Construction of a capillary barrier cover for reactive mine waste management utilizing municipal biosolids

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ABSTRACT
The potential use of municipal biosolids as a replacement for clays and silts in the development of a capillary barrier cover for reactive mine tailings is evaluated at a laboratory scale. Low saturated hydraulic conductivities were observed in biosolids during material characterization (k = 4.21 x 10 $^{-7}$ cm/s), and high degrees of saturation have been shown to be maintained at elevated suctions indicating high moisture retention properties. Numerical modelling results indicate a robust saturated layer can be maintained over a 91-day simulation. Laboratory scale column tests will be analyzed and compared to the findings of simulations.

RÉSUMÉ
La possibilité d'utiliser les biosolides municipaux pour remplacer les matériaux argiles et limons dans la construction des couvercles barrières capillaires pour les déchets minières réactifs sont évaluer au niveau du laboratoire. La conductivité hydraulique des biosolides observée pendant caractérisation était très faible (k = 4.21 x 10 $^{-7}$ cm/s), et les hautes niveaux de saturation étaient élevées aux hautes niveaux de succion qui démontre des fortes capabilités de retenir l'eau. Les résultats des simulations indiquent qu'une couche saturée était maintenue pendant la duration de la simulation de 91 jours. Testes conduit aux niveaux du laboratoire utilisant des colonnes seront évaluées pour comparer les résultats avec seuils obtenus par simulation.

1 INTRODUCTION

Mining and mineral processing play a significant role in the global economy and are essential in delivering metals to markets worldwide.

Waste rock and residual material from mineral processing, referred to as mine tailings, are produced on an extraordinary scale, often representing fifty to ninety-eight percent of total material extracted during mining, depending on the type of ore extracted (Nagaraj, 2005).

Depending on the chemistry of the tailings and waste rock, chemical oxidation of these wastes can create Acid Mine Drainage (AMD) (Lottermoser, 2007). Several strategies exist for the mitigation of AMD, however, costs of tailings management operations and associated liabilities may be reduced through innovative mine closure strategies.

The use of capillary barrier covers to limit oxygen diffusion through to the underlying tailings material has been evaluated in the laboratory and in full scale field applications and shown to be successful in mitigating AMD when properly designed and constructed (Aubertin, Bussière, Pabst, James, & Mbonimpa, 2016).

1.1 Tailings Production and Deposition

Hard rock mining utilizes drilling and blasting to liberate metal bearing ores in open-pit or underground mining operations. Ore is processed through crushing and milling followed by physical and chemical separation processes to extract targeted metals. Crushing is typically conducted in multiple stages, followed by milling which can also comprise of several stages. Water is typically added to the ore material prior and/or during milling to facilitate transportation of the material as a slurry. Crushing typically reduces or fragments to a particle size between 5-20cm, while milling reduces or particles to sizes between 10-100um. Material is typically classified between stages of crushing and milling using screens and hydrocyclones to recirculate oversized material and allow undersized material to proceed through the comminution circuit (Metso, 2015). A simplified comminution process is shown in Figure 1.

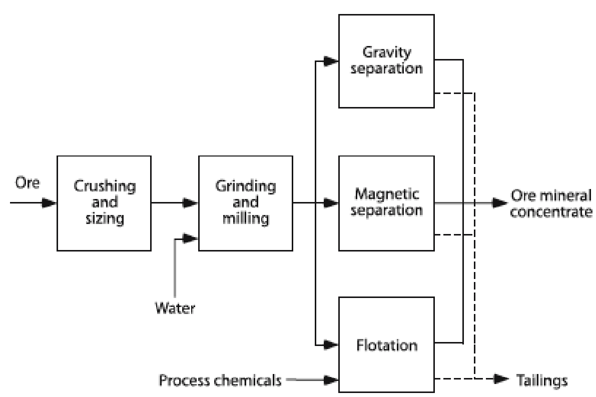

Figure 1. Simplified flow-chart of a mineral processing operation in which ore is processed to yield an ore mineral concentrate and tailings (Lottermoser, 2007)

Following size reduction, ore materials can be processed through a variety of methods which serve to separate the valuable metal particles from gangue and waste rock.

Tailings can be deposited in various ways depending on their water content. Hydraulic deposition of tailings is most prevalent due to the ability to pump tailings slurry over long distances and achieve high rates of deposition. De-watered tailings can be pumped as a paste, or dried and stacked, however, these methods are less common.

