Physical and numerical modelling of a monolayer cover placed on reactive tailings

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ABSTRACT
Unsaturated sulphidic tailings stored in a surface impoundment tend to oxidise and generate acid mine drainage (AMD). The formation of AMD can be limited by reducing the flux of oxygen penetrating the tailings with the implementation of an elevated water table and a monolayer cover. This paper presents the main results of a study on the response of such a simple cover placed on reactive tailings. Results from column tests and simulations indicate that the hydrogeological properties of the cover and position of the water table are the most important characteristics to control AMD.

RÉSUMÉ
Des résidus miniers sulfureux non saturés entreposés en surface tendent à s'oxyder pour former du drainage minier acide (DMA) La formation de DMA peut être limitée en réduisant le flux d'oxygène qui pénètre les résidus à l'aide d'une nappe surélevée et d'une couverture monocouche. Ce papier porte sur l'étude du comportement d'un tel recouvrement placé sur des résidus. Les résultats d'essais en colonne et de simulations montrent que les propriétés hydrogéologiques du recouvrement et la position de la nappe sont les caractéristiques les plus importantes pour contrôler le DMA.

1 INTRODUCTION

1.1 Nature of the problem

Mining activities result in the production of a large amount of solid and liquid wastes such as waste rocks, tailings, and treatment sludge. These must be managed properly to comply with environmental regulations and protect the environment. In this regard, the surface storage of tailings may create significant challenges, particularly when they contain sulphidic minerals.

Tailings are produced from the milling process, where the extracted ore is crushed and treated to concentrate selected minerals and metals. Tailings from hard rock mine usually have a slurry consistency (60 to 70 % of water by weight) with particles size comparable to silt and sand. The tailings are placed in an impoundment where they settle and consolidate (Vick, 1990). When in contact with oxygen and water, the sulphidic minerals (such a pyrite) contained in the tailings may oxidize and generate acid mine drainage (AMD). At the surface of a tailings impoundment, oxygen is readily available from the atmosphere, while water is already contained in the slurry and added by the precipitation. AMD is a major environmental concern because the impacted waters usually show a low pH (< 3) and high concentrations in dissolved sulphates and metals. The recent regulations imply that the mining industry must develop long-term solutions to prevent tailings oxidation and the generation of AMD (e.g. Aubertin et al., 2002; Bussière, 2007).

1.2 Reclamation options

The implementation of closure solutions remains a challenge for acid generating tailings sites. The two most often applied solutions under a humid climate are multilayered covers with capillary barrier effects (CCBE) and water covers (Aubertin et al. 2002). These two types of cover are designed to reduce the influx of oxygen F reaching the tailings and inhibit oxidation reactions leading to the production of AMD. The oxygen transport into the tailings is mainly driven by molecular diffusion, so the effective diffusion coefficient of oxygen D_e is the controlling parameter. Oxygen barriers typically rely on the fact than the rate of oxygen diffusion in water is much less than in air. An efficient oxygen barrier can lead to very low oxygen flux penetrating the tailings (typically close to 1 mol $O_2/m^2/yr$). The value of D_e [L^2T^{-1}] for a given material can be determined from laboratory and field tests or estimated from predictive models (e.g. Aachib et al,, 2004). The diffusive flux F [M $L^{-2}T^{-1}$ or mol $L^{-2}T^{-1}$] through a surface layer can be determined, for a one-dimensional process applicable to a horizontal cover, from Fick's first law, which can be expressed as (Hillel, 1998; Mbonimpa et al., 2003):

$$F(z,t) = -D_e \frac{\partial C(z,t)}{\partial z} \qquad [1]$$

In this equation, C is the oxygen concentration in the gas phase [M L^{-3} or mol L^{-3}], z is the depth or distance [L], and t is the time [T].

