Analysis of monolayer covers for the reclamation of acid generating tailings: Column tests and interpretation

Thomas Pabst[1,4], Michel Aubertin[1,4], Bruno Bussiere[2,4] and John Molson[3]
[1] *Département CGM, École Polytechnique de Montréal, QC, Canada*
[2] *Department of Applied Sciences, University of Québec in Abitibi-Témiscamingue, Rouyn-Noranda, QC, Canada*
[3] *Department of Geology and Geological Engineering, Université Laval, Québec, QC, Canada*
[4] *Industrial NSERC Polytechnique-UQAT Chair, Environment and mine wastes management*

ABSTRACT
This paper presents a study on the reclamation of an acid generating tailings site that has been exposed to natural conditions for decades. One of the goals of this investigation is to assess the behaviour of a monolayer cover placed on the tailings, using laboratory column tests and numerical simulations. The experimental data indicate that the efficiency of the single-layer cover is fairly limited for the imposed conditions. The test results are then compared with simulations conducted with Vadose/W (GeoSlope Inc). Sensitivity analyses are conducted to evaluate the impact of various factors such as water table position, cover thickness and material properties. Alternative configurations are also investigated.

RÉSUMÉ
Cet article présente les principaux résultats d'une étude portant sur la restauration d'un site minier générateur d'acide exposé aux conditions atmosphériques depuis plusieurs décennies. L'un des objectifs de ce projet est de déterminer, au moyen d'essais en colonne et de simulations numériques, le comportement d'une couverture monocouche installée sur ces résidus. Les données obtenues lors des essais au laboratoire tendent à montrer que l'efficacité de la couverture monocouche est limitée dans les conditions imposées. Ces résultats sont ensuite comparés à des modèles numériques développés avec Vadose/W (GeoSlope Inc.). Des analyses de sensibilité ont été réalisées pour évaluer l'impact de la position de la nappe, de l'épaisseur de la couverture ou des propriétés des matériaux. Des configurations alternatives ont également été testées.

1 INTRODUCTION

Mine tailings, produced during ore treatment, are usually stored in surface disposal sites. When left uncovered, the iron sulfides (pyrite, pyrrhotite, arsenopyrite, etc.) that the tailings may contain can react with oxygen and water to generate acid mine drainage (AMD). The resulting acidic effluent, generally characterized by high concentrations of dissolved metals and sulfates, a low pH and a high electrical conductivity (e.g. Jambor, 1994; Nordstrom, 2000), can raise serious environmental issues. Considering that both oxygen and water are required for the main acidification reactions to occur, reclamation methods mainly tend to inhibit access of one of these two components to the sulfide minerals (Aubertin et al., 2002). In humid climates, oxygen access can be decreased using water covers (Romano et al., 2003), covers with capillary barrier effects (Nicholson et al. 1989; Aubertin et al., 1995, 2002 ; Bussière et al., 2001, 2004), or an elevated water table (Orava et al. 1996; Ouangrawa et al., 2009). These techniques take advantage of the fact that oxygen diffusion through water or a saturated porous medium is more than 10 000 times slower than in the air phase (Collin et Rasmusson, 1988; Mbonimpa et al., 2003). Under arid or semi-arid climatic conditions, evaporative and SDR (store-divert-release) covers are usually preferred as a reclamation option (Williams et al., 1997; Aubertin et al., 2009), hence preventing water infiltration into the reactive waste. Each technique needs to be adapted for the specific site conditions so that the design can be optimized. The efficiency is usually improved when reclamation is planned well ahead of the site closure and implementation occurs near the end of operation and shortly thereafter.

Old tailings sites, which have been left exposed for a long time, may have been altered extensively before the reclamation work starts. In such cases, the selected reclamation technique must take into account the site contamination history (Bussière et al. 2005). This is especially important when the waters within the tailings already have the characteristics of AMD. The leachate pH can then be low enough (< 3.5) so that iron sulfide minerals are subjected to indirect oxidation due to the presence of soluble ferric ions (Nicholson, 1994; Nordstrom et Southam, 1997). In such cases, an oxygen barrier may be less efficient to prevent AMD, at least in the short term.

This study focuses on the behaviour of acid generating tailings from the old Manitou mine site located a few kilometres east of Val-d'Or, Quebec, Canada. The tailings on the Manitou site are partially oxidized, and the pore water is already very acidic. The site was operated for decades, but was abandoned almost 20 years ago; it is now managed by the Ministry of Natural Resources (MRNF) of the Province of Quebec. The reclamation method adopted for this site consists of adding onto the surface of the reactive tailings a layer of the slightly alkaline (non acid generating) tailings currently being produced at the recently opened Goldex mine (Agnico Eagle, Val-d'Or). The tailings are conveyed by a 24 km pipeline from the mill. Additional dykes have also been constructed to raise the level of the water table in some parts of the site.

The goal of the present study is to assess the behaviour of the tailings-cover system to determine the efficiency of the monolayer cover. The experimental data obtained from the laboratory column tests are used to validate numerical models constructed with Vadose/W (GeoSlope Inc). Sensitivity analyses are also conducted to evaluate the impact of various factors, such as depth of the water table and material properties, and to investigate alternative cover configurations. Some of the experimental and calculation results are presented and discussed in this paper.

