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Column tests to assess water flow and oxygen transport in a monolayer cover placed on acid generating tailings

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Abstract

This study focuses on the reclamation work being performed on an old acid generating tailings site, located in Quebec, Canada. The tailings are partially oxidised due to extended exposure, so the pore water is already acidic. A monolayer cover, made of non acid-generating tailings, is being considered to control acid mine drainage. The goal of the investigation is to assess the behaviour of the tailings-cover system under various conditions, and also, if needed, evaluate alternative reclamation options. To do so, tailings samples were collected in situ and characterised in the laboratory. Large columns have been set up to evaluate the hydrogeological and geochemical response of the tailings and cover following wetting cycles. The instrumented columns were designed to reproduce some of the existing site conditions and provide representative results for long term analyses. Monthly wetting and drying cycles were repeated to simulate climatic conditions. The water content, suction, and oxygen concentration were monitored over time. Experimental data are used to calibrate and to help validate numerical models constructed with Vadose/W (GeoSlope Inc.). Additional simulations are conducted to evaluate the effect of various influence factors, such as depth of the water table and material properties. Alternative cover configurations are also tested. The results presented in this paper focus on unsaturated water flow in the tailings-covers system, and on the diffusive oxygen flux.

1 Introduction

Tailings from hard rock mines often contain iron sulphides that can react with oxygen and water to generate acid rock drainage (ARD). The resulting effluent is characterised by a low pH, high concentrations of dissolved metals and sulphates, and high electrical conductivities (Jambor, 1994). Different reclamation methods are available to control this problem, such as water covers (Yanful and Catalan, 2002), multi-layered covers (Nicholson et al., 1989; Aubertin et al., 1994, 2006; Bussière et al., 2003, 2006), and single-layer covers with an elevated water table (Orava and Swinder, 1996; Ouangrawa et al., 2009, 2010). These methods rely on a low oxygen flux through water or nearly saturated soils, which is typically more than 104 times slower than in the air phase (Collin and Rasmusson, 1988; Aachib et al., 2004).

Reclamation plans need to be optimised for the site conditions, and their effectiveness is usually improved when defined well ahead of closure. Unfortunately, there still remain some old tailings sites where the reclamation work is being initiated well after the end of the mine operation.

This paper focuses on the behaviour of such an old acid-generating tailings site located in Quebec, Canada. The reclamation method being used on this fairly large site consists of adding a layer of slightly alkaline (non acid-generating) tailings, produced at a new mine nearby, on the surface of the reactive tailings. The reclamation work also involves raising the position of the water table in the tailings to increase their degree of saturation by submersion or capillarity (depending on the location). The goal of this study was to assess the behaviour of the tailings-cover system in order to determine the efficiency of the monolayer cover. Experimental data obtained from laboratory column tests were used to calibrate and validate (in part) the numerical models constructed with Vadose/W (GeoSlope Inc.). Additional simulations were conducted to evaluate the effect of various factors, such as climatic conditions, cover thickness, depth of the water table and material properties. Alternative cover configurations were also analysed. Some of the experimental and calculation results are presented and discussed in the following. Geochemical issues related to this investigation are presented in a companion paper (Pabst et al., 2011).

2 Materials and laboratory set-up

Two large samples of reactive tailings were collected in situ in 2007; these are identified as M1 (fine-grained tailings) and M2 (coarser tailings). Non acid-generating tailings C1, used as cover material, were provided by the operating mine involved in the reclamation work. The materials have been extensively characterised in the laboratory. The programme included the determination of basic properties, i.e. grain size distribution curves, relative density (specific weight) of solids, and mineralogy (XRD). The experimental programme also comprised tests for the water retention curve (WRC) using modified Tempe cells. The measured WRCs have been combined with the MK predictive model (Aubertin et al., 2003) to define the curves for varying grain size and porosity. Flexible wall permeameters were used to measure the saturated conductivity k_{sat}. The experimental results were compared with predictive estimates obtained from the Kozeny-Carman model (Chapuis and Aubertin, 2003) and the KCM model (Mbonimpa et al., 2002), which were also used to adjust the value of k_{sat} for varying conditions. Oxygen diffusion and consumption parameters were also evaluated, using previously developed laboratory (Mbonimpa et al., 2003) and in situ procedures (Mbonimpa et al., 2002; Bussière et al., 2003). Some of the main characteristics of the tailings and cover material are summarised in Table 1. Detailed results are presented in Pabst (2011).