A CCBE typically consists of three to five layers made of different materials with specific hydrogeological and geotechnical properties, to create a capillary barrier (Aubertin et al., 1995, 2006). The objective of such cover is to limit the flow of oxygen penetrating the tailings by keeping a layer highly saturated (e.g. Bussière et al. 2003). In a highly saturated porous medium, the flow of oxygen is much smaller than in a dry medium because the diffusion coefficient of oxygen in water ($D_w^o \cong 2.5 \times 10^{-9}$ m^2/s at 25°C) is four orders of magnitude lower than in air ($D_a^o \cong 1.8\times 10^{-5}$ m^2/s at 25°C). In an efficient CCBE, the moisture retaining layer (MRL) is designed to maintain a degree of saturation S_r higher than about 85 %. To do so, the MLR is made of a fine-grained material presenting a relatively high air entry value (AEV) and a low saturated hydraulic conductivity k_s. The AEV of a material corresponds to the negative water pressure (suction) on the water retention curve (WRC) at which the material will start to desaturate. The MLR of a CCBE can remain highly saturated, even in the presence of a deep water table, due to the capillary barrier effects (e.g. Aubertin et al. 1995, 2002; Bussière et al. 2003). Figure 1 illustrates schematically the WRC of a fine-grained soil (silt) and a coarser material (sand). The MRL is typically made from a material similar to the silt, while the layers situated above and under the MLR are made of the coarser sand, which shows a lower AEV and a higher saturated hydraulic conductivity (see Figure 1). This coarse material tends to desaturate easily (when above the water table), leading to a very low hydraulic conductivity, especially when approaching the material water entry value (WEV, i.e. the suction at the residual water content θ_r). Such a layered configuration can keep the MLR highly saturated by preventing water flow downward (toward the tailings) or upward (evaporation). Many studies have shown that the implementation of a CCBE is an effective means of controlling the oxygen flux (and production of AMD), but also that such layered cover may be complex and expensive to build and maintain.

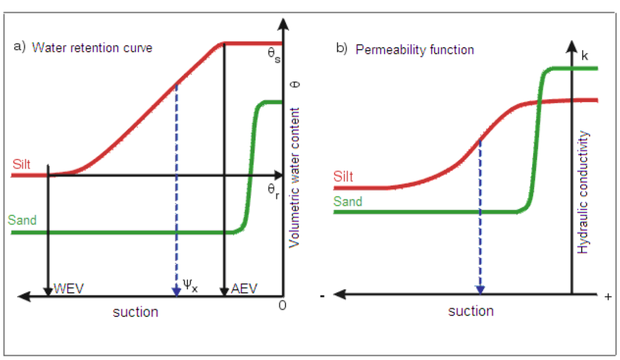


Figure 1 : Schematic view of typical water retention curves and permeability functions for a sand and a silt (adapted from Aubertin et al., 1995)

A water cover is another effective solution to control the AMD problem. This method consists in flooding the impoundment before or during tailings deposition (under water disposal) or after closure (submerged tailings). The flux of oxygen in the water cover is small because of the low oxygen solubility and diffusion coefficient, so oxidation reactions are largely inhibited. For the solution to be effective, the water cover must be maintained in the long term, which is favored by a positive annual water balance. In addition, the water cover must be sufficiently thick to compensate for wind effect that may induce suspension of the tailings and facilitate their oxidation. The implementation of this technique also involves complex infrastructures, such as impervious dykes and spillways that may raise geotechnical stability concerns (Aubertin et al., 2002).

1.3 Elevated water table

Due to the complexity and cost of implementation of the two techniques described above, alternative solutions should be investigated. The elevated water table (EWT) technique is a promising option in this regard. As illustrated in Figure 2, the EWT technique consists in keeping the water table level close to the tailings surface, at a depth h smaller than their AEV (MEND, 1996; Aubertin et al. 1999).

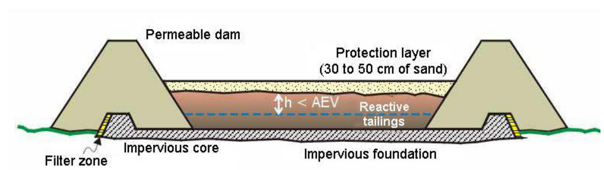


Figure 2 : Conceptual model of the elevated water technique implemented with a monolayer cover placed over reactive tailings (adapted from Aubertin et al., 1999).

