COSIA Tailings EPA

2021 TAILINGS RESEARCH REPORT

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* Five workers walking with testing equipment after taking water samples at Suncor's Lake Miwasin. Fall 2021.

Introduction

This is the fourth summary report from the Canada's Oil Sands Innovation Alliance (COSIA) Tailings Environmental Priority Area (EPA). This report highlights just some of the recent progress in research and technology development work in tailings management at various stages of research: from literature reviews, laboratory projects, and pilot trials; to large field-scale demonstration and commercialization programs. The Tailings EPA, in collaboration with universities, government and research institutes, other companies and partners, is bringing together shared experience, expertise and financial commitment of oil sands mining companies to find new technologies and solutions to tailings management challenges.

Tailings are the sand, silt, clay, water and residual bitumen found naturally in oil sands that remain following the mining and bitumen extraction process. Through the Tailings EPA, member companies are focused on improving the management of oil sands tailings throughout their production and treatment, storage, reclamation and closure phases.

The Tailings EPA has identified key issues facing the industry and is working to address them. The current areas of focus include:

- Managing the accumulation of fluid tailings (FT) within tailings ponds through development of new and improved tailings technologies;
- Minimize net environmental effects from tailings treatment and deposits; and
- Accelerate the reclamation of tailings deposits so they can be incorporated into the final reclaimed landscape sooner.

The research projects summarized in this report are categorized into four principal research areas: tailings treatment technologies, tailings capping, consolidation modelling, froth treatment tailings, tailings characterization, tailings deposition and monitoring. Each research project seeks to advance the understanding of, and improve upon, the risks and uncertainties associated with tailings management.

Tailings deposits can have very different properties: from sand-dominated deposits to fines dominated deposits of varying lift thicknesses and final depths; deposits that will underlie the water cap in pit lakes; and tailings mixed with other materials like overburden. Reclamation of most tailings deposits occurs some time after deposition, so understanding the desired properties of treated tailings requires an understanding of the factors that affect the time for consolidation after the deposit is placed. The industry seeks to better understand tailings treatment processes and consolidation mechanisms so that such knowledge can be applied to enhance reclamation and accelerate closure planning and implementation.

Predicting trajectories of tailings deposits through modelling can reduce uncertainty and aid in the development of robust reclamation and closure plans. Another area of research is the acquisition of real-time tailings process information. In-line or at-line analyzers can provide information on the efficacy of the tailings treatment and help guide treatment optimization strategies.

Please contact the Industry Champion identified for each research project for additional information. Information on many of the projects is also available on the COSIA website (https://cosia.ca/).

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Teck Resources Limited

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COSIA PROJECT NUMBER AND TITLE

COSIA Project Number	Project Title
	Tailings Treatment Technologies
TE0053	Maintaining Permeability for Continuous Mature Fine Tailings Dewatering
TE0065	Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria
TE0067	Combining Worms and Vegetation to Enhance Tailings Dewatering - Building with Nature on Successfully Tested Methods
TE0075	NAIT Industrial Research Chair for Colleges in Oil Sands Tailings Management
TJ0033	Engineered Tailings Research
TJ0108	Fluid Tailings Inline Flocculation and Co-Deposition
TJ0109	Flocculated Tailings and Deposit Monitoring
TJ0112	Geobags Pilot Study
TJ0113	Pressure Filtration for Fluid Fine Tailings Treatment
TJ0117	Inline Flocculation of Fluid Fine Tailings Field Pilot
TJ0128	Physically Upgraded Trafficable Tailings Innovation (PUTTI)
TJ0129	CST Enhanced Fines Beach Capture
TJ0151	Co-Processing of Fresh Tailings And FFT
TJ0153	Thickening of Fluid Tailings and Co-deposition with non-segregating Tailings
	Tailings Capping
TE0052	From Slurry to Soil: Creating Soil from Oil Sands Tailings; Phase 2
TE0084	Constitutive Model Development and Experiment Scale-Up for Fines-Dominated Tailings Deposit Capping
	Consolidation Modelling
TE0072	Comparison of Rapid Centrifuge Consolidation Test, Geotechnical Beam Centrifuge Test and Large Strain Consolidation Test
TJ0145	esNST Geo-Column and Large Strain Consolidation Test and Simulation
TJ0148	Rapid Assessment of Tailings Settlement Using a Benchtop Geotechnical Centrifuge
TJ0149	Large Strain Consolidation Test and Simulation for Weak Tailings in ETF At Horizon
	Froth Tailings Treatment

COSIA Project Number	Project Title
TE0055	Minimization Of Greenhouse Gas Emissions in Froth Treatment Tailings by Manipulation of Electron Acceptors
TE0070	Rheology Of Froth Treatment Tailings
TJ0130	NSERC-Syncrude IRC in Mine Closure Geochemistry
TJ0142	On-Line Measurement of Naphtha
TJ0147	Aerobic Biodegradation Within FTT Affected MFT
	Tailings Characterization
TE0036	Long-Term Dewatering of Amended Oil Sands Tailings: Co-Funded by COSIA And NSERC (An NSERC Collaborative Research and Development Grant)
TE0041	Insitu Real Time Measurement of Solids Content
TE0086	State Of Knowledge of Environmental and Human Health Impacts of The Use of Anionic Polyacrylamides In Oil Sands
TJ0138	Environmental Fate and Implications of Polyacrylamide Addition to Oil Sands Tailings
TJ0146	Offline Measurement of Clay Activity Using X-Ray Diffraction Methods
	Tailings Deposition and Monitoring
TE0010	NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique
TE0054	Modeling Of Co-Deposition of Two Tailings Streams in A Pond Environment
TE0069	Mechanics Of Methane Bubbles in Tailings Ponds
TE0071	Assessment Of Liquefaction Potential of Unsaturated Tailings Subjected to Future Saturation
TE0083	The Role of Bubble Ebullition on The Vertical Transport of Fine Solids in End-Pit Lakes
TE0085	Deposit Instabilities in Subaqueous and Terrestrial Tailings Landscapes
TE0088	Managing Long-Term Settlement of Deep Cohesive Tailings Deposits
TJ0104	Co-Deposition
TJ0144	Depositional Configurations Impact on NST And eNST Fines Capture in A Flume
TJ0152	Modified Atmospheric Fines Drying (MAFD) Pilot

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Tailings Treatment Technologies

Maintaining Permeability for Continuous Mature Fine Tailings Dewatering

COSIA Project Number: TE0053 (IOSI 2017-04)

Research Provider: University of Alberta

Industry Champion: Syncrude

Status: Year 3 of 3 (There will be a year 4 since the project end date was approved to extend to April 30, 2023)

PROJECT SUMMARY

1. Scope

The original scope of the project was to investigate the use of specific process aids that target residual bitumen, which was believed to be the main cause of difficulty in the filtration of the oil sands tailings. The process aids should be able to interact specifically with the residual bitumen.

As the project progressed, it was found that both the residual bitumen and the ultrafine clay minerals in the oil sands tailings may have contributed to the difficulties in filtration. Therefore, the scope was modified to first investigate the roles of different minerals (non-clays, clays, and swelling clays) on filtration in conjunction with residual bitumen, followed by the investigation of methods to eliminate their detrimental effects.

2. Rationale and Methodology

Previous studies on chemical amendments of the oil sands tailings were somewhat “trial-and-error”. The typical polyacrylamide flocculants were thought to flocculate the fine clays. However, our recent work showed that the majority of the added polyacrylamide and polyDADMAC flocculant/coagulant were consumed in countering the effect of residual bitumen (Loerke, 2016; Loerke et al., 2017). It was therefore proposed that the process aids should be selected with specific interactions targeting this main cause is responsible for the difficulty in oil sands tailings filtration.

The plan was to confirm the detrimental roles of the residual bitumen, in different forms, in the oil sands tailings filtration, i.e., bulk bitumen, bitumen-in-water emulsion, and bitumen adsorbed on clay surfaces, then to develop corresponding treatment strategies to eliminate these adverse effects through appropriate chemical amendments. In these investigations, model kaolinite clay and bitumen froth as well as a mature fine tailings (MFT) sample would be used to isolate the effects of the different forms of the bitumen. The ultimate performance measure was the solid content in the filter press cakes, but during the experiments, other measures such as CST and vacuum filtration rates would also be used as intermediate performance indicators.

The research results would be presented to the industry stewards so that progresses could be gauged, and research directions could be modified to ensure that the research was on target, on budget and relevant to the oil sands industry.

3. Significance

The project would help the oil sands industry to identify the specific reasons for the slow dewatering and difficult filtration of the oil sands tailings, rather than attributing everything to "fine clays". With the appropriate techniques to deal with these specific reasons, it was expected that the project would help achieve the plastic limit of the oil sands tailings within a reasonable treatment time economically. The research outcome would accelerate the oil sands tailings reclamation process.

4. Miscellaneous

The project is built on the existing knowledge on the chemical amendments of the oil sands tailings by different polymer flocculants and coagulants. But the project would be different from previous study by mostly focusing on pressure filtration through a laboratory filter press, supplemented by vacuum filtration and CST measurements. Pressure filtration was recently identified as one promising and rapidly adopted method in the global mining industry to generate filter cakes that can be reclaimed (Amoah, 2019; Goldup et al., 2019; Leonida, (2020, 2021); Moreno et al., 2018).

This project, being mostly a fundamental study, was expected to provide a better understanding of the issues of oil sands tailings filtration, and to accelerate the implementation of filter press in oil sands tailings treatment.

PROGRESS AND ACHIEVEMENTS

The major findings from the first 1.7 years of the project (May 2019 to December 2020), reported in last year's annual summary, was that externally added *bulk bitumen* (i.e., bitumen froth) did not markedly affect oil sands tailings filtration. However, an ultrafine fraction centrifuged from MFT at 17340 RCF severely deteriorated the filtration of 35 wt% kaolinite slurries when doped to about 3.5 wt% bitumen. This ultrafine fraction, dubbed "middle layer", was found to contain 12 wt% bitumen and 42 wt% ultrafine <450 nm solids (composed of montmorillonite and kaolinite), representing 13% of the yield from MFT and recovering 45% of the bitumen and 18% of the solids from MFT. The research was then divided into two parts: one was a study of the filtration behaviors of fine size fractions of different types of minerals (without bitumen), and the other was the effects of bitumen coating on the filtration of these minerals. The former was completed and reported in last year's summary, and that study showed swelling clays such as montmorillonite and illite-smectite to be the cause contributing to the difficulties in oil sands tailings filtration. The study on the effects of bitumen was completed in 2021 and reported below.

1. Four minerals were studied: quartz (d_{50} 3.6µm), rutile (0.7µm), kaolinite (4.1µm) and montmorillonite (2.8µm).

2. The mineral surfaces were made hydrophobic by either methylation or coating with bitumen. This was achieved by treating the minerals in toluene solutions of either 3-chloropropytriethoxysilane, or bitumen, at different concentrations. The treated samples were tested in vacuum filtration, and the filtration behaviors were interpreted with the help of contact angle, FTIR, XPS depth profile and X-ray microscope/nanoCT measurements.

3. Methylation of quartz was successful, and the quartz filtration rate displayed a clear linear correlation to the contact angle induced by the methylation treatment. This shows that mineral surface hydrophobicity helps its filtration from an aqueous slurry.

4. Methylation attempts of kaolinite and montmorillonite were not successful. The contact angles of these clay minerals did not increase substantially after the methylation treatment. Methylation was not attempted on rutile.

5. Bitumen-coating treatment significantly increased the contact angle (thus hydrophobicity) of non-clay minerals (quartz, rutile) and the non-swelling clays (kaolinite). But bitumen-coating treatment only marginally increased the contact angle of the swelling clay montmorillonite even after treatment in a 50 wt% bitumen-in-toluene solution.

6. The hydrophobicity resulting from bitumen-coating improved mineral filtration, but only when the coating was not too thick. The thickness of the bitumen coating changed with the concentration of bitumen in toluene and the specific surface area of the mineral. When the minerals were treated with 10 wt% bitumen-in-toluene solution, the filtration of all tested minerals improved, more significantly for the non-clay minerals (quartz and rutile) and non-swelling clay (kaolinite) but only marginally for the swelling clay (montmorillonite). This increased filtration rate was correlated to an increase in the measured contact angle.

7. However, when the minerals were treated at higher concentrations of bitumen in the toluene solution, the filtration of the treated minerals was observed to deteriorate despite the high contact angle. The "*critical*" bitumen concentration was related to the specific surface area of the minerals: minerals with higher specific surface area had a higher critical bitumen concentration when the filtration deteriorated. Thus, when bitumen concentration was increased from 10 wt% to 30 wt%, the filtration rate of quartz and kaolinite decreased, but that of rutile and montmorillonite increased. Further, an increase in bitumen concentration to 50 wt% saw a slight drop of rutile filtration as well. Montmorillonite was not tested at higher bitumen concentrations due to the very marginal improvement in its filtration after bitumen-coating treatment anyway.

8. XPS depth profile measurements on kaolinite showed that bitumen coating on kaolinite was thicker at 30 wt% bitumen than at 10 wt% bitumen. X-ray microscope/nanoCT measurements showed that at the 10 wt% bitumen treatment, larger pores and higher pore volumes were observed in the kaolinite filter cake. However, when the kaolinite was treated at 30 wt% bitumen, smaller pores and lower pore volumes were observed, and the bitumen coated kaolinite appeared to form lumped aggregates in the filter cake. This explained the reduced filtration rate despite the high contact angle at the high bitumen-in-toluene concentration (and high hydrophobicity).

9. Therefore, bitumen coating on mineral surface could benefit filtration due to the induced hydrophobicity, provided that the bitumen coating was not thick. A thick bitumen coating may be mobilized due to the deformable nature of the bitumen, which could migrate under the pressure gradient to plug up the pores in the filter cake, lowering filtration rate.

The investigation of the filtration behaviors of different types of minerals, and of the effects of surface hydrophobicity induced by bitumen coating or methylation on the filtration of the different minerals, meant that the project deviated slightly from the original objectives, which had been geared towards screening different bitumen binding reagents. However, this deviation was necessary because it provided a better understanding of the factors affecting the filtration of the oil sands tailings. This understanding will help guide the development of suitable treatment strategies to improve oil sands filtration.

Similar to last year's report, it is noted that the COVID-19 pandemic continued to have a significant negative impact on this project in 2021, due to the delays and interruptions caused by travel restrictions (which affected hiring) and reduced laboratory accessibilities. As a result, the project was approved for a one-year extension of the end date, from April 30, 2022, to April 30, 2023, without additional budget.

LESSONS LEARNED

Rapid progressive reclamation of the oil sands tailings into terrestrial closure landform requires that the tailings be quickly dewatered to the plastic limit. Currently, pressure filtration is one of the most promising technologies to achieve this goal of fast process water recycle and tailings reclamation.

However, despite the recent trend and successes of commercial implementation of filter presses in mine tailings dewatering (Amoah, 2019; Goldup et al., 2019; Leonida, (2020, 2021); Moreno et al., 2018), using filter press to treat Alberta oil sands tailings either could not generate filter cakes with required solid content for reclamation or required high dosages of coagulants/flocculants that rendered the process uneconomical.

So far this research project revealed the causes that made fine oil sands tailings pressure filtration more difficult than typical mine tailings pressure filtration. These are:

1. Swelling clays such as montmorillonite and illite-smectite in oil sands tailings were the cause that significantly lowered the filtration rate of the oil sands tailings. This was due to the extremely high specific surface areas of the swelling clays, which significantly increased the effective volume fraction of the mineral solids, making filtration difficult. This explains why a high coagulant dosage is required to effectively filter the oil sands tailings, because a high dosage of coagulant, such as alum, can compress the electrical double layer thus reduce the effective volume fraction of the mineral solids. This also explains why acid treatment of swelling clays such as montmorillonite could improve its filtration despite the unaltered MBI and CEC. The proton H^+ helped to release the exchangeable metal cations from the swelling clays and made them available as coagulants.

2. Bitumen coating on clay minerals in the oil sands tailings helped filtration due to the induced hydrophobicity of the mineral surface. However, this research revealed that when the bitumen coating was thick, it in fact would adversely affect the filtration. This was because the thick bitumen coating could be mobilized due to its deformable nature. Under the pressure gradient in filtration, the thick bitumen coating could migrate and plug up the pores inside the filter cake.

3. Effective filtration of oil sands tailings requires solutions to deal with the swelling clays and with thinning the thick bitumen coating on clay surfaces in oil sands tailings.

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Moreno, J.J., Kendall, S, Ortiz, A. (2018). Dewatering options for management of fine gold tailings in Western Australian Goldfields. *Proceedings of the 21st International Seminar on Paste and Thickened Tailings,* Australian Centre for Geomechanics, Perth, Western Australia, 413-424.

