

# Column Study to Evaluate the Biogeochemical and Geotechnical Behavior of Treated Oil Sands Tailings in Pit Lakes

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## ABSTRACT

Pit lakes are a common feature of open pit mines across the globe and have been proposed as a reclamation strategy for Canada's oil sands tailings. Oil sands tailings are a waste stream made up of fine-grained solids, water, salts, and organics. A relatively new approach to oil sands pit lake technology is called Permanent Aquatic Storage Structure (PASS) in which tailings are first treated with alum (a hydrated aluminum sulfate salt) and polyacrylamide (a polymer flocculant) prior to being deposited in a pit lake and capped with water. There is limited information on the effects of alum, polyacrylamide, and pressure (from overlying tailings) on the biogeochemical and geotechnical behavior of pit lakes tailings. As such, 12 x 5.5 L columns have been designed to evaluate the biogeochemical and geotechnical behavior of PASS-treated tailings in pit lakes. Each column contains PASS-treated tailings and a freshwater cap, and tailings in six of the columns are subjected to pressures using a multi-step loading scheme. Results up to Day 180 highlight the importance of sulfur cycling in PASS-treated tailings, with 62 to 97% of the sulfate reduced within 60 days. Sulfate reduction has produced gaseous and aqueous hydrogen sulfide in the columns. The generation of biogenic methane and carbon dioxide gases, and aqueous ammonia/ammonium is occurring in all columns, though the columns under pressure (0.3 to 0.6 kPa) are generating higher volumes and concentrations of these compounds. This suggests that pressure may be increasing metabolite solubility and thereby, microbial activity in the tailings.

*Keywords: mine waste management, reclamation, consolidation, sulfur cycling, methanogenesis, polyacrylamide*

## 1 INTRODUCTION

Pit lakes are common closure landforms in open pit mines, with thousands of pit lakes around the world (Blanchette and Lund 2016; Golder Associates Ltd. 2017; Vandenberg et al. 2022). Pit lakes are decommissioned open pits which are filled with water and often also contain a bottom layer of mining wastes, such as overburden or tailings (COSIA 2021). There are 23 pit lakes planned for the oil sands mines in Alberta, Canada, 11 of which will contain tailings (COSIA 2021). Oil sands tailings that are destined for pit lakes will typically consist of fine-grained (clay-sized) solids, water, dissolved salts, residual heavy oil, and other organic compounds. Untreated fine-grained oil sands tailings can take decades to consolidate (dewater) (Chalaturnyk et al. 2002), and as such, reclaiming these tailings in pit lakes is an attractive, economical option because the tailings can slowly consolidate over time while the pit lake water caps develop into lake ecosystems.

Commercial and pilot scale demonstration pit lakes in Alberta's oil sands are the subject of extensive research and monitoring. Currently, the only commercial scale oil sands pit lake is Syncrude Canada Ltd's Base Mine Lake. Base Mine Lake is 10 years old, spans 800 ha, and contains roughly 45 m of untreated fine-grained tailings and a 9 to 12 m water cap (Syncrude Canada Ltd. 2021). Other oil sands mining operations are investigating the potential for the reclamation of treated fine-grained tailings in pit lakes. Suncor Energy Inc. (Suncor) has developed a relatively new pit lake technology, called Permanent Aquatic Storage Structure (PASS), in which fine-grained tailings destined for pit lakes are first treated in line with a coagulant (alum) and flocculant (polyacrylamide, PAM). The goal of the PASS

treatment process is to improve the quality of pore water that is released into the water cap during tailings consolidation (COSIA 2021).

The biogeochemical and geotechnical behavior of pit lakes is of interest to oil sands operators, regulators, and stakeholders because these behaviors will ultimately impact the development of aquatic ecosystems and performance of the landforms. For example, biogeochemical cycling processes in untreated fine-grained oil sands tailings can lead to biogenic gas emissions, contaminant biodegradation, and mineral transformations and impact pore water quality (Siddique et al. 2007; 2014; Small et al. 2015; Dompierre et al. 2016; Foght et al. 2017). Because PASS is relatively new, there is limited publicly available information on the effects of alum and PAM addition on biogeochemical cycling and geotechnical behavior of tailings. Further, the impact of pressure (from overlying tailings) on biogeochemical cycling in pit lakes is unknown. Previous research has found that microbial activity is hindered at high hydrostatic pressures (10 to 24 MPa) (Tholosan et al. 1999; Abe 2007; Fichtel et al. 2015; Scoma et al. 2019; Barbato & Scoma 2020), but these pressures are well beyond the range expected in a pit lake.

The objective of this research is to evaluate the biogeochemical and geotechnical behavior of PASS-treated tailings in pit lakes with a laboratory column study. Twelve 5.5 L columns have been designed, each containing PASS-treated tailings and a water cap, and half of which are being subjected to increasing pressures using a multi-step loading scheme. The results of this research will indicate potential biogeochemical and geotechnical behaviors that may be important in PASS-treated tailings.