Figure 3 presents the equilibrium distribution of the volumetric water content and hydrostatic pore water pressure near the water table in a tailings impoundment. This shows that a layer of tailings above the water table (capillary fringe) is kept highly saturated due to capillary rise. The retention capacity of a material can be assessed from its water retention curve. A fine-grained material presents a larger water retention capacity (i.e. a higher capillary fringe) than a coarse-grained one due to a higher AEV (see Figure 1). When the suction exceeds the AEV, air enters the porous material, which then progressively desaturates until it reaches the WEV (and its residual water content θ_r). For the EWT to be effective, the water table position h must be smaller than the AEV of the tailings. In practice, Ouangrawa (2007) suggested that the water table depth should be smaller than half the AEV to ensure an optimum long term efficiency (i.e. $h < 0.5$ AEV). The EWT technique is usually implemented with a monolayer cover that acts to reduce evaporation at the surface of the tailings while promoting infiltration (Aubertin et al. 1999). Such cover must be made of a coarse-grained material (sand or gravel, with a low AEV) to easily drain and desaturate. The cover material then shows a low (unsaturated) hydraulic conductivity that prevents moisture flow upward, towards the surface. The minimum thickness of this layer should be in the range of the coarse material WEV; in practice, the thickness for this monolayer cover should be at least 30 cm, so that $\theta \approx \theta_r$ near the cover surface (Dagenais et al., 2006).

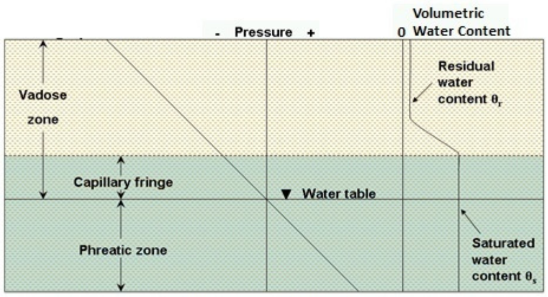


Figure 3 : Schematic view of the volumetric water content and pore water pressure equilibrium distribution above the water table in homogeneous tailings (adapted from MEND, 1996)

In some cases, a monolayer cover may be highly saturated, such as near the lower topographic locations of the impoundment. When the cover is kept permanently at a high degree of saturation, it can act as an oxygen barrier (rather than as an evaporation barrier). It is however difficult to maintain a degree of saturation high enough ($S_r \geq 85\%$) in a single layer cover to ensure its long term efficiency, unless the water table is very close to (or even above) the tailings surface. Otherwise, a layered CCBE is usually more appropriate.

In the following sections, a site specific study of the potential efficiency of a monolayer cover is presented. The study includes laboratory characterization tests and column tests. The tests results are then used to conduct numerical simulations through a sensitivity analysis for three parameters: the thickness of the cover, the properties of the cover material and the depth of the water table in the tailings.

2 CHARACTERISATION AND COLUMN TESTS

An extensive characterization of the hydrogeological properties of the tailings and cover material was conducted in the laboratory. These characterized materials were then placed in the columns mounted for the physical modeling of the tailings-cover system. The columns were submitted to wetting-drainage cycles to assess the response of the system.

The tailings and the cover material were sampled on a mine site situated in the north-west of the Quebec province. The cover material is a glacial till. Fresh unoxidized (S1) and partially oxidized (S2) tailings were collected. The tailings samples were placed in bucked covered with local water to limit further oxidation. The measured properties on these 3 materials include: grain-size distribution, solid relative density, elemental composition, Optimum Proctor unit weight (and water content), water retention curve, saturated hydraulic conductivity, oxygen diffusion coefficient and reaction rate coefficient. Properties that are not presented in this paper (for tailings S1, tailings S2 and the till) are given in Cosset (2009).