PRESENTATIONS AND PUBLICATIONS

Journal Publications

Wang, D., Tao, H., Wang, K., Tan, X., & Liu, Q., (2022). The filterability of different types of minerals and the role of swelling clays in the filtration of oil sands tailings. *Fuel*, 123395. https://doi.org/10.1016/j.fuel.2022.123395.

Conference Presentations/Posters

Wang, D., Tao, H., Wang, K., Tan, X., Liu, Q. (2021). Influence of bitumen coating on the filterability of clay and non-clay mineral solids. *Proceedings of the 2021 Tailings and Mine Waste Conference,* Banff, AB.

Reports & Other Publications

Wang, D., Tao, H., Tan, X., Liu, Q., (2021, May 4). *Maintaining Permeability for Continuous Mature Fine Tailings Dewatering*. COSIA-IOSI May 2021 Stewardship Report.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigators: Qi Liu, Xiaoli Tan

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Qi Liu	University of Alberta	Professor		
Xiaoli Tan	University of Alberta	Research Associate, Adjunct Professor		

Hongbiao Tao	University of Alberta	Postdoctoral Fellow	Sept 1, 2019	August 31, 2021
Dong Wang	University of Alberta	PhD student	January 1, 2018	August 31, 2022

Note:
1. The postdoctoral fellow left the project on August 31, 2021. He found employment in Toronto. The position has not been filled afterwards.
2. The PhD student's expected graduation date is postponed due to the delays caused by the COVID-19 pandemic.

Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria

COSIA Project Number: TE0065 (IOSI19)

Research Provider: University of Alberta

Industry Champion: Syncrude

Status: Year 3 of 4

PROJECT SUMMARY

The production of tailings is an unavoidable consequence of the bitumen extraction process used in the Canadian oil sands. Flocculation of fluid fine tailings with polymeric flocculants followed by liquid-solids separation is one of the most popular processes used in the oil sands industry. As greater quantities of tailings are produced, the need for a complete and economically-viable treatment becomes more urgent. It is proposed that bacteria that are already native to tailings ponds be engineered to actively cause settling and dewatering of mature fine tailings (MFT). By engineering these bacteria with surfaces that mimic the properties of conventional polymers already shown to be useful in tailings treatment, it is expected that these self-replicating bacteria will provide both an environmentally safe and significantly cheaper alternative to polymer flocculants. Moreover, as engineered bacteria will settle along with suspended solids and naturally dewater upon death, it is expected that a more compact mature fine tailings will be formed. Finally, safety through genetic engineering has been considered using best practice principles to ensure no environmental harm occurs through the use of these bacteria.

The objectives of this proposed research include generating DNA sequences encoding both the display domain and two distinct biopolymer domains based on varying polymer architectures, inserting the DNA into bacteria, confirming the production and localization of the biopolymer sequences onto the bacterial surface, and examining how these engineered bacteria affect the settling of MFT. Settling will be examined by testing the flocculation capabilities or the engineered bacteria on MFT, their dewatering ability by pressure filtration, and the floc structures will be further examined using Cryo-SEM. To demonstrate the efficacy of the biopolymeric sequences, control tests will be carried out using additive free MFT, a conventional synthetic organic polymer (FLOPAM A3338), and bacteria modified with the display domain but not the biopolymer domain.

Ultimately, this work will demonstrate the viability of a bio-based approach to treat MFT. This project builds on existing synthetic organic polymer research, while incorporating novel bio-based methodologies to improve the safety and decrease the cost of treating MFT. The engineering of endogenous tailings pond bacteria for enhanced flocculation and dewatering has the potential to lead to a self-sustaining, environmentally safe, *in situ* solution for MFT.

PROGRESS AND ACHIEVEMENTS

In year 1 of 4 good progress was made preparing the DNA which will direct the biopolymer production and cell surface localization. The anchor system for generating the biopolymers and transporting them to the cell surface of tailings-specific bacterial strains was defined. The DNA sequences for this anchor system and biopolymers to be tested were designed and synthesized. The biopolymer DNA sequences were concatemerized to create numerous highly repetitive sequences which were then inserted into the anchor/display sequences. DNA sequencing had confirmed the final biopolymer products were correct and ready for production.

Year 2 of 4 built upon the early progress of the project and the focus was able to shift from DNA sequence assembly to biopolymer production and preliminary flocculation testing. The biopolymer DNA sequences were used to transform *Escherichia coli (E. Coli)* bacteria to assess bacterial survival and biopolymer production. There was no toxicity associated with the introduction of any of the biopolymer DNA sequences to the bacteria. Furthermore, the production of the majority of the biopolymer constructs has been confirmed. The localization of the biopolymers to the bacterial surface is under study, with results indicating ~90% of the lowest molecular weight biopolymers can be properly translocated to the outer membrane. Additional experiments detailed how the temperature of the cultures affected the bacterial growth rate, biopolymer production levels, and localization, with 8°C found to be the best conditions for biopolymer production and localization.

Training and protocol development for 5% MFT flocculation with engineered bacteria has been completed. Flocculation control studies have been carried out on 5% MFT with either no additives, FLOPAM A3338 polymer or engineered bacteria without any biopolymer. The effects of bacteria displaying the lowest molecular weight biopolymer on their surface have also been tested and show accelerated flocculation, with the initial linear settling beginning as quickly as 4 minutes after mixing and finishing as quickly as 50 minutes after mixing, significantly faster than the untreated MFT (>180-1440 minutes) as well as the control bacteria lacking the biopolymer (>20-90 minutes). The 24-hour settling heights of the biopolymer-containing samples were also found to be statistically significantly lower than samples containing bacteria without biopolymer.

Year 3 of 4 saw the completion of the biopolymer production studies in *E. coli*, with the results indicating that as individual biopolymer protein molecular weights increase, the total number of these proteins decreases. The largest constructs, with individual protein molecular weights ≥100 kDa, were not produced in detectable quantities using Western blotting. Only one of the medium sized sequences, with a molecular weight of ~64 kDa was produced in high enough quantities to be detectable. Both of the smallest constructs, at ~47 kDa, were produced in sufficient quantity. It should be noted that the molecular weights of the individual biopolymer chains are not as important a parameter with the bacterial surface display approach as it is with conventional organic polymers. Multiple copies of each biopolymer are attached to the surface of a bacteria, essentially creating a star polymer-type configuration with a radius of hydration ≥ 2μm, an order of magnitude larger than the radius of a conventional ~14 MDa polymer. As such, increasing the number of biopolymer chains, rather than the individual chain molecular weights, might result in improved performance, suggesting studies into lower molecular weight biopolymer chains are warranted. The growth rates of engineered *E. coli* were measured and were not found to have decreased fitness or reproduction times, compared to unmodified strains. This shows the engineered biopolymers and additional metabolic burden associated with their production, does not hamper the survival and growth of the *E. coli*. This information can be used to generate some estimates regarding the costs associated with bacterial production for MFT treatment.

Flocculation testing of 5% MFT continued with longer timescales, up to one week after mixing with engineered bacteria. These results demonstrated that settling of the MFT materials continued, though at a reduced rate, until after 7 days the mudlines reached ~16-22% of their initial mudline height. All treatments resulted in a statistically significantly lower mudline after 7 days when compared to the untreated control ($p<0.05$). Capillary suction time testing training was undertaken and appropriate protocols for both slurry and cake testing were completed. Initial testing indicated that the highest dosage of bacteria (10 g/L) yielded the greatest improvement in CST performance, though no maximum effective dosage has yet been determined. Incubations periods of 1-24 hours for slurry CST and 1-7 days for cake CST were examined. The results showed that for all incubation periods and both sampling methods, the addition of engineered bacteria decreased the CST times by up to 56% relative to untreated samples of the same % solids content. Protocol development for pressure filtration studies was initiated, with experiments starting in January 2022.

Of the objectives listed in the project summary, DNA sequence generation was completed in Year 1. Year 2 progress has allowed for at least partial completion of the creation of all necessary control constructs, confirmation of the production and localization of biopolymers and preliminary settling tests using diluted MFTs. Year 3 allowed for the completion of construct creation in *E. coli*, the determination of the engineered bacterial growth rates, completion of long-term flocculation studies, capillary suction time measurements and preliminary development of pressure filtration protocols.

LESSONS LEARNED

Broadly speaking, these results demonstrate the validity of biopolymeric treatment of MFT, and their potential as environmentally safe, scalable, self-replicating alternatives to conventional synthetic organic polymers. Design principles discovered using conventional organic polymers can, in some instances, be translated into biopolymer sequences and maintain similar functionality. Highly repetitive DNA sequences coding for the biopolymers can be created and used to successfully engineer bacteria to synthesize and display these biopolymers on their surfaces. Furthermore, these engineered bacteria have been shown to accelerate the flocculation of 5% MFT and yield a more compact floc, while also significantly decreasing the capillary suction times, without any purification of the biopolymer.

PRESENTATIONS AND PUBLICATIONS

Journal Publications

Bahniuk, M. S., Alidina, F., Tan, X., Unsworth, L. D., (2022). Bioflocculation of Kaolin: The Last 20 Years. *CLEAN*, submitted.

Conference Presentations/Posters

Presentation at the 2020 COSIA/IOSI Tailings Project Knowledge Dissemination Workshop (unpublished)

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigators: Larry D. Unsworth

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Larry D. Unsworth	University of Alberta	Primary Investigator		
Markian Bahniuk	University of Alberta	Post-Doctoral Fellow		
Xiaoli Tan	University of Alberta	Research Associate, Adjunct Professor		
Fawad Alidina	University of Alberta	Undergraduate Student Researcher		
Simon Yuan	Syncrude	Senior Associate – Chemical		
Michelle A. Young	Imperial	Research Advisor – Environmental		
Tyler Colberg	Imperial	Research Advisor – Environmental		
Jia Ke	University of Alberta	Undergraduate Student Researcher		
Madeleine Barton-Keener	University of Alberta	Undergraduate Student Researcher		

Research Collaborators:

Institute for Oilsands Innovation (University of Alberta)

Combining Worms and Vegetation to Enhance Tailings Dewatering - Building with Nature on Successfully Tested Methods

COSIA Project Number: TE0067 (IOSI2018-4)

Research Provider: Northern Alberta Institute of Technology (NAIT)

Industry Champion: Imperial

Status: Year 2 of 2 (Project complete)

PROJECT SUMMARY

Accelerating the dewatering and consolidation process of Fluid Fine Tailings (FFT) is a major challenge to the oil sands industry in Canada. Significant technology development efforts have focused on engineered solutions, with less attention paid to biological options. Plants are well-suited to removing water from clay-rich substrates, and some species native to Alberta have been demonstrated to thrive in FFT. The present study combines and builds upon previous NAIT research into wetland plants and Deltares' research into aquatic and terrestrial worms, which have been independently shown to facilitate the densification of oil sand tailings. The project hypothesized that a combination of plants and worms could create a synergistic biological system capable of providing a pathway to holistic tailings dewatering. The project work was divided into three phases:

1. A pilot study of the interactions between *Lumbriculus variegatus* and *Lumbricus terrestris* worms, and *Carex aquatilis* (sedge) and *Salix interior* (willow) plants;

2. A screening assessment of worm survival when combined with straw, alfalfa, and hydrochar; and

3. A larger-scale study combining plants and worms in columns (8 L) and barrels (100 L) with centrifuged oil sand tailings for an extended growth period of six months.

The intent of the initial two phases was to determine a set of conditions most conducive to worm and plant cohabitation, while the purpose of the third phase examined the ability for plants and worms to provide shear strength gain to tailings over a six-month, indoor growth phase. Over the course of the third phase, greenhouse gas measurements were regularly taken in the tailings barrels to determine the carbon sequestration potential of the treatments. Results indicated that planted barrels sequestered carbon, and reduced CO_2 and CH_4 emissions.

Overall, plants, especially in combination with worms, were found to effectively dewater a centrifuged tailings product, and increased the solids content from 55 wt% to 75 wt% over the growing phase. During this time, the undrained shear strength of the centrifuged tailings increased from 0 kPa to over 60 kPa when treated with a combination of plants and *L. variegatus* worms. The results of this study are particularly relevant to the challenge of capping tailings, especially for centrifuge cake, which has low load bearing capabilities and cannot readily accept a sand cap. Plants are a promising avenue for increasing the strength of these deposits in preparation for a traditional sand cap while mitigating GHGs simultaneously.

PROGRESS AND ACHIEVEMENTS

The project began in September 2019 and was officially completed in August 2021. Key progress milestones over the project are as follows:

- The upland worm species *Enchytraeus albidus* was initially selected as the terrestrial worm species to be used in this study. However, *E. albidus* was determined to be a potentially invasive species following consultation with the Canadian Food Inspection Agency (CFIA) and therefore deemed inappropriate for further consideration as a tailing's treatment option. *E. albidus* was subsequently replaced in this study with an earthworm species native to the Peace River region in northern Alberta (*Lumbricus terrestris*).

- In phase 1, two species (willow and sedge) were co-planted in columns filled with thickened tailings, amended with alfalfa or straw, and incorporated with worms (*L. variegatus* and *L. terrestris*). Total plant aboveground biomass significantly increased with straw amendment, but not with worm incorporation. Similarly, amending planted columns with straw significantly increased solids content at the top (0-35 cm) and middle (35-65 cm) sampling points. In terms of undrained shear strength, amending planted columns with straw coupled with worm incorporation increased tailings shear strength compared to all treatments. High content of angular sand (sand-to-fines ratio, SFR = 3.13) in thickened tailings was concluded to be harmful for the smaller *L. variegatus* worms. When exposed to this tailings type, *L. variegatus* did not burrow into the substrate and subsequently died on the surface. Benchtop trial with centrifuge cake showed significant improvement in *L. variegatus* worm survival, hence thickened tailings was replaced with centrifuge cake of significantly lower SFR (SFR = 0.03) in subsequent trials.

- In the phase 2 benchtop screening assessment, *L. variegatus* worm survival was poor in centrifuge cake amended with alfalfa and hydrochar, and only slightly better in the straw-amended containers. Due to this observation, alfalfa and hydrochar amendments were not carried forward to the larger growth trial of phase 3. *L. terrestris* survival proved to be more robust, with over 60% survival of earthworms in 1 L of tailings over 21 days both with and without the straw treatment.

- Survival tests performed by Deltares revealed that terrestrial *E. albidus* worms die under prolonged saturated conditions. Conversely, the aquatic *L. variegatus* worm did not survive under unsaturated conditions. *L. variegatus* and other Oligochaetes are known for migrating downwards with the water table in partially unsaturated beds undergoing drying. In our tests, water was fully evaporated throughout the entire bed (0.5 L), resulting in the disappearance of *L. variegatus*. Finally, *L. variegatus* survived when tested in saturated tailings amended with straw as a food source, whereas terrestrial *E. albidus* worms survived under unsaturated conditions regardless of the presence of straw.

- In the 100 L barrel study, the mudline of treatments amended with straw was initially observed to increase for a period, likely due to gas generation associated with straw decomposition. Conditions which incorporated plants, including plants in conjunction with *L. variegatus* worms and *L. terrestris*, showed greater consolidation than unplanted tailings conditions.

- In the 8 L column study, under conditions which incorporated plants alone, and plants in conjunction with *L. variegatus* worms, were showing more rapid consolidation. However, plant health was observed to suffer in columns relative to barrels, likely due to the physical constraints on plant roots in the narrower columns.

- In the barrels, plants alone, plants with straw, and plants with *L. variegatus* worm conditions had the highest root mass overall. Leaf mass of *C. aquatillis* was highest when amended with *L. variegatus* worms. The overall plant mass for *S. interior* (accounting for leaf and shoot mass) was highest for plants alone, and a combination of *L. terrestris* and plants. This suggested that the presence of worms was able to encourage the growth of larger plants.

- Planted barrels provided significant carbon sequestering potential. Maximum carbon sequestration was achieved with the plants alone condition, with a carbon balance over -1000 g C / m^2. Treatments with straw were found to emit carbon in the form of CH_4 and CO_2. The straw alone treatment and straw with *L. terrestris* treatment emitted 300 g C/m^2.

- While the unplanted, unamended control barrels had an undrained shear strength of 0 kPa, planted barrels saw an increase in shear strength to 25 kPa. Maximum shear strength of over 60 kPa in the centrifuged tailings was achieved when treated with a combination of *L. variegatus* worms and plants.

- Similarly, the *L. variegatus* worm and plant treatment was able to increase solids content of the tailings to 75 wt%, compared to the unplanted, unamended control solids content of 55 wt%.

LESSONS LEARNED

1. High SFR thickened tailings was replaced with centrifuge cake of significantly lower sand content to promote *L. variegatus* survival. *L. variegatus* worm-based treatments are not expected to be successful in dewatering tailings with higher sand content.

2. Worm survival is difficult to assess at a larger scale, where individual counts are not feasible. Instead, success of worm-based tailings treatment may be gauged by shear strength gains in the deposit.