## 2 METHODOLOGY

### 2.1 Sample preparation

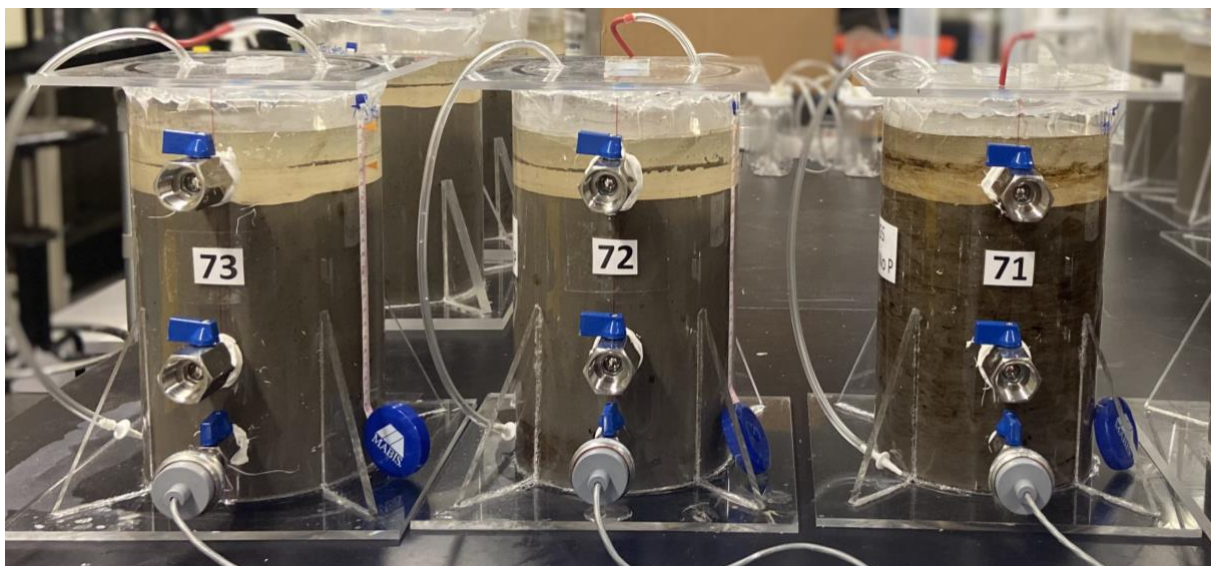
In 2021, untreated fine-grained tailings were collected from an Alberta oil sands mine and transported to the Northern Alberta Institute of Technology (NAIT) (Edmonton, Canada) for processing. Tailings were stored at room temperature until use. Tailings were treated and sheared at NAIT to mimic Suncor's PASS treatment and disposal process. Approximately 100 L of tailings were treated with alum ( $\text{Al}_2(\text{SO}_4)_3 \cdot \text{H}_2\text{O}$ ) at a dose of 950 mg/L and PAM at a dose of 1015 g/tonne of solids. Full details on the PASS treatment and shearing process are available in Cossey and Ulrich (2022).

Fresh water for the column water caps was collected from Beaver Creek Reservoir, the freshwater source for Base Mine Lake, in 2015. Beaver Creek Reservoir water was stored at the University of Alberta (Edmonton, Canada) at 4°C.

### 2.2 Experimental set-up

Twelve 5.5 L columns were designed and constructed for this project, each containing 4 L of PASS-treated tailings and a 0.5 L freshwater cap. A photo of three of the columns on Day 0 (February 22, 2022) is presented in Figure 1. Each column is made up of a roughly 30 cm tall, 14 cm inner diameter (ID) cast acrylic tube (Plastics Plus Ltd., Edmonton, Canada). Six of the columns were built with a 0.6 cm thick tube and 0.6 cm thick cast acrylic sheet base (Plastics Plus Ltd., Edmonton, Canada). The other six columns were built with a thicker (1.3 cm) tube and base to accommodate dead load surcharges (discussed later). All columns have a 0.6 cm thick cast acrylic sheet lid. Two 1.9 cm stainless steel ball valves (FxM NPT, Direct Material, Irving, USA) on each column are used as sampling ports for the tailings and water cap.

To simulate the pit lake tailings environment, each column is stored in the dark and under anaerobic conditions. To ensure the columns are anaerobic, each lid is sealed with silicon. Further, column headspaces are flushed with nitrogen every 60 days (on Day 0 and after every dead load surcharge) to remove any oxygen in the headspace. Each lid has a septum (CLS-4209-14, butyl rubber, Chemglass) to facilitate gas sampling and a gas collection system to ensure the column headspace remains at atmospheric pressure. All columns are being monitored for one year.



