



Laboratory Simulated Tailings Drain Seepage Columns: Flooded and Free-Draining Conditions

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Abstract

The weathering and oxidation of sulphides in tailings disposal areas can contribute significant concentrations of metal(loid)s, and sulphate to the tailings pore water and dam drainage systems. Elevated concentrations lead to the formation and accumulation of secondary minerals in key drainage features, resulting in a change in physical dam fill characteristics.

Test columns were designed to understand the formation of secondary minerals in underdrainage systems under open and flooded conditions. Both test columns resulted in secondary mineral accumulation and results indicate the chemical composition of the tailings and pore water, and availability of oxidants in the drainage system play a role in the formation of secondary minerals.

Keywords: secondary mineral precipitates, laboratory columns, tailings, ARD/ML

Introduction

The oxidation and subsequent dissolution of sulfide minerals in tailings storage facilities (TSFs) results in the release and mobilization of metals, metal(loid)s, sulphate, and acidity, to the tailings surface and pore waters. These processes are commonly known as acid rock drainage (ARD) and metal leaching (ML). Reviews of sulphide oxidation, the formation of acid mine drainage and the mobilization of metal(oid)s are given by, Lindsay et al (2015), Alpers (1999), Blowes (2003) and Lottermoser (2007); among many others.

When ML/ARD is present, the concentrations of Fe and sulphate (among others) within the pore water can reach supersaturation with respect to secondary minerals and form precipitates. Physical changes to the tailings and dam materials, due to the dissolution of primary tailings grains and precipitate accumulation can compromise the physical stability of tailings dams by changing the material permeability and possibly increasing the phreatic surface within the structural shell of the dam. The objective of this assessment was to evaluate the difference in seepage compo-

sition (as it relates to secondary mineral precipitates) from a free flowing (or open drain system) and a flooded (less oxic) drain type to support the design of future tailings dam buttress drains. The sites evaluated in this study consist of legacy tailings dams containing moderately sulphidic tailings (2% to 10% pyrite and pyrrhotite) in Canada.

Methods

Column Testing

Several methods of investigation were employed to meet the overall objective including a field water quality monitoring program, solid-phase and static geochemical leachate testing on tailings materials, and a laboratory column experiment. The laboratory column program was designed to assess the accumulation of precipitates in granular materials under controlled laboratory conditions. The columns simulate the set up of two dam buttress drain designs; a simulated “oxic” free-draining and “anoxic” flooded drain. The experimental set up and analysis program are described further below. A schematic of the test columns is presented in fig. 1.