3. Straw was included in this study with the intent to provide worms with a source of food. However, no positive impact from straw was observed over the duration of the study. Straw decomposed and emitted greenhouse gases and may have produced an initial phyto-toxic interaction with the plants that led to smaller, weaker specimens that sequestered less carbon.

4. The *C. aquatilis* and *S. interior* plants studied in this project have been shown to thrive in oil sands tailings, especially in the larger barrels. This observation reinforces the hypothesis that plants are an environmentally friendly contributor to tailings remediation and warrants further research at a larger scale over longer growth cycles.

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PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Chigbo, C., Schoonmaker, A., Sun, Y. S., Collins, V., Kaminsky, H. W., Delucas Pardo, M., & Walton-Sather, K. (2021). *Case study assessment examining whollistic effects of deploying worms and plants into oil sands tailings* [Conference session]. Tailings and Mine Waste 2021, Banff, Canada.

Reports & Other Publications

Chigbo, C., Collins, V., Sun, Y. S., Xu, B., Schoonmaker, A., & Kaminsky, H. (2021). *Combining worms, amendments, and vegetation to enhance tailings dewatering*. IOSI project final technical report.

RESEARCH TEAM AND COLLABORATORS

Institution: Northern Alberta Institute of Technology (NAIT)

Principal Investigators: Dr. Heather Kaminsky & Dr. Amanda Schoonmaker

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Dr. Heather Kaminsky	NAIT	Research Chair, Principal Investigator		
Dr. Amanda Schoonmaker	NAIT	Research Chair, Principal Investigator		
Simon Sun	NAIT	Research Associate		
Dr. Chibuike Chigbo	NAIT	Research Associate		
Dr. Victoria Collins	NAIT	Research Associate		
Kaela Walton-Sather	NAIT	Research Technician		
Dr. Miguel de Lucas Pardo	Deltares	Senior Researcher		
Floris van Rees	Deltares	Researcher		
Joel Tacas	NAIT	Chemical Engineering Technology Diploma	Sept 2018	April 2022
Ruth Delgado Garcia	NAIT	Chemical Technology Diploma	Sept 2018	April 2021

Katelyn Grado	NAIT	Biological Sciences Diploma	Sept 2018	April 2021
Emma Miller	NAIT	Forest Technology Diploma	Sept 2019	April 2021
Mallory Suvanto	NAIT	Forest Technology Diploma; Biological Sciences Diploma	Sept 2018	April 2022

Research Collaborators: Deltares

NAIT Industrial Research Chair for Colleges in Oil Sands Tailings Management

COSIA Project Number: TE0075

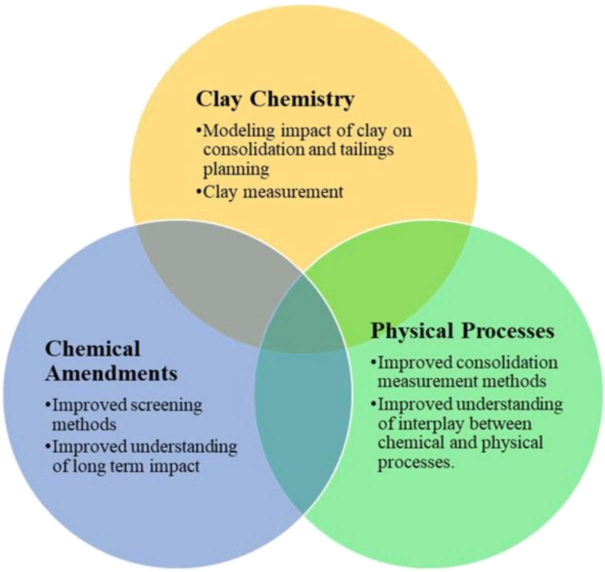
Research Provider: NAIT – Heather Kaminsky

Industry Champion: Imperial

Status: Year 2.5 of 5

PROJECT SUMMARY

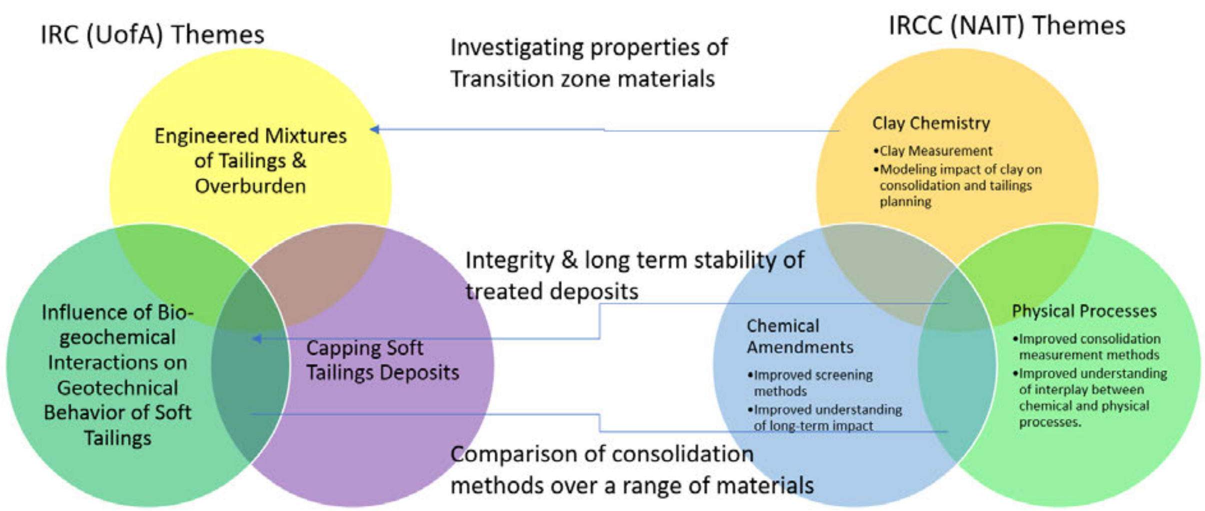
The goal of the Natural Sciences and Engineering Research Council of Canada Industrial Research Chairs for Colleges (NSERC IRCC) oil sands tailings program is to help accelerate industry's efforts in developing and validating treatment methods that are economically and environmentally sustainable so that, by 2030, comprehensive solutions to the challenges associated with treating fluid fine tailings (FFT) have been commercially implemented. Clays are the single biggest contributor to FFT accumulation (Yong & Sethi, 1978), due to their capacity to hold water. Hence, Dr. Kaminsky's research program will explore the importance of three key themes in tailings management each providing greater insights into clays. These are: Clay Chemistry, Chemical Amendments, and Physical Processes.



The theme of clay chemistry will focus on developing improved methods for measuring clays and methods for accounting for their influence in long range tailings planning models. The theme of chemical amendments will focus on developing improved screening methods to select appropriate chemical additives to reduce FFT accumulation. In addition, work will be done to develop a better long-term understanding of the influence of chemical amendments on the geochemical and geotechnical stability of FFT. Finally, the last theme will target improving the understanding of the physical processes that are used to dewater tailings and the interplay between chemical and physical processes.

A large portion of the IRCC project is supporting the IRC in Tailings Geotechnique at the University of Alberta. This collaboration allows college students to expand the experiments led by three PhD students at the University by conducting the characterization of their samples, preparing flocculated materials for the students, and conducting routine test work on hundreds of samples allowing the PhD students to concentrate on the data analysis and project management skills.

The projects are connected as illustrated:



PROGRESS AND ACHIEVEMENTS

Clay Chemistry – Modeling Impact of Clay

Simple stochastic modeling was performed to assess the impact of variability on performance outcomes with different FFT dosing strategies. In the study "What Impacts High Density Flocculation" (Li et al, 2021a)" it was demonstrated that the amount of polymer that needs to be added to achieve optimal performance was proportional to the amount of clay in the tailings rather than the amount of solids in the tailings. The required polymer dosage can then be calculated as a clay-based dosage by dividing a solids-based dosage by the clay content calculated from the methylene blue index. The polymer performance data from that paper was fitted with a 2nd order polynomial over the range of dosages tested with linear relationships assumed for dosages above and below the dosage curve. The model then used the data set from the paper "Variability of fluid fine tailings" (Kaminsky & Omotoso, 2016) to collect a set of 1095 FFT samples which were then used to calculate the expected performance based on different dosing scenarios.

Two scenarios were considered to determine the ratio of polymer added to a given volume of FFT:

1. Fixed ratio of polymer volume to FFT volume (i.e., a “set and forget” strategy). In this case the applied polymer volume would correspond to the optimal clay-based dosage for the average clay and solids content of the data set (62% clay, 33% solids).

2. The ratio of polymer volume to FFT volume varies as a function of solids content with no consideration to clay content (i.e., a solids-based dosing strategy).

The dosing strategy was then applied to the data set of 1095 FFT points and a clay-based dose was calculated. The data set was then used to determine the percentage of time that the dosage would be considered very underdosed, underdosed, optimally dosed, overdosed or very overdosed (Figure 1).

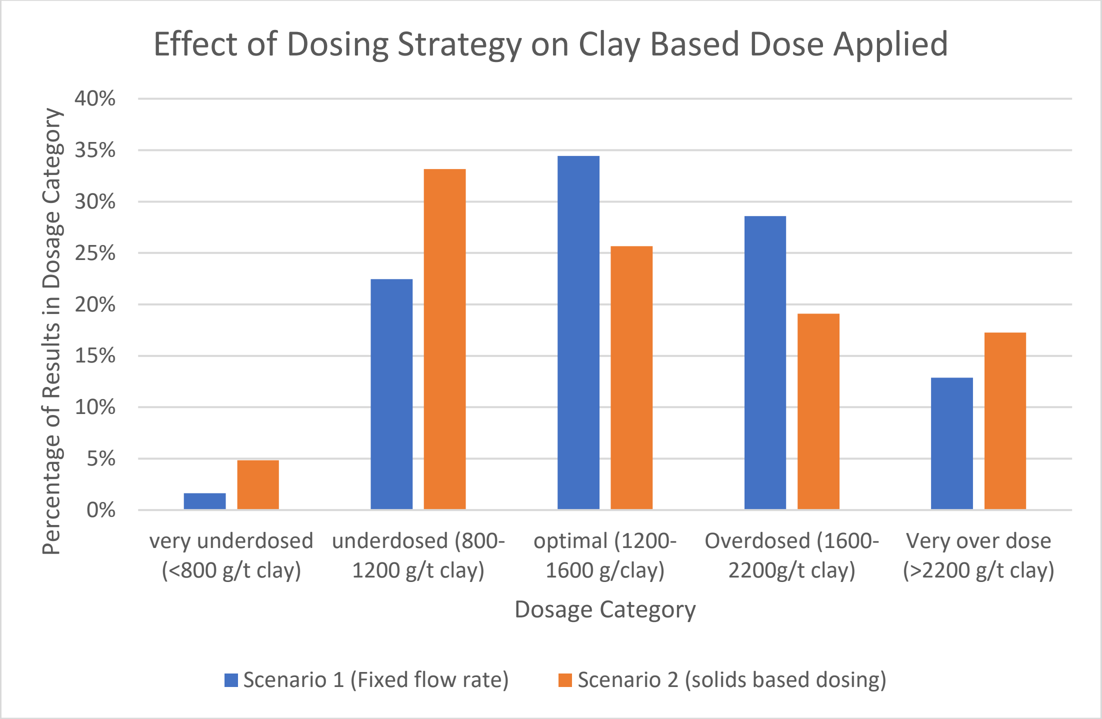


Figure 1 Monte carlo simulation results showing the percentage of time an FFT ended up underdosed, optimally dosed or overdosed on a clay basis for 1095 different FFTs using two different dosing strategies.

The simulation revealed that a “set and forget” strategy predicted better overall performance than a solids-based dosing strategy, with the optimal dose (as determined by calculated clay-based dosage) being applied 34% of the time vs 25% of the time when the dosage applied varied with solids content. This was because for most ponds there is an inverse correlation between solids content and clay content (lower solids FFT usually come from the top of the pond where the more active clays are concentrated). The model further revealed that both strategies tended to overdose on a clay basis with an average of 1619 g/t clay being applied in the set & forget strategy and 1601 g/t clay being applied in the solids-based dosing strategy. This suggests that overall performance could be improved by using a set & forget strategy with intentional underdosing.

The modeling also looked at how different polymers would behave in a solids-based dosing strategy, if lab results indicated that their performance was clay-based. Three simulated polymer curves were created using a 2nd order polynomial to fit the performance within a given dosage window and linear functions above and below a typical range of doses. The three simulated polymers all had similar performance but with slight differences in the same of the curves. Two of the curves showed the typical parabolic dosage curve common for flocculants, whereas the third polymer showed a sharper delineation between underdose and optimal dose but an overall flatter curve (Figure 2).

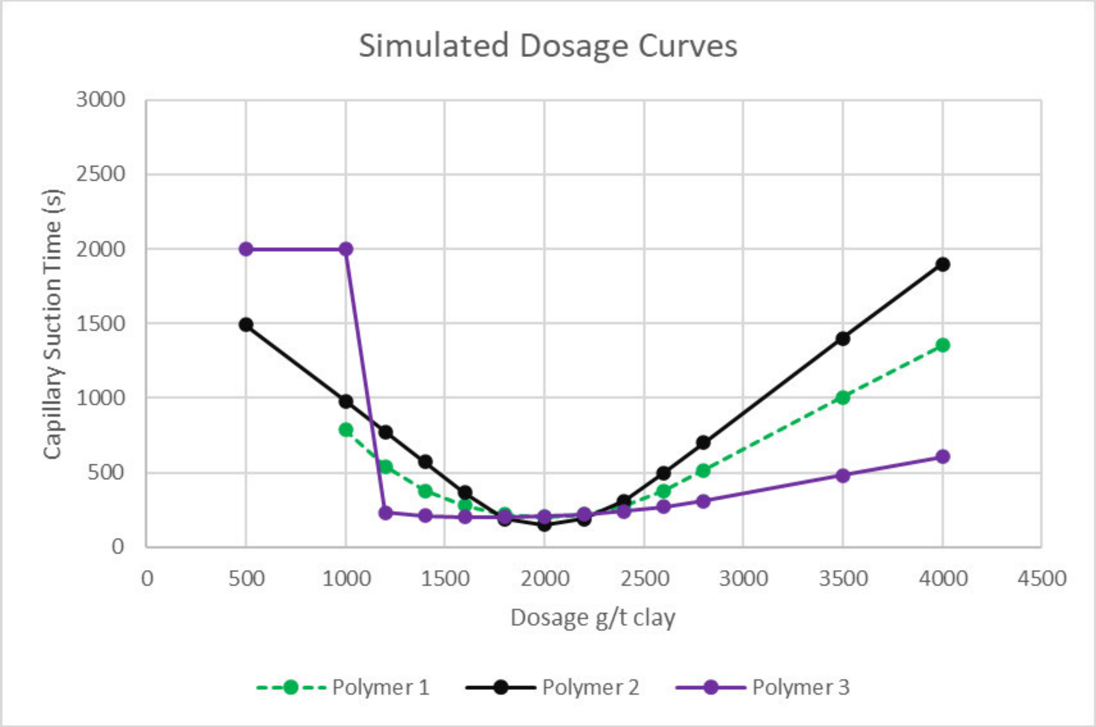


Figure 2: Dosage curves for 3 simulated polymers representative of typical polymer dosage curves.

The results show that while polymer 2 would be predicted to have the best overall performance if only optimal dosing was considered, Polymer 3 is significantly better in the current scenario of performance being controlled by clay-based dosing, but field applied dosing based on solids content or by fix & forget dosing strategy (Figure 3).

