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Geochemical and hydrogeological behaviour of commingled mixtures of tailings and waste rock

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Abstract

The conventional method of segregated disposal of tailings and waste rock is associated with several environmental problems, especially acid rock drainage (ARD) which is a challenging and crucial issue. Previous studies have shown that mixing tailings and waste rock can potentially decrease ARD potential. However, there are limited studies that quantify the effect of mixture ratio of waste rock and tailings on the water quality. This study presents a developed methodology to design and test different waste rock and tailings mixture ratios through leveraging particle packing theory for binary mixtures. The mineralogy and chemical properties of the mixtures is first presented. Three columns of mixture materials were mounted for a series of leaching tests over a period of about two years to experimentally simulate the impact of different mixture ratios on the water quality.

The preliminary results of the leach column tests demonstrate that the ratio of waste rock and tailings of the commingling mixtures influences the unsaturated hydrogeological behaviour and the water quality. The study also provides fundamental data to investigate the hydrogeological and geochemical behaviour of the tailings and waste rock mixtures. The approach used in this study can be implemented to determine an optimised mixture ratio to minimise ARD and alleviate the damaging environmental impacts of segregated disposal.

Keywords: *acid rock drainage, commingled tailings and waste rock mixtures, leaching column tests*

1 Introduction

The mining industry plays a pivotal role in economic prosperity of many countries. Despite the economic benefits of mining and processing of minerals, this industry leaves behind significant volumes of waste that can have a significant impact on the surrounding ecosystems. The first waste stream produced during the mining operations is waste rock, which is the low-grade host rock that needs to be excavated to reach the ore. The waste rock is usually hauled and trucked to waste rock stockpiles then end-tipped. These stockpiles have non-homogeneous structures caused by segregation, with larger cobble to boulder-sized particles tending to roll down to the toe of the slope while the fines are retained near the crest (Azam et al. 2007; Fala et al. 2005; Zevgolis 2018). These piles, with tip faces frequently greater than 4–6 m, develop an internal structure with a high water and air permeability rockfill layer at the base (Wilson 2008). The high porosity of this structure, due to the large void spaces between rock fragments, creates an ideal pathway for air and water ingress which is essential for sulfide oxidation and acid generation (Gowan et al. 2010; Lefebvre et al. 2001). Therefore, acid rock drainage (ARD) is one of the principal challenges with managing sulfidic waste rock piles.

After excavation of waste rock, the profitable ore is extracted and processed at the ore processing plant to separate the valuable component from the gangue. The byproduct of the mineral extraction process are tailings, which is the second main waste stream of mining, frequently in conjunction with large volumes of process water. Tailings are usually transported and pumped as slurry to tailings impoundments surrounded by dykes. These dykes are usually constructed from site-won soils or may be constructed from tailings materials or waste rock or a combination of all three. Without intensive thickening, particle segregation occurs during slurry deposition, which forms a beach of coarser particles near the discharge point with the finer particles transported by water towards the decant pond. Sulfide minerals in tailings have a high specific gravity and tend to concentrate in sand deposits during deposition via hydraulic segregation of tailings (Wilson 2008). Unsaturated tailings contain sulfide minerals are prone to oxidise upon exposure to oxygen and water. Similarly, sulfide minerals in sand tailings embankments and beach sediments that have a drained, unsaturated profile are free to oxidise and generate ARD (Wilson 2008).

Studies have shown that one method to improve the chemical and physical stability of these waste streams is the co-disposal of tailings and waste rock (Bussière 2007). A new co-disposal approach called commingling (also referred to as co-mixing, paste rock and co-mingling in the literature) consists of blending the tailings and waste rock in a manner where the void spaces in waste rock can be filled with tailings, which has low permeability and transmissivity for ingress of water and oxygen (Bussière 2007; Gowan et al. 2010; Wilson et al. 2022). Oxygen supply for the mixtures of tailings and waste rock is then limited to oxygen diffusion that reduces the potential to generate ARD by eliminating the oxygen migration through the advection/convection transport mechanism (Bussière 2007).

Tailings and waste rock have very different geoenvironmental properties and stress-strain behaviours. Therefore, the properties of their mixture greatly depends on the mixture ratio and the methodology used to effectively mix the two together in situ (Wickland 2006). Particle packing theory can be used for the binary mixture design of waste rock and tailings in the ideal case. Furthermore, this theory can be implemented in interpreting the mixture behaviour based on the mixture structure (Wickland 2006).

The density and void properties are important to interpret the material's hydrogeological behaviour since these parameters affect the material's permeability. As declared by Furnas (1928) in Figure 1, the density of binary mixture is affected by particle size ratio, mixture ratio, and the density of the individual components (Wickland 2006). Furnas (1928) indicated that the minimum porosity or maximum density can be achieved through an optimum mixture ratio when the void space of the coarse particles are just filled with the smaller particles (Wickland 2006). In order to achieve the optimum mixture ratio of waste rock and tailings, the void space or porosity of the coarse wastes rock must be filled with tailings that consist of water, finer solids or air (Gowan et al. 2010; Wickland et al. 2010).