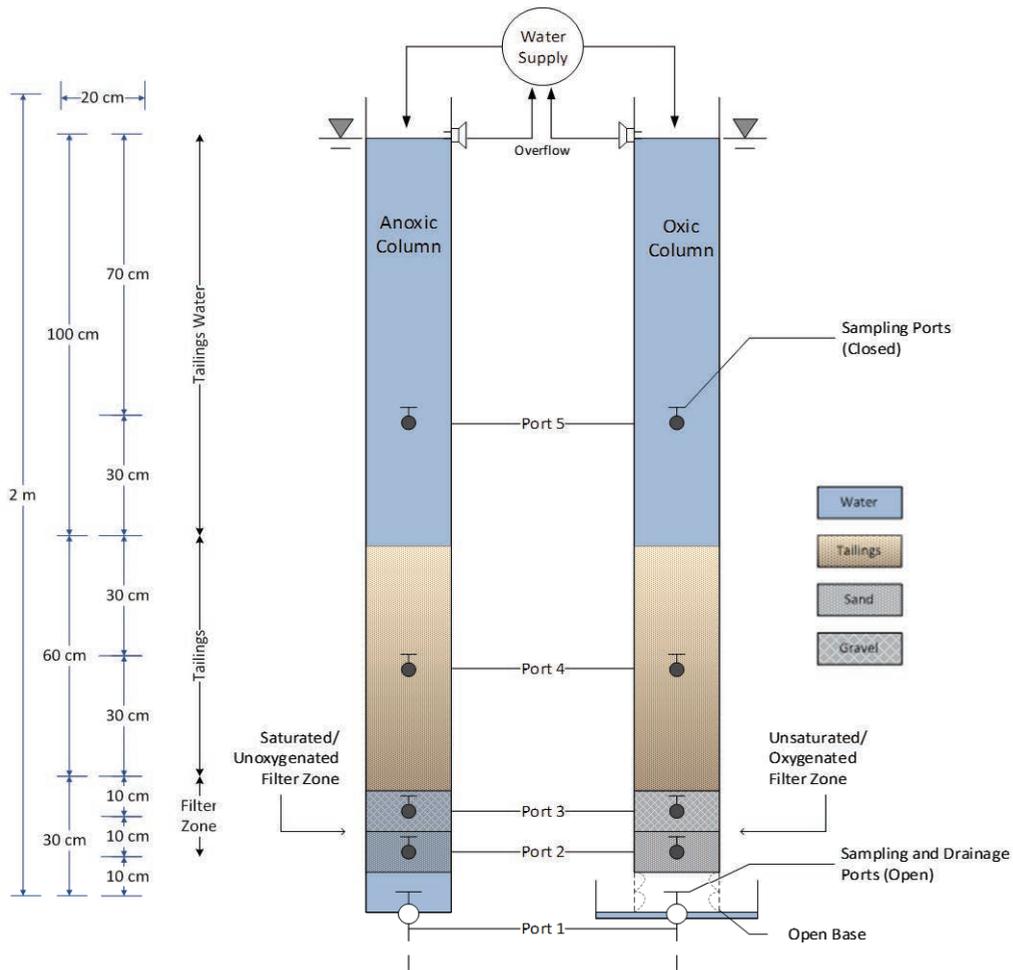


Figure 1 Column Test Schematic.

Flow through the columns and the residence time of pore waters was controlled by the permeability of the materials. The tailings ($K_{sat} \approx 2 \times 10^{-6}$ m/s), filter sands ($K_{sat} \approx 1 \times 10^{-4}$ m/s), and filter gravel ($K_{sat} \approx 1 \times 10^{-2}$ m/s) were excavated from the tailings area, and sourced from local stockpiles, respectively. The tailings were mixed before being split and placed in the columns. Tailings were subaqueously deposited, allowed to settle, and the supernatant was removed. Tailings pond water was filled above the tailings layer and a constant head was maintained by sustaining a constant feed of water and an overflow drain. The top of the test column was open to air and water from the overlying water column was allowed to percolate through each of the layers and drain freely through the bottom of

each column. Flow rate through the columns was approximately 6 L/day.

The upper (Port 5) and lower (Port 1) ports, representing the overlying water and base, respectively, were sampled weekly from both columns and select parameters were measured immediately [pH, redox potential (Eh), temperature (T), electrical conductivity (EC), and dissolved oxygen (DO)]. These parameters were measured every five weeks in the other ports. Pore water was collected every five weeks for laboratory analysis of pH, Eh, T, DO, acidity, alkalinity, chloride, bromide, nitrate (as N), nitrite (as N), sulphate, phosphate, hardness (as CaCO_3), total Fe^{2+} , total Fe^{3+} , dissolved metal(loid)s, and total metal(loid)s. The columns operated for 55 weeks.



Field Testing

Field monitoring of tailings pond water, tailings pore water from sampled monitoring wells, freely flowing embankment drain pore water, embankment drain pipes, freely flowing embankment seepage emergence points, and downstream (DS) seepage collection ponds has occurred for various dam and drain configurations, including a flooded to drain, and open drain conditions (fig. 2).

Select parameters were measured immediately (pH, Eh, T, EC, and DO) and laboratory analysis of the parameter suite described for the column testing was conducted at an accredited laboratory within recommended test hold times.

Results

Tailings Pond and Pore Water

Tailings pond water quality, is assumed to be at equilibrium with the atmosphere and is represented generally by low pH (<5.0), moderate to high Eh (200 mV to 400 mV), and relatively low dissolved and total iron concentrations. Similar characteristics are observed in the column testing, though total iron concentrations are observed to be lower in the column testing. Tailings pore water characteristics are significantly different from the tailings pond water, with sulphide oxidation and secondary mineral dissolution processes resulting in changes in pH, Eh, and metal concentrations (Durocher et al, 2017) (tab. 1).

The pond water, in both columns and on site, has a much lower total iron and sulphate concentrations compared to the tailings pore water. This is due to changes in equilibrium conditions between the pond and tailings and the availability of iron from oxidized and partially oxidized tailings. The total iron concentrations in the field are significantly higher than the column testing due to a lower Eh allowing more Fe^{2+} to remain in solution.