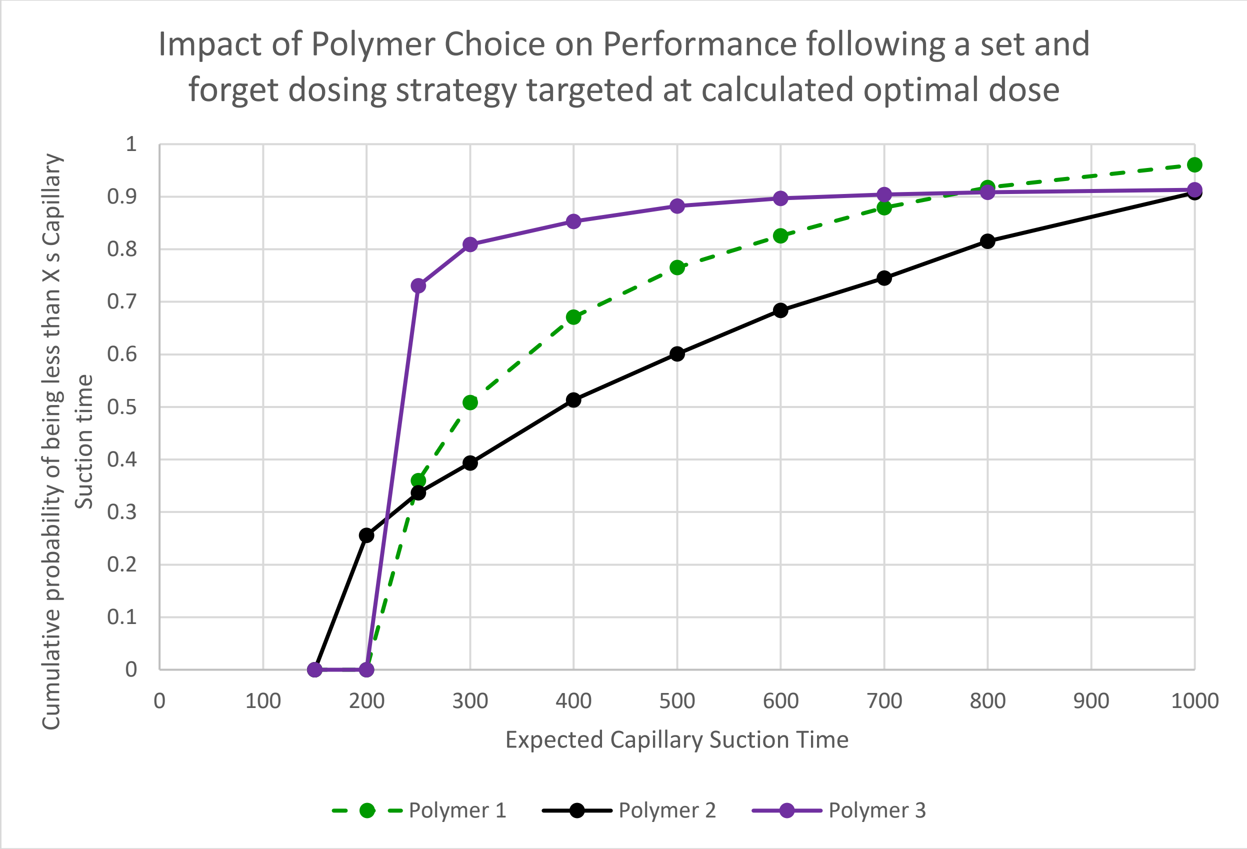


Figure 3: Probability of achieving a given capillary suction time for fixed rate polymer dosing with each of the three simulated polymers.

These results demonstrate the importance of testing new chemistries on a range of FFT to determine what factors truly control performance. The results also highlight, flocculants with a high degree of robustness to feed changes are likely to be more successful in field applications than flocculants with narrow performance windows, at least until better process control strategies can be implemented.

Clay Chemistry – Better measurements

In the theme of better measurements, the Chair contributed to the technical review of the NRCan Clean growth project on developing an automated MBI test. This project was funded by Suncor & NRCAN and executed by NAIT and SRC. This project was successful in creating two prototype methods to measure MBI at line and reduce the potential for operator bias in the results. For details please see Ng et al (2021).

Chemical Amendments- New Screening methods

Several novel chemical amendments were evaluated. The largest study was the evaluation of the "High Fines Sand Tailings" technology from BASF. This study was funded by BASF with input and participation from COSIA via the Chair program. One of the key techniques used in screening the different chemical treatments was the modified specific resistance to filtration test (Li et al., 2021b).

Chemical Amendments- Improved understanding of long-term impact

A literature review paper on the geochemical stability of oil sands tailings in mine closure landforms was written by Heidi Cossey & Anya Batacky, with input from Heather Kaminsky and Ania Ulrich (Cossey et al., 2021). The review highlighted the interaction between consolidation and chemical loading in different scenarios. One can reasonably infer that reducing the amount of consolidation expected post deposition reduces not only the geotechnical risks of the deposit, but also the geochemical risks to the deposit. This in turn, highlights the benefits of treatment technologies that can rapidly dewater the tailings without adding any additional chemicals of concern.

LESSONS LEARNED

1. For polymers whose performance is a function of clay content vs solids content only, a set and forget strategy appears to work better than a solids-based dosing strategy for FFT.
2. Polymers with wide dosage windows are more likely to give good performance in the field than polymers with a narrow dosage window but better optimal performance.
3. It is critical to assess chemical amendments over a range of feeds that will be expected in the field and really understand what operational factors most influence performance.
4. Increasing degree of dewatering (i.e., getting to 85% solids vs 50% solids) is expected to reduce both geotechnical and geochemical risks in oil sands tailings impoundments.

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Li, Y., Kaminsky, H., Romero Calducho, C., Gong, XY, Ghuzi, M., and Tacas, J. (2021b, November 6-10). *Assessing dewatering performance of treated fluid fine tailings with a* *modified bench-scale filter press* [Conference presentation]. Tailings and Mine Waste 2021, Banff, AB, Canada.

Ng,J., Sun,R., Rizvi,S., Sedgwick,A., McGlip, L., Kaminsky, H., Qureshi, T, Gapasin, J, Ortiz, L., and Battle, B. (2021, November 6-10). *Automated clay analyzers to rapidly measure methylene blue index for oil sands and mining slurries* [Conference presentation]. Tailings & Mine Waste 2021, Banff, AB, Canada.

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PRESENTATIONS AND PUBLICATIONS

The tailings book club occurs monthly via Webex to review the reports on tailings submitted by the operators to the Alberta Energy Regulator in compliance with Directive 085. This evolved from the earlier book club meetings held in 2020 to foster networking during the pandemic. This book club is free to attend and is focused on a technical audience to help those interested to understand what data is contained in the regulatory filings. It is particularly useful for professionals working in this area who want to keep up to date with the publicly available data from the operators.

Short Courses

Two short courses have been developed to help mobilize knowledge on oil sands tailings management especially as it applies to the process.

- **Oil Sands Tailings 101** – This 2-day short course will be held annually in Q1. The topics covered include: current state of oil sands tailings management, understanding tailings characterization data, an overview of the first principles behind the tailings treatment technologies applied in oil sands and the methods used to evaluate new technologies.

- **Flocculation & Thickening –** This 2-day short course is offered in collaboration with CSIRO with a focus on thickener operation and flocculation.

- A third, 1-day short course **From Geology to Closure How Clays Influence Mining** is in development and will be offered in September 2022.

Journal Publications

Cossey, H.L., Batycky, A.E., Kaminsky, H., and Ulrich, A.C. (2021) Geochemical Stability of Oil Sands Tailings in Mine Closure Landforms. *Minerals*, *11*(8),830. https://doi.org/10.3390/min11080830

Li, Y., Kaminsky, H., Gong, X.Y., Sun, Y.S., Ghuzi, M., and Sadighian, A. (2021) What Affects Dewatering Performance of High-Density Slurry? *Minerals*, *11*(7),761. https://doi.org/10.3390/min11070761

Li, Y., Kaminsky, H., Sadighian, A., Sun, Y.S., Murphy, F., Gong, Y., Ghuzi, M., and Rima, U. (2022). Impact of Chemical and Physical Treatments on Freeze-Thaw Dewatering of Fluid Fine Tailings. *Journal of Cold Regions Science & Technology*, *193*, 103385. https://doi.org/10.1016/j.coldregions.2021.103385

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Zhu, Y., Gong, Y., Kaminsky, H. Chae, M., Mussone, P., & Bressler, D. C. (2021). Using Specified Risk Materials-Based Peptides for Oil Sands Fluid Fine Tailings Management. *Materials, 14*(7), 1582. https://doi.org/10.3390/ma14071582

Conference Presentations/Posters

Chigbo, C., Schoonmaker, A., Sun, S., Collins, V., Kaminsky, H, Walton- Sather, K., de Lucas Pardo, M., and van Rees, F. (2021, November 6-10) *Case study assessment examining wholistic effects of deploying worms and plants into oil sands tailings* [Conference presentation]. Tailings and Mine Waste 2021, Banff, AB, Canada.

Li, Y., Kaminsky, H., Romero Calducho, C., Gong, XY, Ghuzi, M., and Tacas, J. (2021, November 6-10). *Assessing dewatering performance of treated fluid fine tailings with a modified bench-scale filter press* [Conference presentation]. Tailings and Mine Waste 2021, Banff, AB, Canada.

Li, Y., Kaminsky, H., Romero Calducho, C., Romaniuk, N., Hariharan, N. and Tate, M. (2021, November 6-10). *Stabilization of flocculated fluid fine tailings by lime treatment* [Conference presentation]. Tailings and Mine Waste 2021, Banff, AB, Canada.

Ng,J., Sun,R., Rizvi,S., Sedgwick,A., McGlip, L., Kaminsky, H., Qureshi, T, Gapasin, J, Ortiz, L., and Battle, B. (2021, November 6-10). *Automated clay analyzers to rapidly measure methylene blue index for oil sands and mining slurries* [Conference presentation]. Tailings & Mine Waste 2021, Banff, AB, Canada.

Qureshi, T.H., Li, Y., Sedgwick, A., Kaminsky, H., and Ng, J. (2021). Assessing Oil Sands Tailings Consolidation Using a Modified Benchtop Filter Press, in AB Fourie and D Reid (eds). *Paste 2021: 24th International Conference on Paste, Thickened and Filtered Tailings*, *Australian Centre for Geomechanics*, *Perth,* pp. 43-58. https://doi.org/10.36487/ACG_repo/2115_05.

Reports & Other Publications

Sun, S., Devereux, E., and Kaminsky, H. (2021). *High Fines Sand Tailings: Operability Study Report.* BASF, Canada.

RESEARCH TEAM AND COLLABORATORS

Institution: NAIT

Principal Investigators: Heather Kaminsky, PhD, P.Eng.

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Yunhui Li	NAIT	Research Associate		
Yuki Gong	NAIT	Research Assistant		
Mohammed Ghuzi	NAIT	Research Assistant		
Catalina Romero Calducho	NAIT	Research Assistant		
Kaela Walton-Sather	NAIT	Research Assistant		
Joel Tacas	NAIT	Student Research Assistant/Diploma in Chemical Engineering Technology	September 2018	May 2022
Ruth Delgado-Garcia	NAIT	Student Research Assistant/Diploma in Chemical Technology	September 2018	May 2021
Emily Devereux	NAIT	Student Research Assistant/Diploma in Chemical Technology	September 2019	May 2022

Research Collaborators:

NAIT: Amanda Schoonmaker, Chibuike Chigbo, Victoria Collins, Andrea Sedgwick, Paolo Mussone, Bin Xu, Jason Ng, Taimur Qureshi, Bob Battle, Laura Ortiz,

University of Alberta: Dr. Ward Wilson, Dr. Nicholas Beier, Dr. Ania Ulrich

Purdue University: Dr. Cliff Johnston, Dr. Marika Santagata

Engineered Tailings Research

COSIA Project Number: TJ0033

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Year 6 of 8

PROJECT SUMMARY

Engineered Tailings Research is seeking new technology options for tailings treatment aimed at reducing capital and operating costs and speeding up deposit consolidation and reclamation. Beyond the existing tailings treatment technologies such as composite tailings (CT), paste and thickened tailings (P&TT), centrifugation of fluid fine tailings (FFT), and water capping, etc., the scope of Engineered Tailings Research is to explore other new concepts and leading-edge technologies for tailings treatment. The scope of Engineered Tailings Research varies from year to year based on the priority of research activities. In 2021, the following activity was the scope of Engineered Tailings Research:

- Characterization of high chloride tailings;
- Sampling of tailings from the EXP 4000 pilot tests in collaboration with Bitumen Production Research team-pilot plant operation;
- Baseline settling tests of the samples started in 2021 and continue to monitor in 2022;
- Lab test plans were formulated in 2021; and
- Lab flocculation tests to be performed to study the characteristics of high chloride tailings settling under various conditions in 2022.

PROGRESS AND ACHIEVEMENTS

Here are the main technological advancements achieved in 2021:

- Characterization of high chloride tailings;
- 23 Samples of coarse and flotation tailings from the EXP 4000 pilot tests were collected for subsequent characterization tests;

- Baseline settling tests of the samples started in 2021 and continue to monitor them in 2022;
- Lab test plans were formulated in 2021;
- Lab flocculation tests to be performed to study the characteristics of settling under various conditions in 2022; and
- There is no data to report for 2021. A research progress report will be prepared after completing the lab flocculation and characterization tests.

LESSONS LEARNED

As the characterization of high chloride tailings will be conducted in 2022, there is no data to report in the 2021 report.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigators: Simon Yuan

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Simon Yuan	Syncrude	Senior Associate – Chemical		
Meghan Curran	Syncrude	Chemical Engineer		
Jasmyn Sharp	Syncrude	Technologist		
Kathryn Fraser	Syncrude	Technologist		
Christian Schroeter	Syncrude	Senior Technologist		

Fluid Tailings Inline Flocculation and Co-Deposition

COSIA Project Number: TJ0108

Research Provider: Imperial

Industry Champion: Imperial

Status: Completed

PROJECT SUMMARY

Imperial piloted an advanced fluid tailings (FT) treatment technology using an enhanced chemistry regime to supplement the primary thickening treatment at the Kearl mine. Phase 2 of the pilot focused on learning about co-depositing treated FT with coarse sand tailings (CST) to generate a deposit with a sand-to-fines ratio (SFR) of 3 to 5. The target SFR of 3 to 5 will maximize fines capture and eliminate deposit re-handling. It is anticipated that co-deposition of treated FT using enhanced chemistry with another tailings stream to generate a deposit with higher SFR will reduce freshwater import, accelerate tailings reclamation, and achieve reclamation and closure objectives.

The main objective of the fluid tailings in-line flocculation and co-deposition (phase 2) pilot was to evaluate the maximum fines capture using two different discharge methods: spigot and single pipe discharge, and to understand the operational challenges associated with each scenario.

This pilot and the site investigation from the two deposits were completed in the fall of 2020. The analysis of the test result on samples collected from the deposit was completed in Q2 2021.

During the proof-of-concept lab scale study, different chemical additives were evaluated and optimized (i.e., the enhanced chemistry treatment) for the different types of FT feeds for the field scale (phase 2) pilot. Shearing of the flocs was also studied at a small scale to benchmark against the range of pipeline shearing that would be observed in the field. The main key performance indicators (KPIs) for the process were the dewatering rate and Capillary Suction Time (CST) of the treated FT collected from the sampling point on the pipeline. The KPIs for the deposit were in-situ strength of the co-deposited material and fines capture (i.e., ratio of the fines entrapped within the resultant deposit versus the fines introduced into it).

In the phase 2 pilot, FT was extracted from the tailings pond using the FT barge that typically feeds the thickeners. The FT was treated with a polymer using the existing polymer injection facility for thickeners prior to the enhanced chemistry treatment. Two venturi mixers were installed in the tailings line to optimize mixing and in-line chemical reactions. The treated FT was deposited into two constructed cells that were designed for this trial using two discharge methods: spigots and single discharge pipe. The same discharge method was used for CST deposition in each cell, i.e., spigots and single discharge pipe method.

PROGRESS AND ACHIEVEMENTS

One of the challenges during the pilot commissioning was the lower solids content of the feed and shearing of the flocs after the treatment chemicals were injected in the tailings line. Therefore, during the commissioning period, the chemical dosages had to be optimized based on the real pilot input, i.e., available mixing and feed solids content to get a robust flocculated product. Imperial's research lab evaluated different combinations of chemical dosages based on the solids content of the feed and pipeline shearing to achieve the optimal product. Then the adjusted dosages were applied in the field and after confirmation of flocculated product (from sampling points), the treated FT was diverted to the cell.

The approximate thickness of the deposit was evaluated by comparing the two surveyed surfaces (prior to and after the pour).

A geotechnical site investigation program was conducted at the pilot test cells approximately 2 weeks after the completion of the pour and was concluded in about 11 days. A remote-controlled amphibious rover was also evaluated for geotechnical investigation of soft tailings deposits. The objectives were to:

- Collect representative samples across the tailings deposits to characterize them for solids, water, and fines content;
- Run in-situ tests (Cone Penetration and Vane Shear) to assess the variations of strength across the deposit; and
- The remote-controlled amphibious rover was evaluated for conducting piston sampling, vane shear testing (VST) and ball/cone penetrometer testing (BPT/CPT).

The following characterization tests were conducted on the samples:

- Water and solids content;
- Dean-Stark (bitumen, water, minerals content);
- Laser particle size distribution (PSD);
- MBI (Methylene Blue Index) on selected samples;
- Atterberg Limits on selected samples; and

- Specific gravity on selected samples.

The lab test results and in-situ strength measurement data were analyzed to determine fines capture and deposit characteristics (including distribution of solids content, fines and clay content, SFR and strength).

