Valorization of pre-oxidized tailings as cover material for the reclamation of an old acid-generating mining site

Mari K. Tvedten[1], Gijsbert D. Breedveld[1, 2] and Thomas Pabst[3]

[1]*University of Oslo, Department of Geosciences, Oslo, Norway*
[2]*Norwegian Geotechnical Institute (NGI), Oslo, Norway*
[3]*Polytechnique Montreal, Department of Civil, Geological and Mining Engineering, Montreal, Canada*

Abstract Laboratory column tests were conducted to assess the performance of a cover with capillary barrier effects to control acid mine drainage generation from tailings at Folldal mine site (Norway). Results showed that the pre-oxidized tailings used as the moisture retaining layer remained at a high degree of saturation (Sr > 85%) throughout the tests, thus efficiently limiting oxygen diffusion to the reactive tailings. Valorization of pre-oxidized tailings could provide an alternative to cover materials that may not be readily available at mine sites.

Key words Acid mine drainage (AMD), Pre-oxidized tailings, Oxygen barrier, Cover with capillary barrier effects (CCBE)

Introduction

The area of Folldal in Hedmark, Norway, was extensively mined for copper, sulfur and zinc for over two hundred years. The mine is now closed, but waste rocks and tailings produced by the mining activities and disposed of at the surface were left unreclaimed and have been continuously generating acid mine drainage (AMD). AMD run-off has caused all life to disappear from the local river Folla, located a few hundred meters downstream the mine. The objective set by the Norwegian Environment Agency is to reduce copper concentrations in the river Folla from over 50 µg/L to less than 10 µg/L (NGI 2014). One of the selected remediation methods to achieve this objective is to cover the reactive tailings with a multilayer cover. AMD generation can indeed be reduced by preventing either water or oxygen from entering the reactive mine wastes (e.g. Bussière 2007). Several cover designs exist and have proven efficient to limit the generation of AMD, including water covers, monolayer or multilayer covers (e.g. Aubertin et al. 2016). In a humid climate such as in Norway an oxygen barrier is usually considered the most efficient option for the reclamation of acid generating mine sites. The water table is located several meters below the surface in Folldal, and a cover with capillary barrier effects (CCBE) was therefore assessed in this study. CCBEs have been successfully implemented at several mining sites like for example Les Terrains Aurifères – LTA (Ricard et al. 1997, Bussière et al. 2006,) or Lorraine (Dagenais et al. 2002, Dagenais 2005), both located in Quebec, Canada. A CCBE is typically made of three layers (e.g. Aubertin et al. 1999) and consists of a fine-grained moisture retaining layer (MRL) placed between two coarse-grained layers. The objective is to maintain a high degree of saturation in the MRL to limit the diffusion of oxygen to the underlying reactive mine wastes (oxygen diffusion is approximately 10 000 times slower in water than in air; e.g. Collin and Rasmuson 1988).

The performance of a CCBE mostly relies on the contrast in hydraulic properties (water retention, hydraulic conductivity) between the materials used in the cover. A large contrast between the coarse and fine-grained layer is typically required to develop a strong capillary barrier effect (Nicholson 1989; Aubertin et al. 1995, 1999). Finding the right materials is therefore critical but can be challenging, especially where natural soils are scarce. Pre-oxidized tailings that are no longer acid generating found locally at the mining areas in Folldal were considered as potential materials for the moisture retaining layer in the CCBE. These pre-oxidized tailings are old tailings, where sulfide content has decreased through natural oxidation processes over time and which are consequently not acid-generating anymore. The efficiency of non-acid generating mine wastes or desulfurized tailings as cover materials have been studied by several authors (Demers et al. 2008, Demers et al. 2009, Kalonji et al. 2016), but the use of pre-oxidized tailings has not been documented yet to the authors' knowledge. Valorization of pre-oxidized tailings could provide an alternative to usual cover materials that may not be readily available at mine sites, and reduce the reclamation costs and environmental impact of transporting materials to the mine site. A fine sand from a local gravel pit was also considered for the moisture retaining layer, for comparison purposes. A coarse sand found locally was used for the capillary break layers placed on top and below the MRL.