Four columns were built for this study (Fig 4). Two large columns (SG1 and SG2), made with 170 cm of tailings covered with 30 cm of till, were built to assess the hydrogeological and geochemical behavior of the tailings-cover system. Two smaller columns (SP1 and SP2), made with 50 cm of tailings, were built to investigate the geochemical behavior of exposed tailings (results not presented here). For each type, one column was built with tailings S1 sampled at depth on the site, and the other with tailings S2 collected near the surface of the impoundment. The columns are made of Plexiglas with an interior diameter of 0.10 and 0.15 cm for the small and large columns respectively. A ceramic plate was placed at the base of the large columns to apply suction (negative pore pressure). The leachate is drained and collected at the base of the columns through a valve connected to a U-shaped tube. The results shown here relate to the first five wetting-drainage cycles that were realized on the large columns, by adding water on top and applying suction at the base. The position of the U-shape tube outflow determines the negative pressure applied at the base of each column. At the beginning of each cycle (except for the first one) 1800 ml of water were added on top of the large columns; for the 1st cycle, the columns were submerged under water and allowed to drain (by opening the valve at the bottom). A suction of 1 m was applied at the bottom of the large columns. A typical cycle of drainage lasts about 30 days. During the drainage cycle, water is collected and the flow rate is measured at the bottom of each column. The large columns are instrumented with tensiometers, to follow pore water pressure, and TDR (time domain reflectometry) probes, to monitor the volumetric water content. The instruments are placed in the cover and in the tailings as shown in Figure 4. More details on the column tests are given in Cosset (2009).

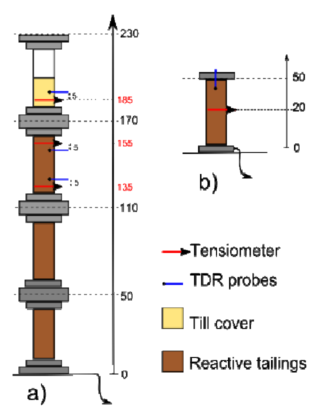


Figure 4 : Representation of the instrumented large (a) and small (b) columns.

In this paper, the focus is placed on the hydrogeological behaviour of the tailing-cover systems, based on the results obtained from the large columns. Cosset (2009) presents the complete results for the first five drainage cycles for the small and large column.

3 COLUMN TESTS RESULTS

Representative results from the first five wetting-drainage cycles conducted on the large columns are presented in the following. The monitored parameters of interest are the volumetric water content (or degree of saturation), pore water pressure, and flow rate at the base of the column. These measured values were later used to develop a numerical model to extend the results of the laboratory study, and to include the influence of specific factors on the system response.

Figure 5 shows the degree of saturation S_r (= θ/n, where θ is the volumetric water content and n is the porosity) in column SG1 during the five cycles of drainage. Results for column SG2 (not shown here) are very similar; these can be found in Cosset (2009).

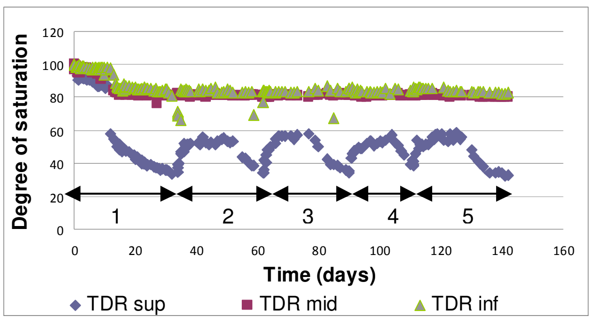


Figure 5 : Degree of saturation values in the large column SG1 for the first five drainage cycles

The green and red dots in Figure 5 correspond to the TDR probes located in the tailings (neat the top and middle of the column). It is seen that the tailings are kept at $S_r \approx 80$ % over the duration of the test (after the initial drainage of the fully saturated system). This value of S_r corresponds fairly closely to the one obtained from the WRC, for an imposed suction of about 15 to 20 kPa (see below, Figure 11). The blue dots in Figure 5 are readings from the TDR probe in the cover. As it can be seen, the local degree of saturation in the cover fluctuates between 40 and 60 % during these cycles. This tends to indicate that the cover is not saturated enough to act as an efficient oxygen barrier. This is confirmed by the numerical modelling results presented in the next section.