Hydraulic deposition of tailings slurry is typically conducted using water contents between 150 to 100 percent by mass of dry solids with a relative density for the slurry typically between 1.3-1.5 (Blight & Bentel, 1983). The tailings typically form a beach of material from which the water decants or bleeds out of the saturated soil matrix. Hydraulic deposition requires that a berm or dam be constructed, or naturally available, to contain the tailings and water during the deposition and drainage process.

1.2 Pyrite Oxidation

AMD occurs when the geochemistry of the tailings and waste rock produces acid as part of the oxidation reaction. Pyrite tailings and waste rocks are one of the most common materials responsible for generation of AMD due to their abundance. The general process for chemical oxidation of pyrite is shown in Equations 1-4 (Lottermoser, 2007).

$$FeS_2 + H_2O + 3O_2 \rightarrow Fe^{2+} + 2SO_4 + 4H^+ \qquad [1]$$

$$Fe^{2+} + \frac{1}{4}O_2 + H^+ \rightarrow Fe^{3+} + \frac{1}{2}H_2O \qquad [2]$$

Under acidic conditions where the pH is less than 4, ferric iron will precipitate, and may become an oxidant, accelerating the oxidation of pyrite and producing greater quantities of hydrogen ions, leading to further acidity.

$$Fe^{3+} + 3H_2O \rightarrow Fe(OH)_3 + 3H^+ \qquad [3]$$

$$FeS_2 + Fe^{3+} + 8H_2O \rightarrow 2Fe^{2+} + 2SO_4^{2-} + 16H^+ \qquad [4]$$

1.3 Oxygen Availability for Oxidation Reactions

Limiting oxidation of tailings can be achieved by reducing the available oxygen. Due to the low dissolved oxygen (DO) concentrations in water (8.6mg DO/L in water and 285mg DO/L in air) and the low oxygen diffusion coefficient of water (2.9×10^{-9} m^2/s at 25^0C for water, and 1.89×10^{-5} m^2/s at 25^0C for air), submersion of tailings beneath a water cover is an effective strategy for limiting AMD (Awoh, Mbonimpa, & Bussière, 2013). Soil covers can be used to reduce exposure of the underlying tailings to gaseous oxygen. While oxygen can be transported through a variety of processes such as advection of dissolved oxygen in soil pore water, the main method of gaseous oxygen transport through soils is by molecular diffusion through gas filled pores in the soil structure (Kimball & Lemon, 1970). Gaseous oxygen diffusion can be described by Fick's law expressed one-dimensionally as shown in Equation 5 where the diffusive flux of gaseous oxygen is shown as F, D_e is the effective diffusion coefficient, C is the concentration of oxygen in the gas phase, and z is the depth. (Nicholson, Gillham, Cherry, & Reardon, 1989).

$$F(t) = -D_e \frac{\partial C(t)}{\partial z} \qquad [5]$$

Incorporating the porosity and degree of saturation into Equation 5 allow for the calculation of the mass flux of oxygen diffused through porous soil material at a defined degree of saturation as shown in Equation 6 and Equation 7. The air-filled porosity θ_a is calculated using the total porosity of the soil (ϑ_t) and the degree of saturation (S_r).

$$\theta_a = \vartheta_t(1 - S_r) \qquad [6]$$

$$F(t) = -\theta_a D_e \frac{\partial C(t)}{\partial z} \qquad [7]$$

The rate of diffusion of gaseous oxygen can be reduced by several orders of magnitude depending upon the degree of saturation of the soil material as shown in Figure 2.

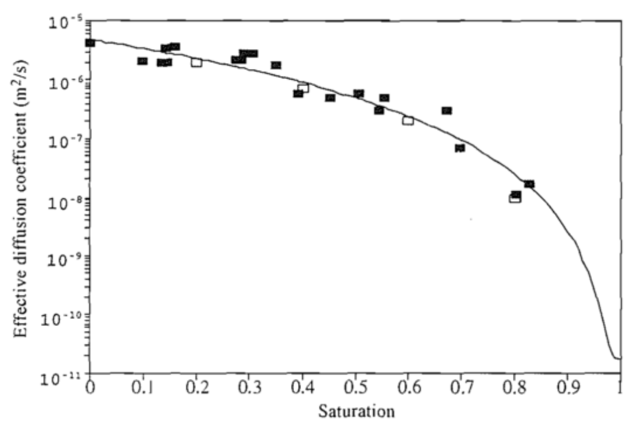

Figure 2. The relationship between the calculated effective diffusion coefficient for oxygen and the water saturation. Data presented in Reardon and Moddle (1985) (■) and data from Elberling et al. (1993) (□) (Elberling, Nicholson, Reardon, & Tibble, 1994)

1.4 Conventional AMD mitigation strategies and associated challenges

Submersion of tailings beneath a water cover has been shown to be effective in limiting oxygen transport and diffusion through to the underlying tailings to mitigate AMD (E. Yanful & Simms, 1997). Water covers pose mechanical risks associated with the maintenance of long term dams and impoundments.