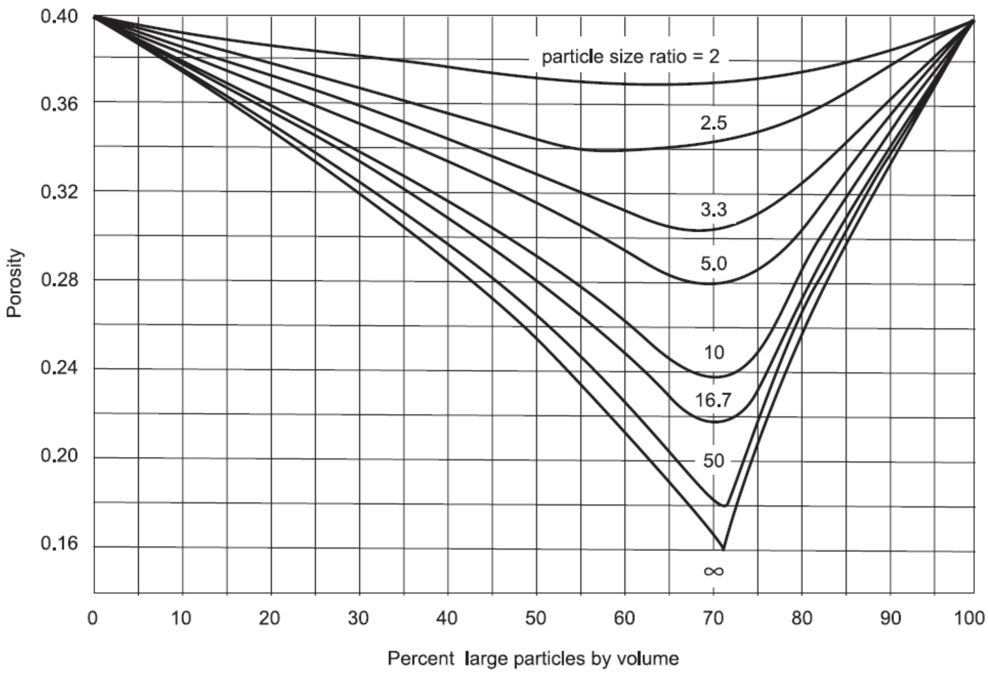


Figure 1 Mixture ratio of binary mixtures (initial porosities are assumed 0.4) (Wickland 2006)

Previous studies have shown that mixtures of tailings and waste rock has the potential to reduce the ARD potential (Pouliot et al. 2018; Wilson et al. 2022). However, there are limited studies to show the effects of mixture ratio of waste rock and tailings on the water quality. This research aims to link the mixture structure with the hydrogeological and geochemical behaviour of the mixture. To investigate the effect of mixture ratio on water flow and leachate quality, different mixture ratios were tested using a series of column leaching experiments. Section 2 reviews the materials and methods implemented in this study. Section 3 discusses the preliminary results that show the influence of the mixture ratio of waste rock and tailings on the quality of the leachate and the onset of ARD generation.

2 Materials and methods

To explore the mixture ratio effect on water quality, three columns of different mixture ratios were constructed at the Université du Québec en Abitibi-Témiscamingue (UQAT) in Rouyn-Noranda. The next sections discuss the properties of waste rock and tailings, the theory behind the mixing design, and the procedure of building the instrumented columns with the commingling materials.

2.1 Parent materials

The waste rock used in this study had a low acid generating potential (CM waste rock) and tailings were obtained from two sources: a low (CM tailings) and high (LR tailings) sulfide content mine tailings. To estimate the acid generation and neutralisation potential of the tailings materials, induction furnace analyses were performed on them and the total sulfur (S) and carbon (C) contents of these materials were measured. The results revealed that the CM tailings has low sulfur content (1.33%; Table 1). Therefore, CM tailings were mixed with LR mine tailings to achieve the desired amount of sulfur for the designed experiments and to accelerate the geochemical response. After analysing the results, the CM tailings and LR tailings were blended in a 55 to 45 mass ratio. This ratio allows to reach a sulfur percentage of 6 to 7%, which assures generation of acidity in the span of design tests.

Other basic physical properties of parent materials are presented in Table 1. It is worth noting that the tailings were sampled at the mill and experienced consolidation during transportation and storage. As a result, their initial solids content were high. Since the designed experiment was targeted at a lower solids content (75%), water was added to the tailings materials to lower their solid content.

Table 1 Initial physical and chemical properties of the mixture parent materials

	CM waste rock	CM tailings	LR tailings	Mix of CM and LR tailings
% S	-	1.33	13.24	6.55
% C	-	0.54	0.07	0.15
Porosity (n)	0.35	0.40	0.42	0.41
Specific gravity	2.73	2.79	3.29	3.02
Water content (%)	1.13	18.74	23.30	20.40
Solid content (%)	98.88	84.21	81.10	83.00

Particle size distribution (PSD) of the parent materials is shown in Figure 2. The PSD of the tailings material were analysed using a Malvern Mastersizer laser test (Merkus 2009). Fine fractions (<1 mm) of waste rock material were examined using the same method as tailings; however, for the coarse fraction, sieve analysis was performed to obtain its PSD (ASTM International 2007).