**Figure 1.** Photo of three 5.5 L columns taken on Day 0. Columns contain PASS-treated tailings amended with hydrocarbons and a freshwater cap

Four experimental conditions are being tested in triplicate for this project, as outlined in Table 1. This experiment has been designed to investigate the effects of both pressure (i.e. effective stress) and hydrocarbon amendments on the behavior of PASS-treated tailings. All 12 columns were allowed to undergo self-weight consolidation for 60 days, after which the tailings in six of the columns are being placed under a series of dead loads (0.3 to 5 kPa) using a multi-step loading scheme. The 0.3 and 0.6 kPa dead loads consist of sand while the 1.2, 2.4, and 5.0 kPa dead loads are 13 cm carbon steel cylinders of varying thicknesses (GC Custom Metal Fabrication Ltd., Edmonton, Canada). Following the application of a dead load, tailings' pore pressure dissipates and vertical deformation of the tailings-water interface is monitored until it plateaus. After 60 days, the dead load surcharge is doubled. The relatively low pressures (0.3 to 5 kPa) used in this experiment will provide preliminary indications of the impacts of pressure on biogeochemical cycling in tailings and will lay the foundation for additional studies which will investigate the effects of higher pressures (up to 200 kPa, the effective stress expected at the bottom of a pit lake).

**Table 1.** Summary of experimental conditions tested in triplicate columns each containing PASS-treated tailings and a water cap

Column	Pressure Applied (P)	Hydrocarbon Amendments (HC)
No HC + No P		
No HC + P	X	
HC + No P		X
HC + P	X	X

Six of the columns were amended with a mixture of hydrocarbons to stimulate and enhance microbial activity and biogeochemical cycling. Microorganisms found in oil sands tailings, such as sulfate-reducing bacteria and methanogens, are known to be capable of using various hydrocarbons as carbon sources (Siddique et al. 2006; 2007; 2011; Stasik & Wendt-Potthoff 2014; Tan et al. 2015; Gee et al. 2017; Siddique et al. 2015; 2020). The following hydrocarbon mixture was used for this experiment and was selected based on successful stimulation of oil sands microorganisms in previous research: 150 ppm toluene ( $\geq 99.9\%$ , Sigma-Aldrich, St. Louis, USA), 50 ppm o-xylene (99%, Alfa Aesar, Ottawa, Canada), 50 ppm m-xylene ( $> 99\%$ , TCI AMERICA, Portland, USA), 50 ppm p-xylene (99%, Alfa Aesar, Ottawa, Canada), 500 ppm n-octane (99+%, Thermo Fisher Scientific, Fair Lawn, USA), 500 ppm n-decane (99.5%, Fisher Scientific, Fair Lawn, USA), 500 ppm 2-methylpentane ( $\geq 99$ , Sigma Aldrich, St. Louis, USA), and 500 ppm 3-methylhexane (99%, ChemSampCo, Dallas, USA). For each of the six columns, the hydrocarbons were added as a free phase and were mixed in with 4 L of PASS-treated tailings on Day 0, prior to placing the tailings in the columns.

### 2.3 Analytical methods

The tailings, pore water, water cap, and headspace in each column are monitored and sampled at regular intervals to evaluate changes over time. Tailings consolidation is being evaluated by measuring interface settlement every 1 to 7 days and collecting pore water pressure readings every 2 hours. Pore water pressure is measured at the base of each column using a pore pressure transducer (0 to 69 kPa, Item # RK-68075-42, Cole Parmer, Montreal, Canada), all 12 of which are connected to a data logger (DAQ973A Data Acquisition System and Keysight DAQM901A 20 channel multiplexers, Santa Rosa, USA). pH and redox potential of the tailings and water caps are measured every 60 days through column sampling ports.

Pore water (separated from tailings via centrifugation) and water cap samples are collected every 60 days and analyzed for anions ( $\text{Cl}^-$  and  $\text{SO}_4^{2-}$ ), major cations ( $\text{Na}^+$ ,  $\text{K}^+$ ,  $\text{Ca}^{2+}$ ,  $\text{Mg}^{2+}$ ,  $\text{Fe}$ , and  $\text{Al}$ ), aqueous total sulfide species ( $\text{S}^{2-}$ ,  $\text{HS}^-$ , and  $\text{H}_2\text{S}$ ), ammonia/ammonium, dissolved organic carbon (DOC), and total alkalinity.  $\text{Cl}^-$  and  $\text{SO}_4^{2-}$  concentrations are measured in filtered (0.45  $\mu\text{m}$ ) samples at the University of Alberta's Natural Resources Analytical Laboratory (NRAL, Edmonton, Canada) using a colourmetric analyzer (Thermo Gallery Plus Beermaster Analyzer, Thermo Fisher Scientific, Vantaa, Finland). Filtered (0.45  $\mu\text{m}$ ) samples are also measured for major cations at NRAL using inductively coupled plasma – optical emission spectrometry (ICP-OES) (Thermo iCAP 600 series, Thermo Fisher Scientific, Bremen, Germany). The USEPA Methylene Blue Method (HACH Method 8131) and a HACH DR 900 Multiparameter Portable Colorimeter (Loveland, USA) are used to measure aqueous total sulfide species. Ammonia and ammonium are also measured using the HACH DR 900 Multiparameter Portable Colorimeter (Loveland, USA), following the AmVer™ Salicylate Test 'N Tube™ Method (Hach Method 10031). DOC is measured in filtered (0.45  $\mu\text{m}$ ) samples using a Shimadzu TOC-LCPH analyzer (Kyoto, Japan) and total alkalinity is measured with a Metrohm Eco Titrator (Herisau, Switzerland).

