

THE USE OF AN ORGANIC CARBON COVER SYSTEM AT A CU-NI MINE IN SUDBURY, ON

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ABSTRACT

Acid rock drainage (ARD) occurs when sulfide minerals oxidize, generating low pH water and the release of dissolved metals. This phenomenon is one of the most significant concerns in the mining industry, where the future loading of dissolved metals from inactive mine sites could continue for decades to centuries. Traditionally, remediation of ARD is focused on collection of water from surface-water bodies and treatment through pH neutralization using lime (CaO). While this approach improves water quality, it represents a recurring cost for mining companies. Therefore, numerous approaches have been developed over the past few decades to passively mitigate and remediate ARD by limiting the supply of $O_{2(g)}$ and water to tailings rich in sulfide minerals. For example, some cover systems utilize organic carbon material such as biosolids, wood-waste, peat and compost. A two-layer cover system was studied at an active Cu-Ni mine site located near Sudbury, ON and comparisons were made between sites with a two-layer cover system, a one-layer cover of desulfurized tailings only, and no cover. Pore-gas results show that the organic layer consumes a portion of the $O_{2(g)}$ ingress from the atmosphere, with most of the $O_{2(g)}$ depletion occurring in the desulfurized tailings layer. Pore-water results show that the organic carbon layer increases the alkalinity and that the presence of the desulfurized tailings vastly improves water quality. Thus, the re-use of waste products within a cover system has the potential to sustainably manage ARD in the near term and further study on their use as a land reclamation measure is warranted.

Key words: Acid Rock Drainage, Passive Remediation, Source Control, Desulfurized Tailings

INTRODUCTION

The generation of acid rock drainage (ARD) and release of dissolved metals are a significant concern in the mining industry. Sulfide oxidation and subsequent ARD can cause future loading of dissolved metals, SO_4 and acid from inactive mine sites for decades to centuries (Moncur et al., 2005). Recent estimates of total liability related to ARD remediation exceed \$10 billion in Canada alone (Mining Watch Canada, 2017).

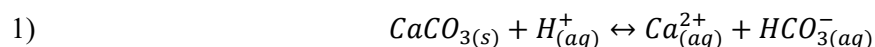
Metal mining takes place predominantly in sulfide (S^{2-}) ore bodies, through the recovery of metals from sulfide minerals of interest, such as chalcopyrite $[CuFeS_2]$ and pentlandite $[(Ni,Fe)_9S_8]$. The ore is extracted

from the subsurface, pulverized and concentrated using chemical processes. The processing of the ore produces a concentrated product and a large amount (sometimes greater than 90% of the ore) of fine-grained waste material called tailings, which contain the primary sulfide minerals of pyrite [FeS₂] and pyrrhotite [Fe_(1-x)S] (Blowes et al., 2014). This material is generally pumped from the mill as a slurry (containing greater than 50% water by volume [v/v]) to tailings storage facilities (such as in tailings ponds or impoundments) for long term storage and management. These tailings slurries are transported by way of a pipeline to the tailings impoundment and may be stored subaerially or subaqueously.

After tailings deposition ceases, tailings stored subaerially will, in time, desaturate. This decrease in moisture content causes an increase in the rate of O_{2(g)} diffusion from the atmosphere into the shallow tailings. When sulfide minerals are exposed to O_{2(g)} in the presence of moisture, they react to produce SO₄, Fe, and acidity (Blowes et al., 2014).

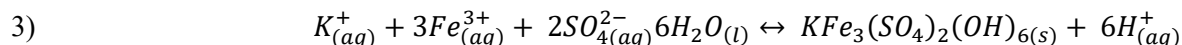
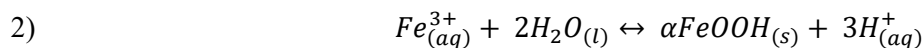
The rate of iron-sulfide oxidation can be greatly accelerated in the presence of Fe and S-oxidizing microorganisms (Baker and Banfield, 2003; Johnson and Hallberg, 2007). Neutrophilic S-oxidizing microorganisms (nSOM) and Fe-oxidizing microorganisms (nIOM) are often detected in neutral-pH mine wastes (e.g., Blowes et al. 1998), while acidophilic species dominate in acidic mine wastes (Johnson and Hallberg, 2007; Johnson, 1998) of which *Acidithiobacillus ferrooxidans* is the most widely studied. Other sulfide minerals found in tailings storage facilities, such as sphalerite [(Zn,Fe)S], bornite [Cu₅FeS₄], arsenopyrite [FeAsS] and galena [PbS] have various resistances to oxidation, and the composition of the tailings porewater is profoundly affected by the redox conditions and mineralogy of the tailings (Jambor, 1994).