4 NUMERICAL SIMULATIONS

A numerical model was created to simulate the behavior of the columns in the laboratory. The model parameters have been obtained from the laboratory characterization, and in some cases adjusted from the column tests results. The numerical model is then used to evaluate the impact of three selected parameters on the behavior of the tailing-cover system. The numerical code used for the calculations is SEEP/W 2007 (GeoSlope International, 2007), a two-dimensional finite-element code that can simulate stationary and transient flow in saturated and unsaturated porous media; this code has been used in many studies conducted in the authors group over the years (e.g. Chapuis et al. 2001; Bussière et al., 2003).

4.1 Model construction and calibration

The developed model specifically represents the column shown in Figure 6. A highly permeable virtual material (Apithy, 2003; Chapuis, 2009) is used to simulate water accumulation on top of the column and the U-shaped tube used to impose suction (i.e. water table position) at the base.

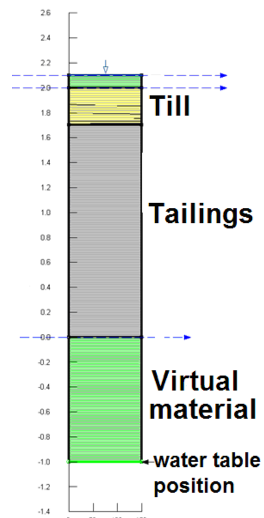
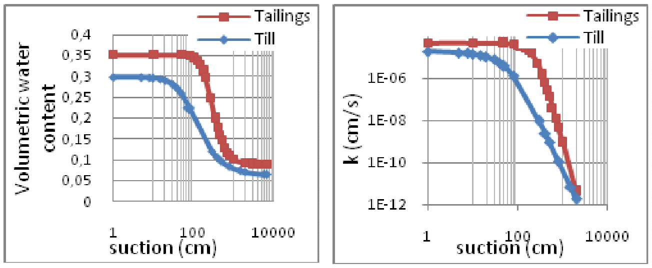


Figure 6 : Numerical model configuration

Some of the numerical model inputs were modified from their initial values (obtained from the basic characterizations) to fit the early column tests results, as some of the actual properties are not fully known at this time. The actual materials state and properties in the columns will become available later, upon dismantling. In the mean time, a calibration exercise was conducted by making adjustments to key parameters that have a significant influence on the simulations outcome. These parameters are the saturated hydraulic conductivity k_{sat} and the WRC (mainly the AEV). Figure 7 shows the WRCs and k_u functions expressed from the van Genuchten-Mualem model (e.g. van Genuchten et al., 1991), and which have been used in these simulations (fitted properties). Alternate properties for the cover material are also used for additional simulations (presented below and in Cosset, 2009).

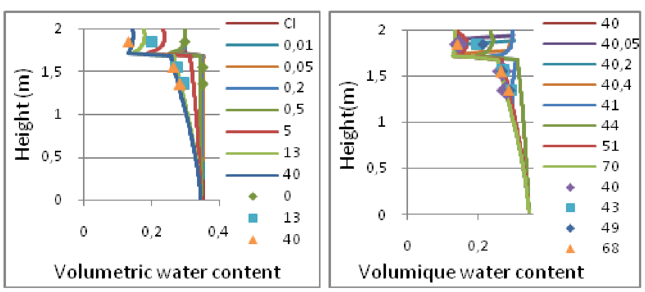
For the first drainage cycle, the column is initially saturated. The water table position (initially 10 cm above the surface) is lowered to the base of the column within 10 seconds (a drop of about 3.7 m). For the subsequent cycles, 10 cm of water is added on top of the column, to completely saturate the virtual material. The water can then progressively infiltrate the till cover, as was observed in the laboratory.



a) b)

Figure 7 : Water retention curves (a) and k_u functions (b) of the tailings and till; these adjusted functions are used for the basic numerical model calculations.

