BENEFICIAL REUSE OF MUNICIPAL BIOSOLIDS AS LOW-PERMEABILITY, LOW COST OXYGEN BARRIER IN CAPILLARY BARRIER COVERS FOR REACTIVE MINE TAILINGS

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ABSTRACT

Financial costs and material quantities required for mine reclamation can be astronomical. Municipal biosolids present a potential low-cost alternative to traditional materials used in construction of multilayer covers for reclamation of mine wastes and disturbed lands. A blended biosolids referred to as Custom Reclamation Mix or CRM (1:1 volumetric mix of anaerobically digested biosolids and leaf and yard waste) was evaluated as a candidate barrier layer in a Capillary Barrier Cover (CBC) through material characterization, laboratory column testing of biosolids CBCs, and numerical unsaturated flow modelling. The CRM exhibited strong potential for use as in oxygen barrier covers, demonstrating low saturated hydraulic conductivities ($k = 4.21 \times 10^{-7}$ cm/s at $e = 4.01$) and an air-entry value of approximately 400 kPa. Throughout laboratory column testing biosolids layers within the CBCs remained highly saturated, acting as a barrier to oxygen diffusion and water flux. Numerical modelling showed reduction in oxygen diffusion by up to three orders of magnitude when using biosolids CBCs relative to uncovered tailings. Biosolids present a promising low-cost alternative to traditional low-permeability materials in multilayer covers for mitigation of acid rock drainage.

Key Words: Reclamation, Sustainability, Waste Management, Mine Closure, Residuals

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INTRODUCTION

Acid rock drainage refers to the generation of low pH conditions in tailings soil matrices, waste rock piles, and mine waters, resulting from the oxidation of sulfide minerals within waste rock and tailings (Singer & Stumm, 1970). Traditional methods for management of acid rock drainage have included submersion of reactive tailings beneath water covers or the construction of solid soil covers.

Water covers present an effective method for reducing tailings oxidation, however, water covers require impoundment and can fail catastrophically, such as in the rupture of the Fundão tailings dam in 2015 in the Minas Gerais region of Brazil (Bianchi, Assumpção, et al., 2016) and, more recently the catastrophic tailings dam failure at the Córrego do Feijão iron ore mine (again in the region of Minas Gerais, Brazil) resulting in the sudden release of impounded tailings. In the Canadian context, the Mount Polley tailings dam failure in 2014 resulted in the release of significant quantities of tailings to the environment. Technical review of the Mount Polley tailings storage facility breach concluded that future implementation of Best Available Technology included reduction in the use of water covers in a closure setting (Independent Expert Engineering Investigation and Review Panel, 2015).

Solid soil covers present an alternative to water covers for management of reactive mine wastes. Engineered soil covers utilize designed thicknesses of soil, geotextile, and aggregate material layers with the specific purpose of controlling water infiltration and oxygen diffusion through to the underlying tailings (Aubertin, Bussière, et al., 2016). 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 1. In Figure 1, and subsequent figures showing saturation, a value of 0 indicates no water present within the soil pore spaces, while a value of 1 indicates that 100% of the soil pore spaces are occupied by water.

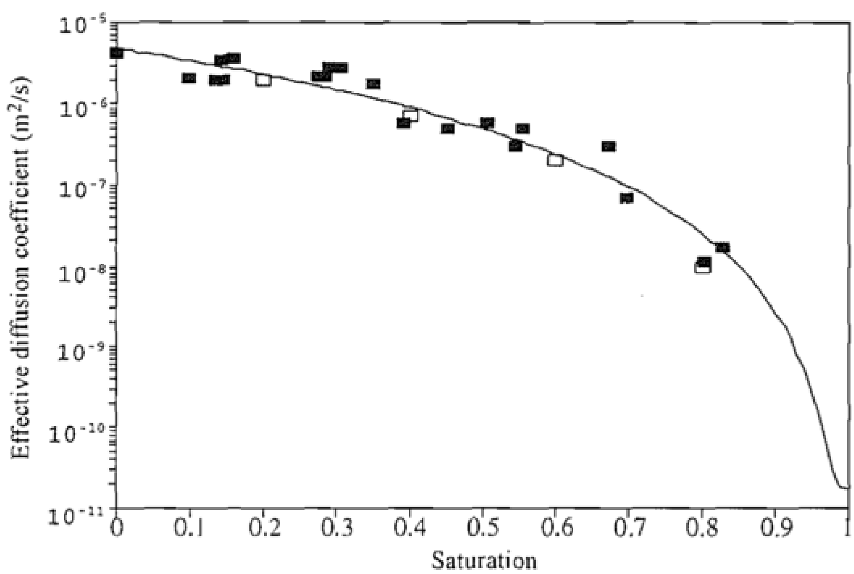

Figure 1. The relationship between the calculated effective diffusion coefficient for oxygen and the water saturation. Data presented in Reardon and Moddle (1985) (■) and data from Elberling et al. (1993) (⊡) (Figure extracted from Elberling, Nicholson, et al., 1994)