Material characteristics

Characterization of the materials sampled *in situ* was performed in the laboratory. Grain size distribution and relative density were measured (Table 1). Water retention curves (WRC) were obtained with a Pressure plate apparatus (Soilmoisture), and the curves were compared with predicted water retention curves obtained with Modified-Kovacs (MK) model (Aubertin et al. 2003). Hydraulic conductivities were measured in rigid wall permeameters. The hydraulic conductivity of the pre-oxidized tailings was one and two orders of magnitude smaller than of the fine sand and the coarse sand respectively. Materials with similar properties proved efficient in CCBEs, like e.g. Demers et al. (2008) and Bussière (2007).

Table 1 *Properties of the tested materials. D_{10}: 10 % passing, D_{60}: 60 % passing, C_U: Coefficient of uniformity, G_s: specific gravity, n: porosity, $AEV_{adjusted}$: Air-entry values based on pressure plate measurements and adjusted (calibrated) to match observations in the column, k_{sat}: hydraulic conductivity.*

Material	D_{10} (mm)	D_{60} (mm)	C_U (D_{60}/D_{10}) (-)	G_s (-)	n = (-)	$AEV_{adjusted}$ (cm)	k_{sat} (m/s)
Reactive tailings	0,002	0,35	177	3,02	0,46	35	$3x10^{-7}$
Pre-oxidized tailings	0,002	0,18	88	2,80	0,38	140	$3x10^{-6}$
Coarse sand	0,17	1,01	6	2,69	0,48	5,3	$2x10^{-4}$
Fine sand	0,02	0,12	6	2,69	0,48	50	$4x10^{-5}$

Column tests

Column test design was based on a methodology developed at Polytechnique Montréal (e.g. Aubertin et al. 1995, Aachib 1997, Pabst et al. 2014). Two large columns (200 cm in height) were set up in the laboratory to assess the efficiency of the proposed cover design and materials. Each column was filled with 1 meter reactive tailings sampled at the mining site, and covered with 40 cm of pre-oxidized tailings (column 1) or fine sand (column 2) placed between two coarse grained layers of 20 cm each. 5TM sensors (Decagon devices) were installed in both columns to measure the volumetric water content, MPS-2 (Decagon devices) were used to measure the water potential (suction), and optical oxygen dipping probes DP-PSt3 (PreSens Precision Sensing GmbH) to measure oxygen concentration in the columns (Figure 1). A water-filled tube was connected to a 5 bar – ceramic plate at the bottom of the columns and lowered 1.5 m to simulate a fixed water table. Monthly wetting and drying cycles where 1.5 L of water was added at the top of the columns, representing a precipitation of 1000 mm/yr, were repeated for four months. The top of the columns was left open to simulate the effect of evaporation; potential evaporation, temperature and relative humidity were measured. Water content, pore water pressure and oxygen concentration in the columns were continuously monitored, and leachate was regularly sampled from the base of the columns and analyzed to assess the evolution of pH, electrical conductivity and metal concentrations.

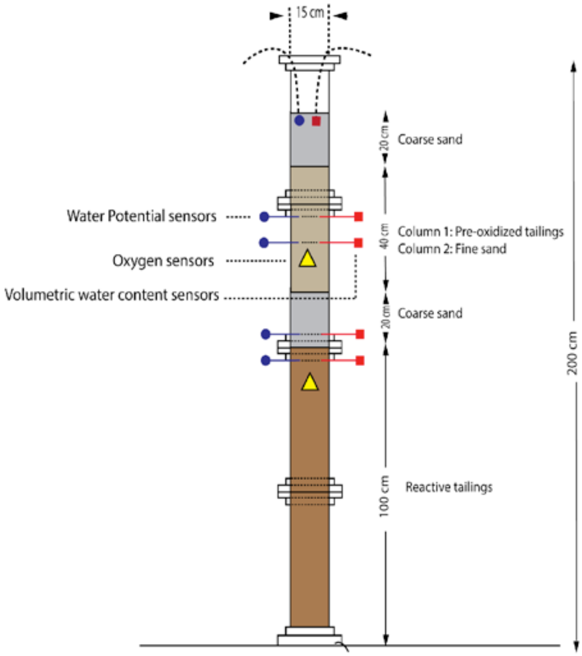

***Figure 1**: Column setup, showing location of the various sensors used to measure volumetric water content, pore pressure and oxygen concentrations.*

Column test results

Degree of saturation

The variations of the degree of saturation S_r, measured at different locations in the columns are shown in Figures 2 and 3. Typically, S_r increases quickly when water is added at the column and then decreases during the rest of the cycle due to the combined effect of drainage and evaporation. The degree of saturation of the MRL (pre-oxidized tailings) in column 1 remained above 85% for the entire test period (Figure 2). The coarse sand layers however desaturate to as less as 20% after a few days. The low degree of saturation in the capillary break layer and the high saturation in the pre-oxidized tailings indicate that strong capillary barrier effects were developed in the column.