Instrumented columns (230 cm in height, and 15 cm internal diameter) were set up in the laboratory to study the hydrogeological and geochemical behaviour of the tailings–cover systems. The column tests follow a methodology developed over several years (Aachib et al., 1994; Aubertin et al., 1999; Bussière et al., 2004; Ouangrawa et al., 2010). The configurations were selected to reproduce some of the site conditions and to provide representative results for the calibration of numerical models. Two large column tests will be discussed here: column M1C1 (170 cm of fine M1 tailings with 40 cm of C1 tailings cover) and column M2C1 (170 cm of coarse M2 tailings with 40 cm of C1 tailings cover). Smaller columns (50 cm in height, 10 cm in diameter) were also included with the reactive tailings only to investigate their geochemical behaviour when left uncovered; these latter tests are discussed in a companion paper (Pabst et al., 2011). The experimental programme also included geochemical analyses of the leachate (not presented here; see Pabst, 2011, for further details); the broad investigation also involved additional column tests and field work (Bussière et al., 2011).

The top of each column was open to the atmosphere during the wetting-drainage cycles, so evaporation played a role during these tests. A ceramic porous plate was placed at the base of the columns to control the pore water pressure, which is defined by the water table position, using a small flexible U-tube (which remained saturated at all time). The reference position of the water table was set at 90 cm below the base of the columns, i.e. about 300 cm below the surface of the monolayer cover. The U-tube was also used to collect leachate for chemical analyses (Pabst et al., 2011). Temperature (T), relative humidity (RH) and pan evaporation were monitored for the duration of the tests.

The type and position of the various sensors was the same in both columns. Three TDR probes (SoilMoisture) were placed 10 cm above and 10 and 30 cm below the tailings-cover interface to measure the volumetric water content (θw). The probes are made of three metallic rods, with the central rod coated when used in acid-generating tailings. These were calibrated prior to the column tests, using several samples of tailings and sand (with water having different electrical conductivities). These measured values of θw were confirmed during dismantling of the columns by comparing the TDR readings with the actual volumetric water content. Capacitance probes (ECH2O EC^{-10}, Decagon) were also placed near the top of each column to measure volumetric water content in the cover. The latter were also calibrated.

Water-filled tensiometers (Omega +/- 5 psi, or 34.5 kPa, within the tailings, and +/- 15 psi, or 103.4 kPa, in the cover) were installed close to the TDR probes to measure pressure head. To maintain full saturation, the ceramic cups were refilled with a small amount of de-aired water prior to each drainage cycle. Both volumetric water content and suction measurements were used to define the actual WRCs of the materials within the columns. Optical oxygen sensors (Oxy10, PreSens) were also installed to monitor dissolved and gaseous oxygen concentrations at two locations: 10 cm above and 10 cm below the tailings-cover interface.

A schematic view of the column set-up is presented in a companion paper (Pabst et al., 2011).

The columns were initially saturated with the water table located above the cover. After a first drainage cycle, monthly wetting and drainage (drying) cycles were applied to simulate, in a simplified (but controlled) manner, the site climatic conditions. Every 30 days or so, 1700 cm^3 (about 10 cm) of deionised water was added at the top of the columns. Free (ponding) water was seen on top of the C1 tailings cover for about 4 days. A total of 19 cycles (692 days) were applied to column M1 and 12 cycles (496 days) to column M2.

Table 1 Material geotechnical characteristics and WRC parameters (D_r: relative density; $C_U = D_{60}/D_{10}$: coefficient of uniformity; k_{sat}: saturated hydraulic conductivity; α_v, n_v, m_v, θ_{sat} and θ_r: van Genuchten (1980) model parameters for draining WRC)

	D_r (-)	D_{10} (cm)	C_U (-)	k_{sat} (m s^{-1})	α_v (m^{-1})	n_v (-)	m_v (-)	θ_{sat} (-)	θ_r (-)
M1	3.136	0.056	12.7	$5.3.10^{-7}$	0.055	1.52	0.34	0.438	0.000
M2	2.766	0.044	42.4	$1.1.10^{-6}$	0.400	1.60	0.38	0.401	0.000
C1	2.769	0.038	10.9	$7.7.10^{-7}$	0.175	1.84	0.46	0.422	0.000
WR	-	-	-	$1.2.10^{-4}$	14.5	3.50	0.71	0.250	0.000