A variety of soil cover configurations have been shown to be effective in the prevention of AMD; this article will focus on Capillary Barrier Effect Covers which utilize a saturated barrier layer to prevent oxygen transport through to the underlying tailings. The capillary barrier cover is generally constructed by layering a coarse material over the tailings, and topping the coarse material with a finer layer material with lower hydraulic conductivity which will remain saturated and create a capillary barrier (Nicholson et al., 1989). The establishment of a capillary barrier relies on the hydraulic conductivity and water retention characteristics of the materials used.

Briefly explained, the hydraulic conductivity in the desaturated coarse sand layer is significantly reduced at a relatively low suction pressure (as shown in Figure 4b) which minimizes flow out of the saturated barrier layer (Williams, Hoyt, Dwyer, Hargreaves, & Zornber, 2011). A simplified illustration of a conventional capillary barrier cover utilizing clay is shown in Figure 3, and depicts the desaturation of the coarse sand layer and the highly saturated fine layer to limit water flux and oxygen diffusion. A layer of relatively coarse material overlying the saturated layer is generally employed to minimize erosion of the saturated layer and protect the barrier layer against excessive evaporative flux from the cover surface (Woyshner & Yanful, 1995).

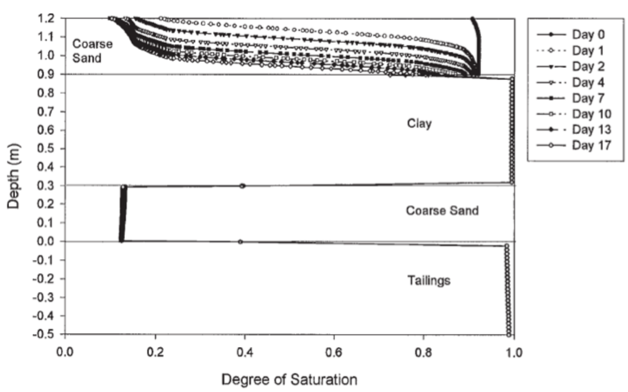

Figure 3. Simulated degree of saturation profile in evaporating multi-layer soil cover (E. K. Yanful & Choo, 1997).

The upper fine layer accumulates water during precipitation events, however, due to the low hydraulic conductivity of the upper fine soil layer the water does not readily flow down into the underlying coarse material. As water accumulates in the fine layer it becomes saturated while the coarse layer remains relatively unsaturated. The capillary barrier is established under suction conditions where the fine soil remains saturated while the underlying coarse soil desaturates as shown in Figure 4a at its air-entry value at point ψ_a. The desaturation of the coarse layer yields a reduction in the unsaturated hydraulic conductivity of the coarse layer which limits the flow of water through the coarse layer. The capillary barrier effect may be overcome should the suction decrease (moving right to left in Figure 4a along a wetting path) to such an extent that the or the residual water content of the coarse layer is passed (ψ_r and θ_r). Should the coarse layer become progressively more saturated, the hydraulic conductivity of the coarse material will increase as shown by the rapid rise of the coarse curve in Figure 4b at suctions below the residual water content. The increase in hydraulic conductivity of the coarse layer allows water to move more readily between the overlying fine layer and the underlying tailings, resulting in a failure of the capillary cover.

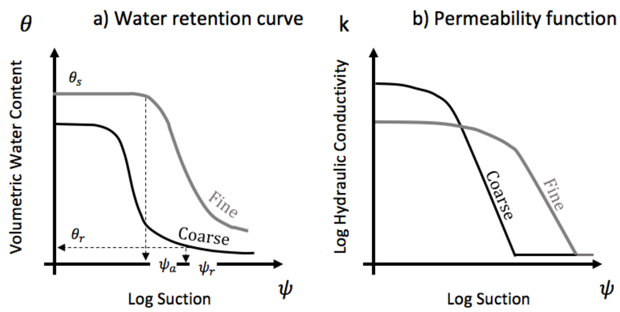

Figure 4. Schematic showing the hydraulic functions of a coarse and fine-grained soil

1.5 Municipal Biosolids

Municipal biosolids are the solid residuals from municipal wastewater and sludge treatment. Solids are settled out and removed from wastewater processes and treated to reduce pathogen and bacterial counts such that the material meets regulatory thresholds. Wastewater treatment is conducted to remove Total Solids, Volatile Solids, Nitrogen (Nitrates, Nitrites, Ammonia, Ammonium), and Phosphorous (Wang, Shammas, & Hung, 2007).

