>
<td>18.0</td>
<td>0.10</td>
<td>0.0</td>
</tr>
</tbody>
</table>

(1) Wi is the initial volumetric water content
(2) sand layer for all columns

2.3 Column preparation

The position of the water table was fixed at different levels as shown in Table 1. Column 1 had the highest suction and therefore the lowest water table. The columns were flushed monthly with approximately 570 cm³ of deionized water. The leachate was collected and analysed for chemical parameters. Redox potential, pH, conductivity, and salinity were measured as soon as possible after sampling with a WTW multilines P3 pH meter equipped with one pH electrode, one conductivity electrode, and a Ag/AgCl redox potential electrode. A spectrophotometer was used to analyze sulfates, iron and alkalinity. Acidity was measured by titration with a HACH Digital Titrator Model 16900 using the Phenolphthalein total method. The main soluble species were analyzed by ICP-AES.

3. RESULTS AND DISCUSSION

3.1. Geochemical data

In this section, the results obtained during the column test investigations are analyzed in relation to the performance of the elevated water table as a method to limit AMD production.

3.1.1 pH and conductivity

The pH remained high (greater than 7) for the four column tests (Figure 4a), over 260 days since the start of the tests. However, the pH decreased slightly for column 1 which had the highest suction. The ORP values showed no significant variation and are therefore not shown here. The conductivity values (Figure 4b) were higher for column 1 which suggested that mineral dissolution was being governed by oxidation and neutralization reactions, as also found by Benzaazoua et al. (2004). For columns 4, 6 and 12, the conductivity values decreased suggesting only limited mineral dissolution.

3.1.2 Sulfate, iron, zinc

The results show that in column 1 there was a net production of sulfate (Figure 4c) while in columns 4, 6, and 12 sulphate was progressively depleted through the flushing cycles. The highest values of iron (Figure 4d) and zinc (not shown) were found in column 1 which reflects oxidation of the sulphide minerals. The low iron concentrations in the other columns was likely related to...
the Eh-pH conditions which favour precipitation of iron oxy-hydroxides. Cu (not shown in Figure 4) was also somewhat higher in column 1. Within the other columns, these components decreased with time.

3.1.3 Calcium, magnesium and manganese
As proposed by Benzaazoua et al (2004), these elements are likely the products of neutralization reactions in the columns. Most of these elements are assumed present as carbonates. The results (Figure 4e) highlight the relative importance of neutralization phenomena in column 1 compared to the other columns (in response to greater sulphide mineral oxidation; see sulphate concentrations). It should also be noted that the evolution of calcium, magnesium and manganese closely followed that of sulfate for all columns.

3.1.4 Silicon, aluminum, potassium, sodium
The presence of these elements is the result of silicate dissolution. According to the results obtained from the leachate (not shown), silicate dissolution seemed to be somewhat effective in column 1 but not in the other columns.
3.2. Oxygen consumption

The specific effect of the degree of saturation on the effective diffusion coefficient $D_e$ and the reaction rate $K_r$ has been intensively investigated over the years (e.g. MEND 2001, Mbonimpa et al. 2003). It has been shown that enhancing water retention impedes the flux of oxygen in reactive tailings and constitutes a practical approach for controlling the production of acidic leachate (e.g. Aubertin et al. 1999).
In this study, oxygen consumption was measured as shown in Figure 3. Measurement data were interpreted using the POLLUTE v6 model (Rowe et al. 1994) to estimate $D_a$ and $K_r$ (see Mbonimpa et al. 2003 for details). $D_e$ was also determined with equation 7 from Aachib et al. (2002; 2004) and $K_r$ with equation 8 from Collin and Rasmuson (1988):