2 MATERIALS AND LABORATORY SET-UP

The samples collected *in situ* in 2007 include coarse-grained and fine-grained tailings from the Manitou site and cover material from the Goldex mill. These materials have been extensively characterized in the laboratory. In addition to basic properties, the experimental program includes the determination of 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. Also, flexible wall permeameters (ASTM D5084) were used to measure the saturated conductivity k_{sat}. These experimental results were compared with predictive estimates obtained from the KCM model (Mbonimpa et al., 2002), which is also used to adjust the value of k_{sat} for varying material conditions. Grain size curves (ASTM D422), relative density (specific weight) of solids (ASTM D854), mineralogy (DRX), and oxygen diffusion and consumption parameters were also determined. Detailed results will be presented in Pabst (2011). Some of the main characteristics of the tailings and cover material are summarized in Table 1.

Instrumented columns (230 cm in height, 15 cm internal diameter) were used to study the hydrogeological and geochemical behaviour of the tailings–cover systems.

The column set-up follows a methodology developed over several years (Aubertin et al., 1995, 1999; Bussière et al., 2004; Ouangrawa, 2007). For this study, the configurations were selected to reproduce some of the existing site conditions and to provide representative results for long term analyses. Two large columns were mounted: column M1 (170 cm of coarse Manitou tailings with 40 cm of Goldex tailings cover) and column M2 (170 cm of fine Manitou tailings with 40 cm of Goldex tailings cover). Small columns (50 cm in height, 10 cm in diameter) were also mounted with the reactive Manitou tailings to observe their behaviour when left uncovered; these later tests will not be considered here. The experimental program also includes geochemical analyses (not presented here; see Pabst, 2011, for further details), and additional large columns with alternative configurations (tested at the UQAT-URSTM laboratory in Rouyn-Noranda, Quebec, Canada; results to be presented elsewhere). In-situ experiments were also conducted from 2007 to 2009. These included oxygen consumption tests, cone tests, and sampling. Piezometers and wells were also installed to monitor the water table level and to assess the groundwater chemical composition. The field measurement results will be presented elsewhere.

The general set-up for the two large columns considered here is presented in Figure 1. The tailings and cover materials were put in place and consolidated under full saturation, layer by layer (15 cm thick). The void ratio along the column was estimated from the mass and height of each layer. These values were checked against ring samples taken upon dismantling. Although the initial void ratios were relatively high (around 0.7), the values didn’t change much during the wetting and drying cycles.

The top of each column was left open to the atmosphere during the wetting-drainage cycles, so evaporation played a role during the tests. Temperature (T) and relative humidity (RH) were also monitored. A ceramic porous plate was placed at the base of the columns, so the water table position could be controlled through a small flexible U-tube (which remained full of water). The default 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.

The position of the various sensors was the same in each column. Three TDR probes (SoilMoisture), placed 10 cm above and 10 and 30 cm below the tailings-cover interface, were installed to measure volumetric water content. The probes are made of three metallic rods, with the central rod coated when used in acid generating tailings. The probes were calibrated prior to the column tests, using several probes and samples of tailings and sand (with water having different electrical conductivities). All results were fairly similar, and the effect of salinity seems to be negligible in an interval of 0 to 8 mS/cm (which encompasses the values generally measured for the leachate). These measured results were confirmed during dismantling of the columns, when a direct correlation was established between the TDR readings and the actual volumetric water content. Although the water in the columns was highly contaminated, probe weathering was not observed during dismantling.

Table 1. Main characteristics of the tailings, cover material and sand used in the column tests and simulations.

Material	e [-]	C_U [-]	D_{10} [mm]
M1 tailing	0.71	12.7	$5.6 \cdot 10^{-3}$
M2 tailing	0.59	42.4	$4.4 \cdot 10^{-3}$
Goldex tailings	0.66	10.9	$3.8 \cdot 10^{-3}$
Sand (simulations only)	0.70	3.3	$3.2 \cdot 10^{-2}$

Water-filled tensiometers (Omega +/- 5psi, or 34.5 kPa, within the tailings and +/- 15psi, or 103.4 kPa, near the surface) were installed close to the TDR probes to measure suction. To prevent desaturation (that may result from cavitation within the cup), the ceramic cups were refilled with a small amount of de-aired water prior to each cycle.

Optical oxygen sensors (Oxy10, PreSens) were also added to monitor dissolved and gaseous oxygen concentrations at different depths. Finally, a capacitance probe (ECH2O EC-10, Decagon) was placed near the top of each column to measure volumetric water content in the cover. The latter were also calibrated with the same method as for the TDR probes.

Monthly wetting and drainage (drying) cycles were repeated to simulate, in a simplified (but controlled) manner, the site climatic conditions. Every 30 days or so (the cycles were not always of the same duration), 1700 cm^3 (about 10 cm) of deionized water was added at the top of the columns. It usually took between 3 to 5 days before a new leachate sample was collected at the base of the columns. The infiltration of free (ponding) water on top of the Goldex tailings cover lasted for about 4 days. A total of 16 cycles were applied to column M1 and 10 cycles to column M2.