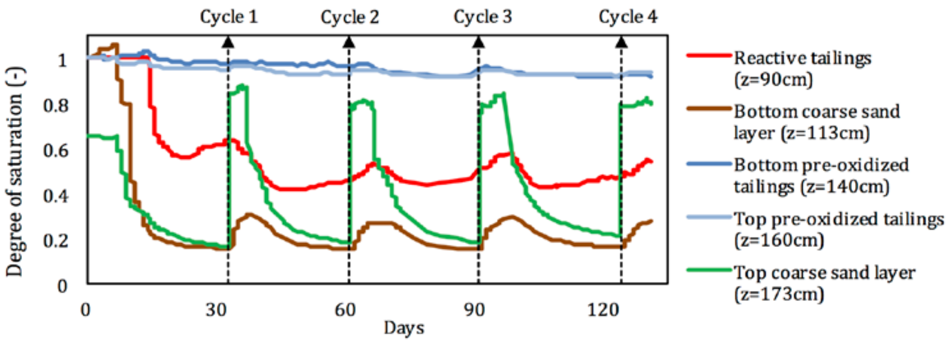

***Figure 2**. Variation of the degree of saturation with time for column 1. The elevation z of the sensors in the column is indicated (also see Figure 1).*

The fine sand used as the MRL in column 2 tend to desaturate during drying periods, reaching saturation as low as 60%. The contrast between the fine sand and the coarse sand was not strong enough to create a capillary barrier effect and prevent the MRL from desaturating (Figure 3).

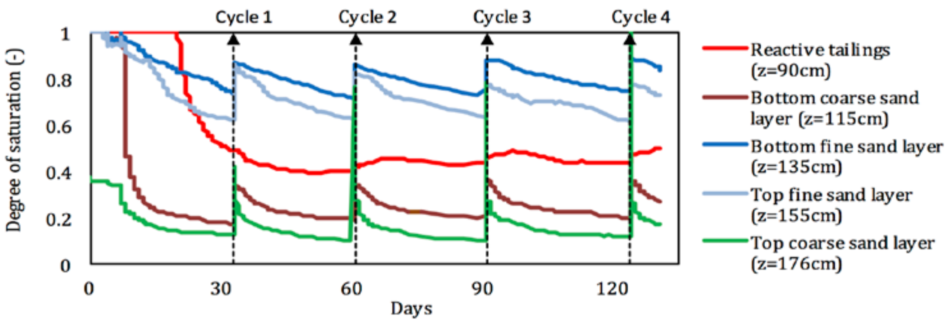

***Figure 3**. Variation of the degree of saturation with time for column 2. The elevation z of the sensors in the column is indicated (also see Figure 1).*

Suction

Suction increases with the distance to the water table, and as a result of evaporation. The top layers in the column were most susceptible to evaporation, which was reflected by high suction values (>5 meters) measured in these layers. The high suction values in the top coarse sand layer compared to the suction in the MRLs show that this layer was effective in preventing evaporation from the layer's underneath (as intended).

Oxygen

Performance of the two covers was further evaluated by comparing the oxygen concentration profile in the columns (Figure 4). An efficient CCBE would limit oxygen diffusion from the surface to the reactive tailings. Monitoring results showed that the oxygen concentration remained between 0.01-0.12 mg/l in the reactive tailings in column 1 and between 0.01-0.28 mg/l in the reactive tailings in column 2, thus indicating a better performance of the cover in column 1.