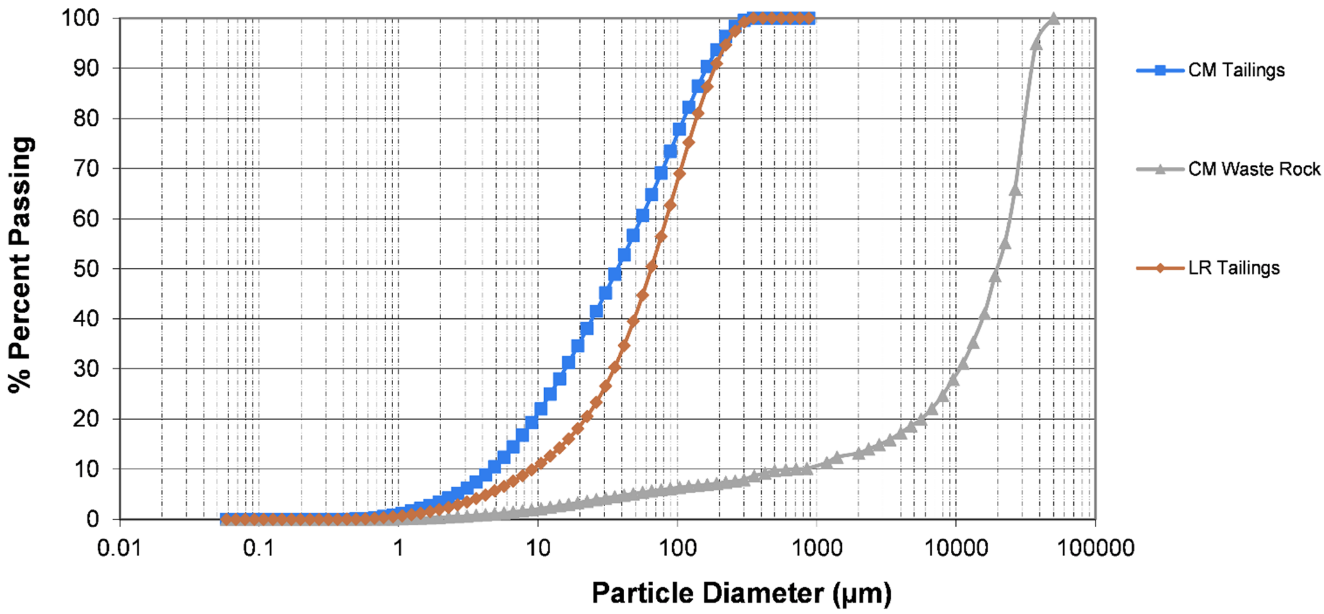


Figure 2 Particle size distribution of the parent materials

2.2 Mixture design

As described in Section 1, and based on the Furnas (1928) study, the optimum mixture ratio can be achieved when the mixture has minimum porosity or maximum density. Maximum density is realised at saturation point when the voids among large particles are fully saturated with small particles. Furnas (1928) used the following equation to calculate the saturation percentage:

$$Saturation\% = \frac{(1-V_1)S_1}{(1-V_1)S_1+V_1(1-V_2)S_2} \tag{1}$$

where:

S1 = specific gravity of small particles.

S2 = specific gravity of large particles.

V1 = voids in bed of large constituent.

V2 = voids in bed of small constituent.

Using Equation 1, the saturation point for the mixture of waste rock material that is filled with the tailings slurry was calculated to be 74% of the large component. In this calculation, waste rock and tailings were considered to be large and small components, respectively. As waste rock is relatively dry, typically <1%, its water content can be neglected when considered as the large constituent. On the contrary, tailings have a high process water content and the tailings slurry (solid and water phase) is considered as the small constituent. It should be noted that for the calculated saturation point of 74%, the dry mass ratio of waste rock to tailings (waste rock: tailings) is 3.8 to 1 (3.8:1).

Wickland (2006) schematically illustrated the different mixture structures for the mixture of waste rock and tailings (Figure 3). As depicted in Figure 3, the saturated condition for mixture can be achieved in the just filled condition. The just filled condition is when all the voids in the large constituent is filled with the small constituents. The just filled condition (saturated) was experimentally replicated in this study by blending waste tock and tailing in 3.8 to 1 dry mass ratio. The other two mixture structures that Wickland (2006) presented in his study were ‘floating’ and ‘partially filled’ conditions (Figure 3). These conditions were experimentally simulated by blending waste rock and tailings in 2.8 to 1 and 4.5 to 1 dry mass ratios, respectively. Three mixture columns mentioned above were constructed for this testing program to investigate geochemical and hydrogeological behaviour of different mixture structures over the period of two years.