3 NUMERICAL MODELLING

3.1 Vadose/W code

Vadose/W 2007 (GeoSlope Inc.) is used in this study to simulate water and gas flow in the columns. This code shares many similarities with the (1D) Soil Cover code (Wilson et al., 1999, 2003) and with Seep/W (also from GeoSlope). Vadose/W is a 2D 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 (e.g. Shakelford and Benson, 2006; Adu-Wusu et al., 2007; Gosselin, 2007; Demers et al. 2009).

3.2 Modelling methodology

The columns are simulated as a 1D vertical flow domain, although a 2D grid was used with one cell per elevation (i.e. each element has the width of the column). The height of each element is 1 cm.

The water retention curves (WRC) for the different materials are expressed using the van Genuchten (1980) equation. Although measurements have been made on a few samples with the modified Tempe cells, some characteristics of the tailings and cover material in the columns are not well known at this point, including the uniformity of their grain size and porosity, and also the difference between the wetting and draining WRCs (due to hysteresis). Some of these details will only be known upon dismantling of the columns, while others will have to be assessed using complementary techniques. For the preliminary simulations presented here, the hydraulic functions (WRC and unsaturated hydraulic conductivity k_u) of the materials in the column have been evaluated by using direct measurements of the volumetric water content and pressure head obtained during the tests. The data collected during the wetting-draining cycles tend to confirm the hysteresis phenomenon. Some similar observations have been reported in previous column tests (Aachib, 1997; Ouangrawa, 2008). Vadose/W doesn't take such hysteresis into account. Here, the water retention curves are modified after the first cycle to better reflect the experimental observations. Figure 2 shows the experimental data and the fitted drying and wetting curves.

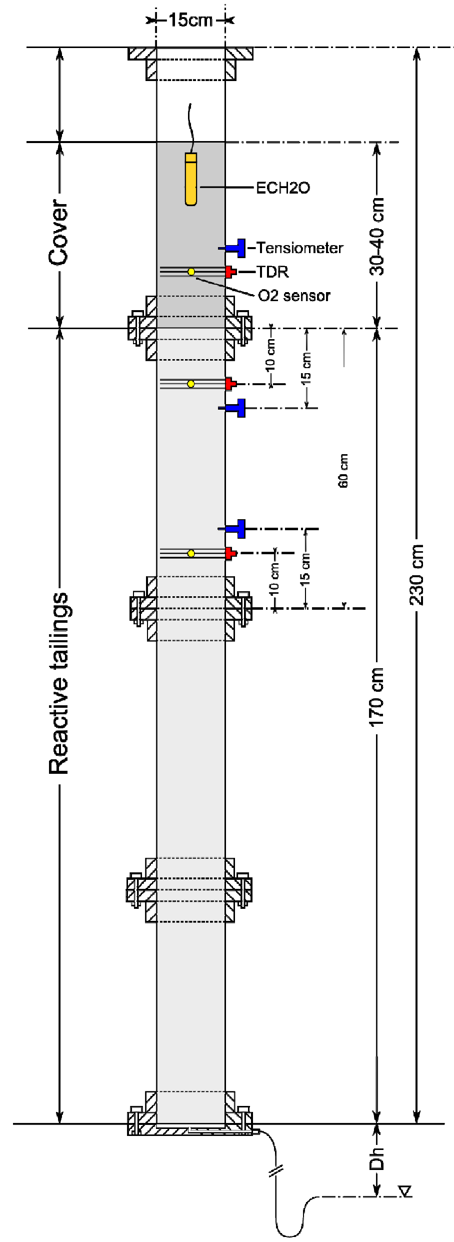


Figure 1. Schematic view of the column set-up, showing the associated instrumentation.

Table 2. Water retention curve parameters used in Vadose/W (based on the van Genuchten (1980) model).

Material	θ_r [-]	θ_s [-]	α_{vG} [m^{-1}]	n_{vG} [-]	m_{vG} [-]	k_{sat} [$m.s^{-1}$]
M1	0.02	0.42	0.20	1.43	0.30	$7.57\cdot10^{-7}$
M2	0.03	0.40	0.35	1.60	0.38	$4.00\cdot10^{-7}$
Goldex	0.00	0.43	0.26	1.35	0.26	$4.70\cdot10^{-7}$
Sand (simulations only)	0.01	0.41	10.1	4.06	0.75	$1.51\cdot10^{-3}$

The function k_u is predicted using the Mualem (1976) formulation, based on the parameters of the WRC expressed with the van Genuchten (1980) equation (see Table 2). 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 expected porosity in the columns. Hysteresis of the permeability functions was obtained by using the Mualem function with both WRCs (for wetting and drying). These assumptions will have to be confirmed when all the information becomes available.