Acid generated during the oxidation of pyrite, pyrrhotite and other sulfide minerals is neutralized to varying degrees by the dissolution of (in the following order) carbonates, (oxy)hydroxides, and silicate minerals (Jurjovec et al., 2002) which can lead to significant declines in the concentrations of dissolved metals released from mine wastes and increases in porewater pH along the flow path (Blowes et al. 2014). An example of a neutralization reaction using calcium carbonate can be found in Equation 1.



The primary minerals are those that are extracted from the orebody for mineral processing. During mineral processing and waste disposal, oxidation of the primary sulfide assemblage can occur and form secondary minerals (Blowes et al. 2014). Tertiary minerals are those that form when a sample of the tailings is extracted from its storage facility (Jambor and Blowes, 1998). These are important to note because the primary minerals evolve into secondary and tertiary minerals as the ore is extracted and processed.

Examples of secondary minerals include (oxy)hydroxides and hydroxysulfates (which vary in solubility). The most common secondary phases of (oxy)hydroxides in sulfide tailings disposal sites include goethite [α -FeOOH] (Equation 2) and ferrihydrite [Fe₂O₃•0.5H₂O]; which is metastable and transforms to goethite or hematite [α -Fe₂O₃] over time (Jambor and Dutrizac, 1998; Waychunas et al., 2005). The most common secondary phases of SO₄ minerals include gypsum [CaSO₄•2H₂O] and jarosite [KFe₃(SO₄)₂(OH)₆] (Equation 3), of which gypsum is more soluble (Blowes et al., 2014).



Reactions 2 and 3 result in the generation of acid, which enhances the solubility of many heavy metals, with adverse consequences for surrounding flora and fauna. Covers are a strategy to reduce ARD by either restricting $O_{2(g)}$ influx (through fine-grained material with a high moisture content) or consume $O_{2(g)}$ (through aerobic degradation of organic materials by microbes).

The goal of the research described herein is to assess the effectiveness of mine waste covers at reducing ARD from sulfide tailings and guide future improvements in cover designs. This paper provides essential background information on the various types of remediation strategies that currently exist to mitigate ARD along with their benefits/drawbacks. A case study is also provided and includes monitoring of both types of covers to assess their performance toward limiting sulfide oxidation.

COVER/COVER SYSTEMS FOR ARD MITIGATION

Numerous approaches have been developed over the past few decades to mitigate and remediate ARD. Mitigation approaches have generally focused on minimizing the production of ARD by limiting the supply of $O_{2(g)}$ and water to tailings rich in sulfide minerals. Examples of these approaches include various types of engineered cover systems (which either consume $O_{2(g)}$ or limit its transport) or water covers. Traditional remediation of ARD generally focuses on collection and treatment of mine-impacted water from surface-water bodies (i.e., ponds, ditches and streams) and treatment through pH neutralization using lime, precipitation as a ferric hydroxide sludge, and then storage (Blowes et al. 2014).

A common type of cover used across several jurisdictions to prevent sulfide mineral oxidation is the use of a water cover. An example of a water cover that has been used with success is subaqueous disposal of tailings. This approach involves depositing the wastes in natural water bodies (such as lakes or oceans) or in constructed impoundments that maintain a water cover (Pederson et al. 1993) and has been found to be one of the most promising and cost-effective methods to reduce or prevent ARD from tailings (MEND, 2001; INAP 2017). The performance of water covers relies on lowering the $O_{2(g)}$ diffusion coefficient for free air (D_a ; $\sim 1.8 \times 10^{-5} \text{ m}^2/\text{s}$), which is almost 10,000 times larger than that of water (D_w ; $\sim 2.5 \times 10^{-9} \text{ m}^2/\text{s}$) (Scharer et al. 1993). This, combined with a relatively low ($8\text{--}13 \text{ mg L}^{-1}$) solubility of $O_{2(g)}$ in water (Blowes et al. 2014), means that the exposure of sulfide minerals to $O_{2(g)}$ is limited in this setting. However, locating a suitable water body has been shown to be challenging, as there are federal regulations regarding disposal, such as Canada's *Metal and Diamond Mining Effluent Regulations* (MDMER, 2002/2020), authorized under the *Fisheries Act*. On a global scale, submarine tailings disposal (STD) is outlawed in jurisdictions that follow the *London Protocol* (Dold, 2014). One option is to avoid using natural water bodies by constructing an engineered water cover using dykes, however their long-term stability is of significant concern (Aubertin et al., 1997). Another challenge is that the deposition of these tailings must take place before any significant oxidation can occur, as oxidized tailings placed subaqueously have been shown to release heavy metals into the porewater requiring treatment of the seepage (Catalan, 2000).