Municipal wastewater treatment varies in configuration and design based upon the volume and composition of water treated, as well as effluent regulations and budget of the operating municipality, however, most plants follow the same general processes. Raw sewage enters the plant where preliminary screening and grit removal separates large and dense solids for disposal. Primary treatment of wastewater uses sedimentation and settling to separate out primary sludge from wastewater. Secondary treatment typically involves either aerobic, anaerobic, or anoxic treatment (often in combination) in aerated lagoons or activated sludge systems where sludge is recirculated through the treatment chamber to enhance biological activity. Following secondary treatment, the wastewater progresses through secondary sedimentation where secondary sludge is separated from effluent water. Tertiary treatment may be implemented to further remove nutrients or chemicals.

Treatment of sewage sludge is conducted to stabilize the sludge mass and reduce volume, vector attraction, and to inactivate pathogens. Generally, sludge treatment requires thickening and conditioning of wastewater sludge prior to stabilization processes. biosolids in this study were obtained from the region of Halton where sludge is thickened to approximately 25% solids by weight.

1.6 Previous use of municipal biosolids as cover for reactive tailings

Laboratory and full scale studies have been conducted investigating the effects of biosolids application to mine tailings with respect to the vegetative yield of the biosolids cover, nutrient and metal mobility, metal uptake by vegetation, and the effects of biosolids addition on tailings pore-water chemistry. Application of biosolids have been found to increase vegetative yields on tailings covers when biosolids are surface applied or incorporated into the top layer of tailings (Verdugo et al., 2011). In general, the addition of biosolids to tailings has been shown to increase the pH of acidic tailings soils (Pond, White, Milczarek, & Thompson, 2005).

There exists a potential for leaching of nutrients such as nitrate when mine tailings are amended with biosolids, especially at high rates of biosolids application. The potential for nitrate leaching from biosolids-amended mine tailings can be reduced by establishing a permanent plant cover. Mixing the biosolids with the tailings has been shown to reduce nitrate transport. (Santibáñez, Ginocchio, & Teresa Varnero, 2007). Varied results have been shown regarding metal mobility and plant uptake of metals following the application of organic covers.

2.0 PARTIALLY SATURATED FLOW THEORY

The ability of a material to retain water within the soil pore matrix at varying degrees of suction as shown in Figure 3 and Figure 4, and is generally represented by the soil-water characteristic curve (SWCC) of the material. Figure 4a shows the volumetric water content – suction pressure relation of a silt and a coarse-grained sand. The magnitude of the suction pressure (negative pore pressure) is controlled by surface tension within the soil pores and is mostly governed by grain size.

The air-entry value shown by point $\psi_a$in Figure 4a is the suction pressure required to overcome the capillary forces exerted by the largest pore in the soil material. As suction pressure increases, water drains from progressively smaller pores until the residual water content of the soil (shown as ψ_r in Figure 4a) is reached.

The saturated hydraulic conductivity reflects the rate at which liquid flows through the pores of a saturated soil. As the soil desaturates and pore spaces drain, fewer and smaller pathways are available for liquid to flow through; this results in a decrease in the hydraulic conductivity of the material. One method for approximating the unsaturated hydraulic conductivity of soil materials is shown in Equation 8 where k_r is the unsaturated hydraulic conductivity at the specific level of suction (ψ), ψ_a is the air-entry value of the soil, and λ is a constant obtained by heuristic fitting to the soil's SWCC according to Equation 9 (Brooks & Corey, 1964).

$$k_r(\psi) = \left(\frac{\psi_a}{\psi}\right)^{2+3\lambda} \qquad [8]$$

$$\left(\frac{\theta_w-\theta_r}{\theta_s-\theta_r}\right) = \left(\frac{\psi_a}{\psi}\right)^{\lambda} \qquad [9]$$

The relationship between suction and hydraulic conductivity is shown graphically in Figure 4b.