Capillary barrier covers (CBCs) and similar multilayer covers are known technologies in mine closure and landfill capping applications; full-scale tailings cover applications include the LTA site near Malartic, the Lorraine mine site in the Temiscamingue area (Dagenais, Aubertain, et al., 2005), and the Rocky Mountain Arsenal (Williams, Hoyt, et al., 2010). CBCs rely on the differences in water retention properties of the different cover layers, governed primarily by differences in grain size between materials, to induce a capillary break between the layers.

Soil suction theory was first developed to understand water movement and holding capacity of soils for agricultural applications; it was initially observed that capillary forces within finer soil spaces were responsible for the movement or retention of water (Buckingham, 1907). Soil pore spaces drain as suction pressures increase; suction pressure are driven by osmotic suction due to solute potential, and matric suction due to capillary potential of the soil pore spaces (L. A. Richards, 1931). Pore water pressure become more negative at decreasing pore radii, indicating that finer soils exert greater suction forces at a given water content (Marinho et al., 2008). The Air Entry Value (AEV) is the level of matric suction required to begin desaturation of the largest pore spaces.

As seen in Figure 2, as levels of soil suction within the cover increase, a quickly draining coarse grained layer will arrive at its residual water content while the oxygen barrier layer, composed of fine grained material is still largely saturated (ψ_a in Figure 2). Once the coarse grained layer drains to the residual water content (ψ_r in Figure 2), its hydraulic conductivity becomes extremely small, limiting liquid water flux.

Under appropriate hydrologic conditions, underlying coarse grained layers can prevent desaturation of a barrier layer or prevent percolation from an overly fine grained layer. The concept originated with Rasmuson and Eriksson (Rasmuson & Eriksson, 1986). This cover technology has been proven and verified through numerous laboratory (E. Yanful, 1994), numerical (Khire, Benson, et al., 2000); (Choo & Yanful, 2000) and field pilot studies (Woyshner & Yanful, 1995); (E. K. Yanful, Simms, et al., 1999); (Ernest K. Yanful, Mousavi, et al., 2003); (Maqsoud, Bussière, et al., 2011).

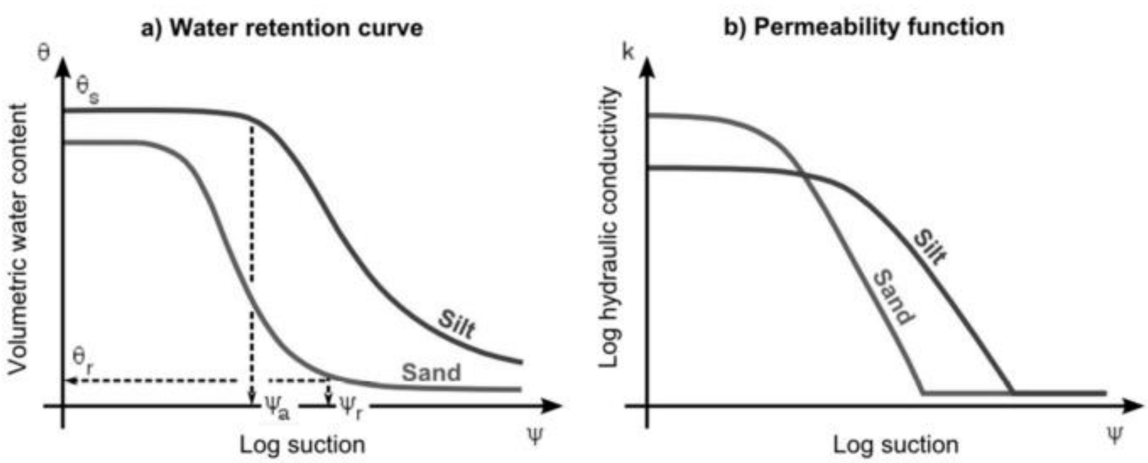

Figure 2. Hydraulic functions of a silt (fine grained soil) and sand (coarse grained soil). (Figure extracted from Aubertin et al., 2016)

CBC limitations include the influence of slopes on barrier layer desaturation, and geotechnical instability along layer interfaces, as well as limitations related to vapour transport. Despite the limitations, the capillary break allows for a wide range of applications for multilayer covers in waste management practice.