The boundary condition imposed at the base of the model is a Type-1 condition (Dirichlet), with a fixed suction that simulates the water table depth. The top boundary is a climate boundary with imposed temperature and relative humidity (maximum and minimum T and RH values, with sinusoidal variations for each day), precipitation, mean wind speed (equal to zero in the laboratory), and potential evaporation rate (measured with a pan). Recharge is simulated as a short duration rain 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 calculated from the head vector norms, based on a tolerance of 0.01%. Adaptive time stepping is used, and adjusted from nodal heads with 2.5 % maximum change for the head 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 column is simulated as a fictional material. The water content of the corresponding water retention curve is set constant (ensuring that it is always saturated) and equal to the ratio of the true tube volume over its modeled volume (i.e. $\theta = 1.56\cdot10^{-4}$). The tube hydraulic conductivity is modeled as a constant, and is taken equal to the conductivity of the ceramic at the base of the columns ($k_{sat} = 3.1\cdot10^{-7}$ m/s).

A cover efficiency can be estimated according to several 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). Comparing oxygen fluxes is a simple and convenient means to obtain a rapid efficiency assessment (although this doesn't take into account water chemistry and other factors such as the indirect

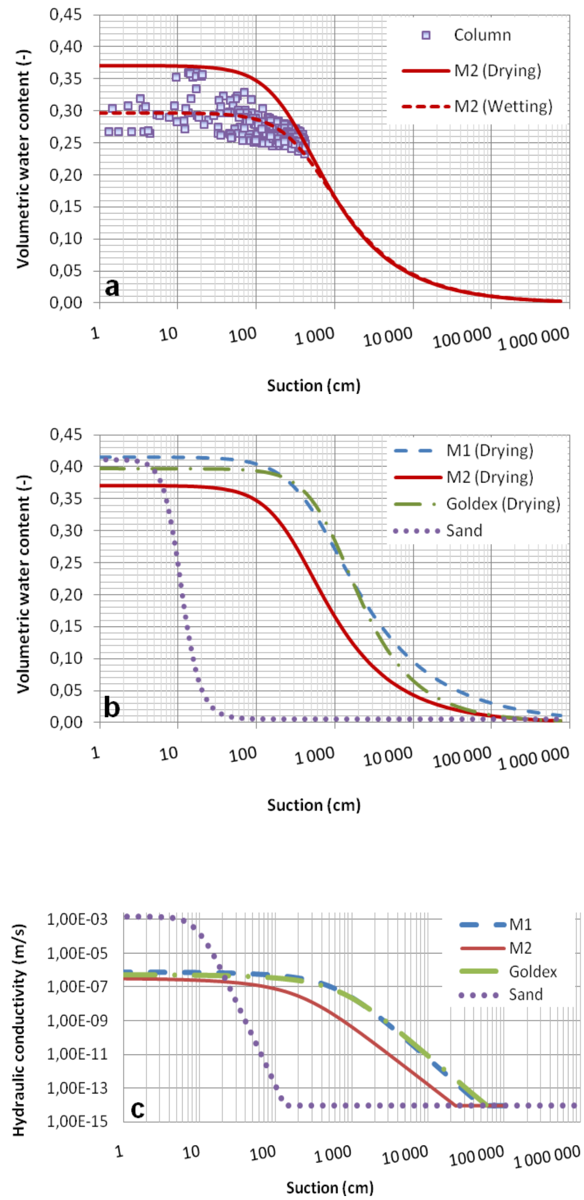


Figure 2. Water retention curves and conductivity functions used in the simulations with Vadose/W (based on the Mualem (1976) – van Genuchten (1980) functions). Figure 2.a. shows fitting of the curves to the column test results (for reactive tailings M2), including the hysteresis function. Figure 2.b. shows the water retention curves of all materials used in the simulations. For clarity, only the drying curves are presented here. The corresponding k_u functions are shown in Fig.2c.

oxidation reactions). Various methods exist to assess gas flux into covered and exposed tailings (Mbonimpa et al., 2002, 2003). Such analyses indicate that a cover can be considered efficient when the flux to the tailings underneath is maintained below about 50 g/m²/yr (Aubertin et al., 1999).

Vadose/W is used to simulate gaseous fluxes. Different cover scenarios have been considered, including those tested in the columns and alternative configurations. A sensitivity analysis was also performed to test the influence of key parameters on the oxygen flux (and cover efficiency). Only the results corresponding to the laboratory conditions over a period of 10 cycles will be presented here.

The reclamation based on a monolayer cover will be compared with a typical layered cover with capillary barrier effects (CCBE; see Aubertin et al., 2002 for more details). The latter cover includes a 50 cm thick coarse sand layer between the Manitou tailings and the Goldex tailings cover, and another 50 cm thick coarse sand layer on top of the Goldex tailings cover. In this CCBE, the layer made from the Goldex tailings plays the role of a water retention layer. The characteristics of the sand are presented in Table 1 and the van Genuchten model parameters are given in Table 2. The simulation parameters are the same as for the other cases, except for the mesh: the finite elements in the sand layers are 0.1 cm high to capture the anticipated desaturation.

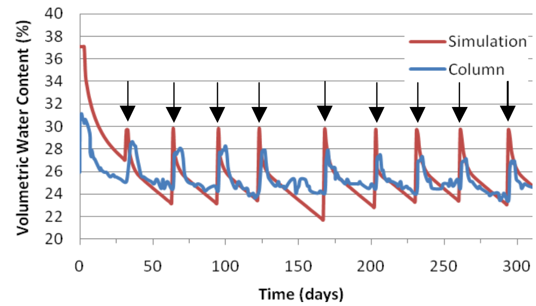
Simulations have also been conducted to evaluate the influence of the water table position, by varying its depth from 0 m to 4 m below the base of the column.