3 Numerical modelling

3.1 Vadose/W

Vadose/W 2007 (GeoSlope Inc.) was used in this study to simulate water flow and oxygen diffusion in the columns. This 2-D code shares many similarities with the (1D) Soil Cover code (Wilson et al., 1999) and with Seep/W (also from GeoSlope). Vadose/W is a finite element code that includes climatic boundaries, surface ponding, and soil-atmosphere liquid and gaseous exchanges. This commercial code is commonly used to assess the behaviour of tailings and covers (Shakelford and Benson, 2006; Adu-Wusu et al., 2007; Gosselin, 2007; Cissokho, 2007; Demers et al., 2009).

3.2 Column tests modelling and calibration

Each column is simulated as a 2-D flow domain (Vadose/W constraint), with one cell per elevation (i.e. each element has the width of the column) and impervious lateral walls which reduces flow to a vertical 1D condition. The height of each element is 1 cm for column modelling (calibration), and 5 cm for the additional field simulations (which are larger and have more complex boundary conditions due to climate fluctuations). Comparisons have shown no difference between both mesh sizes.

The WRCs for the different materials are expressed using the van Genuchten (1980) equation. Their determination follows a systematic method. A first version of the curve is obtained from Tempe cell tests results, which are then corrected for different porosity with the MK model (Aubertin et al., 2003). The resulting curves are compared with volumetric water content and suction values measured during the wetting and drying cycles in the large columns. Preliminary simulations of the column tests are then run to assess if minor corrections are needed for the WRCs (to reproduce experimental data). Figure 1a shows the resulting drying and wetting curves for M1 tailings (similar results are obtained for the other materials). Figure 1b presents the drying WRCs for the different materials, with the corresponding parameters summarised in Table 1.

As can be seen in Figure 1a, the data collected during the wetting-draining cycles tend to show some hysteresis, particularly at low suction. Similar observations have been reported in previous column experiments (Aachib, 1997; Ouangrawa, 2007). Vadose/W does not take hysteresis of the WRC into account. However, this can be an important factor when evaluating cover efficiency. The WRCs for each material have thus been based on the wetting curves (obtained from the column tests) in the numerical calculations (after the first cycle) to better reflect the experimental observations.

The unsaturated conductivity functions (k_u) are predicted using the Mualem (1976) formulation, based on the parameters of the WRC expressed with the van Genuchten (1980) equation (Table 1). The value of the saturated hydraulic conductivity (k_{sat}) was measured in the laboratory, and adjusted with the KCM predictive model (Mbonimpa et al., 2002) for the measured porosity. Hysteresis of the permeability functions was obtained by using the Mualem (1976) function with both WRCs (wetting and drying).

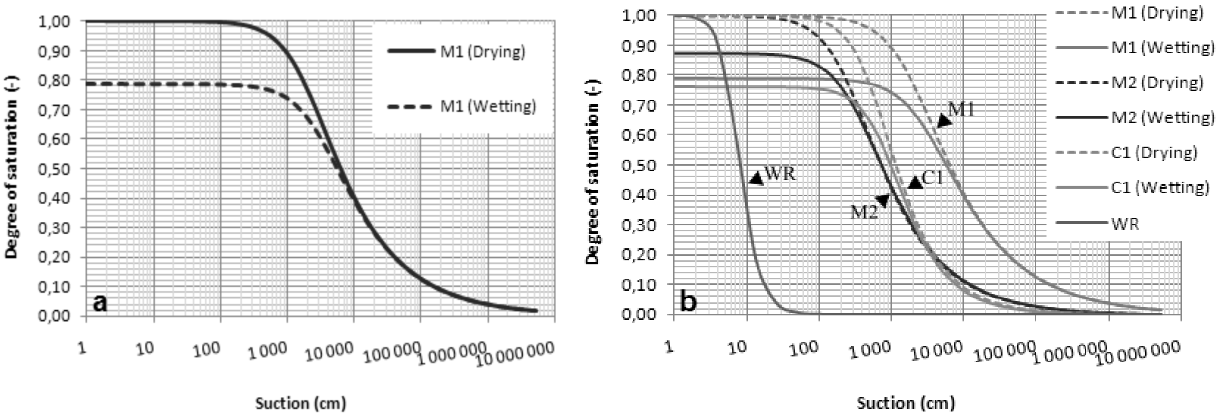

Figure 1 **Water retention curves used in the simulations with Vadose/W (based on the van Genuchten (1980) equation); a) curves adjusted to the column test results (for reactive tailings M1) following initial drainage and further wetting; b) WRC for all materials used in the simulations**