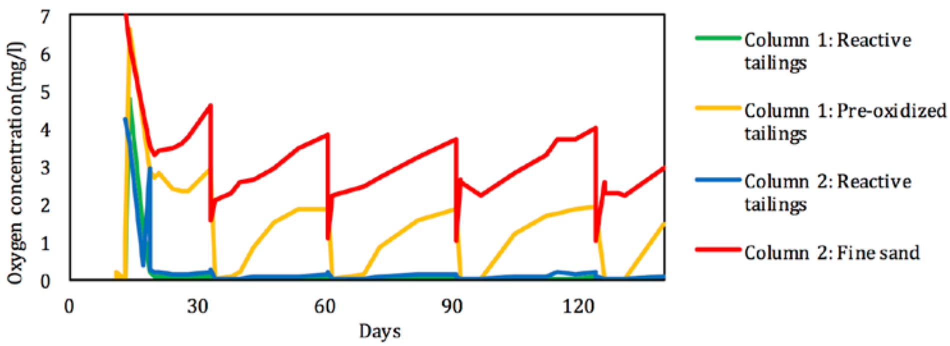

Figure 4. *Variation of oxygen concentrations with time for both columns.*

Analyses of leachate

The pH and electrical conductivity measured in the leachate of the columns was used to further evaluate if the covers were efficient. However, the results of the leachate showed only a small increase of pH from the start to the end of the monitoring periods. By looking at only these results it was not possible to see any significant difference between the two columns. More time and further cycles of water are needed to be able to observe change in the pH. An initial assessment shows that less than 1 pore volume has been leached from the tailings in the columns. In the study by Pabst et al. 2014, it took at least 6 cycles of wetting and drying before significant variations, representative of the efficiency of the cover, were observed in the leachate.

Numerical modelling

Numerical simulations carried out with Vadose/w (GEO-SLOPE International Ltd. 2016) were used to assess the efficiency of the CCBE upon field conditions. Vadose/w is a finite element CAD software developed for analyzing water, vapor, heat and gas in unsaturated media. A one-dimensional model with the same dimensions and properties as the experimental columns was calibrated using laboratory measurements. The oxygen flux was estimated to approximately 6.2 $g/m^2/yr$ in the column with pre-oxidized tailings and 462 $g/m^2/yr$ in the column with fine sand. An oxygen barrier is typically considered efficient when the oxygen flux remains below 50 g/m2/yr (Dagenais et al. 2005, Pabst et al. 2017). Pre-oxidized tailings seem therefore to be an efficient MRL. Simulations of the cover, using field conditions (including daily precipitation and temperature values) from Folldal from June to September 2015 showed that the pre-oxidized tailings remained at a degree of saturation above 90 % at all times and that the fine sand desaturated to levels as low as 60 % saturation (Figure 5).

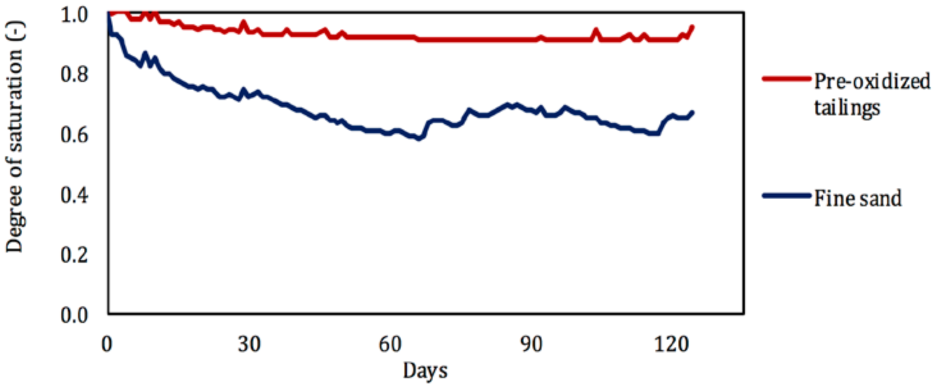

***Figure 5**. Variation of degree of saturation with time for both columns during modeling of field conditions with daily temperatures and precipitation values from Folldal from June to September.*

Conclusion

This study assessed the performance of a cover with capillary barrier effects (CCBE) to control the generation of acid mine drainage from reactive tailings at Folldal mine in Norway. Results from the monitoring and numerical simulations conducted during four monthly wetting and drying cycles showed that the MRL of pre-oxidized tailings remained at a high degree of saturation ($S_r > 85\%$) throughout the tests, thus limiting the diffusion of oxygen down to the reactive tailings. Valorization of pre-oxidized tailings could provide an alternative to soil based cover materials that may not be readily available at mine sites. This hydrogeological study shows promising results, but a further geochemical assessment is required to investigate the geochemical stability of the material and confirm the long-term performance of the cover to limit AMD generation.

Acknowledgements

This research was supported by the Research Council of Norway and by the Norwegian Directorate of Mining. The authors thank Andreas Botnen Smebye at the Norwegian Geotechnical Institute (NGI) for his help in performing the laboratory studies.

References

Aachib M (1997) Étude en laboratoire de la performance des barrières de recouvrement constituées de rejets miniers pour limiter le DMA, École polytechnique de Montréal. Département de génie minéral.