4 RESULTS AND DISCUSSION

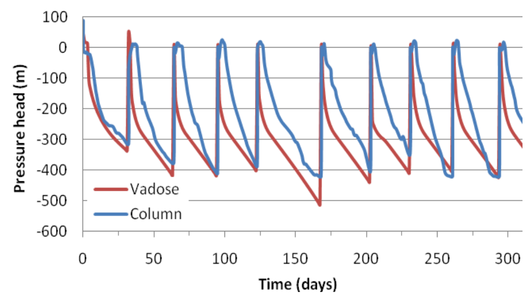
4.1 Column M2

Monitoring of pore water pressure and volumetric water content shows that there is an excellent reproducibility from one cycle to the next during the column tests. However, a few sensors sometimes gave unreliable (unrealistic) results (i.e. constant readings over time, or chaotic variations). Figure 3 shows representative results measured in one of the columns, which illustrate that the data are repeatable for the various cycles.

More specifically, Figure 3a shows the experimental and simulated volumetric water content θ within the tailings of the M2 column, 10 cm below the tailings-cover interface. As can be seen, there is a fairly good correlation between both curves, except for the first cycle. Small discrepancies can nonetheless be observed in these results; the experimental values of the volumetric water content θ varied from 24% to 28%, while the numerical results vary between 22% and 30%. Despite such differences, the trends are clearly seen to be similar. 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 S_r, however, remains below 100% during this phase, as water moves downward without fully saturating the pores. After reaching a peak, the water content decreases rapidly at first and then more progressively. A quasi-



a. Volumetric water content measured and simulated in column M2, 10 cm below the tailings-cover interface. The vertical arrows indicate the beginning of each cycle, when water was added at the top of the column.



b. Pressure head measured and simulated in column M2, 10 cm below the tailings-cover interface.

Figure 3. Comparison between experimental and modelling results.

equilibrium state is reached at about 10 days, after which the decrease in the volumetric water content becomes very slow. This further decrease may then be due (in part at least) to evaporation. The simulation shows the same behaviour, except for the variation of the volumetric water content during the first cycle; the simulation does not accurately capture the initial drainage of the saturated column with free (ponding) water on top. More importantly, the model accurately reproduces the evolution of θ during the subsequent cycles (except for the satiation part of each cycle, which is not well captured by the simulation).

Figure 3b shows the pressure values based on readings from the tensiometer placed 10 cm below the tailings-cover interface in the column with M2 tailings (i.e. at the same location as for the volumetric water content shown in Figure 3a.). 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 immediately, becoming positive. This state lasts for a few days, until the water wetting front passes through. Afterward, there is a steep decrease, and the pore water pressure becomes negative (suction). Later, there is a further pressure reduction that seems to be mainly due to the effect of evaporation. Note that a

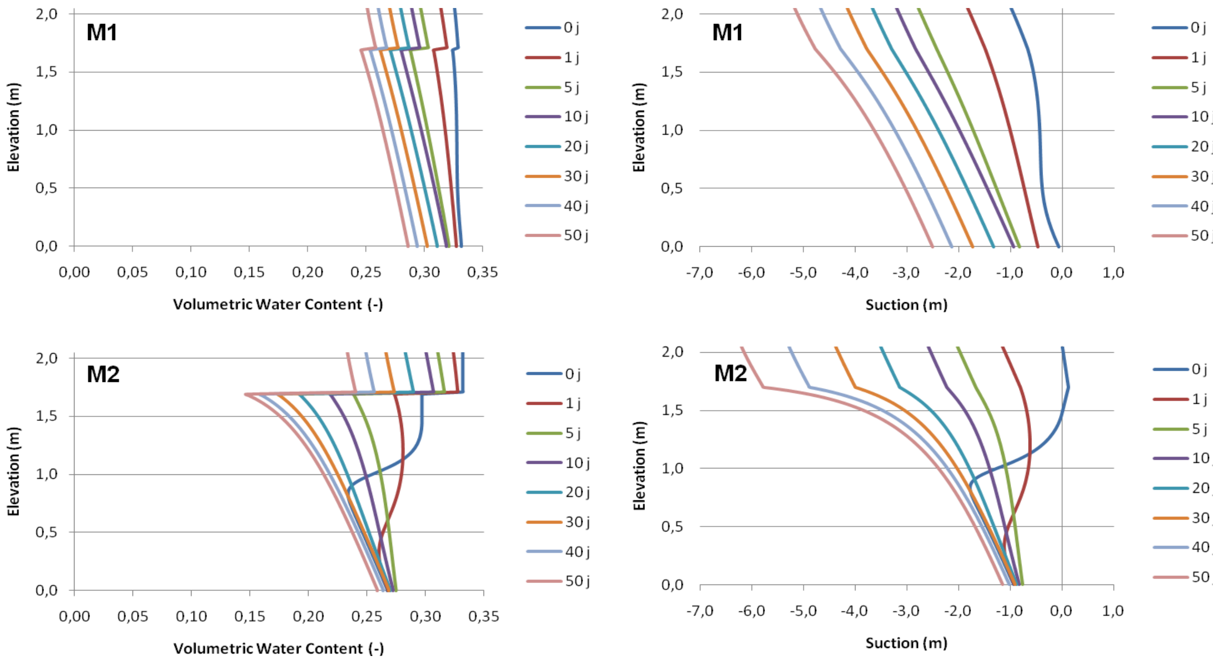


Figure 4. Simulated water content and suction profiles in column M1 and M2 for the last wetting and drying cycle.