Covers composed of synthetic materials have been emplaced at various mine-waste sites to prevent ingress of both $O_{2(g)}$ and water. Traditional geosynthetic clay liners (GCLs) are composed of bentonite that is encased between two geotextiles or attached to a single geomembrane and held together by needle-punching, stitching, and/or gluing with an adhesive (Shackelford et al. 2010). A cover system that includes geosynthetic materials has been installed at the Kam Kotia mine; a closed Cu/Zn mine located in Timmins, Ontario. This cover system includes an uppermost, vegetated soil layer, underlain by a protective layer of sand, a clay moisture-retaining layer, a GCL, and a capillary-break layer of cushion sand and crushed waste-rock (Pakostova et al. 2020). While GCLs are known to have low hydraulic conductivities ($10^{-11} \text{ m s}^{-1}$) the permeation of fluids with high ionic strength (such as mine process water and leachate) can be orders or magnitude higher (Shackelford et al. 2010). Also, installing GCLs can be expensive, costing upwards of \$250,000 per hectare and only having a warranty of 20-30 years (Renken et al., 2005).

Another mitigation approach is to use single-or multi layer cover systems, composed partially or wholly of fine-grained material. The goal of these cover systems is to maintain conditions of near-saturation above the water table, thus limiting $O_{2(g)}$ diffusion. Covers with capillary barrier effects (CCBEs) are one such example, generally consisting of a saturated, fine-textured material placed between underlying and overlying coarse-textured materials and can maintain an average water saturation $> 85\%$ (MEND, 2004a; Hotton et al., 2020). Another example is a monolayer cover along with an elevated water table. Desulfurized tailings (DST) have been shown to be a suitable material for use in the construction of monolayer covers (Bussière et al. 2004, 2007; Demers et al. 2009; Dobchuk et al. 2013) and this method has been shown to have the potential to reduce acid generation and metal loading in the reactive tailings below the cover by limiting the oxygen flux at the base of the cover (Demers et al., 2008; Éthier et al., 2018; Rey et al., 2020). In addition, the low sulfide content in the DST can contribute to a further decrease in the oxygen flux to the reactive tailings, however, the use of DST can sometimes lead to concentrations of metals and sulfates in the pore water of this layer that exceed environmental criteria, particularly in regard to metals that are mobile at neutral pH conditions (Pabst, 2021). In terms of geotechnical considerations, the deposition of DST can be completed using a thickened tailings method; increasing the solids content of discharge tailings from 30% to 45% which has been shown to increase the geotechnical stability of the impoundment (since no retaining dykes have to be built) along with the improved in-situ density and homogeneity of these tailings (Al & Blowes, 1999). However, if these tailings become dry, these fine-grained materials are susceptible to wind-driven erosion, causing fugitive tailings and related human-health impacts.

ORGANIC CARBON COVERS

The use of organic material as a passive treatment tool for ARD has been studied since the 1990's and has been shown to have the potential to:

- 1) Block $O_{2(g)}$ ingress by acting as a physical barrier;
- 2) Consume $O_{2(g)}$ through decomposition of the organic matter;
- 3) Leach compounds that may inhibit the activity of S-oxidizing bacteria;
- 4) Reductively dissolve ferric oxides and prevent indirect sulfide oxidation;
- 5) Reduce hydraulic conductivity and decrease seepage through compaction;
- 6) Use as a substrate for vegetation;
- 7) Prevent erosion of tailings.

