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Reactive transport modelling of the hydro-geochemical behaviour of partially oxidized acid-generating mine tailings with a monolayer cover

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ABSTRACT

The efficiency of a monolayer cover to prevent acid mine drainage (AMD) generation from two pre-oxidized tailings impoundments was assessed using the MIN3P code, a finite volume model for coupled groundwater flow, oxygen diffusion and multi-component reactive transport. Numerical simulations were validated using large column tests set up in the laboratory and monitored during 19 wetting and drying cycles, over approximately two years. Results indicate that a monolayer cover made of either non acid-generating tailings or a till was not able to prevent sulfide oxidation in the underlying reactive tailings, both for the conditions applied in the laboratory and under conditions more representative of field observations. The efficiency of the simulated monolayer cover was highly dependent on the position of the water table. Despite improved water quality, the reactive tailings nonetheless continued to oxidize and generate AMD, even when the water table was close to the surface of the tailings (1 m depth). The results from this study indicate that the efficiency criteria for cover systems on fresh unoxidized tailings may not be directly applicable for pre-oxidized tailings. The paper also presents a few modifications to the MIN3P code that were successfully applied to simulate the hydrogeological and geochemical response of pre-oxidized, already acidic and highly contaminated tailings.

1. Introduction

The large quantities of mine tailings produced during ore concentration processes often contain sulfides that can oxidize when left exposed to oxygen and water. The result is contaminated drainage water, characterized by a low-pH and high concentrations of sulfates and metals (e.g. Aubertin et al., 2002; Blowes et al., 2003, 2014; Lindsay et al., 2015; Nordstrom et al., 2015). Acid mine drainage (AMD) remains a critical issue for the mining industry worldwide, and its mitigation is a considerable challenge. Various control measures, dependent in part on the local climate, have been developed over the last two or three decades to prevent the long-term production of AMD. Under relatively humid climatic conditions, for example, these methods usually aim at limiting the oxygen flux to the reactive tailings, usually relying on the low oxygen flux either through a water layer or through a nearly saturated porous medium (Collin and Rasmuson, 1988; Aubertin et al., 1999; Mbonimpa et al., 2003; Aachib et al., 2004). The most commonly used oxygen barriers include water covers (e.g. Yanful and Catalan, 2002; Mbonimpa et al., 2008; Awoh et al., 2013; Moncur et al., 2015), and multilayer covers with capillary barrier effects (Nicholson et al., 1989; Aubertin et al., 1994, 1999, 2006; Bussière et al., 2003, 2006; Bussière, 2007; Dagenais et al., 2005).

As an alternative, the elevated water table (EWT) technique can also be used to control AMD by raising the water table to a depth less than the air entry value (AEV, the suction at which air first enters a water-saturated material, i.e. when the largest pores start to drain) of the reactive tailings (Dagenais, 2005; Dagenais et al., 2006; Ouangrawa, 2007; Ouangrawa et al., 2009, 2010; Cosset and Aubertin, 2010). A single layer cover coupled with an EWT

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can add further benefit to the method. For example, together with an EWT, a coarse-grained monolayer cover will increase infiltration and limit water loss by evaporation (Dagenais et al., 2006), thus improving water balance, while a fine-grained cover can promote water retention and prevent oxygen diffusion (Mbonimpa et al., 2003; Demers, 2008; Pabst, 2011; Dobchuk et al., 2013). The choice of an adequate cover material is consequently critical to ensure cover efficiency (e.g. Cosset and Aubertin, 2010; Pabst et al., 2016). The EWT technique has recently been shown to be quite efficient to limit the generation of AMD from fresh unoxidized tailings (Dagenais, 2005; Ouangrawa, 2007).

Reclamation plans need to be optimized for specific site conditions, including climate, topography, material properties, and water table position. The cost-efficiency of these reclamation measures is often improved when planned and designed well before closure, preferably from the beginning of the mine planning phase or during mine operation (Aubertin et al., 2016). However, this does not apply in the case of old (often abandoned) tailings disposal sites, where the tailings have already been partly oxidized. In this case, various additional factors, including indirect oxidation reactions (Nicholson, 1994; Williamson and Rimstidt, 1994; Kirby et al., 1999; Nordstrom, 2000), can contribute to the production of AMD and negatively affect the efficiency of an oxygen barrier.