The boundary condition imposed at the base of the model is of Type-1 (i.e. Dirichlet boundary condition), with a fixed suction that simulates the water table depth. The top boundary is climate-controlled, with imposed temperature, relative humidity (maximum and minimum T and RH values, with sinusoidal variations for each day), and precipitation (wind speed is null in the laboratory). Potential evaporation (PE) rates are calculated from these parameters by Vadose/W; observations indicate that the calculated PE tends to be slightly overestimated (when compared with pan evaporation measured in the laboratory). Recharge is simulated as a short duration event during which 10 cm of water are added in one hour (and then left to pond over the surface). The precipitation is zero for the rest of the cycle, during which water is allowed to infiltrate and flow in the column.

Convergence parameters are evaluated from Gauss point conductivities, based on a tolerance of 0.01%. Adaptive time stepping is used with 2.5 % maximum change for the nodal heads per step, with minimum and maximum time steps of respectively 0.01 second and 1 day.

The U-tube used to apply the suction at the base of the experimental columns is simulated as a fictional material. The water content of the corresponding WRC is set constant (ensuring that it is always saturated) and equal to the ratio of the true tube volume over its modelled volume (i.e. $\theta = 1.56 \cdot 10^{-4}$). The tube hydraulic conductivity is taken equal to the saturated conductivity of the ceramic at the base of the columns ($k_{sat} = 3.1 \cdot 10^{-7}$ m/s).

3.3 Simulation of field conditions and alternative covers

Once the column models have been calibrated to reproduce experimental measurements, the same material parameters are used to simulate field conditions. The model geometry is a vertical pseudo-1D model. The thickness of the cover is increased to 1 m to better represent the field configuration. The top condition is a climatic boundary calculated from field data. During the winter months, the surface is frozen, and neither water nor gas can cross the cover. Cryosuction early in the winter and surface infiltration due to snow melt in the spring are assumed to partially resaturate the cover. The draining WRC of the cover material is used in the models until the volumetric water content decreases below the maximum satiation, after which the wetting curve is used again. Only the wetting curves are used for tailings M1 and M2 under the cover.

The final water table elevation in situ may vary over time and space, so several cases have been modelled. The water table was set at 2, 4 or 6 m below the tailings-cover interface; in situ measurements (in 2009) indicate that the water table can be as deep as 7 m below the surface of the reactive tailings.

The response of the monolayer cover is compared with a typical layered cover with capillary barrier effects, (CCBE), aimed at controlling the oxygen flux (Aubertin et al., 2002, 2006). The latter includes a 1 m thick waste rock layer between the reactive tailings and the C1 tailings layer, and another 1 m of waste rock on top of the C1 layer. The layer made from the C1 tailings plays the role of a water retention layer that acts as an oxygen barrier. The characteristics of the waste rock are given in Table 1 and Figure 1. A very thin (0.01 m) layer of fictitious material (with the characteristics of the C1 tailings) is added at the top of the model to improve convergence during infiltration. The simulation parameters are the same as for the other cases. The water table is set at 4 m below the tailings cover interface for the case shown here.

4 Results

4.1 Column tests

Monitoring of pore water pressure and volumetric water content during the column tests shows that there is an excellent reproducibility from one cycle to the next (Figure 2). This figure shows the degree of saturation (S^r) within the tailings of the M2C1 column, 10 cm below the tailings-cover interface, and the corresponding pressure head. At the beginning of each cycle, the volumetric water content increases very quickly as the wetting front passes the TDR probes. The degree of saturation nonetheless remains well below 1 (or 100%) during this phase, as water moves downward without fully saturating the tailings. After reaching a peak, the volumetric water content ($\theta_w = n \cdot S_r$, where n is porosity) decreases rapidly at first and then more progressively. After about 10 days, the decrease in θ_w becomes slower, in part due to evaporation. Figure 2 also shows that the model accurately reproduces the evolution of S^r during all cycles.