Organic carbon covers have also been found to be more economical than other remediation technologies and can be sourced in sufficient quantities for use in tailings storage facilities (SENES, 1994). In Ontario alone, it is estimated that 300,000 dry metric tonnes of municipal sewage biosolids are produced annually, of which 40% are landfilled and 20% are incinerated (CIELAP, 2009). Also, 3.7 million tonnes of food and yard waste were produced in 2015 alone, of which 60% was landfilled (Ontario MOECC, 2015). These values represent a large supply of potential cover material; however, cost depends on transportation from major urban centers where these materials are generated in larger quantities (SENES, 1994). The potential for using certain organic materials to treat AMD in the long-term, such as municipal solid waste (MSW) compost or treated biosolids, requires further study.

Organic matter has been used in the past as a cover material on the surface of sulfide tailings, either as a standalone substrate or in combination with mineral material (Dudeney et al., 2004; Hallberg et al., 2005; Hey & Simms, 2021). Though vegetation cannot remediate ARD on its own, it can be used to improve the aesthetics of tailings impoundments and reduce wind erosion by stabilizing the surface (Blowes et al., 1988; Pierce, 1995). Growth of vegetation on unremediated mine tailings is limited due to a lack of organic matter, which can be overcome by the addition of an organic substrate (Tisch et al., 2012) and can be used as part of a phytostabilization strategy by mine managers (Campbell et al., 2017). Thus, an organic cover has the potential to be vegetated, reduce erosion, and reduce metal mobility.

Microbial Communities

Oxidative dissolution of sulfide minerals can be greatly enhanced by microbial processes. Therefore, the presence and abundance of certain bacteria can be used as a diagnostic tool to indicate cover performance. SO_4 -reducing bacteria (SRB), for example, are strict anaerobes and therefore their presence indicates low $O_{2(g)}$ concentration (Beauchemin et al., 2018) and by implication, minimal ARD production. Conversely, Fe- and S-oxidizing microorganisms, such as *Acidithiobacillus ferrooxidans*, contribute to ARD formation through both the regeneration of aqueous Fe(III) and the oxidation of reduced inorganic S^0 compounds to sulfuric acid (Schippers et al., 2010). Microbial mitigation of ARD production can occur by SRB through bacterially-mediated SO_4 reduction (Shen and Buick, 2004) which is mediated by the heterotrophic microbial community which, in turn, is fueled by an organic-carbon substrate (Table 1). This phenomenon

reduces SO_4 anions and increases the pH, which could result in metal-sulfide precipitation and the subsequent immobilization of metals (Lewis, 2010).

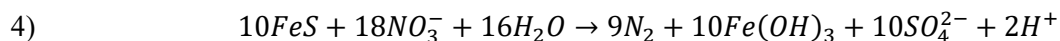
Table 1: Microbially-induced reactions using organic carbon as a substrate. Gibbs Free energy (ΔG°) of the reactions show that they will occur from the top down but will depend on the availability of the reactants (Morel & Hering, 1993). Note: Gibbs Free energy values are denoted for standard temperature and pressure, at pH = 7.

Reaction	Balanced Equation	ΔG° (KJ mol ⁻¹)
Respiration	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} + \frac{1}{4}\text{O}_{2(g)} \rightarrow \frac{1}{4}\text{CO}_{2(g)} + \frac{1}{4}\text{H}_2\text{O}_{(l)}$	- 119
Denitrification	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} + \frac{1}{5}\text{NO}_3^-_{(aq)} + \frac{1}{5}\text{H}^+_{(aq)} \rightarrow \frac{1}{4}\text{CO}_{2(g)} + \frac{1}{10}\text{N}_{2(g)} + \frac{7}{20}\text{H}_2\text{O}_{(l)}$	- 113
MnO ₂ Reduction	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} + \frac{1}{2}\text{MnO}_{2(s)} + \text{H}^+_{(aq)} \rightarrow \frac{1}{4}\text{CO}_{2(g)} + \frac{1}{2}\text{Mn}^{2+}_{(aq)} + \frac{3}{4}\text{H}_2\text{O}_{(l)}$	- 96.9
Fe Oxide Reduction	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} + \text{Fe}(\text{OH})_{3(s)} + 2\text{H}^+_{(aq)} \rightarrow \frac{1}{4}\text{CO}_{2(g)} + \text{Fe}^{2+}_{(aq)} + \frac{11}{4}\text{H}_2\text{O}_{(l)}$	- 46.7
SO ₄ Reduction	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} + \frac{1}{8}\text{SO}_4^{2-}_{(aq)} + \frac{1}{8}\text{H}^+_{(aq)} \rightarrow \frac{1}{4}\text{CO}_{2(g)} + \frac{1}{8}\text{HS}^-_{(aq)} + \frac{1}{4}\text{H}_2\text{O}_{(l)}$	- 20.5
Methanogenesis	$\frac{1}{4}\text{CH}_2\text{O}_{(s)} \rightarrow \frac{1}{8}\text{CO}_{2(g)} + \frac{1}{8}\text{CH}_{4(g)}$	- 17.7