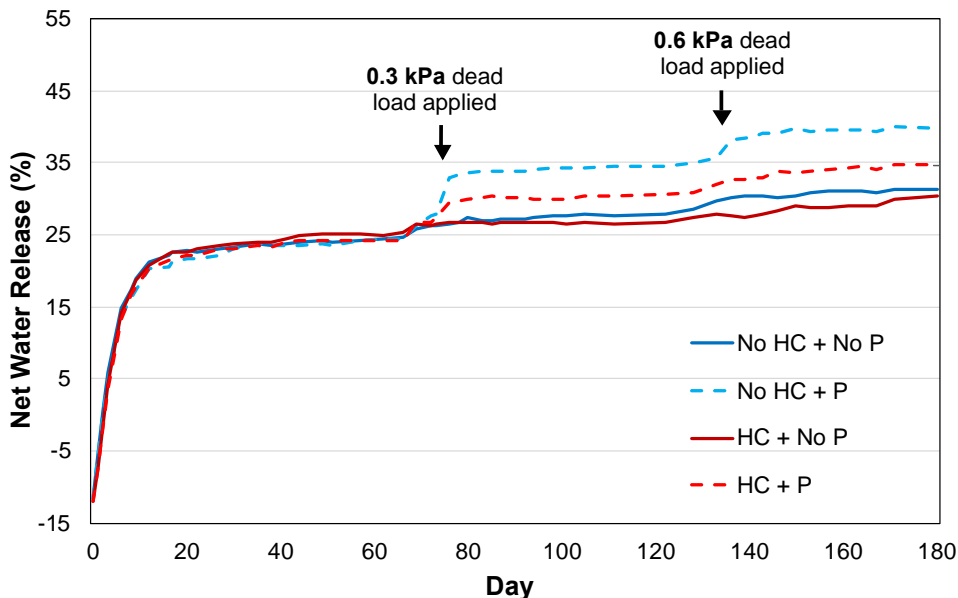
Headspace samples are collected every 60 days to measure the volume and/or concentration of hydrogen sulfide ( $\text{H}_2\text{S}$ ), carbon dioxide ( $\text{CO}_2$ ), and methane ( $\text{CH}_4$ ).  $\text{H}_2\text{S}$  is measured at AGAT Laboratories (Calgary, Canada) using gas chromatography and a sulfur chemiluminescence detector (GC-SCD).  $\text{CO}_2$  and  $\text{CH}_4$  are measured using gas chromatography in combination with a thermal conductivity detector (GC-TCD) and a flame ionization detector (GC-FID), respectively (Agilent 7890A+/5977B GC-MS, Santa Clara, USA).

### 3 RESULTS

This section presents preliminary results up to and including Day 180 of this experiment. Figure 2 presents the average net water release (NWR) from the tailings in each of the 12 columns. NWR indicates the extent to which the PASS-treated tailings have settled and consolidated in the columns and was calculated using Equation 1 below.

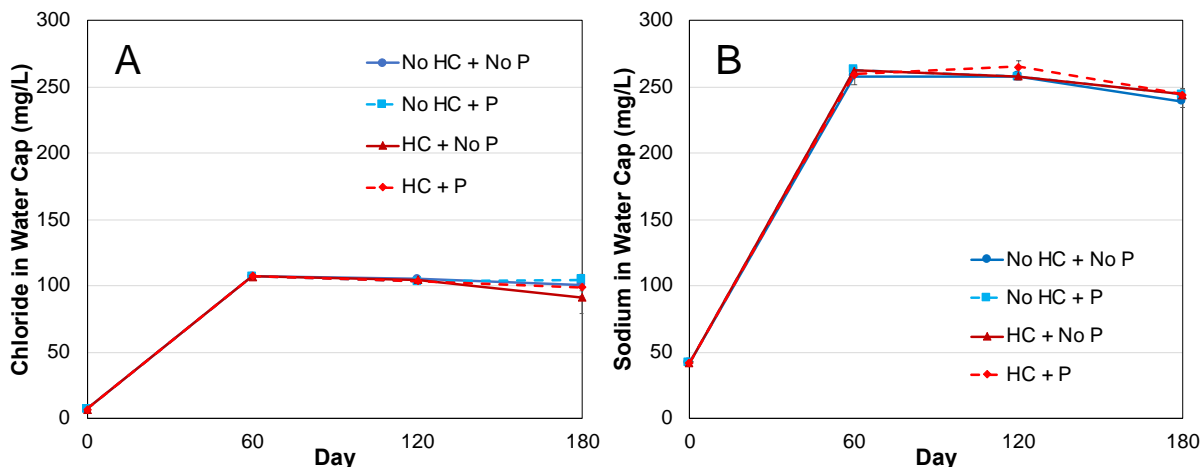
$$\text{NWR (\%)} = \frac{V_{wr} - V_p}{V_w} \times 100\% \quad (1)$$