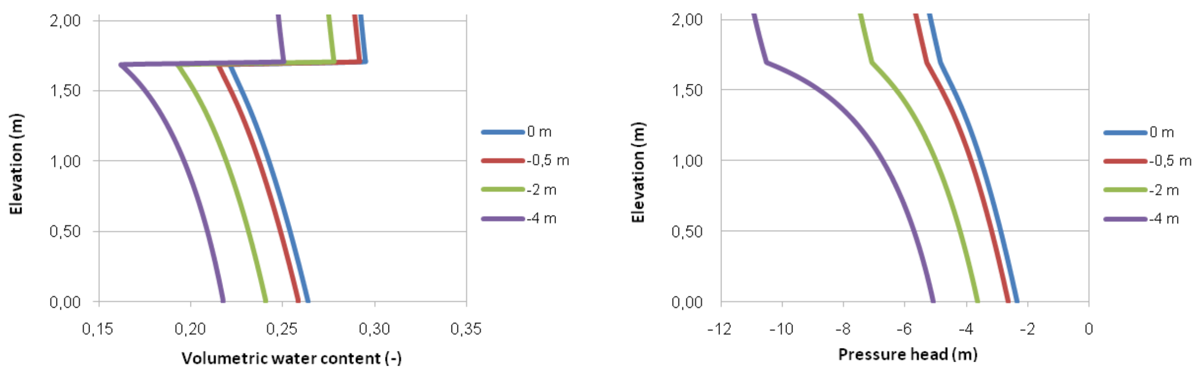


Figure 5. Simulated water content and suction profiles in column M2 after 50 days (last cycle) with variable water table positions. The reference elevation is taken at the base of the column.

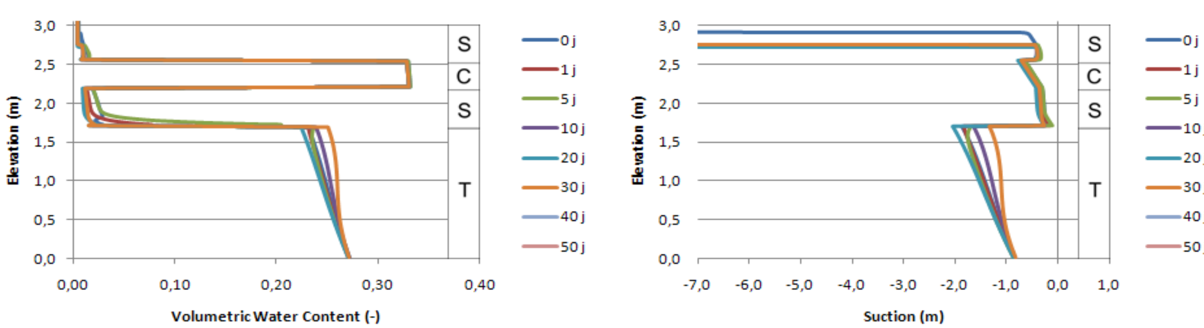


Figure 6. Simulated water content and suction profiles in a column filled with M2 tailings and covered with a CCBE (see text for details).On the right of each figure: T: tailings; S: sand; C: capillary retention layer made of Goldex tailings.

constant pressure head value is reached on some experimental curves at -412cm, which is 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 different (possibly due to a time lag in the sensor response).

4.2 Effect of tailings grain size

Similar comparisons were made with other instruments in the column, and similar trends were obtained. Once the models had been validated against laboratory measurements, additional simulations were conducted to obtain suction ψ and volumetric water content θ profiles for both columns. The simulation results for the last cycle of the testing program, which lasted 50 days (i.e. cycle 16 for column M1 and cycle 10 for column M2), are shown in Figure 4.

The comparison of the water content profiles over the height of the columns for M1 (fine-grained) and M2 (coarse-grained) tailings shows that the θ value in the cover decreases with time. For column M1, it decreases from 33.2% to 25.1% over 50 days, while it decreases from 33.2% to 23.3% in column M2. The difference between the behaviour of the two columns is limited (when the hysteretic wetting curves are used). Figure 5 also shows that the suction decreases rapidly from the top to the base of the M1 tailings column. A suction of about -2.5 m (about 25 kPa) is reached at the base of this column, which is much larger than the hydrostatic value of about -0.9 m. This can be explained by the very strong effect of evaporation, which appears to be responsible for a large part of the drying of the tailings and cover. Because the cover material and the reactive tailings characteristics (grain size, hydraulic conductivity) are fairly similar, the suction varies in the column as if it was a single layer.