The results for the first and second cycles of drainage for column SG1 are presented in Figure 8. Similar results have been obtained for subsequent cycles, and for column SG2; these additional results are presented in Cosset (2009). In Figure 8, the lines represent the simulated profiles at different times (in days) and the dots are the laboratory measurements. The results show a fairly good correlation between the laboratory test and the numerical simulations. Nonetheless, it is seen that the simulated θ of the cover tends to exceed the measured values early during the 2nd cycle.



a) b)

Figure 8 : Experimental results (dots) and numerical simulations (lines) for the first (a) and second cycles (b) of drainage; the results are presented in terms of volumetric water content (θ) at different times (in days).

The outflow rate at the base of the column was also used to validate the model. Figure 9 shows the cumulated outflow at the base obtained from the simulation (in green) and measured during the laboratory test (in red) for the 5 cycles. It is seen that, except for the first cycle of drainage, the values compare well.

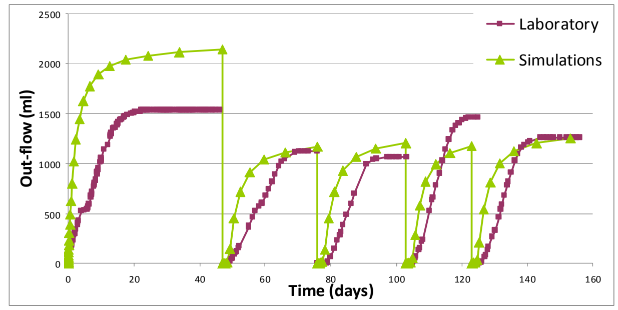


Figure 9 : Evolution of the cumulated outflow at the base of column SG1 measured in the laboratory (red) and obtained from the simulations (green).

4.2 Sensitivity analysis

The numerical model used for the calculations shown above was then used to conduct additional simulations to assess the effect of specific parameters on the tailings-cover system response. For these calculations, one cycle of drainage lasting 56 days was simulated. This duration corresponds approximately to the longest expected period without rain in the Abitibi region (where the actual mine site is located). The column is initially saturated with the water table initially at the surface; there is no virtual material on top of the cover. Also, the virtual material at the base was replaced by a thicker layer of tailings. It should be recalled also that this model does not take into consideration the effect of evaporation.

Thirteen cases were studied, based on the results of each large column (SG1 and SG2). These cases are summarized in Table 1, for SG1. Cases 1 and 2 served to investigate the effect of the cover thickness; cases 3 to 6 focused on properties of the cover material (considering 4 different grain-sizes); cases 7 to 13 assessed the effect of the water table position. The reference thickness of the cover is 1 m; the reference cover material refers to the one tested in the column; the reference (standard) water table depth is 2.7 m below the top of the tailings (i.e. below the cover).

Table 1 : Thickness of the cover, grain-size of the cover material, and water-table depth below the cover for the 13 cases simulated.

Case	Thickness of the cover (m)	Cover material grain size -	Water table depth (m)
1	1	Standard	2.7
2	2	Standard	2.7
3	1	Very fine	2.7
4	1	Fine	2.7
5	1	Average	2.7
6	1	Coarse	2.7
7	1	Standard	1
8	1	Standard	1.5
9	1	Standard	2
10	1	Standard	2.7
11	1	Standard	5
12	1	Standard	10
13	1	Standard	15

4.2.1 Effect of cover thickness (Cases 1 and 2)

To evaluate the effect of the cover thickness, two values were selected based on the information obtained *in situ*. The thickness of the actual cover placed on the tailings typically varies between 1 and 2 meters. Figure 10 presents the simulation results for a thickness of 1 m and 2 m, after 0, 6, and 56 days of drainage. It is seen that there is no difference in the degree of saturation of the tailings at 56 days ($S_r \approx 75\%$) for these 2 cases. The cover material stays slightly more saturated for the 2 m cover ($S_r \approx 66\%$ for 2 m and $S_r \approx 58\%$ for 1 m), but this difference would not be enough to improve significantly the cover efficiency as an oxygen barrier. The results also show that the cover remains too wet (with $\theta > \theta_r$) to act as a good evaporation barrier on the tailings.