This project was aimed at two pre-oxidized tailings disposal sites located in Québec, Canada. The first, site A, has been abandoned for decades, during which time the highly reactive tailings were left exposed to oxidation. As a result, the pore water within the tailings is very acidic, with a pH often <2, and the metal and sulfate concentrations are very high, showing the typical characteristics of AMD. The site is now under reclamation, and the option that was considered at the time of the study included a monolayer cover made of non acid-generating, slightly alkaline tailings produced at a nearby mine. The second site, site B, was covered by approximately 1–2 m of till (moraine), not long after the production stopped (about 3 years before this study started). Nevertheless, it continues to generate AMD which is collected and treated (using lime neutralization) before drainage water is released to the environment. Field investigations also showed signs of ongoing oxidation beneath the cover, without being able to distinguish the extent of oxidation before and after the addition of the single layer cover. Under these conditions of very acidic pore water and probable long-term oxidation, the conditions are thus prone to indirect oxidation reactions at both sites (via Fe^{3+}; e.g. Nicholson, 1994; Williamson and Rimstidt, 1994; Nordstrom, 2000).

Designing an efficient cover for pre-oxidized tailings impoundments may therefore be complex. Numerical models can offer versatile and flexible tools to help assess long-term efficiency of such cover systems. In this study, the code MIN3P (Mayer et al., 2002) was applied to analyse and interpret laboratory column experiments and gain insight into the efficiency of monolayer covers placed on pre-oxidized acid-generating tailings in order to prevent AMD generation. The reactive transport code was used to simulate a series of column tests (intermediate scale physical models) carried out in the laboratory. The numerical models were validated and calibrated based on the experimental results, then extended to include conditions which were more representative of field observations (in terms of climate, water table position and other site characteristics) to assess if these reclamation measures were suitable for the two sites. The duration of the simulation period was also extended to evaluate the long-term hydrogeochemical behaviour of the tailings-cover systems under realistic field conditions.

2. Column test set-up and material properties

2.1. Column tests

Four large instrumented columns, 230 cm in height, 15 cm internal diameter, were set up in the laboratory to assess the hydrogeochemical behaviour of the reactive tailings and the monolayer covers upon repeated wetting and drying cycles. The set-up and the tests followed a methodology developed over several years by the authors and collaborators (e.g. Aubertin et al., 1995, 1999; Aachib, 1997; Bussière et al., 2004; Dagenais, 2005; Ouangrawa, 2007; Demers et al., 2011). As part of the study, different combinations of tailings and cover materials were tested (Pabst, 2011).

The tests presented here involved two large columns filled with 170 cm of reactive tailings (TA from site A and TB from site B) which were covered with approximately 40 cm of cover material (CA and CB; Fig. 1); these will be referred to as TACA and TBCB. The tailings and cover material were put in place and consolidated layer by layer (15 cm thick), under full saturation (Sr = 100%). A ceramic porous plate was placed at the base of the column to control the water table position using an imposed suction. The position of the water table was typically maintained 90 cm below the base of the column, i.e. about 300 cm below the surface of the monolayer cover, which represents approximately what was measured at site A; the water table at site B could be much deeper in some places. Leachate was regularly sampled at the column base for chemical analyses, and the top of the column was left open to evaporation. Although somewhat different than in-situ conditions, the column test configurations were selected to provide representative results for long-term analyses.

Small columns, 50 cm in height, 10 cm in diameter, were also prepared (Fig. 1) in order to study the behaviour of uncovered tailings to better quantify the efficiency of the cover systems. These tests were conducted with more or less the same procedures as for the large columns. The suction applied at the base of the small columns was about 2 m and the top was left open to evaporation. A 3 cm-thick sand layer was added on the surface of the column to limit the formation of desiccation cracks in the tailings.

Every 30 days or so, 1700 mL (corresponding to a precipitation of about 10 cm/m^2) of deionized water was added at the top of the large columns, and 500 mL (also corresponding to a precipitation of about 10 cm/m^2) added to the small columns. It usually took between 2 and 3 days before seepage appeared at the base of the large columns, compared to only one day for the small columns. The infiltration of free ponding water across the cover surface lasted for about 5–6 days. A total of 19 cycles were applied to the large columns over a period of about 700 days; while 10 and 14 cycles were applied to the small columns, TA and TB respectively.

Several sensors were installed in the columns to monitor the hydrogeological behaviour of the tailings and covers during the wetting and drying cycles (Fig. 1). Volumetric water contents were measured using TDR (Time Domain Reflectometry, SoilMoisture) probes, while pore water pressures, both positive and negative, were monitored by water-filled tensiometers (Omega PX243). More information regarding instrumentation can be found in Pabst et al. (2014).

Two leachate samples of about 100 mL each were collected from the large columns during each wetting cycle: the first sample was taken at the beginning of drainage and the second sample about three days later. Because of the smaller amount of water leaching out the base of the small columns, only one 100 mL sample was taken for each wetting cycle. The pH values, measured using an