Leachable Products

Organic materials, such as wood waste, have been noted to have the potential to leach organic acids, which subsequently move into the underlying tailings (Blowes et al., 2014). These natural organic compounds can subsequently influence the transport and infiltration of heavy metals beneath the cover (Bolan et al., 2014) and increase phosphorus availability through solubilization and decreased adsorption (Bolan et al., 1994). Extraction experiments completed by Ribet et al. (1995) on weathered tailings found that > 50% of total Fe, Ni, Co, Cr and K were within ferric bearing secondary minerals (i.e., the reducible fraction) and therefore susceptible to release via reductive dissolution by an $\text{O}_{2(g)}$ consuming organic layer. The redissolution of these secondary Fe (oxy)hydroxides, formed through reactions such as that described in Equation 2 and Equation 3, could create further contamination by re-introducing metals into the pore water such as Fe^{3+} , which could further oxidize sulfide minerals. Therefore, it is important to understand which products are being leached from the organic cover and the status of the tailings (i.e., weathered vs. unweathered). Nitrate leaching from the covers has been demonstrated to induce microbial oxidation of pyrite or pyrrhotite even under reducing conditions where nitrate serves as an electron acceptor for autotrophic Fe and S oxidizing bacteria (Cravotta III, 1998; Li et al., 2016), as shown in Equation 4. Despite these challenges, organic carbon covers have been installed at some Canadian mine sites because they are cost-effective and successful at controlling wind and water erosion, while also improving revegetation success. As indicated by Beauchemin et al. (2018), there is a need for more field investigations to study

whether organic covers are a viable approach for the rehabilitation of acid-generating tailings in temperate climates.



Longevity

To perform effectively, organic covers must maintain high moisture content and minimize hydraulic conductivity (Peppas et al. 2000). Saturated hydraulic conductivity (K_s) values and porosity can vary depending on the origin and maturity of the organic material. In an experiment conducted by Pierce et al (1995), K_s values decreased from $10^{-4} \text{ cm s}^{-1}$ in fresh compost to $10^{-6} \text{ cm s}^{-1}$ in mature compost, while the volume shrunk by 10% to 20%; indicating a decrease in porosity. As organic material matures, this decrease in porosity could lead to a higher moisture content and a decrease in hydraulic conductivity within the organic cover, helping it to remain an effective $\text{O}_{2(g)}$ barrier over time.

The long-term reactivity of organic material is a concern for its use as a long term $\text{O}_{2(g)}$ -consuming layer. Tassé et al. (1994) studied a cover composed of wood waste and found that it would only be an effective $\text{O}_{2(g)}$ barrier for the short term, due to the measured decrease in reactivity over time. According to Nason et al. (2016), total organic matter (TOM) decomposition rates are highest at the beginning of deposition. It has also been found that the integrity of the material will diminish over time as organic carbon is consumed. However, the addition of decayed plants, grasses, and leaves from established vegetation present on the organic cover may add a fresh source of biodegradable material (Peppas et al., 2000).

Temperature is a major controlling parameter in the rate of biodegradation, and it will vary seasonally. Experiments conducted by Nason et al. (2016) found that the total organic matter (TOM) decreased by 14.8, 27.2, and 26.7 % at ambient, mesophilic, and thermophilic temperatures; illustrating that peak biodegradation occurred at mesophilic temperature ranges (i.e., optimum growth temperatures of $20^\circ\text{C} - 45^\circ\text{C}$). However, biodegradation was found to be much slower in the field, due to lower mean annual temperatures. Thus, biodegradation rates will vary over time and be affected by varying climatic conditions.