Figure 2b shows the pressure head values based on readings from the tensiometer placed at the same elevation as the TDR probes. Again, it is seen that the correlation between the experimental measurements and modelling results is good. When water is added, the pore water pressure increases quickly (becoming positive). After the wetting front has passed through, there is a steep decrease, and the pore water pressure becomes negative (suction). In the later part of the cycle, there is a further pressure reduction that seems to be mainly due to the effect of evaporation. The constant pressure head value reached on some experimental curves (at -4.1 m) corresponds to the limit of the sensor. The variation of pressure head obtained with Vadose/W follows the same trend, although the rate of pressure variation can be slightly different, possibly due to a time lag in the sensor response.

Similar comparisons were made with the other instruments installed in the column, and similar trends were obtained. The combined volumetric water content and suction values measured in the columns have been used to correct the WRC for the wetting and drainage cycles (Figure 2a).

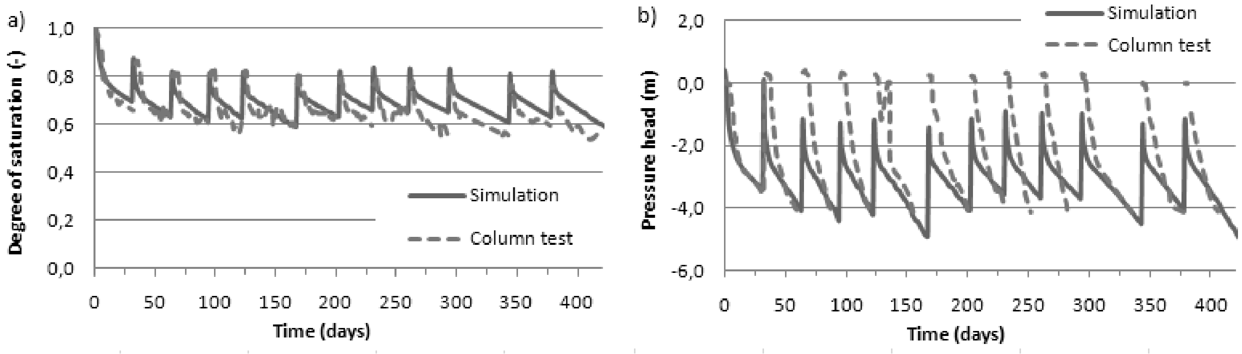

Figure 2 **Experimental and numerical modelling results showing the degree of saturation and pressure head in column M2C1 during the test, 10 cm below the tailings-cover interface(the water table is located 2.60 m below the tailings-cover interface)**

Once the numerical models had been validated against laboratory measurements, additional simulations were conducted to obtain pressure head and degree of saturation profiles along both columns. The simulation results for the last cycle of the testing programme, i.e. cycle 19 for column M1C1 and cycle 12 for column M2C1are shown in Figure 3.

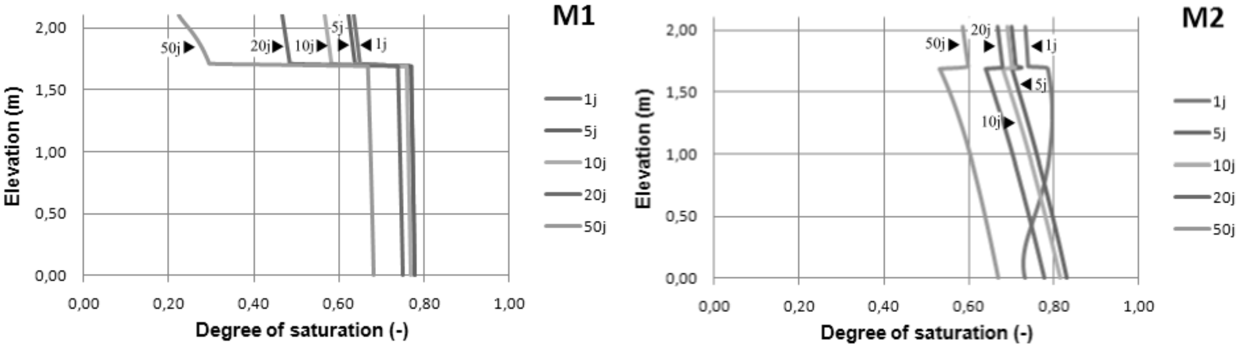

Figure 3 **Simulated profiles for the degree of saturation and suction(1-50j) in column M1C1 and M2C1 for the last wetting and drying cycle (the watertable is located 2.60 m below the tailings-cover interface)**

The comparison of the degree of saturation over the height of column M1C1 (fine-grained tailings) and column M2C1 (coarser tailings) shows that S_r in the tailings (C1) covers decreases with time during the cycle. For column M1C1, it decreases from 65 to 22% over 50 days, while it decreases from 73 to 58% in column M2C1 over the same period. In the latter, the coarser tailings M2 tend to desaturate more quickly, but the cover material is not fine enough to create an efficient capillary barrier with the C1 cover. Also, the simulations show that the cover material C1 is not coarse enough to prevent evaporation in the top layer, so the underlying tailings are not protected from this effect.