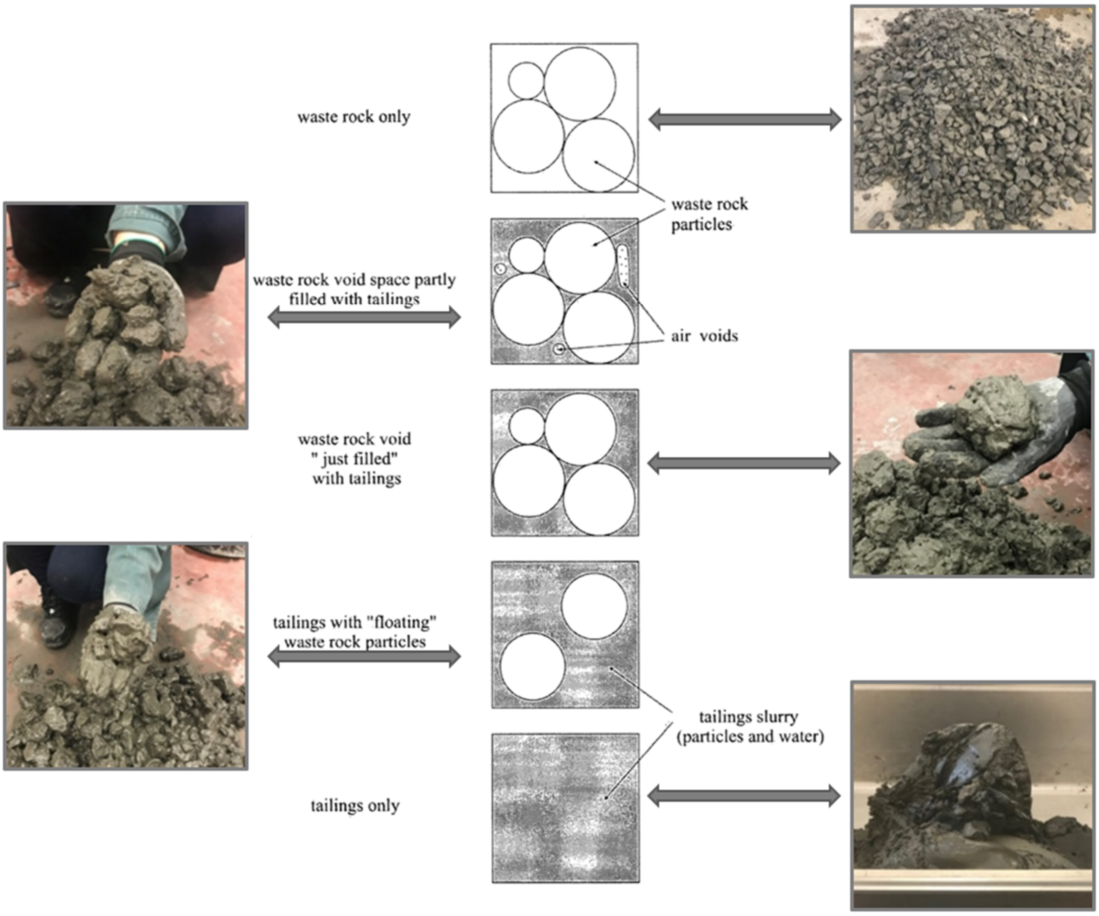


Figure 3 Different mixture ratios of the mixtures after (Wickland 2006)

2.3 Column tests

Column tests were conducted to investigate the geochemical behaviour of different mixture of tailings and waste rock. In this study, three columns of mixtures were constructed using black high-density polyethylene. The columns were 30 cm in diameter and 50 cm in height.

Figure 4 schematically depicts the designed columns and instrumentation utilised in this setup. It is also worth adding that a ceramic plate was placed at the bottom of columns and 1 m of suction was applied below the columns to experimentally simulate water level that exists in a typical field condition.

As can be seen in Figure 4, space was left at the top of each column to perform monthly wetting-drying cycles. Ten litres of deionised water were added to the columns for each cycle to replicate field condition. Water recovered from the columns after complete drainage was used to measure the acidity and concentrations of a series of elements, using the ICP-AES spectrometer.

Oxygen sensors were fixed on caps that were installed for a short period of time (three hours) to measure oxygen consumption rate. Also, oxygen flux was estimated using gas sampling through gas ports at different depth into material. A more detailed description of oxygen consumption and oxygen gradient tests can be found in Mbonimpa et al. (2020). The columns were also equipped with GS3 probes and Watermark sensors (see Bussière et al. 2020 for more details on these equipment), installed at different elevation in the columns (at 40, 25, and 10 cm from the base), for volumetric water content (VWC) and suction measurements respectively. In the following, the emphasis was on water quality and VWC measurements; the other monitored parameters will be presented in subsequent publications.

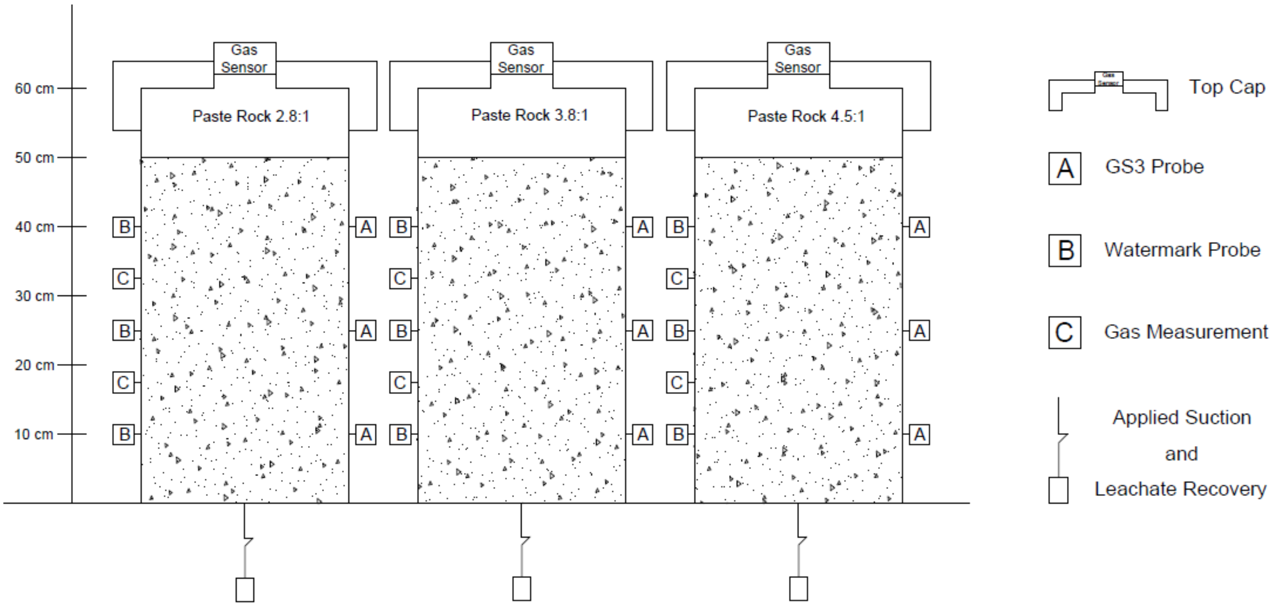
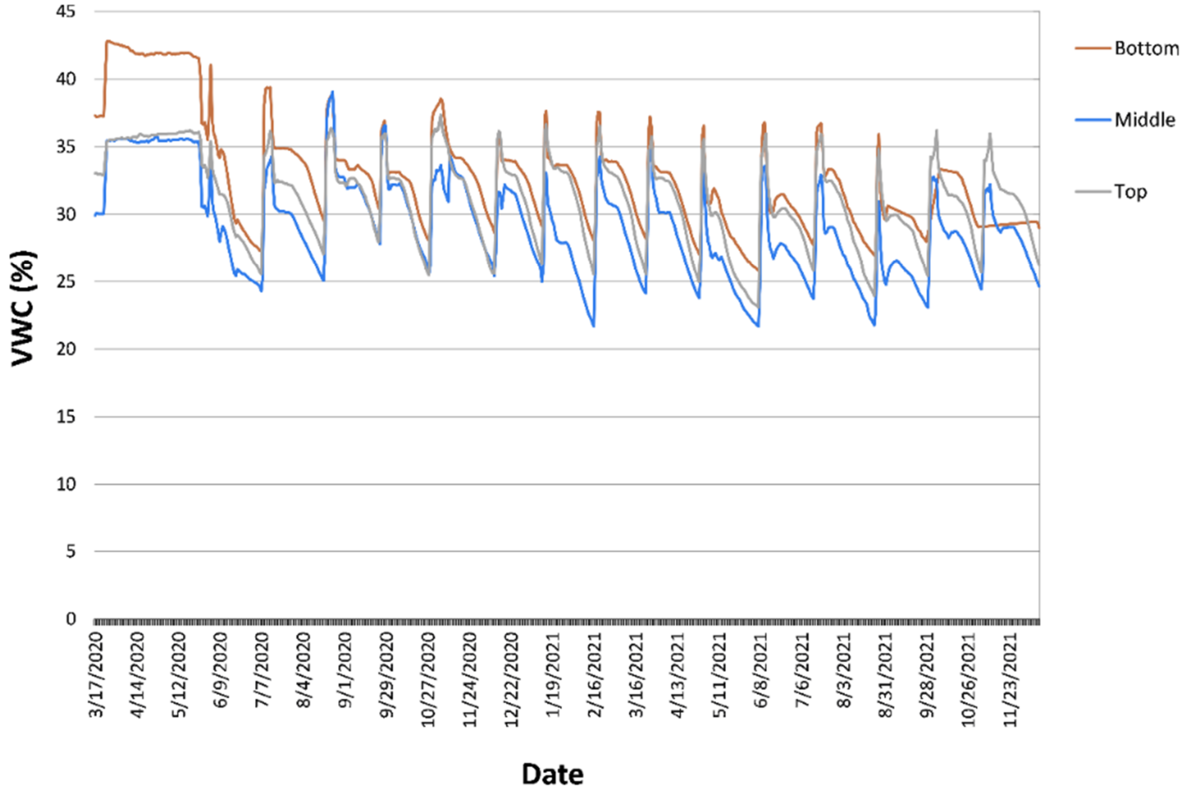