where  $V_{wr}$  is the volume of water released,  $V_p$  is the volume of alum and polymer solutions added during the PASS treatment process, and  $V_w$  is the volume of pore water in the initial (untreated) tailings on Day 0. A negative NWR value indicates the volume of alum and polymer solution that remains in the tailings while a positive NWR value indicates the volume of pore water released from the tailings. NWR in all columns increased quickly, reaching approximately 21% after 12 days of self-weight consolidation. NWR has since plateaued at roughly 25% in the six columns that are only undergoing self-weight consolidation (No HC + No P and HC + No P). NWR continues to increase in No HC + P and HC + P columns each time a dead load is applied to the tailings. As of Day 180, the columns without hydrocarbon amendments had a higher NWR under pressure (No HC + P, 40%) than columns with hydrocarbon amendments under pressure (HC + P, 35%). Hydrocarbon amendments are hindering NWR in the HC + P columns and this is likely due to formation and entrapment of a larger volume of biogenic gases, such as  $\text{H}_2\text{S}$ ,  $\text{CO}_2$ , and  $\text{CH}_4$ , in the hydrocarbon amended tailings.



**Figure 2.** Net water release from PASS-treated tailings in 12 columns over 180 days. Results are averaged from triplicate columns

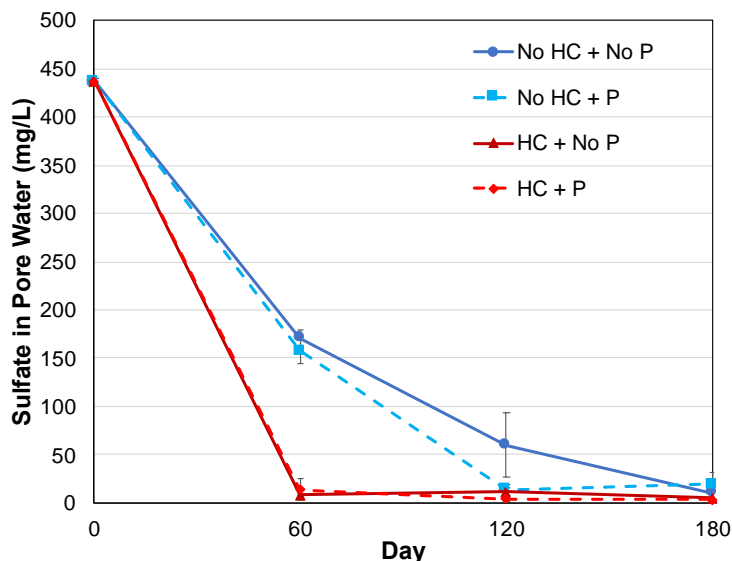
Figure 3 presents water cap concentrations of chloride ( $\text{Cl}^-$ , Figure 3A) and sodium ( $\text{Na}^+$ , Figure 3B) from Day 0 to 180. Day 0 concentrations indicate the initial concentration of chloride and sodium in the freshwater cap prior to tailings consolidation. Between Day 0 and 60, water cap concentrations of chloride and sodium increased to approximately 107 mg/L and 261 mg/L, respectively, in all 12 columns. This initial increase can largely be attributed to advective pore water fluxes because it is consistent with the self-weight consolidation NWR trends seen in Figure 2. Water cap concentrations of chloride and sodium have since plateaued and are similar in all columns, regardless of the dead load surcharges in half of the columns. This is because water cap concentrations of the respective ions are now similar to that of the PASS pore water, and as such an increase in the volume of cap water does not correspond to an increase in water cap concentrations of these ions.