Sourcing, producing, and transporting the vast quantities of materials required to develop multi-layered covers can present significant economic and environmental challenges. Therefore, cheaper alternative materials for construction of the coarse-grained or fine-grained cover layers are often explored, such as crushed concrete (Rahardjo, Santoso, et al., 2013) and crushed rock-bentonite (Boulanger-Martel, Bussière, et al., 2016). This project examines the use of a blended biosolids material as the low permeability oxygen barrier layer in a CBC. The use of biosolids is not a completely new concept in the mining industry; biosolids are already in use at several mining operations and tailings facilities as a means to promote revegetation of tailings, waste rock, or other disturbed land.

Municipal wastewater is processed to remove suspended and volatile solids, nitrogen and phosphorous, and to produce an effluent suitable for discharge to receiving water bodies. Wastewater treatment produces sludges which can be further thickened and dewatered into biosolids to reduce volume and facilitate transport and disposal (Fernandes, Lopes, et al., 2007). Sludge treatment is intended to achieve vector reduction and pathogen stabilization; anaerobic digestion is a common method of sludge treatment and biosolids production (Metcalf & Eddy, Tchobanoglous, et al., 2014). Conventional disposal of biosolids includes landfilling, incineration, and agricultural application. Both sludges and biosolids can be beneficially reused.

The objective of this research was to assess the suitability of municipal biosolids as a low-cost alternative to traditional low-permeability materials used in CBCs for management of reactive tailings.

METHODOLOGY

Material Characterization

Two biosolid materials were tested for their suitability as construction materials in capillary barrier covers. A straight biosolids material referred to as the Toronto Amendment (TA) was obtained from Terratec Environmental's field application site in Sudbury, and a second biosolids material referred to as the Custom Reclamation Mix (CRM) was sampled from stockpiles of biosolids blended with leaf and yard waste on a one to one volumetric basis. Approximately 132 litres (seven 5-gallon buckets) of each biosolid material was sampled from representative surface locations throughout the stockpiles. All sampled material was fully blended by type prior to laboratory testing. Column testing and numerical modelling focused primarily on the performance of CRM as the material presents significant practical advantages with respect to odour control and ease of mechanical application relative to the unmixed Toronto Amendment biosolids.

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 Canada Ltd.'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, and falling and constant head tests (ASTM D5856-15) to determine saturated hydraulic conductivity. The soil water characteristic curve (SWCC) of the cover materials was developed using combined results of axis-translation (ASTM D6839 – 16 Method C), the filter paper method (ASTM D5298 -16) and a Decagon Devices WP4C dewpoint hygrometer (ASTM D6839 – 16 Method D).

Column Testing of Biosolids CBC

Three acrylic columns were constructed to assess the effectiveness of CRM biosolids materials as the low permeability oxygen barrier layer in CBCs at a laboratory scale. The column layer configurations are provided in Table 1.

Table 1. Laboratory column cover layer thicknesses

Depth (m)	Column A	Column B	Column C
0.80 – 0.95	Sand	N/A	Sand
0.65 – 0.80	CRM	N/A	CRM
0.50 – 0.65	Sand	CRM	Sand
0.00 – 0.50	Pre-oxidized Tailings	Pre-oxidized Tailings	Unoxidized Tailings

Each acrylic column was constructed with interior dimensions of 25 cm x 25 cm and a total column height of 110 cm. Instrument ports were milled in the column walls to accommodate soil suction sensors, volumetric water content (VWC) sensors, and soil pore water sampling equipment at the mid-height of each soil cover layer, with the exception of the tailings where ports were milled 5 cm below the tailings interface and 5 cm from the base of the columns. Decagon Devices 5TE VWC sensors and METER Environment Teros 21 soil suction sensors were installed during soil placement within the columns.

Lascar Electronics EasyLog Temperature & Humidity data loggers placed within each column throughout the duration of testing. A drainage port was milled in the base of each column and connected via plastic tubing to a constant head reservoir 2 m below the base of the columns to simulate a water table.

Field weather conditions were not simulated during column testing. Instead, "worst-case" drying and wetting conditions were simulated by subjecting the columns to 35 days of drying without precipitation, followed by a period of flushing of 16 days, and a second drying phase of 90 days. A bucket of known surface area was partially filled with water and placed on a balance for the duration of the column testing. The mass of water, and height of water within the bucket was used as a proxy for the actual evaporation affecting each column. During flushing, the height of water ponded above the surface of each columns was used to corroborate the data obtained from the evaporation measurement bucket.