$$D_e = \frac{1}{n^2} (D_a^{p_a} + 3D_w^{p_w})$$  \hspace{1cm} [7]$$

$$K_r = K' \frac{6}{D_H} (1 - n) C_p$$  \hspace{1cm} [8]$$

where $n$ is the porosity, $p_a$ and $p_w$ are exponents which are assigned $p_a = p_w = 3.3$, as suggested by Aachib et al. (2002), in the air and water phases, respectively, $H$ is Henry's constant $\geq 0.03$, $D_a^{p_a} [L^2T^{-1}]$ is the free oxygen diffusion coefficient in water $\geq 2.5 \times 10^{-7} m^2/s$, $D_w^{p_w} [L^2T^{-1}]$ is the free oxygen diffusion coefficient in air $\geq 1.8 \times 10^{-9} m^2/s$, $D_H [L^2T^{-1}]$ is the intrinsic reactivity of pyrite with oxygen ($K' = 15.8 \times 10^{-3} m^3O_2/m^2 pyrite/year$), and $C_p [\cdot]$ is the pyrite content per mass of dry tailings. $D_H [L]$ is determined by equation 9 from Aubertin et al. (2003):

$$D_H = [1 + 1.7 \log(C_p)]D_{10}$$  \hspace{1cm} [9]$$

The results show that oxygen diffusion seems to be more important in column 1, and that experimental results are similar to the numerical results obtained with POLLUTE v6. For example, with an estimated degree saturation of 0.93, $D_e$ is $5.98 \times 10^{-10} m^2/s$ and the reaction rate $K_r$ in column 1 is $1.81 \times 10^{-4} s^{-1}$ whereas in column 4 with a saturation of 0.97, $D_e$ is $8.53 \times 10^{-11} m^2/s$ and $K_r$ is $1.04 \times 10^{-9} s^{-1}$.

These results are consistent with the geochemical data which show that sulphide oxidation and sulphate production are more important in column 1. More work is needed, however, to further confirm these results and to extend the use of the reactivity prediction model (eq. 8) to highly saturated tailings.

4. ONGOING WORK

Large columns with a length of 150 to 200 cm (depending on the tailings’ AEV) and an inside diameter of 15 cm have also been filled with Louvicourt mine tailings and other tailings mixtures and have been prepared in approximately the same manner as the small columns described in this article. The small columns will help understand how the large columns function. The suction applied at the bottom of all columns (small and large) will be changed with time in order to better evaluate the critical effect of the position of the water table on sulphide oxidation. Monitoring of bacterial activity is also ongoing and will be used to determine the influence of bacteria on oxidation. The experimental results will be compared with numerical simulations using the MIN3P reactive transport model (Mayer et al., 2002). MIN3P includes fully coupled transient unsaturated flow, saturation-dependent oxygen diffusion, sulphide mineral oxidation, mineral buffering and transport of the aqueous reaction products.

5 CONCLUSIONS

Reactive mine tailings management is one of the most important environmental problems of the mining industry. Water covers have been recognized as effective techniques among several alternatives for preventing or controlling the production of acid mine drainage (AMD). However, one of the greatest difficulties related to the application of this technology is to maintain functional infrastructure over the long term. The elevated water table technique, which can be regarded as a particular case of water cover, constitutes an interesting alternative in which the tailings above the water table are maintained in a near or total saturated state by capillarity. If properly applied, this technique works well because the diffusion coefficient of oxygen is orders of magnitude less in water compared to that in air. The main goal of this research project is the evaluation of the effectiveness of the elevated water table technique. Although this technique has recognized advantages including a rate of oxidation comparable to that found under water covers, a low installation cost and improved geotechnical stability, the optimal conditions and parameters are not well defined and little lab or field data exist. By analyzing the existing data, one can surmise that the most important factors which control the effectiveness of this technique are the hydraulic parameters of the tailings, and their mineralogical composition. This is clearly evident from the results of our laboratory experiments. The results obtained in this study show that fixing the position of the water table at a value of about half the Air Entry Value of the Louvicourt tailings is sufficient to inhibit sulphide oxidation and to prevent acid mine drainage.

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