LESSONS LEARNED

The results showed that using spigots for co-deposition of enhanced in-line flocculated (eILF) FT and CST produced better distribution of fines across the deposit (i.e., more uniform SFR across a larger area of the deposit). Use of two single pipes rather than spigots generated a fines dominated zone close to the treated FFT discharge area. This suggests that on an operational scale, interchanging CST and treated FFT pour locations might provide better co-deposition. The average SFR and strength of resultant deposits is comparable to other composite deposits in the industry (CT, NST) without all the pots and pans required on the process side (Cyclones, Mix Tanks etc.). Entrapment of fines (either as fine layers within coarser tailings layers, or as fine particles/agglomerates within the void space of coarse tailings) reduces the volume of fines dominated zones and accelerates closure. In this specific trial, co-deposition of eILF FT and CST resulted in a deposit with an average fines content of ~17%, which is significantly higher than the fines content of regular CST beaches. The results of the investigation will be used for scale up purposes including lay out of discharge locations for co-deposition of treated FT with other tailings streams.

While the remote-controlled amphibious rover enabled sampling and in-situ testing of soft zones of the deposits, there were challenges collecting samples and running in-situ strength measurements, in sandier/stronger zones of the deposits.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Sakuhuni, G., Moussavi Nik, R. (2022, March 29). *Enhanced in-line flocculation (eILF) for FFT Treatment*. Fundamentals of Oil Sands Extraction Seminar, University of Alberta. Edmonton, Canada.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigators: Atoosa Zahabi

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Flocculated Tailings and Deposit Monitoring

COSIA Project Number: TJ0109

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Ongoing

PROJECT SUMMARY

Flocculated tailings (also known as Accelerated dewatering- ADW or rim ditching) is a tailings treatment process that involves the in-line mixing of a chemical amendment with fluid fine tailings (FFT) and deposition into a containment structure. This is followed by prompt removal of the initial water release, and subsequently, careful control of the deposit surface water in order to promote atmospheric drying and self-weight consolidation. The surface water is controlled by creating perimeter and lateral ditches around the edges, and on the surface of the deposit, respectively. The lateral ditches direct surface water towards a decant structure where the water is removed. The perimeter ditches promote the lowering of the phreatic surface, promoting atmospheric drying and desiccation. Dewatering and densification of the treated FFT is accomplished through a combination of self-weight consolidation, atmospheric drying and under-drainage. To date, three sets of pilot deposits have been created at the Syncrude Mildred Lake site, each involving the use of different chemical amendments. Details regarding the historical development and the latest improvements to the flocculated tailings technology at Syncrude have been previously published (COSIA 2020).

The geotechnical performance of the latest flocculated tailings pilot deposits created in 2017 and 2018 at Syncrude's Mildred Lake site is being monitored through in-situ monitoring, testing and sampling. The geotechnical performance of the latest flocculated deposits was superior compared to the earlier (2009) flocculated tailings deposit. In addition, large-strain consolidation material properties determined for the latest flocculated tailings deposits showed superior mechanical and hydraulic properties compared to the 2009 flocculated tailings deposit. This observation confirms the preliminary findings previously reported (COSIA 2020) that the chemical amendment and mixing improvements implemented for the latest flocculated tailings deposits are effective in improving the geotechnical performance of the resulting deposits. All the pilot flocculated tailings deposits are being continuously monitored in order to assess their long-term geotechnical performance. Learnings from monitoring these deposits will help inform the design, operation and closure of deep cohesive deposits. Also, the performance data collected is important for calibrating numerical models for predicting the long-term performance trajectories of deep cohesive deposits. A commercial-scale demonstration of the flocculated tailings technology will be started at the Syncrude Mildred Lake site in the summer of 2022.

PROGRESS AND ACHIEVEMENTS

The improvements in the geotechnical performance observed for the latest flocculated tailings deposits (2017 and 2018) over the 2009 flocculated tailings (as previously reported in COSIA 2020) continue. Two of the newer deposits (Cells 1 and 3) had a coagulant plus polymer as the chemical amendments. The coagulant for Cell 1 was gypsum, while that for Cell 3 is Syncrude's Flue Gas Desulphurization Solids (FGDS). The initial dewatering, settlement, profile solids content and fines-over-fines-plus-water (FOFW) for Cell 3 deposit were slightly higher compared to Cell 1. However, the initial profile undrained shear strength for both deposits are similar. The solids content, FOFW and undrained shear strength profiles continue to increase year over year, for the entire depth of the deposits. For both deposits, the solids content, FOFW and shear strength increase with depth, signifying that large strain consolidation is the main dewatering mechanism. Also, the density-shear strength relationship for both deposits is similar, with comparatively higher shear strength at the same density when compared to other chemically-amended FFT deposits. The performance trends are consistent with the compressibility and hydraulic conductivity functions for both deposits being respectively lower and higher compared to the 2009 flocculated tailings deposit. These observations confirm that the improved flocculated tailings process was successful in creating tailings deposits with superior geotechnical properties and performance trajectory compared to the 2009 flocculated tailings deposit. This demonstrates the geotechnical competence of flocculated tailings and its suitability for incorporation into the final closure landscape. A commercial-scale demonstration of the technology is scheduled to commence in the summer of 2022 at the Syncrude Mildred Lake site.

LESSONS LEARNED

The process improvements implemented for the flocculated tailings technology in 2017 and 2018 were effective in terms of both the initial dewatering and on-going geotechnical performance of the resulting deposits. Efficient in-line mixing and pre-conditioning of the FFT using either gypsum or FGDS prior to flocculation, produced treated FFT deposits with improved dewatering and consolidation performance. FGDS was as effective as gypsum, with both resulting in improvement in the compressibility and hydraulic conductivity of the treated FFT deposit, compared to FFT flocculation alone. This improvement in the consolidation material properties confirmed that the improved flocculated tailings process is capable of producing geotechnically-competent reclamation substrate that is on a trajectory to becoming ready for integration into the final closure landscape.

REFERENCES

COSIA, (2020). 2019 Tailings Research Report. Report available and downloadable at https://cosia.ca/sites/default/files/attachments/2019%20Tailings%20Research%20Report_FINAL.pdf

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

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Geobags Pilot Study

COSIA Project Number: TJ0112

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Pilot Completed, Deposit Monitoring Completed

PROJECT SUMMARY

In the oil sands industry, there are opportunities which require incorporation of fluid fine tailings (FFT) into a dry, terrestrial landform. To accomplish this, rapid dewatering and consolidation of the high fines material is required. Geobags are a technology for treating FFT where a terrestrial (or uplands) landscape is required. Geobags are simply large bags (upwards of 100 m long and 40 m circumference) made of a permeable geotextile. FFT is treated with a chemical amendment such as a polymer or alum, and then pumped into the bag. Water is released through the pores of the bag, leaving a denser, stronger material contained within the bag. The intent is to stack the bags on top of one another, creating a landscape compatible with mine closure plans. The ultimate height to which the bags can be stacked depends on the strength achieved by the FFT.

The goal of the pilot was to collect all the necessary information to create a commercial design for evaluation and comparison against other technologies.

FFT was drawn from an existing transfer line from the Muskeg River mine (MRM) external tailings facility (ETF) and stored in a holding pond with 10 000 m^3 of storage. The FFT was pumped from the pond through a system where it was treated with chemical amendments and exposed to a variety of mixing and shear regimes prior to flowing into the bags. A site was prepared that enabled drainage while maximizing the use of the bag volume. Bags of different sizes were used to test the effects of scaling. Bags were stacked one on top of the other. Run-off water from the bags was collected for analysis. Much attention was paid to operational issues as well. Safety and efficiency were principal operational considerations for the pilot study. Lessons learned from the pilot study will be valuable for future commercial evaluation of the technology.

As a result of the pilot study, treating FFT at a commercial scale, through the use of geobags is considered viable. Geobags technology provides another tool available for the oil sands industry when incorporating FFT in the terrestrial closure landscape.

PROGRESS AND ACHIEVEMENTS

The test program ran throughout the summer and fall of 2018. The following key objectives were met:

- A total of 11 geobags were filled. Four were "recipe" geobags testing different chemical amendments; four were "stacking" geobags, one on top of the other; three were "scaling" geobags. The three scaling geobags were of varying size, ranging from one full scale commercial geobag (100 m length by 40 m circumference), one medium scale geobag (30 m length by 27 m circumference), and one small scale geobag (30 m length by 18 m circumference);

- Chemical amendment (treatment) recipes tested included commercially available polymers (flocculants) and alum. The polymers included Dow XUR, SNF 3338, and BASF 1047; and

- Operational lessons learned will inform the design for a viable commercial operation.

The bags continued dewatering over time. The impact of freeze-thaw was evaluated in 2019. Three geotechnical sampling campaigns were completed in June 2019, September 2019, and March 2021. The solids content and shear strength values increased between the original deposition in 2018 and the sampling in 2019 and 2021. The geobags containing the deposit were mined out with the underlying overburden material in spring 2021, after the final sampling and testing program.

The extrapolation of the pilot study results should enable prediction of solids content and strength for a commercial operation. The number of bags required for a given amount of FFT to be treated and the ultimate height to which the bags may be stacked will be determined from these extrapolations. Further optimization may be possible, specifically with the chemical amendment evaluation, as the polymers are being developed rapidly. A plan can then be formulated incorporating geobags into a final landform. The detailed designs will provide information to incorporate geobags as part of the technologies to help with final landforms.

LESSONS LEARNED

As a result of the pilot study, treating FFT at a commercial scale, through the use of geobags and chemical amendments is viable. Geobags are another tool in the tailings treatment toolkit for incorporating FFT into the terrestrial closure landscape.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural, Chevron

Principal Investigator: Gavin Freeman

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Brittany Skinner	Canadian Natural	EIT, Tailings		
Jason Hill	Canadian Natural	Engineer, Process Innovation		
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Pressure Filtration for Fluid Fine Tailings Treatment

COSIA Project Number: TJ0113

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Pilot Completed; Deposit Monitoring Year 3 of 4

PROJECT SUMMARY

The filter press is a well-known technology that delivers rapid water recovery from fluid fine tailings treatment (FFT) by mechanically pressing water out of the fine clay slurry to form a dense cake suitable for immediate transport to a reclamation area. The added step of chemically treating the FFT before mechanical filtration is a crucial part of the process. This multi-year project culminated in a large-scale pilot that aimed to deliver the information required to design a full commercial plant, including:

- The effect of a live and variable FFT feed on the operating parameters and the final products;
- Throughput as defined by filtration cycle times and product quality;
- Chemical amendment dosages and types (flocculation and coagulation);
- The effect of shear on the treated FFT feed;
- Evaluation of the feed solids concentration and value of partial dewatering of the slurry prior to filtration;
- Testing of the filter cake handling and discharge system;
- Evaluation of the effect of bitumen on the process;
- Evaluation of cloth durability, blinding, and lifetime of the cloth;
- The preliminary capital and operating costs of the technology; and
- Geotechnical evaluation of a large filter cake deposit.

The site pilot consisted of two 10 m^3 scale presses complete with 100 chambers of 2 m by 2 m and various thicknesses varying from 25 mm, 30 mm to 35 mm. One press was equipped with a membrane squeeze technology. The plant had multiple options for feed conditioning and initial dewatering options prior to the pressure filtration step.

PROGRESS AND ACHIEVEMENTS

The site pilot program was completed in September, 2019. It has provided results and confirmed previous assumptions to inform the commercial design assumptions. In summary, the main findings of the pilot program include:

- The FFT filter press technology is reliable and can be operated continuously at a commercial scale;
- Chemical treatment of the FFT feed (flocculation and coagulation) is required for the success of the technology;
- There was no significant effect of shearing the feed (using a centrifugal pump) on the produced cake or filtrate observed;
- The minimum filtration pressure requirements of 700 kPa was confirmed (the use of the membrane squeeze did not add significant benefit); and
- The large deposit area prepared was immediately trafficable after solids placement with a D6 dozer.

The deposit is expected to consolidate over time. Two geotechnical sampling campaigns were completed in 2019 and 2021. The solids content and shear strength increased between the 2019 and 2021 investigations.

LESSONS LEARNED

The pressure filtration technology is able to immediately produce “upland reclamation ready” products from FFT.

The filter presses consistently produced de-watered tailings with solids content greater than 60% over the ~215 runs performed between July and August 2019. The measured solids content has increased to 70% two years after deposition. There is a strong correlation between the shear strength and solids content.

The advantage of the filter press technology is the production of a final product that is immediately suitable for earthworks. There will be minimal additional consolidation of these deposits. The quality of the filtrate was very good in terms of low total suspended solids; however, due to the addition of coagulant, it may require chemical treatment depending on the final destination of the filtrate stream.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigator: Gavin Freeman

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Research Collaborators: Teck, Ledcor Nalco Services (Lab scale pilots)

Inline Flocculation of Fluid Fine Tailings Field Pilot

COSIA Project Number: TJ0117

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 3 of 6

PROJECT SUMMARY

Inline flocculated fluid tailings (ILF FT) have been used successfully in the oil sands in combination with atmospheric drying and mechanical re-handling to produce ready-to-reclaim deposits. This project focuses on using ILF FT that is supplementary to thickening and co-deposited with high sands-to-fines ratio (SFR) materials (e.g., thickened tailings) to increase fines treatment volumes and enhance the consolidation of the ILF FT in a deep deposit. Figure 4 illustrates a FT line that can produce ILF FT when one or both thickeners are offline.

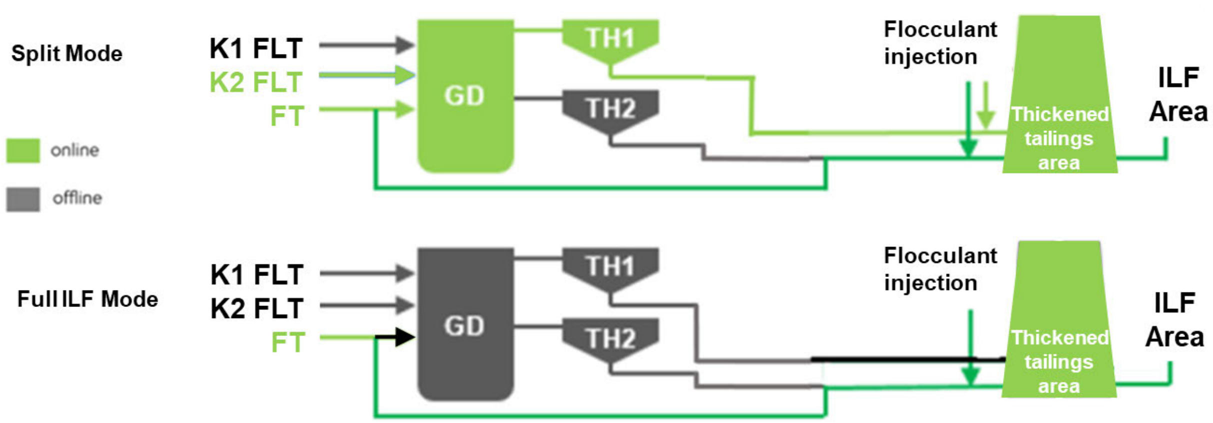

Figure 4: Schematic diagram of In-line Flocculation Process

K1 Kearl Plant 1	K2 Kearl Plant 2	FLT flotation tailings	FT fluid tailings	GD gravity distributor
TH1 Thickener 1	TH2 Thickener 2	ILF In-line flocculation		

The initial project phase was focused on evaluating optimal treatment conditions and material properties of ILF FT using laboratory testing and a field pilot. Phase 2 of the project comprises evaluation of ILF FT co-deposited with high SFR materials in the laboratory and in a field pilot. Phase 3 of the pilot began in 2021 with the objective to evaluate performance of ILF which has been co-deposited / interlayered with a relatively high sands to fines ratio (SFR) thickened tailings (TT) and/or coarse sand tailings (CST) within the TT deposition area. The co-deposition/ interlayering of ILF and TT is expected to follow a similar trajectory of solids content increase as TT.

Imperial intends to conduct the ILF trial only during planned or unplanned shutdowns of the thickener or extraction plant, to continue FT treatment. During 2021, ILF was intermittently operated between April and September during periods of downtime. During ILF operation, FT was extracted from the West External Tailings Area (WETA) using the FT barge and directly pumped to the inline polymer injection location. After polymer injection, ILF treated FT is sent to TT deposition area in East External Tailings Area (EETA). ILF deposition was mainly directed to west side of TT deposit.

PROGRESS AND ACHIEVEMENTS

Laboratory testing was conducted on samples of ILF FT to evaluate optimum polymer dosage and large strain consolidation parameters followed by a field trial to evaluate capabilities of the infrastructure, determine optimum operation conditions, and evaluate deposit characteristics.

Different combinations of density and flow rates were systematically assessed to determine optimum dosages for various flowrates and density using capillary suction time and initial solids content of collected samples, which were then applied in the field pilot to evaluate feasibility and deposit characteristics at a larger scale. The field trial created a 40 m by 40 m deposit that was about 2 m thick, which achieved about 45% - 50% solids content and 3 kPa - 5 kPa peak undrained shear strength after about 3 months.