Column Drying and Flushing

Column flushing was conducted with the intent of fully saturating the columns prior to a second round of drying, and to obtain pore water samples from regions of the columns which were otherwise too dry to obtain pore water samples without flushing. Flushing was also conducted in order to assess the effectiveness of biosolids covers to limit infiltration of water into the underlying tailings by simulating a "worst-case" scenario of hugely excessive precipitation. Flushing was conducted by initially adding 1 L of water to the top of each column and observing the effects of the added water. When it was determined that water was not penetrating the biosolids layer, additional water was added in 1 L increments to a total of 12 L added. It was observed that the upper sand layers in both capillary barrier columns became fully saturated without any noticeable effect on the underlying biosolids layer. In the monolayer column, some water was initially absorbed by the partially desaturated surface of the biosolids layer. Following initial saturation of the uppermost layers of each column, water was not observed to flow through the biosolids layers and a shallow depth of water remained ponded above the soil surface of each column.

The depth of water ponded in the columns was measured over the course of the flushing period to observe the actual rate of evaporation affecting the surface of each soil column. The measurements from the weigh bucket and the temperature & humidity sensors were used to supplement the evaporation observations. At the end of the flushing period the excess ponded water was removed from the columns using a peristaltic pump. Secondary drying was observed for 90 days following removal of ponded water.

Biosolids CBC Numerical Modelling

1D finite element transient analysis was conducted using the commercial Soil Vision SV-Flux software, an unsaturated-saturated flow model. Due to physical constraints of the equipment used at Vale Canada Ltd.'s Copper Cliff Tailings Facility, biosolids application is limited to a 15 cm layer of material, and as such, the modelling and column testing were designed to simulate covers with a 15 cm layer of biosolids to assess their practical use in limiting oxygen transport and diffusion; this was also replicated the laboratory columns created in this study. 1-D models were used to simplify model development and analysis and were used to predict saturation and vertical water flux within the monolayer and capillary barrier covers, as well as the sand layers and underlying tailings.

Model Calibration Using Laboratory Column Data

Drying conditions for the laboratory columns were recreated using measured temperature and relative humidity data collected with EasyLog sensors. Wind speed was back calculated from measured rates of evaporation in a proxy bucket and in the columns during flushing. Potential evaporation was assumed to be equal to the quantity of water evaporated from the proxy bucket measured by the change in depth in millimeters and verified by change in weight. Average wind speed was back calculated from the potential evaporation using the Penman-Montieth equation. Actual Evaporation (AE) was calculated using the Modified Wilson Equation (Wilson et al., 1997), which regulates AE through the calculated suction at the cover surface.

Simulated Climate Conditions

Climate data for the City of Greater Sudbury was obtained from historical weather data (Government of Canada, 2018); a period of 90 days during the summer of 2016 from June 1 to August 30 was used to model average weather summer conditions affecting the Copper Cliff Tailings Facility. In addition to simulating historic weather, extreme drying conditions were simulated by applying a constant 20^0C with 60% relative humidity and no precipitation for the 90-day simulation period. The depth from ground surface to the water table was modelled by implementing a constant head boundary condition at the base of the tailings.

RESULTS AND DISCUSSION

Material Characterization

The specific gravity and saturated hydraulic conductivity of the materials is shown in Table 2.

Table 2. 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	1.11×10^{-4}
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 2 it can be seen that the municipal biosolids materials (TA and CRM) have very low saturated hydraulic conductivities resembling those recorded in fine silts (Ernest K. Yanful et al., 2003), which can be used as the saturated layer in capillary barrier covers (Nicholson, Gillham, et al., 1989). Particle size distributions for the characterized materials are provided in Figure 3.