Above the water table the matric suction at a specific point in the soil can be determined solving a nonlinear partial differential equation (Equation 10). In Equation 10, θ is the volumetric water content, t is time, z is the elevation, k_r is the unsaturated hydraulic conductivity at z, and h is the matric suction in meters of head which can be converted into kPa (Richardson, 1922). A modification to Equation 10 shows the same relationship stated in terms of total head in Equation 11with S_s representing the specific storage of the soil material (Witteman, 2013).

$$\frac{\partial\theta}{\delta t} = \frac{\partial}{\partial z}\left[k_r\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad [10]$$

$$-S_s\frac{\partial h}{\delta t} = \frac{\partial}{\partial z}\left[k_r\left(\frac{\partial h}{\partial z}+1\right)\right] \qquad [11]$$

3.0 MATERIALS AND EXPERIMENTAL PROCEDURES

Two biosolid materials were tested for their suitability as construction materials in capillary barrier covers. Straight biosolids from the Halton region were obtained from Terratec Environmental's field application site in Sudbury and are referred to as Toronto Amendment (TA). A second biosolids material was sampled from stockpiles of biosolids blended with leaf and yard waste from the City of Sudbury. The biosolids mixed with leaf and yard waste will be referred to as the Custom Rehabilitation Mix (CRM).

Two types of tailings were characterized for this experiment; an unoxidized tailings sample and a heavily weathered and oxidized tailings material were obtained from Vale's Copper Cliff Tailings Facility. A coarse sand was characterized for use as the unsaturated layer in the capillary barrier cover.

Characterization tests included determining the specific gravity of each material using calibrated pycnometers (ASTM D854-14), sieving (ASTM E276-13) and hydrometer tests (ASTM D7928-17), for particle size distribution, falling and constant head tests (ASTM D5856-15) to determine saturated hydraulic conductivity.

The SWCC of the cover materials was developed using combined results of multiple suction measurement techniques due to the applicable range of each method. Axis-translation was used to develop the water content – suction relationship at low levels of suction (ASTM D6839 – 16 Method C) by measuring the gravimetric loss of water through drainage at specific suction pressures with an effective range of 10-350kPa. The axis translation technique also allowed for measurement of volumetric deformation and shrinkage for the materials during testing using a GCTS Fredlund SWC 150 device.

The filter paper method of total suction and matric suction (ASTM D5298 -16) was used to develop the SWCC at suction values greater than 350KPa; this was done by equilibrating soil samples in individual air-tight specimen jars with filter papers. The water retention properties of the filter papers were calibrated using a saline solution of specific concentrations to induce suction. The suction induced by the soil samples was calculated by measuring the change in mass of the filter papers after equilibrium had been reached. The water content of the soil sample and the filter papers was used to determine the total and matric suction of the soil as per calculations in ASTM D5298-16. A Decagon Devices WP4C dewpoint hygrometer was used according to ASTM D6839 – 16 Method D for total suction measurement.

4.0 MATERIAL CHARACTERISTICS

The specific gravity and saturated hydraulic conductivity of the materials is shown in Table 1.

Table 1. Characteristics of tested cover materials

Material	Specific Gravity (g/cc)	Saturated Hydraulic Conductivity (cm/s)
Unoxidized Tailings	2.98	5.06×10^{-3}
Oxidized Tailings	3.02	4.81×10^{-5}
Sand	2.76	1.06×10^{-2}
TA (biosolid)	1.76	1.84×10^{-6}
CRM (biosolid)	2.06	4.21×10^{-7}

From Table 1 it can be seen that the municipal biosolids materials (Toronto Amendment and Custom Rehabilitation Mix) have very low saturated hydraulic conductivities resembling those recorded in fine silts (E. K. Yanful, Mousavi, & Yang, 2003) which can be used as the saturated layer in capillary barrier covers (Nicholson et al., 1989).

The results of the suction tests were combined to create SWCCs for the tailings, sand, and biosolids materials and are shown in Figure 5.

In observing the conceptual model shown in Figure 4 where a difference in volumetric water content between the coarse and fine layers at a given suction indicates suitability for establishing a saturated capillary barrier, the results from Figure 5 can be used to assess the suitability of the biosolids as water retaining layer. The difference in the hydraulic conductivities of the sand and biosolids materials also indicate potential for developing a low permeability de-saturated sand layer between the biosolids and the tailings according to the conceptual model shown in Figure 4.