Figure 4 Schematic diagram of column tests instrumentation

3 Preliminary results

This section presents the hydrogeological and geochemical behaviour of the columns with different mixture ratios. Figures 5a to 5c illustrate the evolution of the VWC for the three mixture columns. It is worth recalling that the columns were subjected to wet–dry cycles to favour the reactivity of the material and the VWC was followed at three elevations (40, 25, and 10 cm height from the base of the column). The peaks in Figures 5a to 5c show the start of each cycle when water was added to the columns, and the VWCs decrease when the columns are drained. The evolution of VWC demonstrates that the conditions are favourable to geochemical reaction for the period of the test due to the significant presence of air during and after drainage. The mixture columns showed similar trends related to the evolution of VWCs during the monthly cycles. However, in the mixture column of 2.8:1 (Figure 5a), higher VWCs were observed. This might be due to the higher tailings content of this column which cause a greater porosity and higher VWC (between 22 and 42%). The other two columns have a lower porosity that reduce the maximum and minimum VWC (typically between 10 and 25%). There are additional parameters that could influence the VWC behaviour of the mixture for example tortuosity introduced by particles. A further interpretation of the results is presently ongoing. Maximum, minimum, and average VWC that the columns experienced are shown in Table 2.



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VWC (%)
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Middle
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3/17/2020
4/14/2020
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8/4/2020
9/1/2020
9/29/2020
10/27/2020
11/24/2020
12/22/2020
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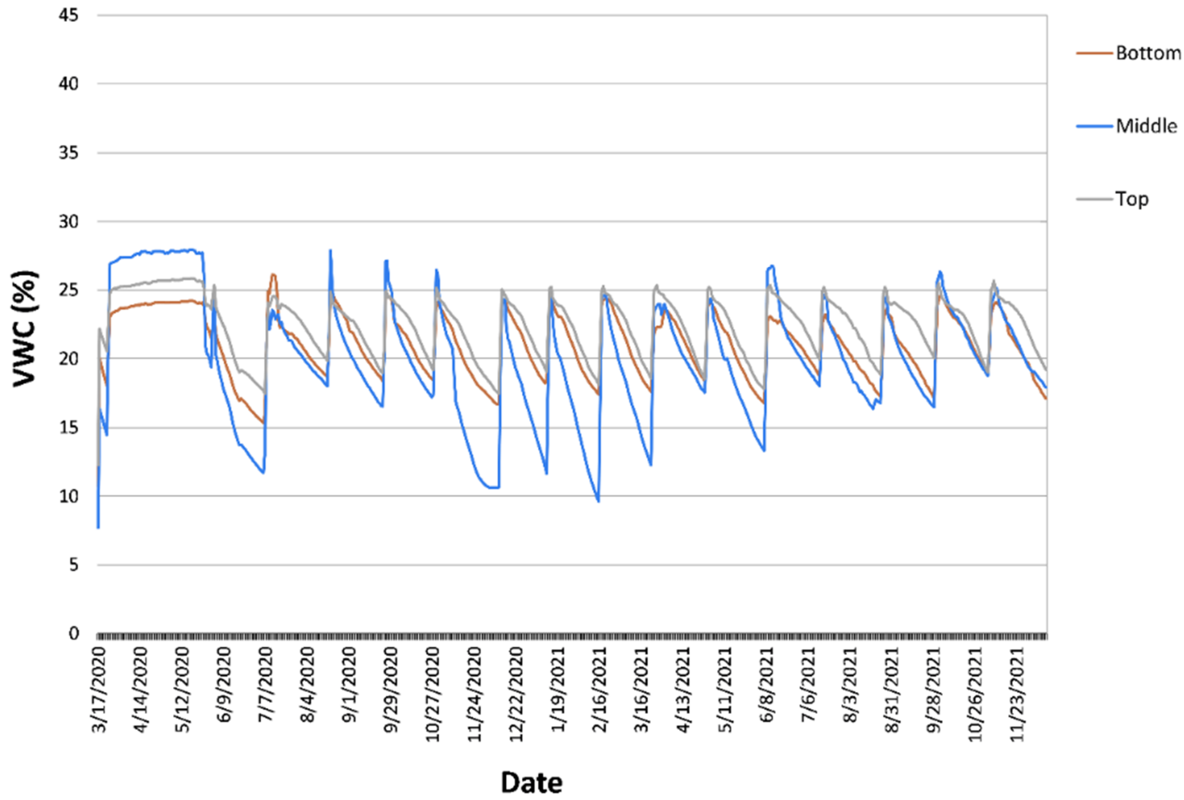
(a)