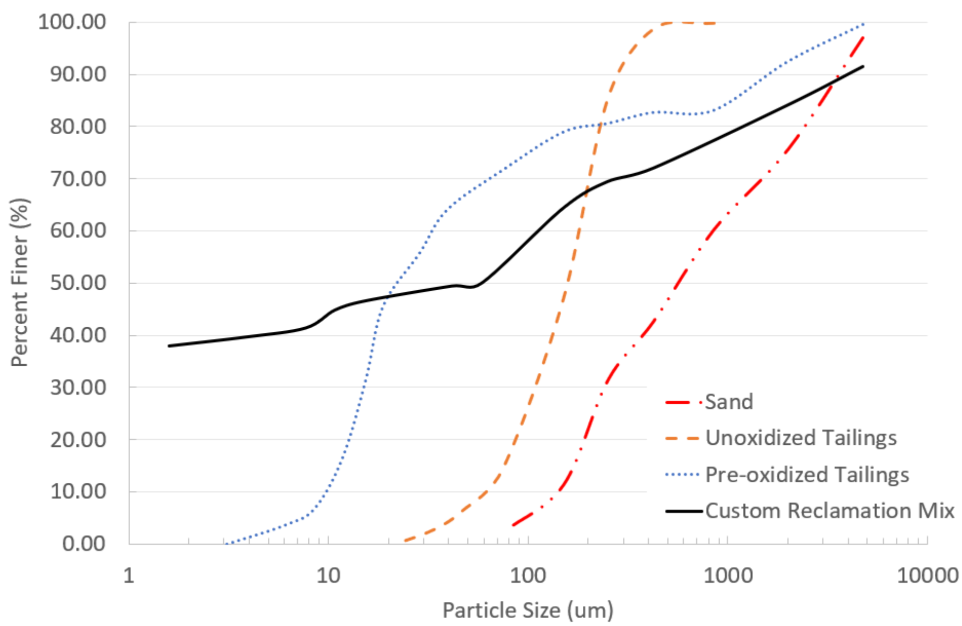

Figure 3. Particle Size Distributions of Characterized Cover Materials and Tailings

The results of the soil suction tests were combined to create SWCCs for the coarse sand and biosolids materials and are shown in Figure 4.

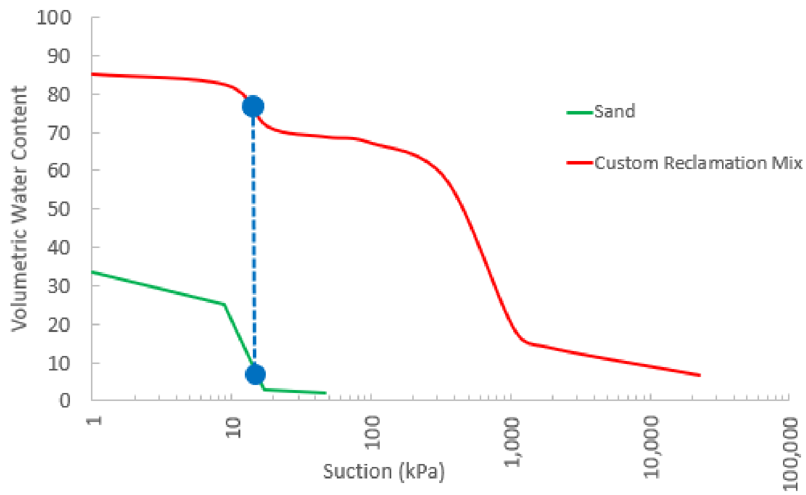

Figure 4. Soil-water characteristic curves developed for cover materials shown as volumetric water content – suction relation.

The SWCCs shown in Figure 4 for the biosolids and sand material show the requisite differential in VWC at suctions from 10 kPa up to approximately 500 kPa to establish a capillary barrier cover.

Column Testing Observations and Results – Initial Drying and Flushing

During the initial drying stage the biosolids within upper 5 cm of the monolayer cover were visually observed to undergo drying and volumetric deformation with shrinkage and cracking occurring on the biosolids surface. The biosolids within the capillary barrier covers underwent no visually observable drying. Water contents immediately below the tailings surface were not observed to increase throughout the flushing period indicating that percolation was not occurring through the biosolids covers into the underlying tailings. During flushing, the depth of water ponded on the cover surfaces were found to decrease at rates similar to or less than those observed in the proxy bucket used to determine Potential Evaporation, further indicating that the biosolids covers were effective as low-permeability covers.

Preservation of the Municipal Biosolids Capillary Barrier

Following the second phase of drying, columns were deconstructed and VWC was determined through oven drying of sampled soil volumes. The final saturation profiles of the columns are shown in Figure 5 and indicate the establishment and preservation of a saturated biosolids layers within the CBC covers. A 5 cm thick surface crust was observed in the biosolids of the monolayer column (Column B), and a layer of precipitates was visually observed during deconstruction approximately 2 cm below the biosolids surface. Below the crust, the biosolids were found to have a water content similar to the water content at initial column construction, and similar to the biosolids in the capillary barrier columns. This indicates that drying does not occur uniformly throughout the biosolids layer and that the drying front within the biosolids progresses slowly downwards from the biosolids surface. Additionally, this indicates that the oxygen infiltration barrier does not become fully compromised even after long durations of no applied precipitation.