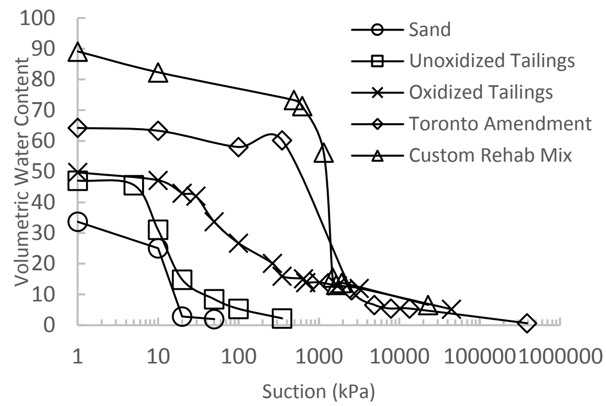

Figure 5. Soil-water characteristic curves developed for cover materials shown as volumetric water content – suction relation.

The SWCCs shown in Figure 5 for the biosolids and sand material show the desired difference in volumetric water content at suctions from 10kPa up to around 500kPa for the straight biosolids (TA) and over 1000kPa for the blended biosolids (CRM).

Figure 6 shows the SWCCs for the materials with respect to the degree of saturation maintained at varying levels of suction. The degree of saturation plot indicates that although the volumetric water content of the biosolids materials drop slightly before the final rapid desaturation at higher suctions, the volumetric deformation due to shrinkage results in reduced void ratio and available pore space. As the pore spaces present in the biosolids shrink, the remaining pore spaces maintain saturation, resulting in a high observed degree of saturation even at high suction levels.

From Figure 5 and Figure 6 it can be inferred that biosolids demonstrate potential for forming the saturated layer of a capillary barrier cover when placed over top of a coarse sand layer. The CRM material may be preferable to the straight TA biosolids due to the higher degree to saturation. From the SWCC plots it can be seen that the capillary barrier can be maintained between approximately 10kPa and 1000kPa, indicating that the covers may be effective where the depth to the water table is between approximately 1 and 10 meters according to Equation 10.

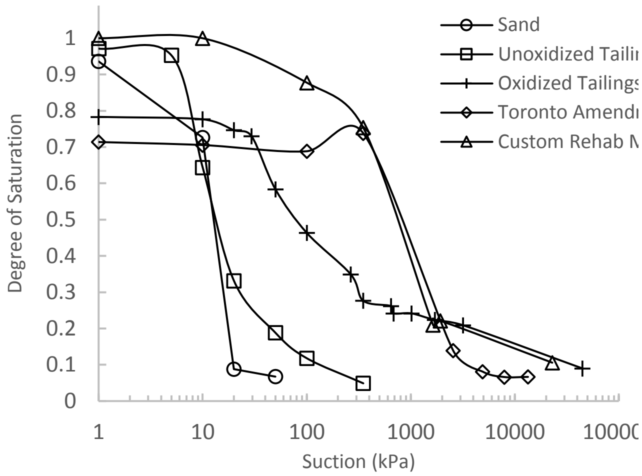

Figure 6. Soil-water characteristic curves developed for cover materials shown as degree of saturation – suction relation.

5.0 UNSATURATED FLOW MODELLING

Using the characteristic obtained in the laboratory testing phase, numerical modelling was conducted to predict unsaturated flow within potential cover configurations using SoilVision SV Flux software. A one-dimensional model was created to observe water flux vertically through the proposed cover configurations. For the model a 50cm layer of tailings was covered with 15cm of sand, with a 15cm layer of biosolids overlying the sand, and a final 15cm of sand as the top layer for control of erosion and excessive evaporative fluxes from the biosolids layer (see Figure 7).

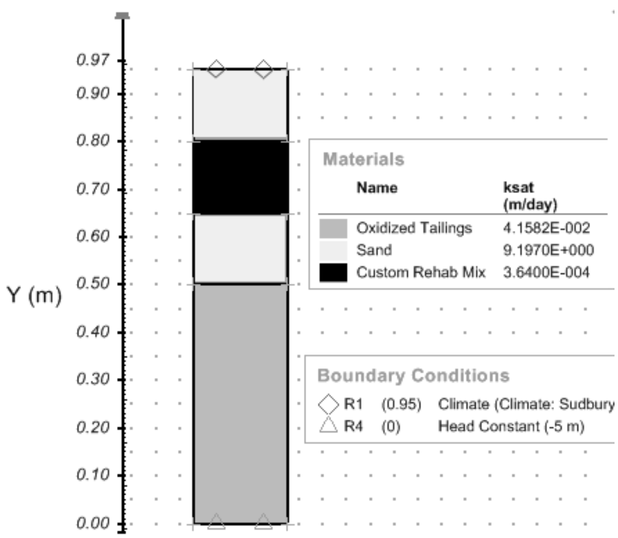

Figure 7. 1D column configuration for computer simulation

The volumetric water content – suction relations for each cover material were added to the model, and