In the case of the M2 tailings column, the simulated suction profile is quite different. Here, the tailings are coarser, and this tends to limit (slightly) water flow through the tailings/cover interface. As the drying front progresses through the column, the unsaturated hydraulic conductivity of the tailings decreases, limiting the flow of water from the cover, due to the creation of a capillary break. Because of this capillary barrier effect, the evaporation has a lesser impact and the suction at the base of the column remains close to -0.9 m.

In this case, the coarse-grained tailings tend to desaturate quickly. Nonetheless, the cover material is not fine enough to develop an efficient capillary barrier effect in the long term, so its efficiency to prevent oxygen diffusion is marginal. Also, this cover layer is not coarse enough to prevent evaporation, so the underlying tailings are not protected from this effect.

4.3 Effect of water table position

Figure 5 shows simulation results that illustrate the effect of varying the water table depth on the suction and volumetric water content profiles for the M2 tailings column. These profiles were obtained on the 50th day of the 10th drying cycle (the last one). It is seen that moving the water table down to 4 meters below the base of the column increases the maximum suction near the top of the column. The volumetric water contents are then reduced accordingly. As anticipated, a deeper water table increases the suction and reduces the volumetric water content. A capillary break is still observable, but it is insufficient to prevent desaturation of the cover.

4.4 Mono- and multi-layered covers

The monolayer cover and CCBE simulations were conducted as described above, with the same boundary conditions and parameters for the reactive and Goldex tailings (except for the mesh). The imposed climatic conditions are based on laboratory measured values. The results show a very good reproducibility for the various cycles (not presented here).

Figure 6 shows the volumetric water content and suction profiles during the last cycle. These results show that for the CCBE, the volumetric water content remains very high within the moisture retention layer. Both sand layers drain very quickly and reach the residual water content after only 5 days. The suction profile confirms the development of a strong capillary break: in the water retention layer, the suction is much lower than the hydrostatic (equilibrium) value for the corresponding elevation. It is also seen that in the surface layer, the suction can increase significantly (up to 3500 m) due to the effect of evaporation. As water is unable to move up to resupply the water loss in this surface layer, the suction increases to these very large values.

5 CONCLUSION

The behaviour and efficiency of a monolayer cover placed over reactive tailings depend on many factors such as its hydraulic properties and water table position. For the conditions assessed in this investigation, it seems that a relatively thin monolayer cover would not be able to prevent acid mine drainage. Simulation results indicate on the other hand, that a CCBE would be much more efficient in reducing the oxygen flux.

ACKNOWLEDGEMENTS

This research was supported by the Natural Sciences and Engineering Research Council of Canada (NSERC) and by the partners of the Industrial NSERC Polytechnique/UQAT Chair in Environment and Mine Wastes Management (www.enviro-geremi.polymtl.ca).

REFERENCES

Aachib, M. 1997. Etude en laboratoire de la performance des barrières de recouvrement constituées de rejets miniers pour limiter le DMA. Ph.D. Thesis, Mineral Engineering, Ecole Polytechnique de Montréal, 298p.

Adu-Wusu, C., and Yanful, E.K. 2007. Post-closure investigation of engineered test covers on acid-generating waste rock at Whistle Mine, Ontario. *Can. Geotech. J.*, 44(4): 496-506.

Aubertin, M., Chapuis, R.P., Aachib, M., Bussière, B., Ricard, J.F., and Tremblay, L. 1995. *Evaluation en laboratoire de barrières sèches construites à partir de résidus miniers*. Ecole Polytechnique de Montréal, NEDEM/MEND Projet 2.22.2a.

Aubertin, M., Bussière, B., Monzon, M., Joanes, A.M., Gagnon, D. Barbera, J.M., Aachib, M., Bédard, C., Chapuis, R.P., and Bernier, L. 1999. *Etude sur les barrières sèches construites à partir des résidus miniers. Phase II: Essais en place. Rapport de Recherche, Projet CDT P1899*. NEDEM/MEND 2.22.2c.

Aubertin, M., Bussière, B., and Bernier, L. 2002. *Environnement et Gestion des Rejets Miniers*. Published by Presses Polytechnique Int.

Aubertin, M., Mbonimpa, M., Bussière, B., and Chapuis, R.P. 2003. A model to predict the unsaturated hydraulic conductivity from basic geotechnical properties. *Can. Geotech. J.*, 40(6): 1104-1122.

Aubertin, M., Cifuentes, E., Apithy, S., Bussière, B., Molson, J., Chapuis, R.P. 2009. Analyses of water diversion along inclined covers with capillary barrier effects. *Can. Geotech. J.*, 46(10): 1146-1164.

Bussière, B., Aubertin, M., and Julien, M. 2001. Couvertures avec effets de barrière capillaire pour limiter le drainage minier acide : aspect théoriques et pratiques. *Vecteur Environnement*, 34(3): 37-50.

Bussière, B., Benzaazoua, M., Aubertin, M., and Mbonimpa, M. 2004. A laboratory study of covers made of low-sulphide tailings to prevent acid mine drainage. *Environmental Geology*, 45(5): 609-622.