The phase of the project which began in 2021 was to design an inline flocculated FT co-deposit with high SFR TT or coarse sand tailings to create a product, which can achieve ready-to-reclaim criteria. During 2021, the ILF pilot produced 1.9 Mm^3 of ILF treated tailings. During ILF operations, dosage was maintained around 1000 g/t and fluctuated between 800 g/t and 1200 g/t. As expected, initial solids content was maintained around 20%, tended to reach a solids content of 30% after 7 days. Over 80% clay content and around 0.5 SFR demonstrated the fines and clay dominant nature of this FT material.

The deposition area was sampled twice to help delineate the ILF material within the TT deposit. One of the field investigations was carried out in between ILF deposition and other one was conducted towards the end of an ILF deposition period. Therefore, some of the samples might be relatively new in the deposit and some other samples could be up to 6 months old. The samples collected during the field investigation were tested for material characterisation. The analysed material properties included solids content, sand-to-fines ratio and clay content. In situ properties of the material in the deposit such as in-situ strength and pore pressure were also measured using in-situ tests.

LESSONS LEARNED

The trial verified the difficulty in maintaining constant FT density and flow rate and that a successful operation requires real time product quality feedback using appropriate performance indicators such as initial solids content or capillary suction time to maintain product quality.

Deposit sample results indicate relatively high solids content compared to solids content observed from process samples. The measured solids content values from deposit samples are comparable to thickened tailings solids content values. Atmospheric drying, mixing with high SFR TT, extended dewatering time and some segregation within the deposit might help for better solids content results observed for ILF deposit samples.

In summary, ILF process data demonstrated expected ILF treatment performance. The results of the field pilot deposit surveillance demonstrated better-than-expected performance from ILF treated FT material compared to the laboratory estimates. Co-deposition/interlayering of ILF product with relatively high SFR/low clay, thickened tailings and/or coarse sand tailings may further improve overall deposit performance. This will be an area of investigation and the field pilot is expected to continue over the next few years.

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Canada's Oil Sand Innovation Alliance (COSIA). (2015). *Guideline for Tailings Deposit Sampling and Measuring Tools.*

Oil Sands Tailings Consortium (OSTC) and Canada's Oil Sands Innovation Alliance (COSIA). (2012). *Technical Guide for Fluid Fine Tailings Management.*

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigators: Sidantha Weerakone

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Physically Upgraded Trafficable Tailings Innovation (PUTTI)

COSIA Project Number: TJ0128

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 2 of 3

PROJECT SUMMARY

Filtration offers an opportunity to turn fluid tailings (FT) storage to dry stackable tailings, reducing the time required to reclaim tailings deposits. Filtration is an established tailings treatment technology in hard rock mining. Some of the challenges associated with using filtration for oil sands tailings include high clay content compared to hard rock mining tailings and the existence of residual bitumen in the tailings, which tends to blind filter cloths. The first industry filtration application attempt for oil sands tailings was a field trial by Canadian Natural in 2019. The trial aimed to demonstrate the feasibility (operational robustness, scalability, along with geotechnical and closure aspects) of Plate and Frame filtration of oil sands fluid tailings. Prior to mechanical dewatering, the tailings were conditioned by a combination of a coagulant and a polymer. The plate and frame filtration process were essentially a batch process and there is an appetite to assess continuous filtration options to enable higher treating capacity. Syncrude completed a lab study assessing the application of a novel continuous filtration technology (the volute screw press). The results showed filter cakes of more than 60% solids were achievable with a filtrate of less than 1% solids. Syncrude also assessed the effect of different chemical treatment schemes, which showed performance was a function of chemical treatment; in particular, a combination of polymer and coagulants produced superior filtration results.

Imperial recently developed and field tested an enhanced chemical treatment (eILF) process without mechanical dewatering, which combines a polymer, coagulant, and colloidal silica. The treatment demonstrated superior performance when compared to single polymer treatment but was not benchmarked with polymer + coagulant treatment. It is desirable to know if the enhanced chemical treatment produces superior performance for both batch and continuous filtration performance.

The aim of the project is to evaluate the performance of alternative chemical treatment technologies including Imperial's Enhanced Chemical Treatment for mechanical dewatering (both batch and continuous filtration) and identify an efficient chemical treatment suitable for mechanical dewatering.

Phase 1

The main objective for this phase is lab scale evaluation of different chemical schemes for mechanical dewatering. The specific tasks will include:

1. Benchmarking enhanced chemical treatment to flocculant coagulant treatments for application in mechanical dewatering (both batch and continuous);
2. Chemical treatment optimization including evaluation of alternative chemical treatments to mitigate filter cake plugging and cake discharge challenges; and
3. Investigate different tailings flowsheets to provide the best solution with proper equipment selection and process information.

Phase 2

The main objective for phase 2 is to evaluate the performance of the selected tailings flowsheet in order to assess operational robustness of the process, deposit stability and trafficability and scalability of the technology. The specific tasks for this phase will include:

1. Pilot plant design construction, commissioning, testing; and
2. Deposit geotechnical and closure assessment.

PROGRESS AND ACHIEVEMENTS

A bench scale study was completed to evaluate eILF treatment for mechanical dewatering (both pressure and vacuum filtration). For FT with an SFR of 0.1, vacuum filtration did not form a cake in a reasonable timeframe, increasing the SFR to 0.5 resulted in formation of a dewatered cake with 70% solids content but at a long filtration time. Pressure filtration on the other hand, showed promising results, achieving a filtration rate of 29 $kg/m^2/hr$. Generally, long cycle time was required to form a dewatered tailings cake (40-45% solids) using pressure filtration. Pressure filtration with membrane squeeze for SFR 0.5 was able to achieve higher cake dewatering (80% solids content) but had a longer filtration time. Laboratory mechanical dewatering testing to evaluate performance of pressure and vacuum filtration for enhanced inline flocculated fluid tailings and benchmarking with alternative treatment is still in progress. When testing is completed, the results will be incorporated into process and technology evaluation to provide process design recommendations at the conceptual level for mechanical dewatering of fluid fine tailings.

LESSONS LEARNED

Filtration rate improved with increasing sand-to-fines ratio (SFR). Increasing SFR from 0.01 to 0.2 doubled the filtration rate, whilst increasing SFR from 0.2 to 0.5 resulted in an order of magnitude increase in filtration rate. Membrane squeeze in addition to pressure filtration has potential to further improve performance of mechanical dewatering of fluid fine tailings. SFR modification maybe required to make mechanical dewatering of FT an economic process.

PRESENTATIONS AND PUBLICATIONS

Patent

Imperial Oil Resources Limited. (2021). *Oil sand tailings treatment using flocculation and treatment with a coagulant and a silicate* (Patent No. CA3048297). Canadian Intellectual Property Office.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

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Thuan Ngo	Imperial	Research Technologist		

CST Enhanced Fines Beach Capture

COSIA Project Number: TJ0129

Research Provider: Imperial

Industry Champion: Imperial

Status: Ongoing

PROJECT SUMMARY

The use of carbon dioxide (CO_2) for treatment of oils sands tailings has been studied by other oil sands operators to reduce fluid tailings (FT) volumes and is currently implemented for production of Non-Segregating Tailings (NST) at Canadian Natural's Horizon operations. The objective of the present project is to reduce FT generation in the first place by injecting CO2 into the coarse sand tailings (CST) stream and increasing the fines capture in the tailings deposit beaches (above and below water).

In 2018, Imperial's tailings research team conducted a laboratory program to evaluate the increase in fines capture by CO_2 injection, determine the dosage requirements and the effects on pH and rheology, and water release. Results of the lab program indicated a significant increase in fines capture after CO_2 injection, a reduction in pH which recovered with time, no significant impact on rheology, and an increased rate of water release. The CO_2 dosage was also determined for commercial scale trial.

Based on the positive results from the 2018 lab program, Imperial planned for, and conducted, a commercial field scale trial in 2019 and Q3 and Q4 2020, respectively. The objectives of the trial were to:

- Evaluate the changes in fines content and fines capture of the beaches formed because of CO_2 treatment; and
- Understand the potential impact on geotechnical characteristics and behaviour of the deposit.

For the commercial field scale trial, the selected deposition area had to meet the following:

- Be within one of the existing internal dykes at the Kearl External Tailings Facility; and

- Accommodate typical hydraulic upstream construction technique and equipment (i.e., dozers) to build two cells and beaches for pouring untreated CST and CO_2-treated CST streams.

Dozers constructed and compacted the cells but beaches were not track packed. A site investigation program was conducted in December 2020 to carry out in-situ tests and to collect samples.

PROGRESS AND ACHIEVEMENTS

The field deposition trial and the subsequent site investigation program were concluded in Q4 2020. The laboratory testing of the samples collected during the trial was completed by Q2 2021, followed by analysis of the results.

The field deposition trial was partially completed due to seasonal and operational complexities. The cells were constructed at sufficient thickness to allow for geotechnical and fines content assessment. However, the beaches were insufficiently thick for geotechnical assessment.

Process data was collected during the trial as well as tailings deposit data after completion of deposition. For the process data, the tailings and CO_2 injection flow rates were recorded using in-line flow meter. The stream density was measured using an in-line density meter upstream of the CO_2 injection. Tailings stream samples were collected using an auto-sampler at the plant. The samples were then sub-sampled and tested for solids and fines contents. For the tailing deposit data, tailings samples were collected using a sonic aqua-lock sampler. The samples were then subsampled and tested for solids and fines contents.

The fines content measured and the fines capture calculated based on the process and tailings deposit data is summarized in Table 1.

<table>
<tr><th>Material</th><th>Fines content, FC_{44} (%)</th><th>SFR</th><th>Fines capture (%)</th></tr>
<tr><td>Non-CO2 CST stream to beach</td><td>11.4</td><td>7.8</td><td rowspan="2">60</td></tr>
<tr><td>Non-CO2 CST beach</td><td>7.2</td><td>12.9</td></tr>
<tr><td>CO2 treated CST stream to beach</td><td>13.0</td><td>6.7</td><td rowspan="2">71</td></tr>
<tr><td>CO_2 treated CST beach</td><td>9.6</td><td>9.4</td></tr>
</table>

Table 1. Average Fines Content and Calculated Fines Capture for the Beach Above Water

A liquefaction assessment was carried out based on cone penetration tests (CPTs) conducted in the deposit. The deposit thickness in the beach area was insufficient for the liquefaction assessment. Both cells were constructed hydraulically with dozer track packing as part of routine upstream cell construction.

The liquefaction assessment indicates that the track-packed CST in both cells (the CST with and without CO_2 addition) is dilative and non-liquefiable based on the normalized tip resistance-corrected for clean sand method (Qtn,cs) and the state parameter methods (ψ). The results are presented in Figure 5 below. Plot (a) shows Qtn,cs (Robertson, 2010 and 2018) and the Qtn,cs = 70 boundary, while plot (b) shows ψ (Robertson, 2010) and the ψ = -0.05 boundary. For comparison purposes plot (c) shows ψ as per Jefferies and Been (2016); using the Plewes et al. (1992) method for estimating λ. The two different state parameter methods both indicate that the material is non-liquefiable, although the state parameter values estimated from Jefferies and Been (2016) are slightly higher than those estimated from Robertson (2010).

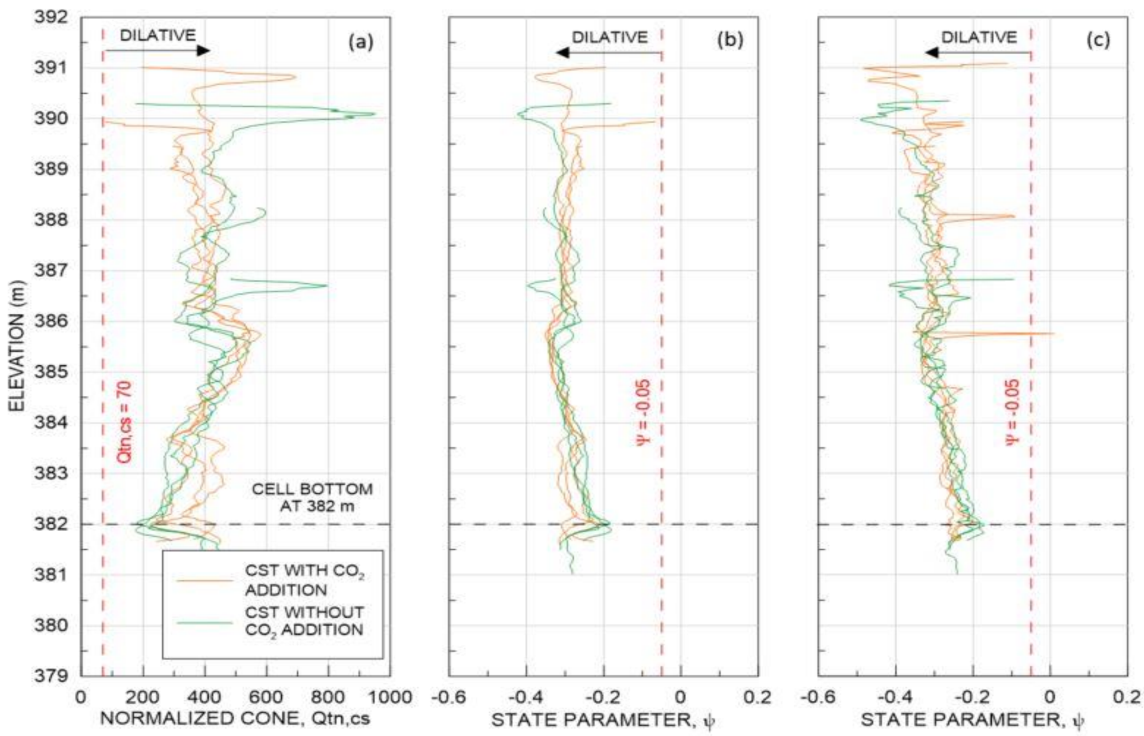

Figure 5: Liquefaction assessment plots: a) normalized cone, Qtn,cs, method from Robertson (2010 and 2018); b) state parameter method from Robertson (2010); and c) state parameter method from Jefferies and Been (2016)

LESSONS LEARNED

Operationally, it was identified that a significant portion of the beaches eroded during the pour due to fluctuations of the feed (flow rate and density). The open-ended pipe was switched to a spoon to minimize the erosion and facilitate building the beach. For future trials, duration of the pour should be long enough to create a representative beach deposit for the field operational conditions (i.e., the resultant channels/gullies should not be a significant event affecting the results).

The field trial data and associated data evaluations indicate that CO_2 addition to CST potentially enhances both fines content and fines capture of the CST BAW deposit. Considering that for the CST with CO_2 deposition, the discharge method was switched from an open-ended pipe to spoon, part of the additional fines capture is due to the lower energy discharge environment created by the spoon. Therefore, this significant increase in fines capture cannot be all attributed to the effect of CO_2 treatment. In other words, in absence of a spoon, the increase in fines capture in day-to-day beaching operations will likely be lower than the values observed in this trial.

The liquefaction assessment found that the track-packed CST in both cells (the CST with and without CO_2 addition) is dilative and non-liquefiable, based on the Qtn,cs method and the state parameter methods. However, the pilot was partially completed due to weather and operational restrictions and therefore the liquefaction assessment for the beach was not completed. Future steps for the enhanced beach fines capture technology will be determined pending review for a subsequent pilot.

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Robertson, P.K. (2010). Evaluation of flow liquefaction and liquefied strength using the cone penetration test. *Journal of Geotechnical and Geoenvironmental Engineering*, *136*, 842–986.

Robertson, P.K. (2018). Evaluation of liquefaction in tailings and mine waste: an update. In *Proceedings of Tailings and Mine Waste 2018 Conference*.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigators: Anu Saini and Reza Moussavi Nik

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Research Collaborators: Amy Rentz, Sam Proskin, Silawat

Co-Processing of Fresh Tailings And FFT

COSIA Project Number: TJ0151

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Year 1 of 5

PROJECT SUMMARY

This project deals with co-processing of fresh tailings, such as coarse tailings and flotation tailings from the extraction plant, and legacy FFT inline with a polymeric flocculant to produce paste tailings without the use of thickeners and cyclones. The objective of the project is to develop an efficient and low-cost tailings management technology to enable faster creation of trafficable landforms that are ready for reclamation. The hypothesis of the project is that increasing SFR (sand to fines ratio) could increase hydraulic conductivity of co-processed deposit. Compared to CT (Composite Tailings) with SFR of 3 to 5 and centrifuge cake/flocculated FFT with SFR of 0 to 0.1, the target SFR of co-processing is 1 to 3 with optimal SFR of 2. Co-processing was converted to gated project in 2021 from KD-Engineered Tailings Research, in which some research activities have been conducted since 2012. Based on work to date co-processing is a promising technology that warrants further proofing.