Weather data of temperature highs/lows and precipitation from Sudbury, Ontario (Environment and Natural Resources Canada, 2018) was used for the time-period of 01/06/2018 (dd/mm/yyyy) to 31/08/2016 (91 days) and applied as a climate boundary using the Penman method of calculating evaporative flux (Equation 11).

Freeze thaw behaviour was not evaluated as part of the simulations.

6.0 RESULTS AND DISCUSSION

In Figure 8 and Figure 9 the results are shown for four tests. Clockwise from the top left 1) TA with a constant head boundary of -1m applied to the bottom of the column 2) TA with a constant head boundary of -5m applied to the bottom of the column 3) CRM with a constant head boundary of -5m applied to the bottom of the colum 4) CRM with a constant head boundary of -1m applied to the bottom of the column. These figures show results from modelling with the oxidized tailings only for the sake of available space. The columns modelled with unoxidized tailings behaved similarly. The water flux down into the tailings from the cover is shown in Figure 8 and is observed to be minimal with respect to the quantity of precipitation received by the columns. Where the water table is higher up in the tailings strata a negative flux is observed in several instances, indicating movement of water upwards from the tailings into the sand and biosolids layer due to evapotranspiration pulling water up towards the cover surface.

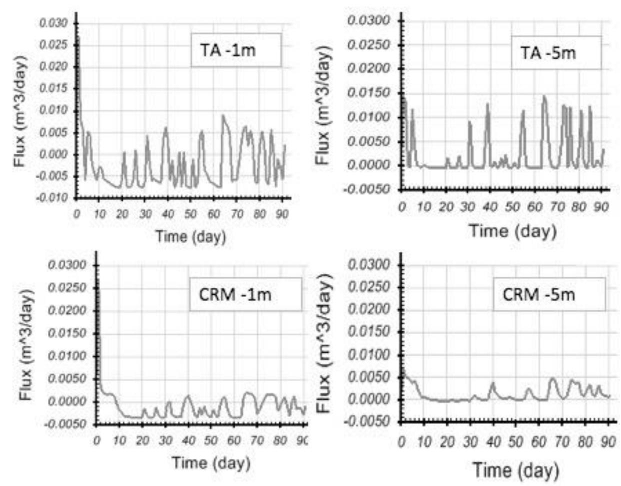

Figure 8. Water flux moving in the downwards direction (denoted as positive flux) at the sand/tailings interface

Figure 9 shows the preservation of highly saturated conditions within the biosolids layers for all tests throughout the duration of the simulations. The order of the results shown is the same as in Figure 8. The biosolids layers maintain a high degree of saturation throughout the duration of the 91 day simulation period. The sand layer becomes almost totally desaturated for the duration of the simulation.

It can be seen that with a lower water table (simulated using a more negative constant head boundary) the sand layers desaturate further, and water fluxes through the sand layer are reduced. This is likely due to the reduction in water available for transport within the tailings as the tailings desaturate, and due to a reduction in hydraulic conductivity of the sand impeding water flux.