Bussière, B., Aubertin, M., Zagury, G.J., Potvin, R., and Benzaazoua, M. 2005. Principaux défis et pistes de solution pour la restauration des sites miniers abandonnés générateurs de drainage minier acide. *2e Symposium sur l'Environnement et les Mines*, March 15-18, 2005, Rouyn Noranda, QC.

Collin, M., and Rasmuson, A. 1988. A comparison of gas diffusivity models for unsaturated porous media. *Soil Sci. Soc. Am. J.*, 52: 1559–1565.

Demers, I., Bussière, B., Mbonimpa, M., and Benzaazoua, M. 2009. Oxygen diffusion and consumption in low sulphide tailings covers. *Can. Geotech. J.*, 46: 454–469.

Gosselin, M. 2007. Etude de l'influence des caractéristiques hydrogéochimiques des résidus miniers réactifs sur la diffusion et la consommation de l'oxygène. M.Sc.A. Thesis, Mineral Engineering, Ecole Polytechnique de Montréal, 216p.

Jambor, J.L. 1994. Mineralogy of sulfide-rich tailings and their oxidation products. In *Short Course Handbook on Environmental Geochemistry of Sulfide Mine-Wastes*. Edited by D.W. Blowes and J.L. Jambor.

Mbonimpa, M., Aubertin, M., Chapuis, R.P., and Bussière, B. 2002. Practical pedotransfer functions for estimating the saturated hydraulic conductivity. *Geotech. and Geol. Eng.*, 20(3): 235-259.

Mbonimpa, M., Aubertin, M., Aachib, M., and Bussière, B. 2003. Diffusion and consumption of oxygen in unsaturated cover materials. *Can. Geotech. J.*, 40(5): 916-932.

Mualem, Y. 1976. A new model for predicting the hydraulic conductivity of unsaturated porous media. *Water Resources Research*, 12: 513–522.

Nicholson, R.V., Gillham, R.W., Cherry, J.A., and Reardon, E.J. 1989. Reduction of acid generation in mine tailings through the use of moisture-retaining layers as oxygen barriers. *Can. Geotech. J.*, 26: 1-8.

Nicholson, R.V. 1994. Iron-sulfide oxidation mechanisms : Laboratory studies. In *Short Course Handbook on Environmental Geochemistry of Sulfide Mine-Wastes*. Edited by D.W. Blowes and J.L. Jambor, 164-183.

Nordstrom, D.K., and Southam, G. 1997. Geomicrobiology of sulfide mineral oxidation. In *Geomicrobiology : Interactions between microbes and minerals*. *Rev. Mineral.*, 35: 361-385.

Nordstrom, D.K. 2000. Advances in the hydrogeochemistry and microbiology of acid mine waters. Internat. *Geol. Rev.*, 42: 499-515

Orava, D.A., Swinder, R.C. (1996). Inhibiting acid mine drainage throughout the mine life cycle. *CIM Bulletin*, 98(999): 52-56.

Ouangrawa, M. 2007. Etude expérimentale et analyse numérique des facteurs qui influencent le comportement hydro-géochimique de résidus miniers sulfureux partiellement submergés. Ph.D. Thesis, Mineral Engineering, Ecole Polytechnique de Montréal. 428p.

Ouangrawa, M., Molson, J., Aubertin, M., Bussière, B., and Zagury, G.J. 2009. Reactive transport modelling of mine tailings columns with capillarity-induced high water saturation for preventing sulfide oxidation. *Applied Geochemistry*, 24: 1312-1323.

Pabst, T. 2011. Analyse de divers recouvrements pour la restauration d'anciens parcs à résidus miniers générateurs d'acide. Ph.D. Thesis, Mineral Engineering, Ecole Polytechnique de Montréal (in preparation).

Romano, C.G., Mayer, K.U., Jones, D.R., Ellerbroek, D.A., and Blowes, D.W. 2003. Effectiveness of various cover scenarios on the rate of sulfide oxidation of mine tailings. *Journal of Hydrology*, 271: 171-187.

Shakelford, C.D., and Benson, C.H. 2006. Selected factors affecting water-balance predictions for alternative covers using unsaturated flow models. *GeoCongress 2006: Geotechnical Engineering in the Information Technology Age*, 2006.

van Genuchten, M.Th. 1980. A closed-form equation for predicting the hydraulic conductivity of unsaturated soils. *Soil Sci. Soc. Am. J.*, 44: 892–898.

Williams, D.J., Wilson, G.W., and Currey, N.A. 1997. A cover system for a potentially acid forming waste rock dump in a dry climate. *4th International Conference on Tailings and Mine Waste 97*, Fort Collins, Co.

Wilson, G.W., Albright, W.H., Gee, G.W., Fayer, M.J., Ogan, B.D. 1999. *Alternative cover assessment project : Phase 1 report final technical report*. US Environmental Protection Agency, Wash, USA, 202p.
Wilson, G.W. 2003. The design and performance of mine-waste cover systems. In *Environmental Apects of Mine Wastes*. Edited by J.L. Jambor, D.W. Blowes, and A.I.M. Ritchie.