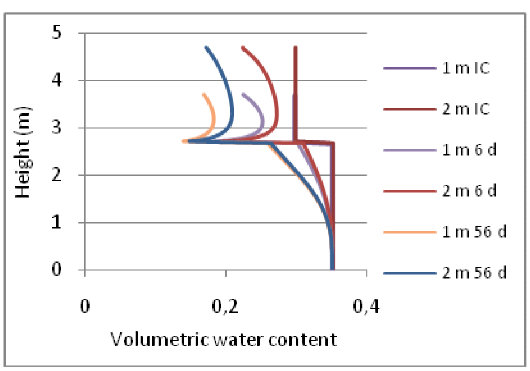
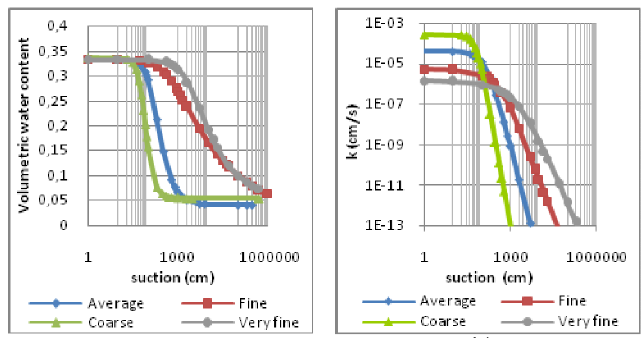


Figure 10 : Volumetric water content profiles for the two cover thicknesses at different times (in days)

4.2.2 Effects of hydrogeological properties of the cover material (Cases 3 to 6)

A total of 33 samples of cover material were collected on the studied mine site. The grain-size distribution of each sample was determined in the laboratory. Based on the grain-size curves of the till, four representative cover materials (with different grain-size distributions) were retained for the simulations. The selected hydraulic functions for these 4 cover materials (i.e. very fine, fine, average, and coarse grain size) have been obtained from the laboratory tests in combination with the predictive equations developed by Mbonimpa et al. (2002) for k_{sat} and Aubertin et al. (2003) for the WRC (to correct for the different gradations). Figure 11 presents the WRCs and the k_u functions used for the calculations conducted with SEEP/W (for the 4 cover materials). The functions implemented in the numerical code are again based on the van Genuchten-Mualem equations (van Genuchten et al., 1991), which have been adjusted to the above mentioned testing and predictive results. The model parameters are given in Table 2.



a) b)

Figure 11 : WRCs (a) and the k_u functions (b) for the cover materials introduced in the simulations with SEEP/W

Table 2 : AEV and k_{sat} for the 4 cover materials.

Case	Grain-size distribution	AEV (cm)	k_{sat} (cm/s)
1	Very fine	1000	$1,5\times10^{-6}$
2	Fine	300	$1,5\times10^{-6}$
3	Average	80	$4,1\times10^{-5}$
4	Coarse	40	$9,3\times10^{-5}$

The degree of saturation profiles for the 4 covers materials after 56 days of drainage are presented in Figure 12 (for a water table depth of 2.7 m). The results indicate that the property of the cover material (i.e based on four grain-size distributions) has no impact on the θ profile in the tailings, but these hydraulic functions have an important impact on the volumetric water content in the cover. For instance, when the cover material is very fine, the surface layer can remain highly saturated (with $S_r \approx 99\%$); in this case, the cover could act as an effective oxygen barrier (although it would need a protection layer on top to be stable). When the cover is made of a coarse-grained material, it tends to desaturate quickly and almost completely (S_r ≈30 %); in this case, the cover could be used as an evaporation barrier (considering that evaporation would bring θ close to the residual volumetric water content θ_r), However, the cover would not be very useful to prevent AMD in this case, as the tailings would tend to oxidize (at such a low S_r).