Tailings Drain and Seepage Water

Significant differences are observed between the flooded and free draining systems in the columns and field conditions within the drain water (Port 2 and Port 3). The flooded drain was observed to be more effective at keeping iron in solution than the free draining column (fig. 3).

The testing indicates that the operational conditions of the columns are sufficiently different to result in different water quality. The pH (fig. 4) and Eh (fig. 5) in the drain layers of the columns were similar, however the flooded column maintained higher total iron concentrations in the drain for longer. A decrease in total and dissolved iron was also observed in the flooded column from the tailings pore water to the base indicating a mass loss through precipitate formation at times during the testing. Precipitates were observed forming at the top and bottom of the sand layers and in the gravel layers in both columns.

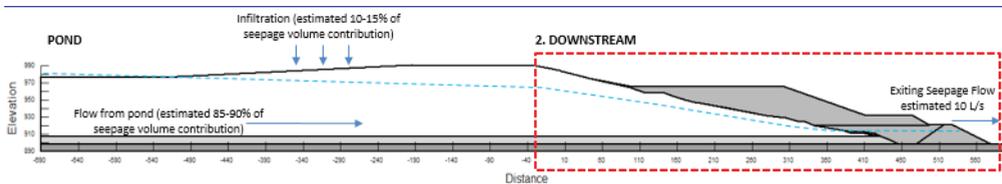


Figure 2 Field Monitoring Location Schematic.

Table 1. Average Results for Tailings Pond and Pore Water

Parameter	Port 5 – Flooded	Port 5 – Free Draining	Tailings Pond Field Results	Port 4 – Flooded	Port 4 – Free Draining	Tailings Pore Water Field Results
pH (units)	3.7	3.7	3.4	4.4	4.4	5.7
Eh (mV)	279	288	329	201	178	55
SO ₄ (mg/L)	979	981	947	1206	1163	4875
T-Fe (mg/L)	0.45	0.17	1.4	39	32	1767
D-Fe (mg/L)	0.20	0.13	1.0	35	30	1542