**Figure 3.** Water cap concentrations of chloride (A) and sodium (B) in 12 columns over 180 days. Results are averaged from triplicate columns and error bars represent one standard deviation of triplicates

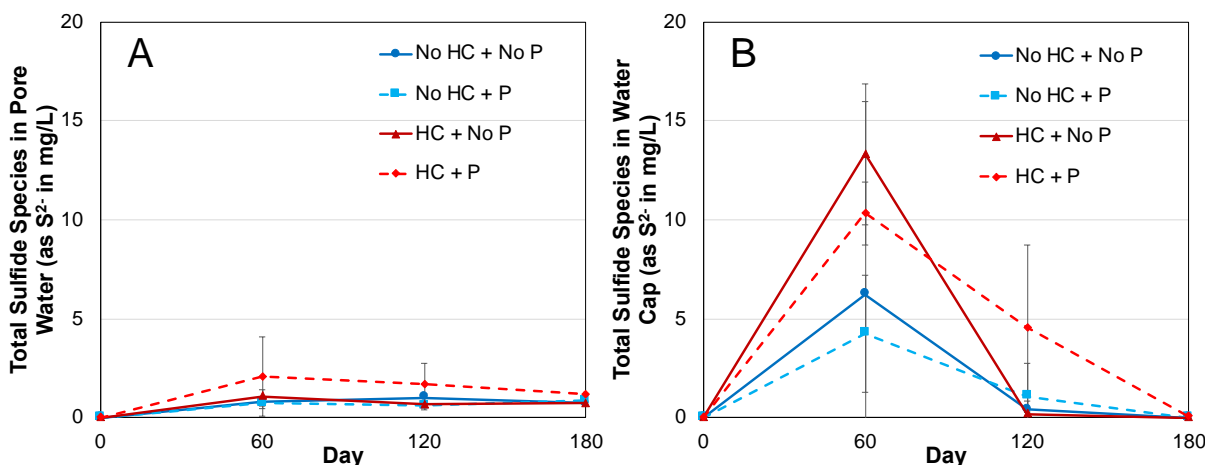
Because of the alum addition during the PASS treatment process, sulfur cycling was of particular interest in this experiment. Figure 4 shows the pore water sulfate ( $\text{SO}_4^{2-}$ ) concentrations measured from Day 0 to 180 in all 12 columns. Within the first 60 days, sulfate pore water concentrations decreased from 438 mg/L to approximately 11 mg/L in the hydrocarbon amended columns (HC + No P and HC + P). The columns without hydrocarbon amendments also underwent sulfate reduction but at a slower rate, with average pore water sulfate concentrations in No HC + No P and No HC + P columns decreasing to roughly 15 mg/L by Day 180. This indicates that the hydrocarbon mixture of toluene, xylenes, n-octane, n-decane, 2-methylpentane, and 3-methylhexane added to the tailings in six columns accelerated

sulfate reduction, though sulfate reduction occurred in all 12 columns. Accelerated sulfate reduction in hydrocarbon amended tailings was anticipated as previous research has found that sulfate-reducing bacteria in oil sands tailings can utilize n-alkanes and some BTEX (benzene, toluene, ethylbenzene, and xylenes) compounds as carbon sources (Stasik & Wendt-Potthoff 2014; Tan et al. 2015; Gee et al. 2017).



**Figure 4.** Pore water sulfate concentrations in 12 columns over 180 days. Results are averaged from triplicate columns and error bars represent one standard deviation of triplicates

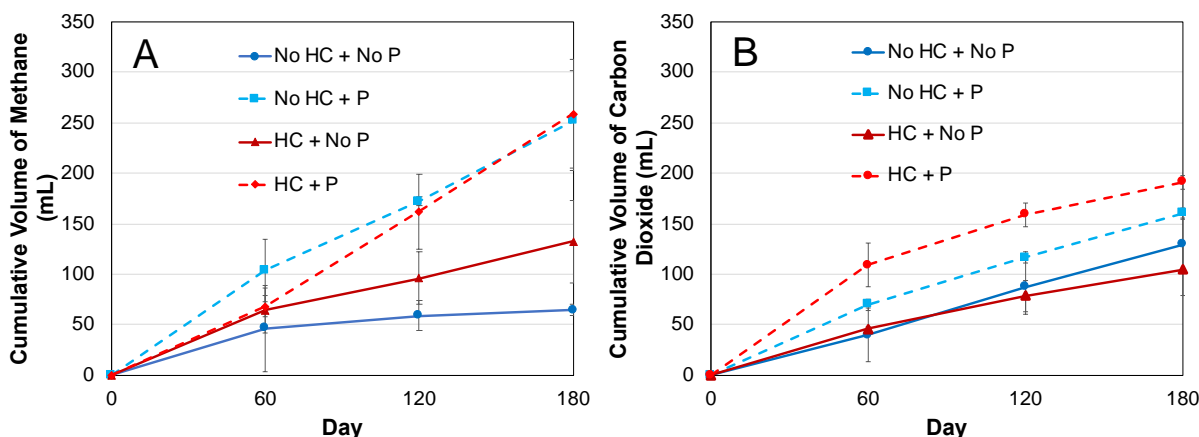
As a result of the sulfate reduction shown in Figure 4, reduced sulfur species should be present in all 12 columns, potentially in the aqueous, gaseous, and solid phases. Figure 5 shows average total sulfide species ( $S^{2-}$ ,  $HS^-$ , and  $H_2S$ ) concentrations in the pore water (Figure 5A) and water cap (Figure 5B) in all 12 columns from Day 0 to 180. Day 0 total sulfide species concentrations in both the pore water and freshwater cap were 0 mg/L. Further, because of the neutral pH of both the tailings and water caps (data not shown), the aqueous sulfide species should primarily be  $HS^-$  and  $H_2S$ . Columns with hydrocarbon amended tailings had higher concentrations of aqueous sulfide species in the cap water and pore water which is consistent with the sulfate reduction shown in Figure 4. Comparing Figures 5A and 5B, it is apparent that concentrations of total sulfide species are higher in the water caps than in the pore water. This is likely a result of both the time-sensitive nature of the aqueous total sulfide species measurement (pore water sulfide species may be underestimated because tailings samples must be centrifuged before pore water concentrations can be measured) and the precipitation of sulfide species as metal sulfides in the tailings. Though reduced sulfur species in the solid phase have not been measured yet, the tailings in many of the columns are black in color which likely indicates  $FeS_{(s)}$  formation.