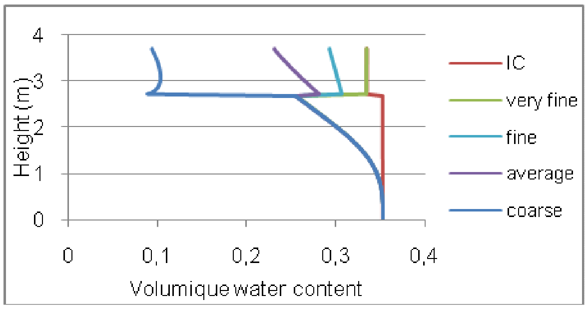


Figure 12 : Volumetric water content profiles for the four types of cover material (shown after 56 days of drainage)

4.2.3 Effects of the water table position (Cases 7 to 13)

Seven cases were simulated to evaluate the effect of the water table depth on the behavior of the tailings-cover system. For all cases, the thickness of the cover is 1 m, and the cover material (and properties) corresponds to the one tested in the column. Depths of 1, 1.5, 2, 2.7, 5, 10 and 15 meters were imposed in the simulations. A depth of 2 m corresponds approximately to the AEV of the tailings, while 1 m corresponds to half the AEV (which is the criterion suggested by Ouangrawa, 2007). Figure 13 presents the results of the simulations after 56 days of drainage.

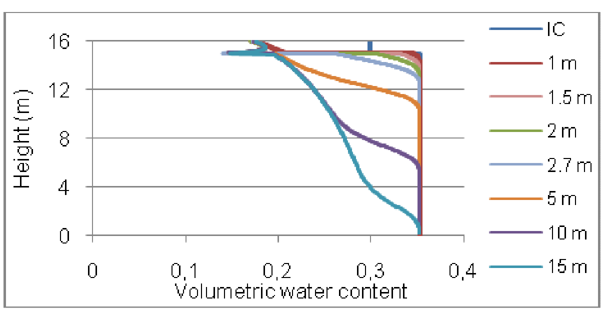


Figure 13 : Volumetric water content profiles for the seven values imposed for the water table depth (shown after 56 days of drainage)

It is seen that the water table position has little impact on the volumetric water content of this cover. However, it has a great impact on the degree of saturation of the tailings. The degree of saturation S_r in the cover fluctuates between 64 % for a water table depth of 1 m and 49% for a depth of 15 m (please note that equilibrium is not yet reached after 56 days for the deeper WT). These results also show that in the presence of a shallow water table (h ≤ 0.5 AEV), the tailings are kept highly saturated (S_r ≈ 98%), while a deep water table induces a marked desaturation of the tailings.

5 CONCLUSION AND RECOMMENDATIONS

The column tests results provide useful insights on the behavior of the tailings-cover system. They show that in the presence of a relatively shallow water table, the tailings can be kept at a relatively high degree of saturation. However, the degree of saturation in the cover fluctuates significantly during the wetting drainage cycles.

The numerical simulations presented in the paper also bring additional insights on the behavior of a monolayer cover placed on the tailings. The results show that, for the studied configurations, the thickness of the cover (1 m and 2m) has a negligible impact on the water content in the tailings and in the cover itself. However, the grain size distribution of the cover material has an important effect on its degree of saturation. The water table position has an important effect on the degree of saturation profile of the tailings, and to a lesser extent in the cover.

The results suggest that a monolayer cover used in the presence of a shallow water table (h ≤ 0.5 AEV), where the tailings are kept highly saturated, should be made of a coarse-grained material so it can desaturate rapidly and limit water loss by evaporation. When the water table is deep in the tailings, the reactive minerals would tend to oxidize so the cover should rather act as a barrier to limit the flux of oxygen reaching the tailings. To create an effective oxygen barrier in the long-term, it is preferable to implement a multi-layered cover, where capillary barrier effects will help attain the required efficiency. Hence, the water table position in the tailings impoundment tends to dictate the purpose of the cover, and also the selection of the cover material(s) and configuration.

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