The technical gap assessment for co-processing recommended that we need to resolve the following technical uncertainties in Stage B before moving to Stage C: Field pilot tests.

- Optimal pipeline flow regimes/velocities post polymer injection.
- Dynamic mixer scale-up parameters.
- Optimal feed density/solids content.
- Feed mineralogy sensitivity effect.
- Static and dynamic segregation.
- Different chemical recipes.
- Geotechnical study-LSC and beam centrifuge tests.

- Geochemical study on pore water.
- Effect of release water on bitumen extraction.

To overcome the technological uncertainties identified above, a test plan was developed to close the technical gaps in two phases.

Phase 1: Lab tests:

- Feed solids contents from 20-45%.
- Feed SFRs from 1 to 3 with optimal SFR 2.
- Polymer dosage tests.
- Various chemical recipes: A single polymer, gypsum + polymer, FGD + polymer and polymer + alum, poly aluminum or cationic polymer.
- Static segregation.
- Sensitivity of feed mineralogy and water chemistry.
- Effect of release water on bitumen extraction.

Phase 2: Small pilot tests:

- Continuous small pilot tests, + long pipeline + Flume tests.
- Dynamic segregation.
- LSC (Large Strain Consolidation) tests of sediments.
- Beam centrifuge tests of the same sediments.
- Geochemistry study of deposit pore water.

PROGRESS AND ACHIEVEMENTS

With respect to the technological advancements achieved in 2021, here is a preliminary summary of the test results:

Phase 1: Lab tests:

The optimal feed solids content was found to be 35-40% solids. The optimal SFR was 2. The optimal polymer dosage was found to be 1000-1100g/t on <44µm fines basis. Various chemical recipes were developed, including:

- A single polymer
- Gypsum + polymer
- FGD solids + polymer
- Polymer + alum
- Polymer + XL6 (poly aluminum)
- Polymer + XL8 (poly aluminum)
- Polymer + cationic polymer

It was found that the recipes of polymer alone, FGD solids + polymer, and gypsum + polymer had similar good flocculation performances and initial dewatering behavior. However, the effect of It was found that the recipes of polymer alone, FGD solids + polymer, and gypsum + polymer had similar good flocculation performances and initial dewatering behavior. However, the effect of FGD (Flue Gas Desulphurization) solids and gypsum on long term deposit consolidation could not be demonstrated in 24 hours settling tests. The Flocculation-Coagulation (FC) process by adding polymer first and then alum clearly outperformed the conventional Coagulation-Flocculation (CF) process in which alum was added first and then polymer at the same chemical dosages. This is consistent with our previous findings where FC, FCF and CFC processes outperformed CF [1].

It was verified that there was no static segregation in the sediments by taking samples from top, middle and bottom of the sediments and analyzing the OWS (oil, water and solids) and PSDs (particle size distributions) of the samples. The tests of sensitivity of feed mineralogy and water chemistry and the effect of release water on bitumen extraction are ongoing, which will be reported in 2022. The technological uncertainties were resolved, and the relevant technical gaps were closed in Phase 1. The optimal test conditions were recommended for use in Phase 2 Small pilot tests.

Phase 2: Small pilot tests:

The continuous small pilot tests have been progressing at Coanda. The LSC (Large Strain Consolidation) and Beam centrifuge tests of sediments and geochemistry study of deposit pore water are planned to be completed in 2022.

LESSONS LEARNED

The lab tests in Phase 1 closed the technical gaps as planned and the optimal test conditions were recommended for use in Phase 2 Small pilot tests. As the Phase 2 work is ongoing, it is too early to report the lessons learned.

REFERENCES

Yuan, X.S. and Shaw, W. (2007) Novel processes for treatment of Syncrude fine transition and marine ore tailings. *Canadian Metallurgical Quarterly*, *46* (3), 265–272.

RESEARCH TEAM AND COLLABORATORS

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Thickening of Fluid Tailings and Co-deposition with Non-segregating Tailings

COSIA Project Number: TJ0153

Research Provider:

Industry Champion: Canadian Natural

Status: Year 2 of 2

PROJECT SUMMARY

It is believed that dewatering Fluid Tailings (FT) prior to co-deposition with Canadian Natural's Non-Segregating Tailings (NST) would improve fines capture as increasing the Fines Over Fines Plus Water (FOFW) moves the segregation boundary. For this project, a slipstream of FT was drawn from the commercial FT reclamation system and fed to a 5 m diameter thickener. In 2021, the pilots focus was on creating deposits with a range of recipes and tracking their geotechnical performance, as well as measuring fines capture in a cell where it was co-deposited with NST. In 2022, the focus was on optimizing the thickener performance.

PROGRESS AND ACHIEVEMENTS

2021 Program

The pilot was originally constructed in such a way that coarse material could be added to the thickener to adjust the sand to fines ratio (SFR). Six test cells were constructed to allow for testing a variety of recipes with varying SFR and chemical dosage. There was also a 75 m long test cell where thickened FT could be deposited alongside NST.

The pilot was plagued by operability issues primarily related to debris in the FT that would not be a problem at commercial scale but frequently plugged the small bore piping and valves of the pilot. It was also found that adding coarse material to the thickener just resulted in segregation. As a result, the modified SFR trials were very limited. The thickener product did not perform well geotechnically on its own and is not viewed as a viable stand-alone product.

For the co-deposition test, NST and FT products were introduced to the cell from adjacent pipes. Sampling of the deposit showed that the two products mixed very well in the plunge pool and did not segregate along the length of the deposit. This test was considered successful as the fines capture for both products were high and virtually identical.

2022 Program

The results from the 2021 co-deposit were encouraging but the thickener operational performance was not. For this to be a viable commercial operation, it would have to be demonstrated that the thickener could be reliable and consistently deliver a quality product which became the focus for the 2022 program.

An additional screening step and surge tank were installed ahead of the thickener plant to manage the debris. The rake drive system was improved to allow operation over a wide range of rake speeds. Upgrades were also made to some of the instrumentation. As of this writing, the test program is still in progress, so data is not yet available.

LESSONS LEARNED

The FT was drawn from the commercial system and was screened to an appropriate level for that scale of equipment. At times there was a significant quantity of debris and it was large relative to the pilot scale equipment, which caused plugging issues. A debris management system was added to manage this for the 2022 program.

For the 2021 program, the pilot had the ability to add coarse solids with the FT in the thickener feed to adjust the SFR. This did not work well as the coarse material segregated rapidly.

Coming out of the 2021 campaign it appeared the thickener performance may have been limited by rake torque. The drive mechanism was modified for 2022 to allow for higher rake speed and torque.

PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

2021 Canadian Natural Tailings Management Report

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Jiangying Wu

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Tailings Capping

From Slurry to Soil: Creating Soil from Oil Sands Tailings; Phase 2

COSIA Project Number: TE0052 (IOSI 2017-12)

Research Provider: Northern Alberta Institute of Technology (NAIT)

Industry Champion: Canadian Natural

Status: Year 1 of 1 (Project Complete)

PROJECT SUMMARY

In 2019, the viability of creating an artificial soil prototype was investigated that can support plant growth by amending the chemically treated fluid fine tailings (FFT) with supplemental nutrients, with the goal of achieving better FFT dewaterability and bearing capacity (COSIA, 2020). Building upon the previous study, the present study aimed to understand the following:

1. The best combination of organic and/or inorganic amendments for developing an artificial soil prototype that can support plant growth and development over an extended period of three months (six weeks were considered in the previous study). The longer growth period can provide insights regarding the expected outcomes in the field (multi-year time frame concerning plants).

2. The tolerances of selected plant species to growing in the artificial soil prototype.

3. The effect of sand addition on flocculation and plant growth in a larger scale context (20-liter vs. 1-liter potted pails as in the previous study).

4. The viability of introducing amendments into a tailings process stream to deploy the nutrient amendments and flocculated tailings to deposit in one step (inline flocculation vs. batch flocculation as in the previous study)

Therefore, this study was conducted in two stages. The first stage involved the preparation of the medium for plant growth through initially amending the FFT with a combination of nutrient and sand additives. The amended FFT was then treated using a polymer flocculant (A3338) via a continuous dynamic in-line flocculator. The second stage involved a 3-month greenhouse trial, growing two species: slender wheatgrass [Elymus trachycaulus] & sandbar willow [Salix interior]) in the treated FFT.

FFT with two different sand-to-fines ratios (SFR), namely 0.12 (raw FFT) and 1.5 (combination of raw FFT and sand), was amended with alfalfa & inorganic fertilizer, compost & inorganic fertilizer, urea & inorganic fertilizer, or inorganic fertilizer, peat, & urea. These amendments were evaluated against a no-amendment condition as a control group. The inline flocculation process of amended FFT was evaluated in terms of the operational challenges encountered and the quality of the flocculated material produced (e.g., dewaterability, solid content, optimal polymer dosage required, nutrient availability, and chemical properties). The greenhouse trial was evaluated based on the seed emergence for slender wheatgrass and the survival rate for sandbar willow over a period of 3 months, with above-ground plant biomass being assessed at the end of the growing period. In addition, the geotechnical properties of the artificial soil (i.e., drained shear strength and final solid content) were also evaluated.

PROGRESS AND ACHIEVEMENTS

The project work was carried out in two stages over 2021, where the first stage (flocculation) began in April and was completed in May while the greenhouse trail lasted for 13 weeks, from 29th of June until 27th of September. The key progress milestones over the project are as follows:

Stage 1- Flocculation Study:

The amended FFT with the targeted SFRs (0.12 and 1.5) was flocculated and allowed to settle for one week. It was found that the inorganic fertilizer, peat, and urea can be added to a flocculation process stream without having any adverse effect on the flocculation performance. In contrast, the addition of alfalfa and compost to FFT prior flocculation aided the formation of bitumen lumps that caused pipe clogging issues which in turn disrupted the flocculation performance. Consequently, alfalfa and compost were surface applied after the flocculation. Similarly, flocculating FFT with SFR 1.5 was more challenging when compared to that of FFT with SFR 0.12 due the sand settling in the process stream; which consequently required more operator intervention to maintain the optimal flocculation conditions (Figure 6). Overall, the polymeric chemical treatment increased the solids content of tailings from 23% to an average of 33% for SFR 0.12 and from 38% to 49% for SFR 1.5 after settling for one week, with SFR 1.5 requiring more polymer volume to achieve optimal flocculation dosage.

The artificial soil produced was rated as non-saline to weakly saline (EC<4 dS/m) and as mildly alkaline to moderately alkaline (pH 7.5-8.0) soil with a yield stress of 0.25 and 0.50 kPa for SFR 0.12 and SFR 1.5, respectively. The addition of amendments generally improved the nutrient availability for SFR 0.12 more than that of SFR 1.5 because sand addition was found to be a nutrient diluting agent even when the amendment application rate for SFR 1.5 was increased by a factor of 1.125 compared to that of SFR 0.12. The produced artificial soil for each amendment treatment was then divided into five replicates of non-draining 18-liter or 9-liter pails per plant and per targeted SFR, resulting in a total of 100 pails.

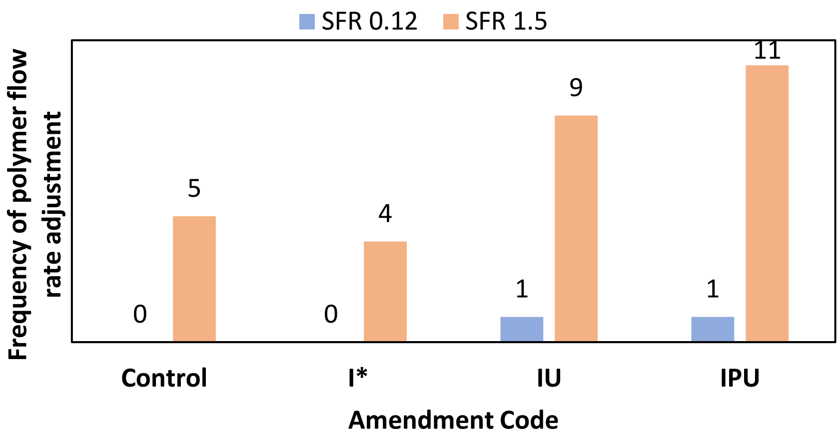

Figure 6. Frequency of manually adjusting the polymer flow rate per amendment treatment to maintain the optimal flocculation condition at sand-to-fines ratios of 0.12 and 1.5. * FFT was only flocculated with inorganic fertilizer, and alfalfa or compost were manually added later onto the flocs after flocculation. (Control= no amendments, I= inorganic fertilizer, P= peat, U= urea).

Stage 2- Greenhouse Study:

Once the pails filled with the artificial soil, five cuttings of sandbar willow were planted in each pail, while seeds of slender wheatgrass were hand sown from seed at first, and following limited germination after 13 days, more seeds were seeded and thinned to 5 plants per pail after 14 days. All pails were watered as required throughout the trial, and the plant response to each SFR/nutrient amendment combination was evaluated.

Sandbar willow demonstrated an overall survival rate of 80% for both SFRs while slender wheatgrass had a seed emergence of 40% and 20% for SFR 0.12 and SFR 1.5, respectively. The addition of sand, as in SFR 1.5, increased tailings electrical conductivity and significantly inhibited seed germination of slender wheatgrass whereas sandbar willow showed better salt tolerance. However, the addition of sand improved tailings solids content, which could be related to higher evapotranspiration rates as the increase in solids content at SFR 1.5 occurred even when sandbar willow planted in tailings with SFR 1.5 received 14% significantly more water, but not necessarily more plant growth. For both native plant species tested, inorganic fertilizer plus urea and/or inorganic fertilizer plus urea and peat were the ideal combination of nutrient amendment that improved plant biomass and increased tailings geotechnical properties mostly at SFR 0.12 (Figure 14). Alfalfa pellets and compost were surface applied after flocculation, but they did not improve plant growth or other tailings geotechnical properties.

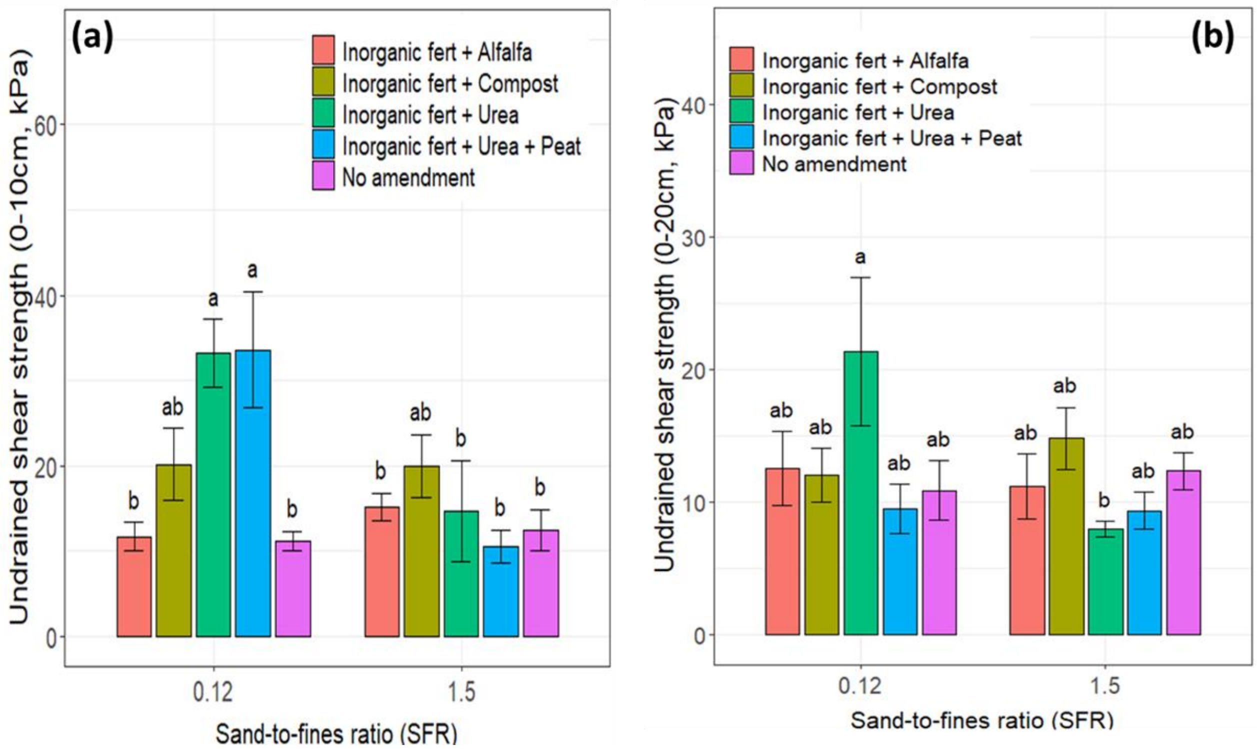

Figure 7. Mean undrained shear strength of artificial soil prototype (0.12 and 1.5 SFR), planted with E. trachycaulus (slender wheatgrass) (a) & with S. interior (sandbar willow) (b), and amended with 5 amendments (Inorganic fertilizer + alfalfa pellets, inorganic fertilizer + compost, inorganic fertilizer + urea, inorganic fertilizer + urea + peat and no amendment). Error bars represent one standard error of the mean (± SE, n = 5). Different letters indicate a significant difference ($p < 0.05$) amongst different amendments.