A second controlling parameter in the rate of biodegradation is the amount of $\text{O}_{2(g)}$ available for the degradation of the organic matter. In a study by Forsberg and Ledin (2006), 50 % of the organic fraction of biosolids placed at the surface, under aerobic conditions, degraded after 5 years. In contrast, Ahlberg (2006) reported only a 5 to 10 % removal of the organic fraction of biosolids that were placed in a buried sub-surface layer after 16 years, with this loss being attributed specifically to anaerobic degradation processes. These findings show that the gradual loss of organic matter from the cover over time poses a challenge to their use as long-term solutions to ARD.

A summary of select cover/cover systems for the passive treatment and source control of ARD are listed in Table 2.

Table 2: Summary of select cover types. DST = desulfurized tailings, EWT = elevated water table, CCBE = covers with capillary barrier effects, GCL = geosynthetic clay liner.

Cover Class	Cover Type	Benefits	Drawbacks	References
O ₂ Transport Barrier	Water	<ul style="list-style-type: none"> Strongly limits O₂ diffusion Minimal maintenance 	<ul style="list-style-type: none"> Most jurisdictions no longer allow for disposal in a natural water body Engineered systems can be expensive and carry geotechnical risk 	1) Blowes et al. (2014) 2) Dold (2014)
	Monolayer cover of DST with EWT	<ul style="list-style-type: none"> Can be less expensive than other reclamation techniques Potential for long-term efficiency 	<ul style="list-style-type: none"> Very sensitive to climatic condition Specific design criteria required for pre-oxidized mining sites 	1) Éthier et al. (2018) 2) Rey et al. (2020)
	CCBE	<ul style="list-style-type: none"> Can maintain high water saturation (i.e., > 85%) Material can be sourced onsite 	<ul style="list-style-type: none"> Long-term effects of freeze/thaw, desiccation, root penetration and erosion are unclear 	1) Hotton et al. (2020) 2) Proteau et al. (2020)
	GCL	<ul style="list-style-type: none"> Extremely low hydraulic conductivity ($10^{-12} - 10^{-10} \text{ m s}^{-1}$) 	<ul style="list-style-type: none"> Installation can be expensive for large tailings facilities 	1) Makusa et al. (2014) 2) Shackelford et al. (2010)
O ₂ Consuming Barrier	Wood Waste	<ul style="list-style-type: none"> Inexpensive Source material usually found close to the mine 	<ul style="list-style-type: none"> Reaction rate will decrease as the material matures 	1) Germain et al. (2009) 2) Tassé, N. (2004)
	Peat	<ul style="list-style-type: none"> Inexpensive Source material can typically be found near mine 	<ul style="list-style-type: none"> Material may not sufficiently limit O₂ ingress in the long term 	1) Rakotonimaro et al. (2021) 2) Smart et al. (2016)
	Biosolids	<ul style="list-style-type: none"> High material availability Avoids landfilling Can be vegetated 	<ul style="list-style-type: none"> Reaction rate will decrease as the material matures 	1) Jia et al. (2014) 2) Nason et al. (2016)
	Compost	<ul style="list-style-type: none"> High material availability Avoids landfilling Can be vegetated 	<ul style="list-style-type: none"> Reaction rate will decrease as the cover matures 	1) Arvizu-Valenzuela et al. (2020) 2) Asemaninejad et al. (2021)

CASE STUDY: GREATER SUDBURY, ON

A field-based study was performed on a two-layer cover system located on a tailings facility in the greater Sudbury Area. The cover system at the studied locations was between 5 and 8 years old and was composed of a 0.5 m organic cover underlain by a 2 m layer of thickened DST that was designed to utilize the elevated water table technique to raise the water level to be above the surface of the reactive tailings. This cover system was instrumented in late 2016, and solid, aqueous and gas-phase samples were collected. A comparison was made between sites with a two-layer cover system, a one-layer cover, and no cover. To evaluate and improve the understanding of its operation and to discern its effectiveness as a source control measure for the reduction of ARD through the following methodology:

- 1) Characterization of the hydrology, aqueous geochemistry and solid-phase geochemistry of the cover system and the underlying tailings;
- 2) Assessment of the presence and structure of microbial communities;
- 3) Determination of its effect on porewater quality and of $O_{2(g)}$ ingress into the subsurface;
- 4) Evaluation of groundwater flow, pore-water geochemistry and pore-gas concentrations of oxygen and carbon dioxide; and
- 5) Determination of its impact on the water quality in the adjacent receiving environment.