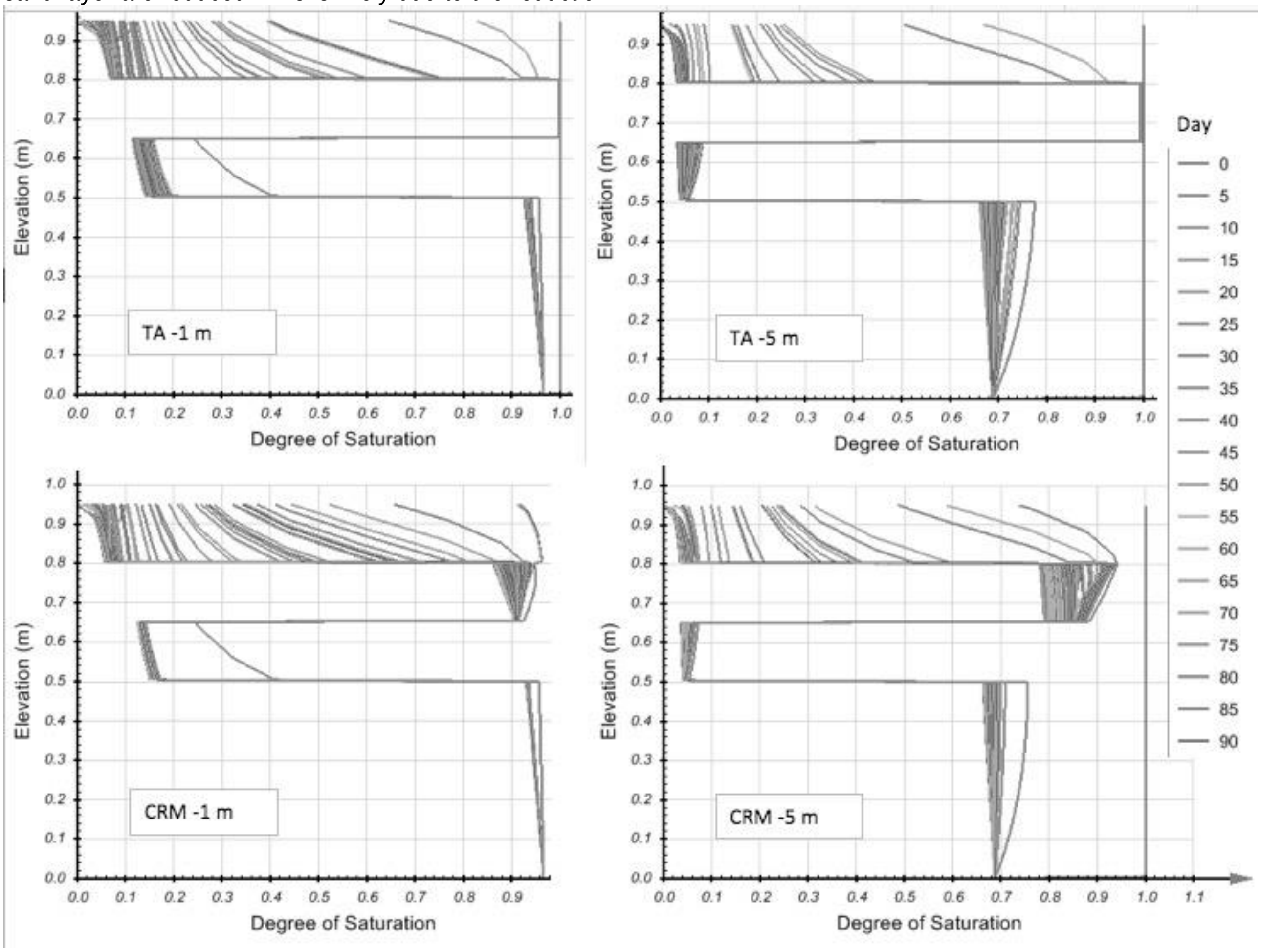

Figure 9. Simulation results of biosolids capillary barrier cover (TA & CRM materials) maintaining saturation over 91 day period on oxidized tailings. Clockwise from the top left 1) TA with a constant head boundary of -1m applied to the bottom of the column 2) TA with a constant head boundary of -5m applied to the bottom of the column 3) CRM with a constant head boundary of -5m applied to the bottom of the colum 4) CRM with a constant head boundary of -1m applied to the bottom of the column

The results of simulations with covers constructed on unoxidized tailings were similar to those shown in Figure 9 using oxidized tailings, however, these were omitted due to space restrictions.

7.0 SUMMARY AND CONCLUSIONS

The results of characterization and unsaturated flow modelling indicate that municipal biosolids present a potential alternative to silt and clay materials in the construction of capillary barrier covers for reactive mine tailings.

Municipal biosolids demonstrate the following suitable properties for developing saturated capillary barriers:

- Low saturated hydraulic conductivity of straight biosolids (1.84 x 10^{-6} cm/s) and biosolids mixed with leaf and yard waste (4.21 x 10^{-7} cm/s)
- High volumetric water content and degree of saturation at elevated suction pressures
- Simulation of precipitation/evaporation events with 91 days of weather data indicate a robust saturated layer with minimal water flux through the cover.

Further work on this subject is required to understand the potential for reducing acid generation and metal mobility within the tailings. Laboratory scale column tests are currently being conducted as part of the research project underway at Carleton University.

Recommendations for study of freeze-thaw behavior of biosolids capillary barrier covers, and other investigation into cover longevity due to degradation of the biosolids material are being considered for future study.

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