**Figure 5.** Total sulfide species concentrations in pore water (A) and cap water (B) in 12 columns over 180 days. Results are averaged from triplicate columns and error bars represent one standard deviation of triplicates

Gaseous H<sub>2</sub>S in the column headspaces peaked at Day 60, with concentrations ranging from <0.1 ppmv to 73.9 ppmv (equivalent to 0.05 mL of H<sub>2</sub>S). This is consistent with the pore water sulfate concentrations (Figure 4) which were reduced by at least 62% in all 12 columns by Day 60 and the Day 60 peak in water cap concentrations of total sulfide species (Figure 5B). Gaseous H<sub>2</sub>S generation has since slowed, with 2.3 ppmv being the highest concentration measured since Day 60 (note: column headspace is flushed with nitrogen every 60 days, removing all previously generated biogenic gases).

Figure 6 displays the cumulative volume of biogenic methane (CH<sub>4</sub>, Figure 6A) and carbon dioxide (CO<sub>2</sub>, Figure 6B) generated in the 12 columns over 180 days. These gases are assumed to be products of methanogenesis occurring in the tailings. Columns amended with hydrocarbons may be generating more CH<sub>4</sub> and/or CO<sub>2</sub> than their comparable unamended columns, though the trends are not consistent for both CH<sub>4</sub> and CO<sub>2</sub>. As such at this stage of the experiment, the impact of hydrocarbon amendments, if any, on methanogenesis is not clear, though methanogens should be capable of degrading the BTEX, n-alkanes, and iso-alkanes used in this experiment (Siddique et al. 2006; 2007; 2015; 2020). However, both CH<sub>4</sub> and CO<sub>2</sub> are highest in the headspaces of columns with dead load surcharges (No HC + P and HC + P). Further, on Days 120 and 180, DOC concentrations were higher in both the pore water and water caps of columns with dead load surcharges (data not shown). Taken together, these interesting results may indicate that the applied pressures are increasing metabolite solubility, which then increases microbial activity. Further investigation is needed to confirm this notion. The pH of the tailings in all columns decreased slightly (from 7.1 to 6.9, on average) during the first 60 days, which is consistent with the CO<sub>2</sub> production seen in Figure 6B. However, the presence of bitumen likely impacted the accuracy of the tailings pH measurements, and as such, this data is not presented.