45
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VWC (%)
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7/7/2020
8/4/2020
9/1/2020
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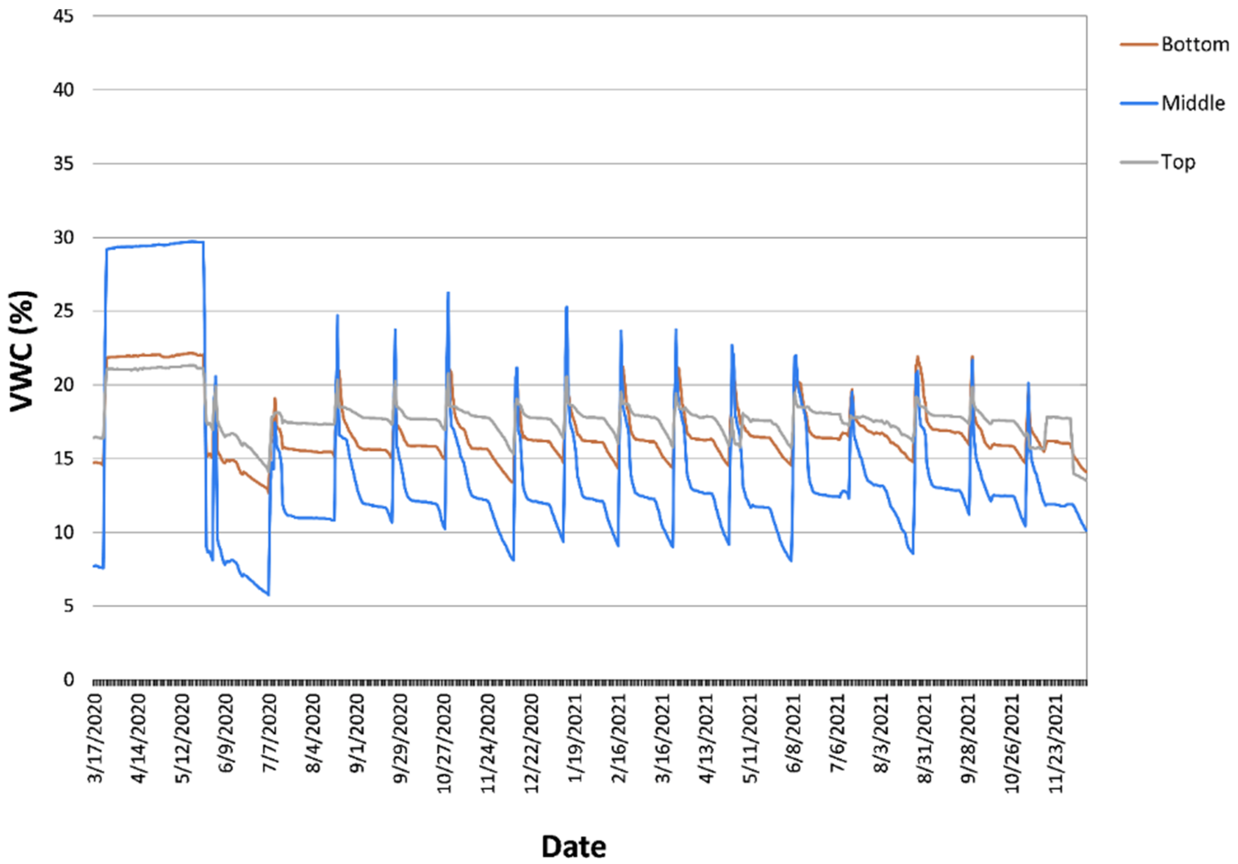
(b)



(c)

Figure 5 Evolution of volumetric water content. (a) Mixture 2.8:1; (b) Mixture 3.8:1; (c) Mixture 4.5:1

Table 2 Maximum, minimum, and average VWC that mixtures experienced during the test

	Mixture 2.8:1	Mixture 3.8:1	Mixture 4.5:1
Bottom maximum	38.9	24.9	21.9
Bottom average	31.9	20.9	16.5
Bottom minimum	25.8	16.7	13.4
Middle maximum	39.0	27.9	26.3
Middle average	28.4	19.3	13.1
Middle minimum	21.7	9.6	8.1
Top maximum	37.4	25.7	20.8
Top average	30.6	22.2	17.6
Top minimum	23.1	17.5	13.5

To assess the influence of mixture ratio on the water quality, leachate samples were analysed following each wetting–drying cycle. Different mixture ratios showed different geochemical behaviour. To illustrate this behaviour, pH, calcium (Ca) and sulfur (S) evolution are presented in the following.