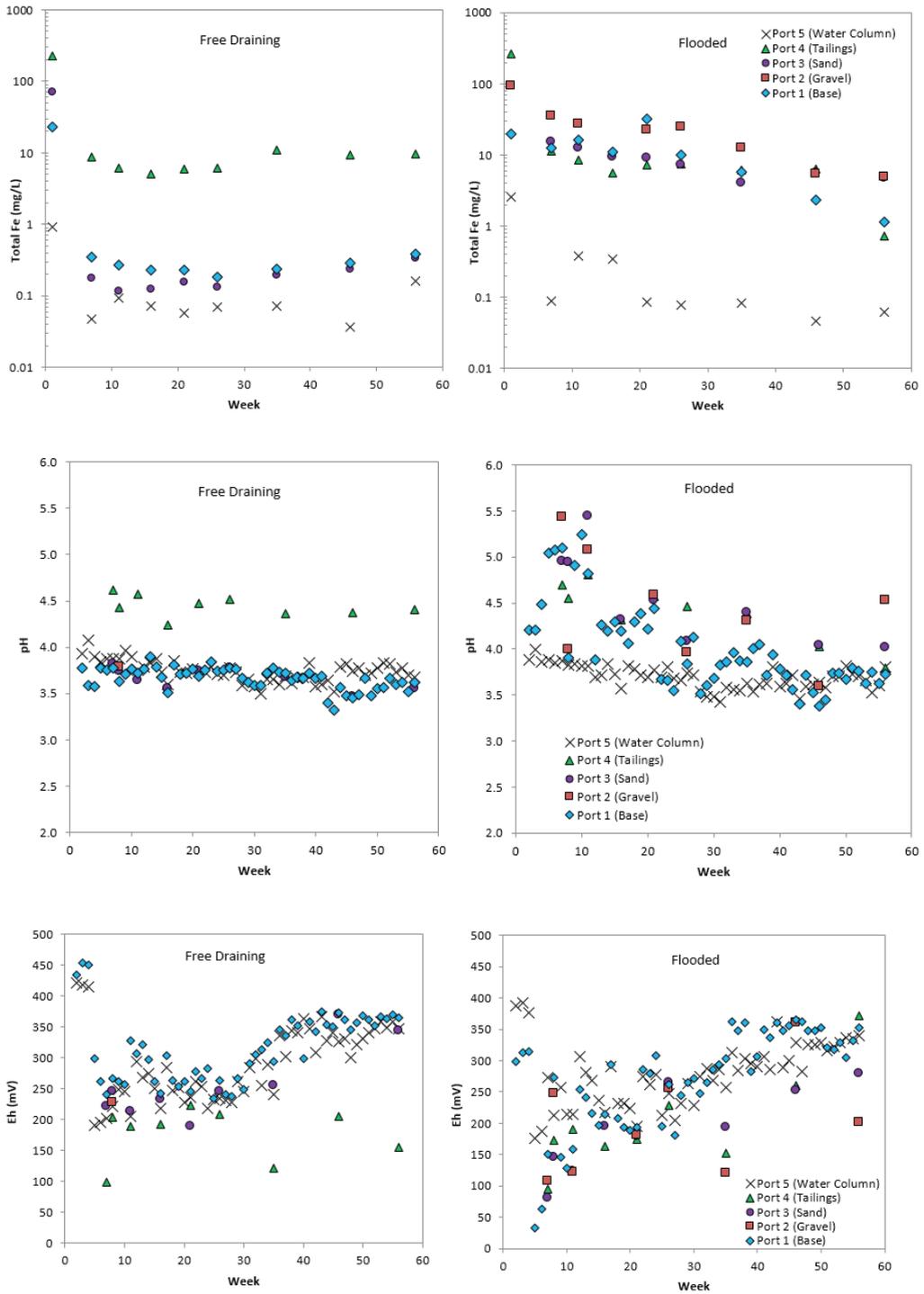


Figure 5 Eh over Time (Both Columns).



Water quality measured at the base of the columns at the start of testing were significantly different between columns between set-up and operation (flooded and free draining), however, over the test period, the pH and Eh at the base of the columns became similar as new pond water percolated through the columns (fig. 4 and fig. 5). These changes in pH and Eh, also resulted in changes to the dissolved and total iron concentrations at the base of the flooded column, with a decrease in total iron from 20 mg/L to 1 mg/L and dissolved iron from 13 mg/L to 0.3 mg/L. Total iron concentrations in the free-draining column were steady over the test period (fig. 3).

The drain and seepage water observed in the field exhibited similar trends to the column testing between the tailings porewater and seepage emergence points (tab. 2). The total and dissolved iron concentrations in the free draining dam are much lower than the flooded drain due to the age and operation of the facility behind the dam. In the field, the flooded drain system exhibited a larger decrease in both total and dissolved iron outside the drain more immediately than the free draining system where the change in total and dissolved iron concentrations are observed largely within the dam drain.

The flooded drain system does not achieve anoxic conditions (under field or laboratory conditions), with Eh values reported between 33 mV and 350 mV in the columns and between 156 mV and 450 mV in the field. The flooded system does however result in less oxidic conditions overall than the free draining system. The DO ranges from 4.4 mg/L to 9.0 mg/L in the columns and 4.2 mg/L to 11.1 mg/L in the field (DO is greater than 9 when T is less than 10°C). This was also observed by (Awoh *et al*, 2014) with a similar size column

set-up. Their findings indicate that the oxygen contained within the overlying water is replenished in the tailings pore water leading to mildly oxidic conditions. This mechanism is important when evaluating the continued oxidation of sulphides, and changes to equilibrium conditions in the pore water.

Saturation Indices and Mineral Precipitation

The geochemical software PHREEQC_i was used to understand aqueous speciation, saturation and potential geochemical reactions in the column pore waters. This geochemical modelling was compared with field observations and mineralogical testing for the different drain configurations.

The saturation index (SI) for various iron minerals including those previously observed in SEM investigations were predicted for pore waters using PHREEQC_i (WATEQ4f). Results indicate the average pore water in both columns is supersaturated with respect to many mineral phases including Goethite ($\alpha\text{FeO}(\text{OH})$), Hematite (Fe_2O_3), Jarosite ($\text{KFe}_3(\text{SO}_4)_2(\text{OH})_6$), Maghemite ($\gamma\text{Fe}_2\text{O}_3$), Ferrihydrite ($\text{Fe}_{10}\text{O}_{14}(\text{OH})_2$), and Melanterite ($\text{FeSO}_4 \cdot 7(\text{H}_2\text{O})$). While direct precipitation of many of these phases are not expected under the conditions in the pore waters, these minerals have been observed as secondary coatings as a result of ageing and crystallization of ferric sulphates and hydroxides like Schewertmannite ($\text{Fe}_{16}\text{O}_{16}(\text{OH})_{12}(\text{SO}_4)_2$) and Ferrihydrite.