Aubertin M, Chapuis R, Aachib M, Bussière B, Ricard J & Tremblay L (1995) Évaluation en laboratoire de barrières sèches construites à partir de résidus miniers. Mine Environment Neutral Drainage (MEND) Report, 2.

Aubertin M, Aachib M, Monzon M, Joanes A, Bussière B & Chapuis R (1999) Étude de laboratoire sur l'efficacité de recouvrements construits à partir de résidus miniers. Rapport MEND/NEDEM, 2.

Aubertin M, Mbonimpa M, Bussière B & Chapuis, R (2003) A model to predict the water retention curve from basic geotechnical properties. Canadian Geotechnical Journal, 40, p 1104-1122.

Aubertin M, Bussière B, Pabst T, James M & Mbonimpa M (2016) Review of reclamation techniques for acid generating mine wastes upon closure of disposal sites. Proc. Geo-Chicago: Sustainability, Energy and the Geoenvironment, Chicago, August 14-18.

Bussière B (2007) Colloquium 2004: Hydrogeotechnical properties of hard rock tailings from metal mines and emerging geoenvironmental disposal approaches. Canadian Geotechnical Journal, 44, p 1019-1052.

Bussière B, Maqsoud A, Aubertin M, Martschuk J, McMullen J & Julien M (2006). Performance of the oxygen limiting cover at the LTA site, Malartic, Quebec. CIM Bulletin, 1(6), p 1-11.

Collin M, Rasmuson A (1988) A comparison of gas diffusivity models for unsaturated porous media. Soil Science Society of America Journal, 52, p 1559-1565.

Dagenais A-M (2005) Techniques de contrôle du drainage minier acide basées sur les effets capillaires. École polytechnique.

Dagenais A-M, Aubertin M, Bussière B, Cyr J & Fontaine R (2002) Auscultation et suivi du recouvrement multicouche construit au site minier Lorraine, Latulipe, Québec. Défis & Perspectives: Symposium sur l'Environnement et les Mines, Rouyn-Noranda, p 3-5.

Dagenais A-M, Aubertin M, Bussiere B & Martin, V (2005) Large scale applications of covers with capillary barrier effects to control the production of acid mine drainage. Proceedings of Post-Mining, 16-17.

Demers I, Bussière B, Benzaazoua M, Mbonimpa M & Blier A (2008) Column test investigation on the performance of monolayer covers made of desulphurized tailings to prevent acid mine drainage. Minerals Engineering, 21, p 317-329.

Demers I, Bussière B, Mbonimpa M & Benzaazoua, M (2009) Oxygen diffusion and consumption in low-sulphide tailings covers. Canadian Geotechnical Journal, 46, p 454-469.

Demers I, Bussière B, Aachib M & Aubertin M (2011) Repeatability evaluation of instrumented column tests in cover efficiency evaluation for the prevention of acid mine drainage. Water, Air, & Soil Pollution, 219, p 113-128.

Kalonji Kabambi A, Bussière B & Demers I (2017) Hydrogeological Behaviour of Covers with Capillary Barrier Effects Made of Mining Materials. Geotechnical and Geological Engineering, 1-22.

NGI (2014) Folldal gruver. Vurdering av mulige tiltak mot avrenning fra tidligere gruvevirksomhet. http://www.dirmin.no/.

Nicholson RV, Gillham RW, Cherry JA & Reardon EJ (1989) Reduction of acid generation in mine tailings through the use of moisture-retaining cover layers as oxygen barriers. Canadian Geotechnical Journal, 26, p 1-8.

Pabst T, Aubertin M, Bussière B & Molson J (2014) Column Tests to Characterise the Hydrogeochemical Response of Pre-oxidised Acid-Generating Tailings with a Monolayer Cover. Water, Air, & Soil Pollution, 225, p 1-21.

Pabst T, Molson J, Aubertin M & Bussière B (2017) Reactive transport modelling of the hydrogeochemical behaviour of partially oxidized acid-generating mine tailings with a monolayer cover. Applied Geochemistry, 78: 219-233.

Ricard J, Aubertin M, Firlotte F, Knapp R, McMullen J & Julien, M (1997) Design and construction of a dry cover made of tailings for the closure of Les Terrains Aurifères site, Malartic, Québec, Canada. Proceedings of the 4th International Conference on Acid Rock Drainage, Vancouver, BC, p 1515-1530.