Figure 6 shows that in general, it took about 400 to 500 days to get the pH down to 7 under forced suction through the columns. It takes about 440 days for the mixture 3.8:1, 465 days for the mixture 4.5:1, and 535 days for the mixture 2.8:1 to reach a pH of 5. Furthermore, compared to other columns, it took more time for the mixture 2.8:1 which has less waste rock and more tailings to become acidic.

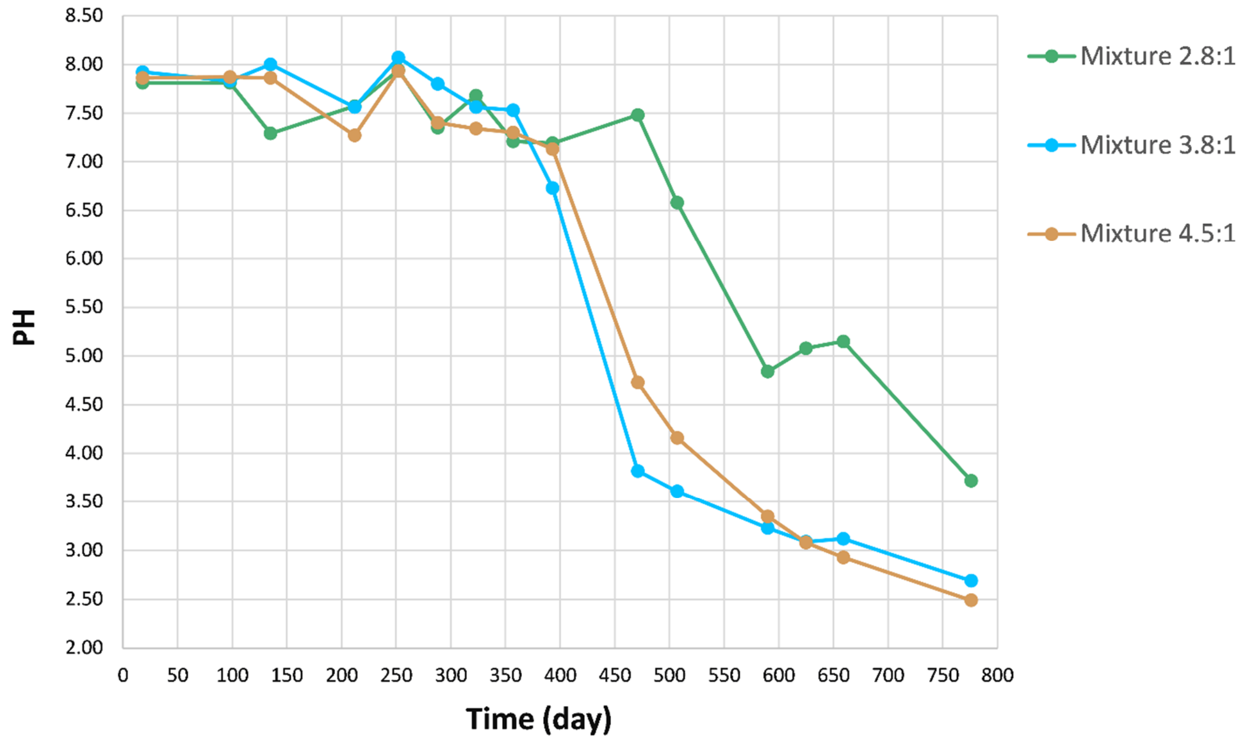


Figure 6 Evolution of pH for mixture columns

Figures 7 and 8 show the cumulative mass of Ca, associated to acid neutralisation, and S, associated to sulfide oxidation, respectively. The graphs illustrate that mixture 2.8:1 has more Ca and S compared to the other mixtures. This mixture contains more reactive tailings material which means the specific surface of this mixture is greater than the other ones. Therefore, this mixture has more oxidation and neutralisation potential compared to two other mixtures. The other two mixtures have similar Ca and sulfur generation rate.

The preliminary results of leaching column tests reinforce the hypothesis that mixture of waste rock and tailings can have a significant influence on the ARD generation potential. The ratio of waste rock and tailings influences the specific surface, the total mass of S and Ca, and the hydrogeological behaviour of the mixtures which affect the geochemical behaviour.

The next step in this study is to incorporate the results presented above with the outcomes of other tests and measurements (e.g. oxygen consumption test, oxygen concentration and suction measurements) and compare them with the parent materials to further investigate the link between hydrogeological and geochemical properties of the tested mixtures. The ultimate goal is to provide recommendations to optimise the mixture ratio of the tailings and waste rock that take into account both geotechnical and geochemical considerations.