Precipitates were observed in both columns throughout the testing. This was also observed in the field investigations, however the field accumulation of precipitates in the free-flowing drain system were significantly higher than the accumulation in the flooded

Table 2. Average Results for Dam Drain and Seepage Water

Parameter	Tailings Pore Water - Flooded	Dam Drain - Flooded	Seepage - Flooded	Tailings Pore Water - Free Draining	Dam Drain - Free Draining	Seepage - Free Draining
pH (units)	6.4	5.2	4.9	5.6	6.3	3.8
Eh (mV)	37	140	193	52	101	287
SO ₄ (mg/L)	6138	3978	3315	3100	1280	1432
T-Fe (mg/L)	1540	1242	687	80	31	35
D-Fe (mg/L)	1085	1010	681	35	1	25



drain. Field observations and testing of precipitates show good correlation with predicted minerals including iron oxy-hydroxides, iron oxy-sulphates, and sulphate minerals.

Summary

In the free draining system, as water moves through the tailings, total and dissolved iron, sulphate, and other parameters increase due to oxidation and dissolution of sulphides and secondary minerals. Equilibrium conditions in the tailings pore water (low Eh) allow for total and dissolved iron concentrations to remain high in the pore water. When tailings pore water moves through the drain, equilibrium conditions change, and the increased availability of oxidants (both O₂ and Fe³⁺) and increased Eh cause aqueous Fe²⁺ in porewater to oxidize and form secondary Fe³⁺ oxy-hydroxides and/or sulphates along the emerging seepage pathway.

In the flooded system, the tailings pore water characteristics are similar to the free draining system until seepage reaches the flooded drain. In the flooded drain, the availability of oxidants (and change in Eh) is limited. The equilibrium conditions change, but the reaction processes responsible for the formation of secondary minerals are also limited, resulting in sustained total and dissolved iron concentrations in solution.

Conclusions

The objective of the column testing was to obtain a better understanding of the geochemical reactions occurring in simulated drain conditions under a controlled laboratory setting. The columns were designed to assess the differences between the free-draining and flooded drain types and whether the flooded drain provided a significant improvement in reducing precipitate accumulation and geochemical changes within the system.

Based on the work performed to-date, pore waters in both columns were elevated in iron and sulphate concentrations. The reduction in concentration of total and dissolved iron observed between the tailings pore water and drain effluent in the free draining column

indicates that more iron is lost to secondary mineral precipitation in the free draining column than the flooded column. However, visual observations indicate that the small loss of iron between the tailings pore water and seepage in the flooded system is also resulting in precipitate formation. These laboratory observations compliment the field observations including changes in water quality and observed precipitate accumulation in the dam drains. Additional work is ongoing to assess the rate of precipitate accumulation and to further quantify the effectiveness of the flooded drain on reducing precipitate accumulation.

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References

- Alpers Boorman, R.S., and Watson, D.M. 1976. “Chemical processes in abandoned sulphide tailings dumps and environmental implications for North Eastern New Brunswick”. Canadian Inst. Min. Bulletin., Vol 69, pp. 86-96.
- Awah, A.S., Mbonimpa, M., Bussiere, B., Plante, B., and Bouzahzah, H. 2014. “Laboratory study of highly pyritic tailings submerged beneath a water cover under various hydrodynamic conditions.” Mine Water Environ, Vol 43, pp. 241-255.
- Blowes, D. W., Ptacek, C. J., Jambor, J. L. and Weisener, C. G. 2003. “The geochemistry of acid mine drainage”. 9.05. In Treatise on Geochemistry, Ed. Sherwood, B., Holland, H.D., and Lollar K.K.T Vol. 9. pp. 149-204
- Durocher, J.L., Robertson, L.A., and Usher, B.H. 2017. “Sulphide oxidation in TSFs and its influence on long term dam stability”. Paper presented at Tailings and Mine Waste, Banff, AB.
- Lindsay, M.B.J., Moncur, M.C., Bain, J.G., Jambor, J.L., Ptacek, C.J., and Blowes, D.W. 2015. “Geochemical and mineralogical aspects of sulphide mine tailings”. Applied Geochemistry, Vol 57, pp. 157-177.
- Lottermoser, B.G., 2007., Sulfidic Mine Wastes. In Mine Wastes-Characterization, Treatment, Environmental Impacts., Second Ed. Springer.