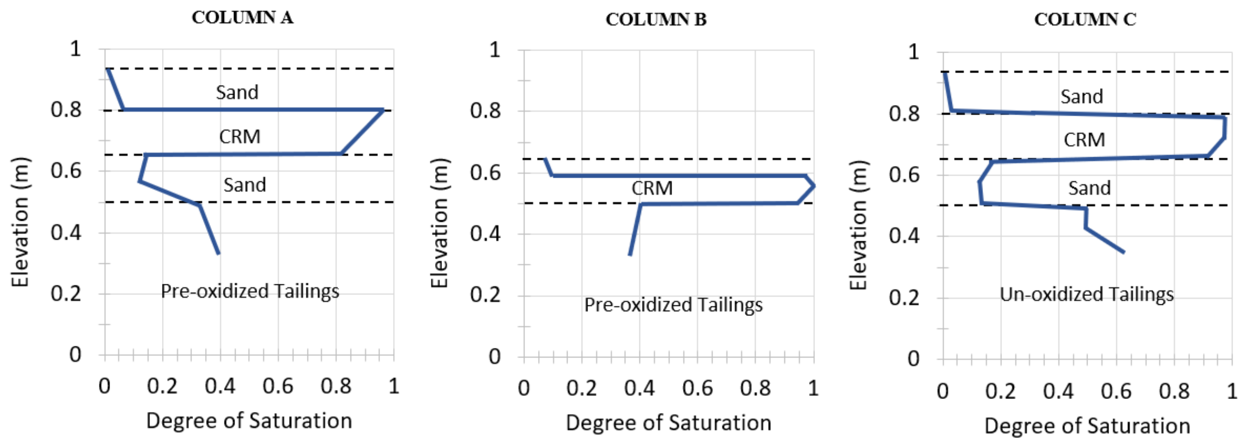

Figure 5. Saturation profiles of deconstructed laboratory columns (data obtained from oven drying).

Soil suction and saturation profiles indicate that extensive drying occurs in the upper sand layer of the capillary barrier covers, while underlying cover layers are not exposed to elevated levels of soil suction. Figure 6 shows the large increase in recorded suction within the surficial sand layer of the CBC in Column A while no change in suction was observed within the underlying biosolids layer.

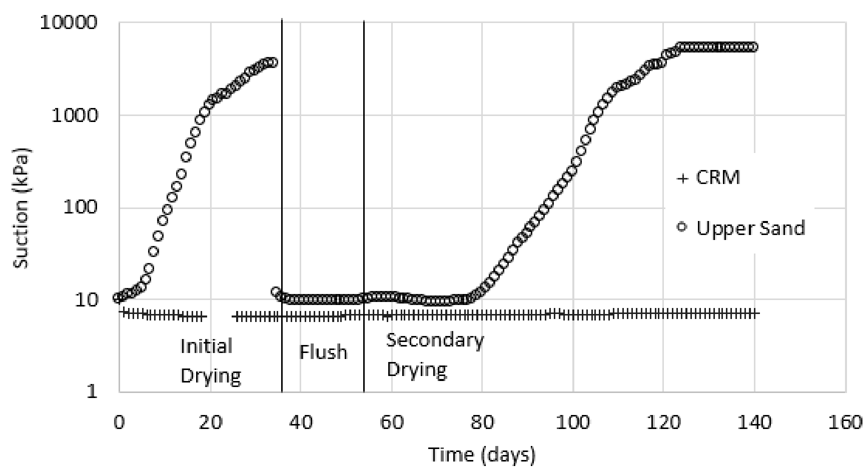

Figure 6. Suction profile in Column A measured by Teros 21 sensors throughout test duration.

Column Testing Discussion

VWC readings from instrumentation were found to be impacted by changes in soil electrical conductivity and soil volume due to consolidation and decoupling from the surrounding soil medium. As a result, final VWC instrument readings were significantly different from the true final VWC determined through oven drying during column deconstruction (see Figure 5). Therefore, VWC instrument readings were only used for coarse estimation of cover saturation profiles and monitoring of potential water flux through the cover layers during flushing. Column deconstruction oven-drying tests were taken to represent the true VWC and degree of saturation at the end of the secondary drying phase.

Numerical Modelling Results

Modelling of biosolids capillary barrier covers demonstrated the theoretical robustness of the covers under a variety of imposed boundary conditions. Saturation profiles from SV-Flux show the strong water retention properties of the biosolids layer, and the desaturation of the enveloping sand layers. Figure 7 compares numerical modeling saturation profiles to those observed from the initial drying phase (VWC sensor data) and the secondary drying phase (column deconstruction – oven dried VWC data) for the CRM biosolids CBC over unoxidized tailings (replicating Column C). In Figure 7, a VWC of 0 represents a complete absence of water (ie. that the layer is completely composed of solids and air voids), while a VWC of 1 would indicate that the layer in question is 100% water by volume.