Such results indicate that the tailings and cover would remain partly saturated (S_r between approximately 60 and 80%), thus allowing oxygen ingress, causing ARD. The efficiency of both covers to prevent oxygen diffusion is thus marginal.

4.2 Field conditions

Simulations of the in situ tailings-cover system use the material parameters obtained from the column test modelling. The climatic data (hourly measurements, obtained from Environment Canada) and water table position are adjusted to field conditions. The models were run for two full years, from January to December, but only the results over the first year are presented here (the results are quite similar for the two years).

Figure 4 shows the evolution of the degree of saturation in the monolayer cover, 10 cm above the interface, for the two tailings (M1 and M2) and for different water table depths. Both cases give similar results.

The results indicate that the evolution of the degree of saturation over time follows three stages. First, during winter, the cover is frozen and the water content remains constant. Upon thawing, the degree of saturation rapidly increases due to the snow melt, reaching 100% in a few weeks. Then, after the melting snow has infiltrated, the degree of saturation begins to progressively decrease. When it reaches its minimum, the WRC of the cover material is changed (from the draining to the wetting curves) to simulate hysteresis (as observed in column tests). However, when the water table is located 2 m below the interface, the cover does not desaturate enough to reach the lower satiation. Consequently, in this case, the draining WRC is retained for the rest of the year (and the subsequent year).

Minimum values of the degree of saturation around mid-season of a typical summer, reach around 55% when the water table is 6 m below the interface, 60% for -4 m, and more than 85% when the water table is only 2 m below the tailings-cover interface.

Figure 5 presents the complete profiles for the degree of saturation in the middle of the summer (for the lowest Sr, around day 200). It is seen that the trends are similar in the cover but differ for the tailings. Tailings M1 are finer grained (with a larger air entry value) and tend to remain close to full saturation even when the water table is 6 m deep. Tailings M2 are coarser (lower air entry value), so these tailings are more prone to desaturation. Their degree of saturation is between 50 and 70% depending on the water table position. Pore water pressure profiles (not shown here) also indicate that a minor capillary barrier effect develops in the M2C1 model, due to the hydraulic contrast between the M2 tailings and C1 cover

(Figure 1b). However, the effect is not sufficient to maintain a high degree of saturation in the cover, except when water table is high enough (higher than -2 m).

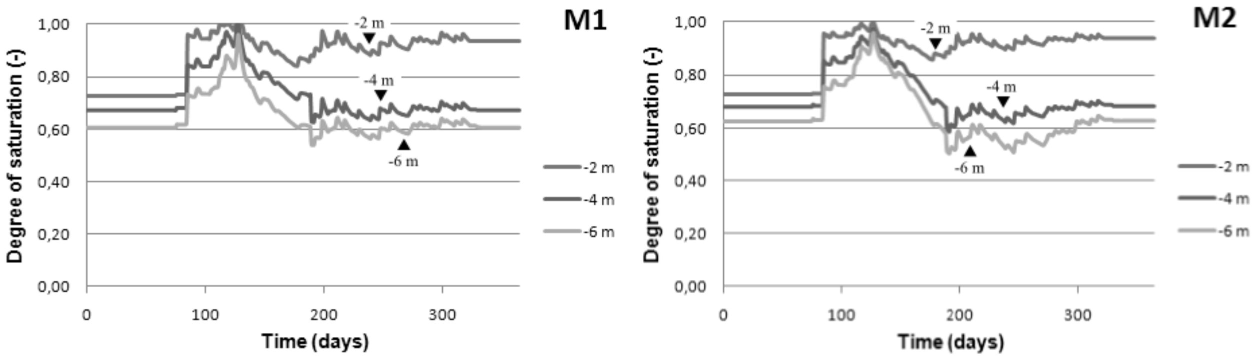

Figure 4 **Simulation results showing the evolution of the degree of saturation in the cover (10 cm above tailings interface) over one year, for M1 and M2 tailings; each curve refers to a specific water table depth below the tailings-cover interface**