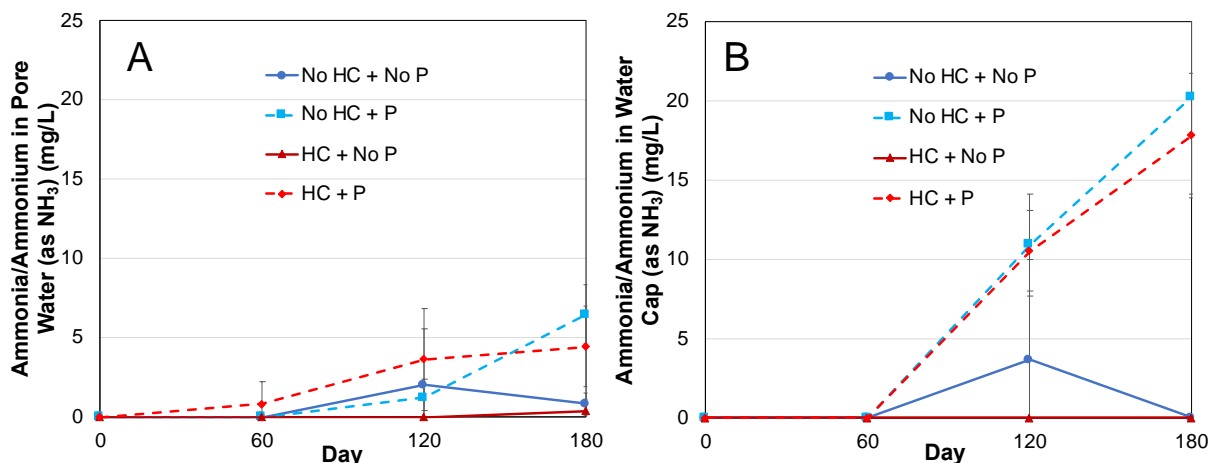


**Figure 6.** Cumulative volume of gaseous methane (A) and carbon dioxide (B) emitted in 12 columns over 180 days. Results are averaged from triplicate columns and error bars represent one standard deviation of triplicates

The environmental fate of PAM is also of interest in PASS-treated tailings. Previous research has suggested that PAM may be biodegraded and used as a nitrogen source under the anaerobic conditions that exist in pit lake tailings (Grula et al. 1994; Haveroen et al. 2005; Hu et al. 2018). If PAM is biodegraded through hydrolysis of the amide nitrogen, it would generate ammonia or ammonium (Kay-Shoemake et al. 1998). Figure 7 shows pore water (Figure 7A) and water cap (Figure 7B) concentrations of ammonia/ammonium measured from Day 0 to 180 in all 12 columns. Day 0 concentrations of ammonia/ammonium in the pore water and freshwater cap were 0 mg/L. Ammonia/ammonium generation during this experiment may be the result of PAM biodegradation, though it could also be the result of nitrogen fixation (Collins et al. 2016). The authors are in the process of measuring PAM concentrations in all columns to determine whether the parent compound is being degraded over time. Similar to Figure 6, the highest pore water and water cap concentrations of ammonia/ammonium occur in columns with dead load surcharges (No HC + P and HC + P). This may be due to increased metabolite solubility under pressure, which is stimulating microbial activity in these columns.

Charge balance calculations were performed to confirm the accuracy of the water chemistry results presented in this paper. Calculations were performed using the average concentrations of all measured cations and anions in the pore water and water caps on Days 0, 60, 120, and 180. All charge balance calculations were acceptable, within  $\pm 5\%$ , for all columns except for the Day 120 pore water in No HC

+ P columns which had an error of -6%. However, the larger error in No HC + P pore water on Day 120 is likely the result of a cation measurement error.



**Figure 7.** Ammonia/ammonium concentrations in pore water (A) and cap water (B) in 12 columns over 180 days. Results are averaged from triplicate columns and error bars represent one standard deviation of triplicates

#### 4 CONCLUSIONS

Column monitoring is ongoing, however, results to date indicate that sulfur cycling is an important biogeochemical process in PASS-treated tailings as all 12 columns have undergone extensive sulfate reduction. Sulfate concentrations were reduced (from 438 mg/L) to 11 mg/L by Day 60 in hydrocarbon amended tailings and 15 mg/L by Day 180 in unamended tailings. As a result, aqueous and gaseous reduced sulfur species are present in all columns. Methanogenesis is also occurring in all 12 columns. However, higher volumes of gaseous CH<sub>4</sub> and CO<sub>2</sub> are being generated in the columns with dead load surcharges. Similarly, aqueous ammonia/ammonium generation is highest in columns with dead load surcharges. Taken together, these results suggest that the pressures applied to the tailings may be impacting metabolite solubility and thereby, microbial activity.

While this column study has been designed to mimic pit lake behavior, numerous mechanisms are important to pit lake behavior at the commercial scale that cannot be represented by this study. The quiescent conditions in these columns do not account for the physical mixing that occurs in pit lake water caps, due to events such as lake turnover or wave activity (Lawrence et al. 2016). Further, while the anaerobic conditions used in this work are representative of pit lake tailings in the field (Dompierre et al. 2016), they do not necessarily reflect water cap conditions, as oxygen may be present in pit lake water caps depending on the season (Lawrence et al. 2016; Risacher et al. 2018). As such, additional biogeochemical cycling processes that may occur in pit lake water caps, such as oxidation of reduced sulfur species or methanotrophy, are not represented by this study (Risacher et al. 2018). Further, the columns are stored at room temperature which is greater than the annual average temperature expected in northern Alberta pit lake tailings (Dompierre et al. 2016; Tedford et al. 2019) and may impact both microbial activity and consolidation. Lastly, column size is a limitation of this study as geotechnical behavior is impacted by both shape and scale and is likely to be different at the commercial scale. Despite these limitations, the results of this research provide an indication of which biogeochemical cycling processes are important in anaerobic PASS-treated tailings deposits. These biogeochemical processes will subsequently influence both pore water quality and pit lake water cap quality due to upward advective fluxes of pore water during tailings consolidation.

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