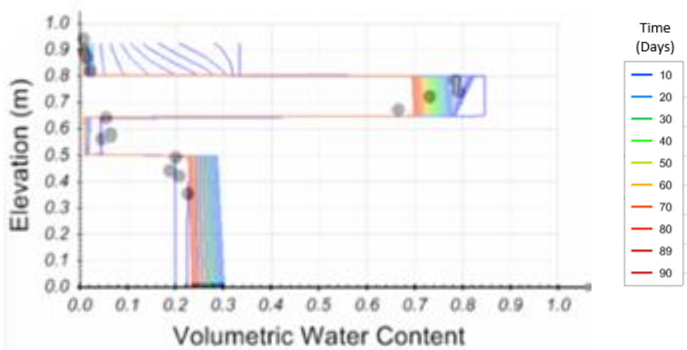

Figure 7. Biosolids CBC numerical modelling results superimposed with oven dried VWC samples from column deconstruction.

Numerical modelling of the flux at the tailings interface was conducted to compare cover effectiveness in reducing water percolation into the underlying tailings precipitation was applied using weather data from the region of Sudbury. Figure 8 shows the water flux when no cover is applied.

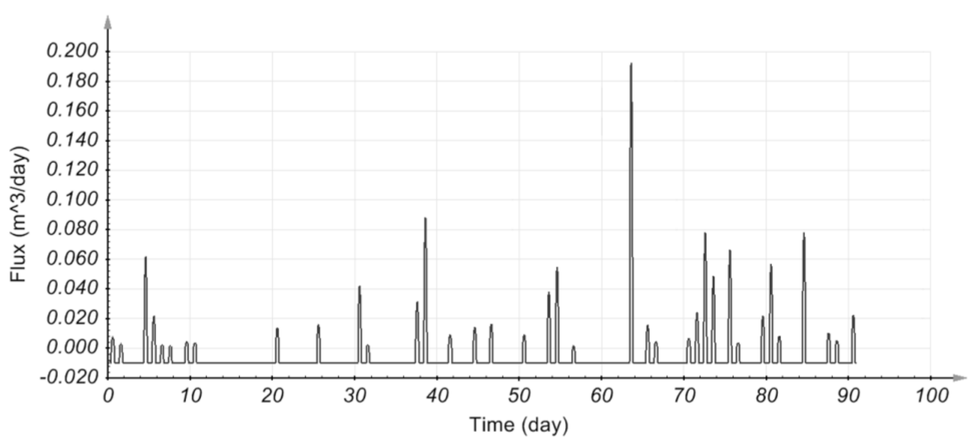

Figure 8. Flux at the tailings surface when no cover is applied over pre-oxidized tailings with a -2 m constant head boundary at the base of the tailings.

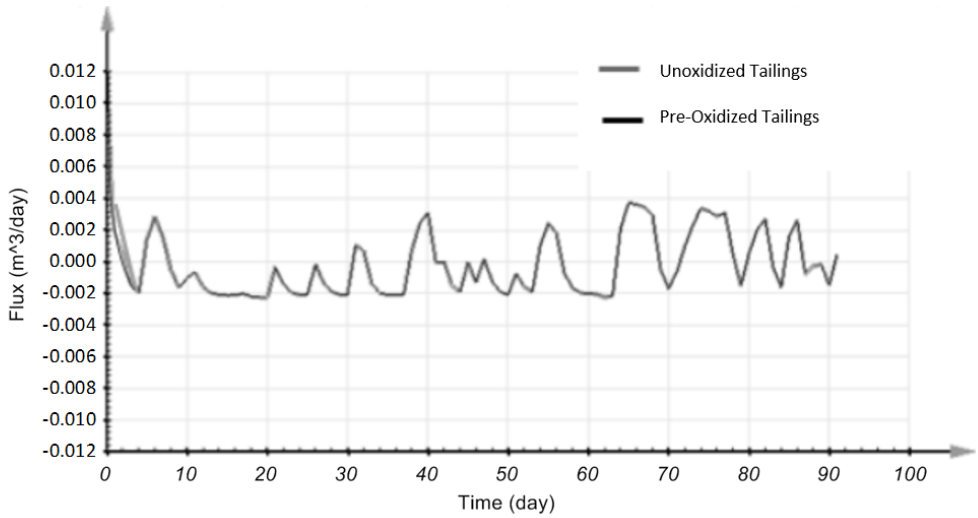

Figure 9. Flux at the tailings interface in a CBC cover with CRM biosolids and a -2 m constant head boundary at the tailings base

In addition to greatly reducing the water flux through at the tailings interface as shown in Figure 8 and Figure 9, modelling results indicated robust performance of the saturated CRM oxygen barrier layer within the CBC. The degree of saturation within the biosolids layer of modelled CBCs with a -2 m constant head boundary and applied weather conditions is maintained between 85% and 90% as shown in Figure 10, which may serve to reduce oxygen diffusion by 2 to 3 orders of magnitude (see Figure 1).