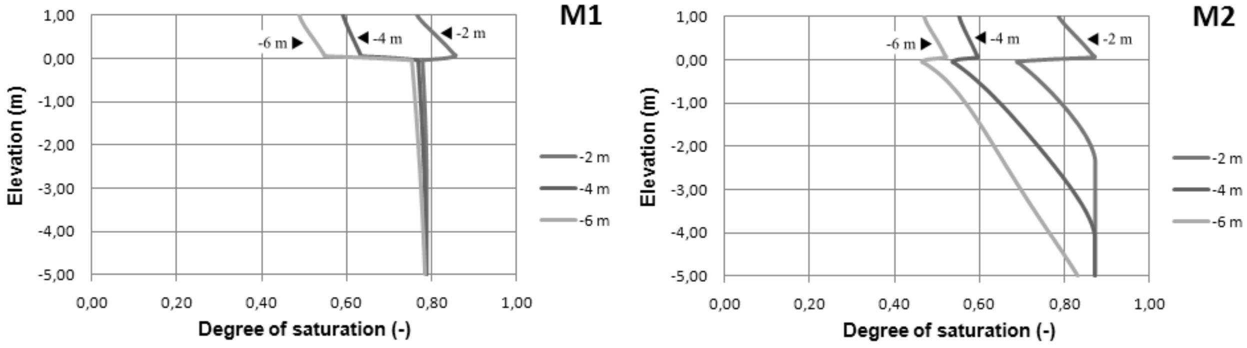

Figure 5 **Simulation results showing the degree of saturation profile in the tailings (M1 and M2) and cover (C1); z = 0 m corresponds to the tailings-cover interface; each curve refers to a specific water table position at day 200**

The simulations of the field conditions show that the monolayer cover would not be efficient to prevent oxygen flux (see below) in tailings M1 and M2 when the water table is deeper than about 2 m below the interface. In the former cases, the degree of saturation within the cover in the middle of the summer is less than 80%. A water table located less than 2 m below the interface could improve the cover efficiency for a typical (wet) year (~80 cm of precipitation/yr). However, for a dryer year (with two summer months without precipitations (~60 cm of precipitation/yr) and more evaporation), the cover would desaturate and loose its efficiency (Pabst, 2011). Under such conditions, a one metre monolayer would be inefficient to reclaim this tailings site.

4.3 Layered cover

Multilayered covers with capillary barrier effects constitute a practical and efficient technique to reclaim acid generating tailings sites (Aubertin et al., 2006; Bussière et al., 2006). The layered cover considered here is made of a 1 m thick waste rock layer placed between the reactive tailings and the C1 tailings 1 m layer, and another 1 m waste rock layer added on top of the C1 layer.

Figure 6 shows the degree of saturation profiles for this CCBE, at day 200 (in the middle of the summer). These results show that both waste rock layers are fully drained, while the moisture retention layer (made of C1 tailings) remains nearly saturated in both cases ($S_r > 95\%$). It is clear that the two capillary break layers create a strong contrast with the C1 tailings. The WR layer below the retention layer prevents water from flowing down, while the WR layer on top of the retention layer prevents evaporation from desaturating the C1 tailings. The retention layer can thus remain nearly saturated even during dry spells.

A highly saturated water retention layer in a cover can limit oxygen flux and ARD generation. Because of this, a CCBE appears as a more efficient reclamation method than a monolayer cover when the water table is too deep.