Following these objectives, the effectiveness of the cover system was determined based on two performance metrics: 1) the degree to which the cover system consumed/limited transport of $O_{2(g)}$; and 2) whether the cover system stabilized metals through metal-sulfide precipitation or through the formation of secondary-S phases. The goal of this research was to use these two metrics as criteria to evaluate the performance of this cover system at suppressing sulfide oxidation.

For performance metric 1, pore-gas samples were collected within the cover system using a modified technique of Reardon & Poscente (1984) in the summer and fall of 2019 to understand the change in pore-gas O_2 throughout the year and with depth. Oxygen consumption tests were also performed throughout the spring, summer and fall of 2019 to determine the amount of oxygen being consumed by the cover system through aerobic degradation of the organic material and/or sulfide oxidation in the DST, following methods similar to those described in Elberling and Nicholson (1996). Pore-gas O_2 concentrations with depth show that pore-gas O_2 was completely consumed within the cover system (i.e. no $O_{2(g)}$ could interact with the high-sulfide tailings below). Additionally, the organic material was found to be the component that consumed more $O_{2(g)}$, while the DST limited $O_{2(g)}$ transport by maintaining a high degree of saturation. Seasonal observations of oxygen consumption tests and pore-gas O_2 indicate that the organic material is the most reactive in the summer, and is more efficient at limiting pore-gas O_2 in the fall, due to the higher degree of saturation within the cover system. In most cases, the water table was found to be within the cover system, thus maintaining saturation in the high sulfide tailings below.

For performance metric 2, solid-phase samples were collected within the cover system in 2019 following methods described in Starr and Ingleton (1992). Carbon-sulfur analysis was completed as well as solid-phase sulfur speciation, following methods described by Dold (2003) to confirm sulfide content and understand degree of historical sulfide oxidation. It was found that most locations showed evidence of

sulfide oxidation in the DST. Additionally, pore-water was collected in 2018 and 2019 following the methods described in Bao et al. (2020) to understand the water quality in the cover system. The results show lower levels of dissolved metals and sulfate when compared to locations without a cover system. Subsequent geochemical modelling suggest that the cover system was stabilizing metals in the shallow porewater through the formation of secondary sulfur phases.

SUMMARY

Using covers/cover systems as passive treatment/source control options to manage ARD is becoming more commonplace as options for mine managers. These covers/cover systems generally rely on either limiting $O_{2(g)}$ transport and/or consuming $O_{2(g)}$. Most of the options have benefits and drawbacks, therefore, the selection of an appropriate cover/cover system will depend on the jurisdiction that the mine is in, along with other factors, such as hydrology, mineralogy, prior sulfide oxidation, freeze-thaw cycling, geotechnical properties, and availability and cost of materials.

Several types of organic carbon covers have been studied, including MSW compost, biosolids fertilizer, wood waste, and peat. These materials can sometimes be found close to mine sites and are considered waste materials; therefore, they present a potential cost savings when compared to other cover types. They also have the added benefit of being a substrate for vegetation and can reclaim land of former degraded quality while also limiting erosion of the tailings.

CONCLUSION

Results from this case study show that, although organic covers represent a potential for re-use of waste materials and have the potential to be cost-effective, their usefulness as a long-term passive-treatment technique depends on maintaining the moisture content, and limiting aerobic degradation rates. These rates, in turn, will be impacted by the moisture retention, application method, age of material, presence of vegetation and cover composition. In this case, the use of an organic cover in conjunction with thickened, low wt.% S tailings has improved the likelihood of long-term ARD mitigation at locations with this two-layer cover system and have an added benefit of reclaiming land of former degraded quality by acting as a substrate for vegetation. Therefore, organic carbon covers are a promising tool for reducing acid generation at tailings storage facilities and additional research is recommended. However, results from this research show the importance of using organic material as part of a cover system and not as a standalone approach.

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