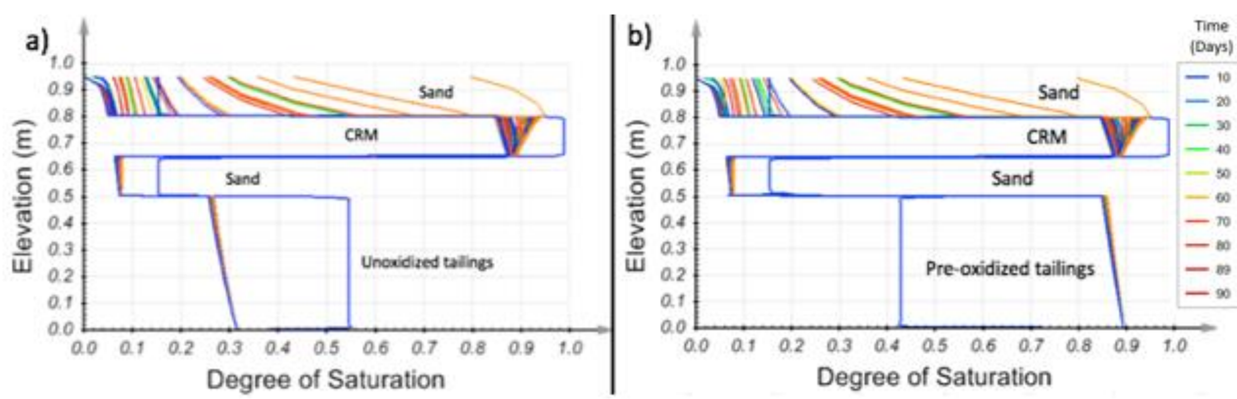

Figure 10. Saturation profiles of modelled CBCs over unoxidized (a) and pre-oxidized tailings (b) with -2 m constant head boundary at the base of tailings.

Numerical modelling results indicated the preservation of a robust oxygen barrier over the course of simulation regardless of the underlying tailings type.

CONCLUSIONS AND RECOMMENDATIONS

The results of characterization, column testing, and numerical modelling indicate that capillary barrier covers made with municipal biosolids may provide effective reduction in flux at the tailings interface and in maintaining a saturated oxygen diffusion barrier layer. This is supported by:

- The biosolids materials exhibit low hydraulic conductivity (4.21 x 10^{-7} cm/s) and good water retention properties as determined by establishment of the biosolids soil water characteristic curve.
- Laboratory column testing showed the successful establishment of a capillary barrier using municipal biosolids to cover both coarse and fine mine tailings. The biosolids layers were shown to remain almost fully saturated throughout extensive drying periods of 34 and 90 days without precipitation. The biosolids layers were also found to significantly limit water flux during flushing, where water was ponded on the surface of the columns for 16 days.
- The biosolids initially slowly lose water as they shrink, but their water contents stabilize before the AEV of the material is reached, limiting desaturation of the oxygen barrier layer.
- Numerical modelling results show reduction of water flux at the tailings interface by 98% under identical climate and precipitation conditions when using a CBC compared to uncovered tailings.

As this was the first test of municipal biosolids in capillary barrier covers, there were several avenues for research which were not explored, but which could have significant impact on the long-term viability biosolids CBCs. With respect to changing material properties, the study of any of the following mechanisms would be of great use in understanding the long-term suitability of biosolids for use in engineering applications:

- Improvement in sensor function within biosolids materials to obtain water content and suction readings without interference from dissolved salts and metals.
- Examination of freeze-thaw behaviour of biosolids materials with a particular emphasis on the water retention properties and hydraulic conductivity would provide a vastly improved understanding of how biosolids CBCs would perform over multiple seasons in a variable climate.
- Long-term composting effects on SWCC and cover function of municipal biosolids. Organic degradation of the biosolids materials may have significant effect on performance in the long-term. The oxygen consumption during the aerobic stages of biosolids composting may be worth investigating as this mechanism may help to further reduce oxygen flux through to the underlying tailings; this process may also be finite in duration as biosolids undergo structural and biological change

In summary, laboratory studies and numerical modelling indicate that municipal biosolids exhibit the necessary properties for use in capillary barrier covers to reduce reactive tailings oxidation and subsequent acid rock drainage in the short term. Municipal biosolids present a potential low-cost alternative to traditional low-permeability materials employed in engineered soil covers. The potential for biosolids for use as barrier layers in covers should be explored in larger scales field trials, as is conventionally done for mine waste covers.

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