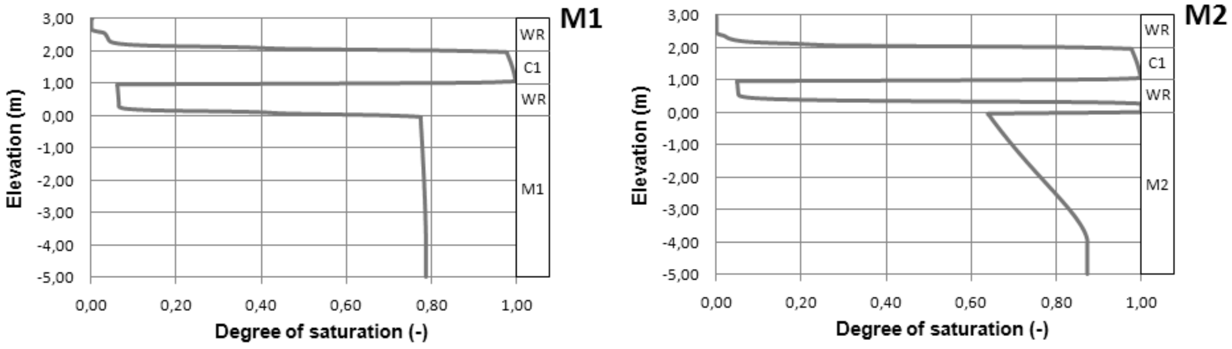

Figure 6 **Simulation results showing the degree of saturation profile in the tailings and in the CCBE; z = 0 m is located at the tailings-cover interface; the curves are drawn for day 200**

4.4 Oxygen flux

The efficiency of a cover can be estimated using different parameters. For instance, comparing the geochemistry of the column leachate with and without a cover may provide useful information, but this doesn't give a precise estimate of the efficiency over a long period of time, unless it is accompanied by geochemical modelling (Ouangrawa et al., 2009; see also Pabst, 2011 and Pabst et al., 2011). Comparing oxygen fluxes is a simple and convenient means to assess efficiency (although this doesn't take into account water chemistry and other factors such as the indirect oxidation reactions). Gas flux into covered and exposed tailings can be estimated by different means (Mbonimpa et al., 2003). Previous studies indicate that a cover can be considered efficient when the flux to the underlying tailings is maintained below about 50 g/m^2/yr or 0.15 g/m^2/day (Aubertin et al., 1999).

Vadose/W has been used in the calculations presented above to evaluate oxygen fluxes using modified Fick's laws (Mbonimpa et al., 2003). A reaction rate coefficient ($K_r = 2.5.10^{-5}$ s^{-1}, equivalent to 2.16 days^{-1} and 789 yr^{-1}) was determined for tailings M1 and M2, through oxygen consumption tests conducted for this project (not presented here). The cover material C1 and waste rock are considered non-reactive.

The oxygen flux through the cover varies during the year depending on the degree of saturation (with Vadose). Estimated fluxes (average of daily values calculated over one year) are summarised in Table 2.

Table 2 **Oxygen fluxes at the top of the cover for tailings M1 and M2 for various cover configurations (estimated with Vadose/W)**

	O_2 flux (in g/m^2/day)	
	M1	**M2**
Exposed surface	> 14	> 14
Monolayer cover (depth of water table: -2 m)	0.06	0.05
Monolayer cover (depth of water table: -4 m)	0.86	0.66
Monolayer cover (depth of water table: -6 m)	2.78	1.98
CCBE (depth of water table: -4 m)	$6.3.10^{-3}$	$6.8.10^{-3}$

The oxygen flux through the cover obtained with Vadose/W is directly linked with the degree of saturation of the cover and tailings. Table 2 shows that when the water table is lower than about 2 m below the interface, the oxygen fluxes are larger than the typical design criteria. Further calculations (not shown here) indicate that this single layer cover becomes less efficient during dry years. With a CCBE, the oxygen flux is much smaller ($<7.10^{-3}$ g/m^2/day).

5 Conclusion

Instrumented column tests were conducted in the laboratory to investigate the hydrogeological and geochemical behaviour of two reactive tailings and their monolayer cover. Volumetric water content and pressure heads were monitored during monthly wetting and drying cycles and then used to calibrate numerical models. Water flow and oxygen diffusion in the columns were simulated using Vadose/W 2007. The models, once calibrated, reproduced experimental observations reasonably well. They were then used to evaluate the effect of various factors, such as water table position and material properties (with variations based on actual in situ measurements). An alternative layered cover configuration, with capillary barrier effects, was also simulated.

The simulations showed that the behaviour and the efficiency of a monolayer cover placed over reactive tailings depend on many factors such as its hydraulic properties and water table position. Laboratory and field simulations show that the tested cover is prone to desaturation, especially when the water table is deep (>4 m) below the tailings-cover interface. It seems as a result that, in tested conditions, a relatively thin monolayer cover would not be able to prevent oxygen ingress, except with an elevated water table (>-2 m). Flux estimates corroborate this conclusion. Simulation results also indicate that a CCBE would be more efficient under the same conditions than a monolayer cover in reducing the oxygen flux and thus in preventing acid drainage generation.

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