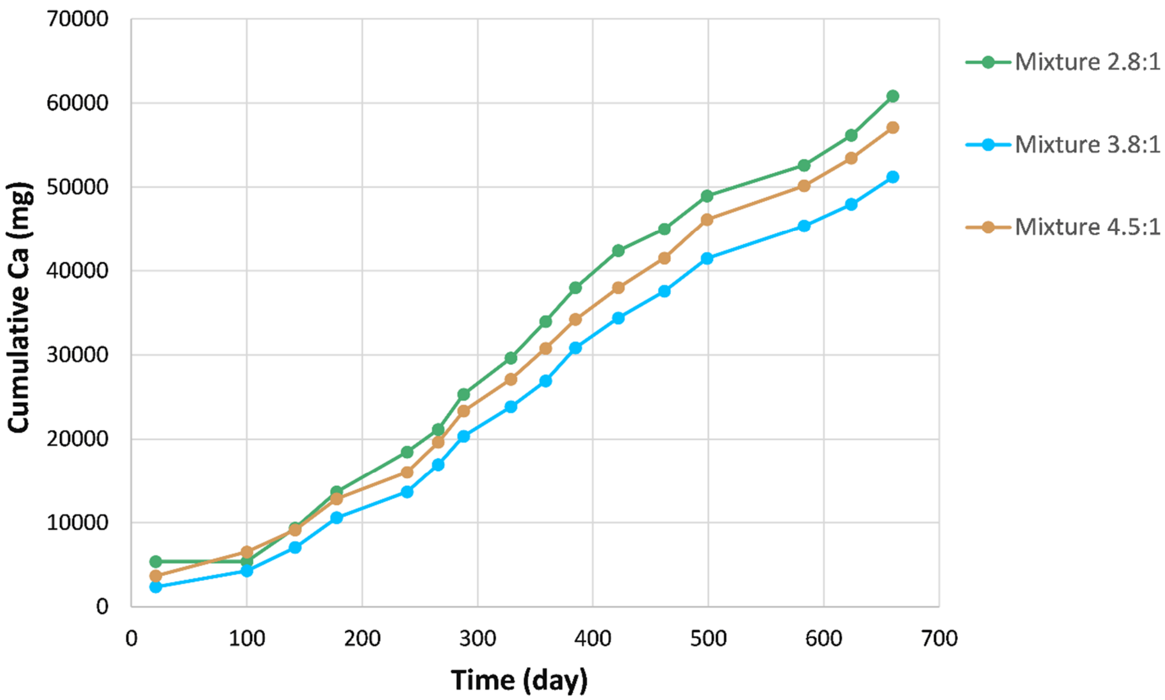


Figure 7 Cumulative Ca for three mixture columns during the test

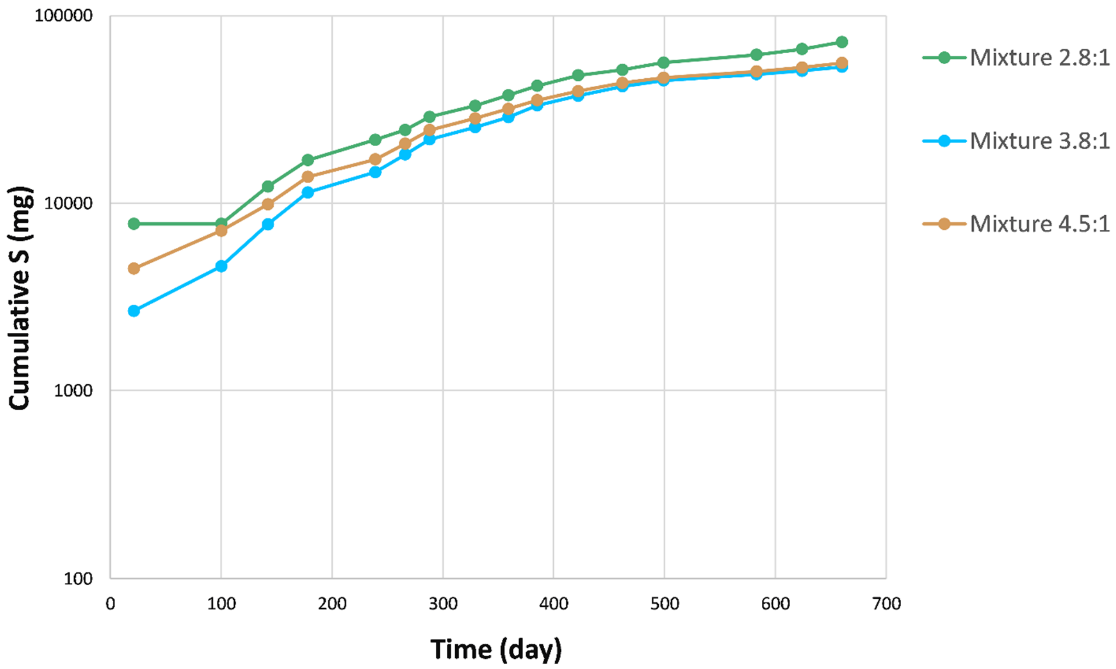


Figure 8 Cumulative S for three mixture columns during the test

4 Preliminary conclusions

Segregated method of disposal of waste rock and tailings can lead to environmental problem of ARD. However, studies have revealed that mixing these mine wastes and disposing them together can potentially reduce the ARD issue and impact the onset of the phenomenon. In this study, three columns of different mixtures of waste rock and tailings were mounted in a test rig at UQAT to evaluate the influence of the commingling mixtures on the water quality.

Preliminary results proved that the various mixture ratios demonstrate different behaviours in terms of unsaturated and geochemical behaviour. In general, there is a time lag for the mixtures to reach the pH below neutral under forced suction conditions, and the ARD potential is retarded because of low permeability. However, analysis of the results indicated that the mixture with a higher ratio of tailings maintained higher pH during the period of the test. However, this mixture had higher cumulative mass of Ca and S due to its fines content.

The results provided the fundamental understanding required to plan and execute the future phases of this research which is correlating these obtained results using other tests performed on the columns. Understanding the hydrogeological and geochemical behaviour of the mixture helps to find an optimum mixture ratio of the tailings and waste rock to minimise ARD generation potential.

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