LESSONS LEARNED

Stage 1- Flocculation Study

1. The addition of inorganic fertilizers, urea and peat was found to be feasible in inline flocculation causing no operational challenges or flocculation performance issues. This indicates that such nutrients and tailings can be jointly deployed in one step which would be beneficial in creating a final deposit that is more friendly for revegetation.

2. The release water due to settlement of flocculated tailings for one week demonstrated low content of nitrogen and phosphorus, which implies that nutrient pollution associated with adding amendments due to runoff and leaching could be insignificant.

3. Alfalfa and compost lent structure and stability to bitumen, resulting in building large masses and causing pipe clogging, which was exacerbated when flocculating FFT with SFR 1.5 because of the presence of sand (Figure 15).

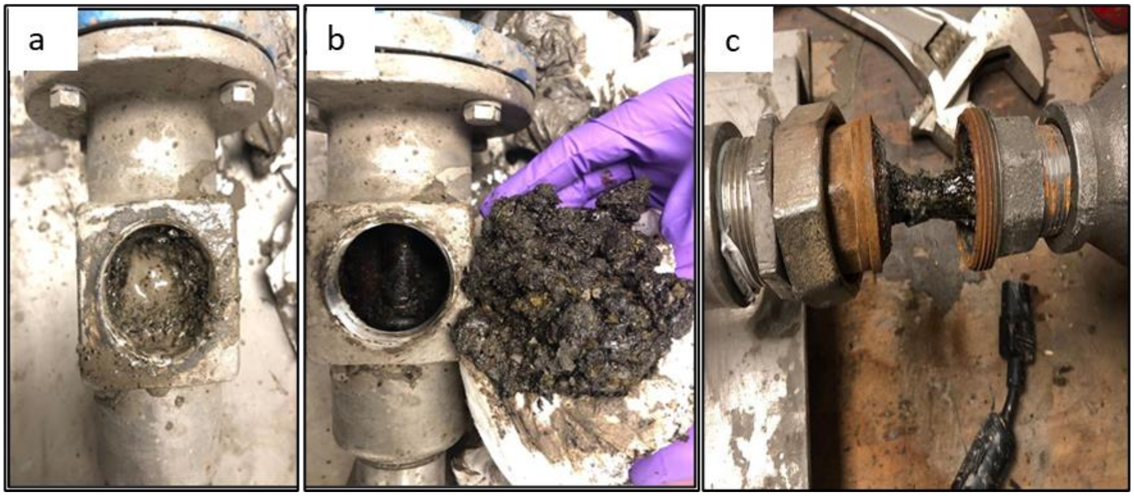

Figure 8. Progressive cavity pump inlet before (a) and after (b) removing the bitumen/ alfalfa clog. Accumulation of compost/bitumen clump (c) in the pipe.

4. The pipe clogging issues caused by alfalfa and compost occurred at a pipe size of one to two inches in diameter. Such issues might not occur at field scale.

5. An in-house test method was developed to evaluate the potential for clogging where a pump-and-mesh set-up was utilized to assess the formation of bituminous lumps when organic materials (e.g., alfalfa) was added to tailings.

6. Sprinkling alfalfa on flocculated tailings and storing the substrate in closed containers promoted the generation of hydrogen sulfide, and this could present a hazard that needs to be evaluated before implementation at scale.

7. The addition of sand was operationally challenging at the small scale but feasible and is expected to become easier at larger scale, with a system better designed for sand.

Stage 2- Greenhouse Study

1. The addition of inorganic fertilizers, urea, and peat without sand in flocculation increased the total nitrogen and other macro and micronutrients leading to increased plant biomass of both species and improved tailings shear strength.

2. The addition of sand did not only change the physical properties (e.g., SFR) of the artificial soil but also brought its own chemical conditions (e.g., high salinity, acid generating nature, nutrient diluting effect) that negatively impacted plant growth. Therefore, the chemical conditions of sand selected for modifying the SFR of an FFT should be taken into consideration.

3. Sand served to dilute the existing nutrient content of the amended FFT even when extra nutritional amendments were applied to compensate for the dilution effect.

4. Seed inhibition of slender wheatgrass in SFR 1.5 can be mitigated by increasing the quantity of seeds broadcasted, understanding that there could be reduced emergence and slower growth. Overtime, slender wheatgrass has shown to be tolerant to tailings substrate.

5. Sandbar willow showed tolerance to elevated salinity caused by the addition of sand suggesting that this is an ideal species for future tailings studies.

6. The Greenhouse trial was carried out in closed containers that did not allow for leaching which will normally occur in the field and can move salts beyond the root zone, which in turn can alleviate the plant response to salinity stress. Therefore, the effect of sand in similar field conditions can be further evaluated.

REFERENCES

COSIA. (2020). *2019 Tailings Research Report. From Slurry to Soil: Creating Soil from Oil Sands Tailings*. https://cosia.ca/sites/default/files/attachments/2019 Tailings Research Report_FINAL.pdf

RESEARCH TEAM AND COLLABORATORS

Institution: Northern Alberta Institute of Technology (NAIT)

Principal Investigators: Dr. Heather Kaminsky & Dr. Amanda Schoonmaker

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Constitutive Model Development and Experiment Scale-Up for Fines-Dominated Tailings Deposit Capping

COSIA Project Number: TE0084

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Syncrude and Imperial

Status: Complete

PROJECT SUMMARY

This research project contributes to the trajectory the Oil Sands industry has been pursuing to find robust, cost-effective methods to cap soft, fines-dominated tailings deposits and support reclamation construction activities. The intent of this "deltaic capping" approach (also called subaerial hydraulic capping or beaching) is to provide a safe, efficient way to cap soft tailings. Deltaic capping promises to be the lowest-cost method of capping large areas, for both soft tailings and stronger accessible deposits.

This work builds on the 2018-2019 project, "Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings", (COSIA project number TE0059) and "Modelling the Cap Placement with Tailings Deformation and Consolidation", (COSIA project number TE0073). Each of these prior projects demonstrated that deltaic capping held promise, justifying further assessment. The current project takes that a step further to improve the constitutive model defining tailings behaviour and examining the issue of how bench scale results can be scaled-up for planning a pilot scale field trial.

Specifically, this research addresses important uncertainties regarding the appropriate methods to use in predicting capping success or failure. There have been legitimate questions regarding how well common geotechnical methods and models represent the relationships which govern the behaviour of weak fines-dominated tailings deposits, and what the implications are for modelling the capping of these tailings. These weak materials lose strength when sheared - to the extent that they behave like a non-Newtonian fluid - and regain some of the lost strength over time when quiescent. Therefore, this project addresses three key elements that are needed for the development of a reliable capping design approach:

Constitutive model advancement: a quantitative description of the way the tailings behave in the short term as well as the long term under the influence of both self-weight and external loads, in a form that can be implemented in a constitutive model for use in numerical tools.

Geometric modelling of the sand capping process: testing two numerical models to see if they produce a correct description of the geometry change because of sand cap placement, based on comparison of modelled and measured observations from a bench-scale test.

Accounting for the importance of scale in capping process development: identifying and preliminary application of principles important for planning, measuring, and scaling up laboratory and bench-scale work to reliably build the knowledge operators will need to design and evaluate pilot-scale and eventually commercial-scale capping programs.

PROGRESS AND ACHIEVEMENTS

The main thrust of this work, improving industry's ability to model deltaic capping, was advanced because of this research. Two lines of analysis were pursued in parallel: 1) constitutive models for representing thixotropic behaviour of soft tailings in response to capping were identified; and 2) a bench-scale experiment of capping very soft tailings was modelled with two numerical models to assess whether they could reasonably represent the observed behaviours.

This project extended two well-established constitutive models, both of which describe soft soils' rate-dependent response to shear, by adding a time-dependent thixotropic effect on the shear strength. The first constitutive model was developed in the framework of total stress analysis, which can capture the shear-rate-dependency and thixotropy of the shear strength for undrained conditions. The second constitutive model was developed in the framework of effective stress analysis and can account for the contribution of pore pressure dissipation (consolidation) on the deposit stability because of sand capping.

The first of these models, the total stress thixotropic constitutive model, was used to perform large-strain numerical simulations of a bench-scale test of sand capping. The bench-scale test had been performed as part of COSIA project number TE0059. The data from the bench-scale test was revisited to provide more detail than previously published and better interpret the experiment. The model delivered satisfactory representation of tailings instability and the evolution of the tailings and cap geometry showing that the model can provide valuable insight for design of soft tailings capping.

A well-known deformation-based geotechnical mode, FLAC (Fast Lagrangian Analysis of Continua), was the other numerical model used to simulate the bench-scale experiment and was found to acceptably represent the behaviour of the soft tailings, despite the tailings' appearance of being more fluid-like than soil-like. However, the extreme deformation of the tailings caused the model to suffer numerical instabilities if multiple lifts of cap placement were to be represented. That limitation was not seen when applying the total stress thixotropic constitutive model.

FLAC was then applied to hypothetical pilot-scale deltaic capping scenarios for placement of the first lift of a cap. The numerical model showed that the deposit depth has a significant effect on the minimum tailings strength needed to support placement of a deltaic cap.

A realistic tailings strength distribution, supplied by Syncrude, was also modelled as a hypothetical deltaic capping pilot. The modelling indicated that deltaic capping could be expected to successfully place a first lift of sand on the deposit, although additional modelling of the specific geometry and other conditions of the deposit would be needed for planning a pilot test. In addition, subsequent lifts would require modelling with fewer simplifying assumptions.

In summary, this project found the following:

1. FLAC, a deformation-based geomechanical software, can acceptably represent behaviours of tailings and cap in response to capping, even when the tailings are at moisture contents well above the liquid limit and at undrained shear strengths as low as 100 Pa.

2. The FLAC model can be applied to scale-up experimental results to provide credible pilot-scale predictions, which still need to be confirmed by pilot-scale operations and measurements.

3. Constitutive models were identified to address missing or deficient elements in the relationships that govern the time-dependent thixotropic effects on the shear strength behaviour of fines-dominated tailings deposits in response to capping.

4. A numerical model Deltares has been developing in collaboration with others, called MPM, was specifically designed to handle soil-water interactions including this non-Newtonian fluid mechanics and soil mechanics problem. MPM provided a very good match to bench-scale experimental observations and measurements.

This research is a breakthrough step towards bridging the gap between the “fluid mechanics” approach and the “porous media mechanics” approach for what concerns flow-like failure problems, such as extended flow failure behaviour of soft sediments. This is particularly relevant for applications like sand capping and resulting potential slope instabilities.

LESSONS LEARNED

The MPM model has features that allow it to model successive lifts of the bench-scale experiment with these very weak tailings, which was a challenge with the FLAC model. Regardless, both models need to be validated against data collected at larger (pilot or commercial) scale, because of the inherent limitations in the bench-scale test used for model testing in this research and remaining uncertainties regarding the behaviour of weak fines-dominated treated tailings.

This pilot-scale modelling and the modelling of the bench-scale test have demonstrated important factors to recognize in planning deltaic capping programs: 1) recognize that the depth of the tailings and boundary effects can constrain the failure modes expressed during the trial, 2) position monitoring instruments based on pre-test modelling – it can significantly enhance the value of the data collected, and 3) design a trial so that neither the simplifying assumptions used in the model nor the limitations of the measured data (accuracy and sensitivity range) would confound interpretation of the results; and 4) be prepared to adjust the conceptual framework of tailings and cap behaviour based on the trial observations – there may be elements missing or mis-represented in the model and interpretive framework. Models can be critical tools in interpreting trials and the trial should always be modelled beforehand. This not only guides where and what type of measurements should be collected during the trial, but also provides a basis for recognizing deficiencies in the conceptual framework. When results do not match expectations based on pre-trial modelling, post-trial modelling can be used to illuminate whether the problem was inadequacies of the model or differences in input parameters, or more fundamental errors in the conceptual framework that need to be corrected to avoid future failures.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

No conference presentations have been made as of the first half of 2022, but it is the intention of the authors to present these findings at one or more conferences in the forthcoming years.

RESEARCH TEAM AND COLLABORATORS

Institution: Barr Engineering and Environmental Science Canada Ltd.

Principal Investigators: Jed Greenwood, Dirk Luger

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Jed Greenwood	Barr Engineering and Environmental Science Canada Ltd.	Principal Investigator, P.Eng., P.Geo., Vice President, Sr. Geotechnical Engineer		

Dirk Luger	Deltares	Co-Principal Investigator, Strategic Adviser, Soil and Structure Department		
Mario Martinelli	Deltares	PhD, Advisor/Researcher, Soil and Structure Department		
Claudio Tamagnini	University of Perugia	PhD, Professor of Soil Mechanics and Geotechnical Engineering		
Farzaan Abbasy	Barr Engineering and Environmental Science Canada Ltd.	PhD, P.Eng., Geotechnical Engineer		
Jim Langseth	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Sr. Civil Engineer, Project Manager		
Ebi Meshkati Shahmirzadi	Deltares	PhD, Researcher, Eco-system and Sediment Dynamics Department		

Research Collaborators: Deltares, University of Perugia

Consolidation Modelling

Comparison Of Rapid Centrifuge Consolidation Test, Geotechnical Beam Centrifuge Test and Large Strain Consolidation Test

COSIA Project Number: TE0072 – IOSI 2018-07

Research Provider: Thurber Engineering Ltd.

Industry Champion: Imperial

Status: Year 2 of 2

PROJECT SUMMARY

Large strain consolidation (LSC) tests are essential for predicting the long-term performance of tailings deposits. Predicting the performance is critical to deposits planning, design, deposition, operation, stabilization, capping and closure. Currently, the conventional LSC test method for oil sands tailings takes from several months to up to a year to complete on fine-grained tailings. The rapid centrifuge consolidation (RCC) test technique subjects the specimen to inertial radial acceleration, simulating an increased acceleration gravity many times that of the earth's gravity. The increased level of acceleration improves the rate of hindered sedimentation and consolidation, allowing the processes to be completed within a shorter time frame. Reducing the test time from several months to several days is invaluable to the oil sands industry in various ways, including accelerated analysis and planning, more testing and in-depth assessment of options, additional tailings quality assurance and control, and a probabilistic tailing planning approach.

PROGRESS AND ACHIEVEMENTS

The literature review, laboratory test program and comparative data analyses have been completed.

This research investigated the use of an RCC test to promptly obtain tailings consolidation parameters for oil sands tailings materials. These parameters were assessed by benchmarking them against those from geotechnical beam centrifuge and conventional LSC testing. Three tailings specimens were investigated for this study, including raw fluid tailings (FT) with an average SFR of 0.01, polymer treated FT with an average SFR of 0.2 and thickened tailings (TT) with an average SFR of 0.9. The RCC, LSC, and verification standpipe were executed at the Thurber Calgary tailings laboratory using Thurber's existing test methodologies. The beam centrifuge tests and additional LSC tests were conducted by two independent research units at the University of Alberta.

The final report for COSIA is being completed at the time of this summary.

LESSONS LEARNED

Based on the results obtained from this study, the following conclusions can be made:

- Both RCC and Beam Centrifuge are found to provide a considerably shorter test duration over the conventional LSC testing. Test duration was two days for the Beam Centrifuge, two weeks for RCC and about five months for LSC.
- The RCC and Beam Centrifuge tests are both applicable for the treated FFT and comparable to conventional LSC testing. RCC test was completed for untreated FFT and showed reasonable comparison with LSC testing, however Beam Centrifuge test on untreated FFT was not completed in this study.
- For a fine tailings-sand mixture such as TT, RCC is currently not applicable due to segregation in a centrifugal field. Beam Centrifuge has the potential to reduce segregation under a lower acceleration of 25G and its application to the fine tailings-sand mixture like TT requires further evaluation.
- For fine tailings-sand mixtures such as NST or TT with hydraulic conductivity that is relatively higher and the consolidation test time is not typically long, it is advisable that the conventional testing such as large strain consolidation and seepage induced consolidation testing be practiced at this time.

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RESEARCH TEAM AND COLLABORATORS

Institution: Thurber Engineering Ltd.

Principal Investigators: Silawat Jeeravipoolvarn, Ph.D., P.Eng. Geotechnical Engineer

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Silawat Jeeravipoolvarn	Teck (Formerly Thurber Engineering Ltd.)	Principal Investigator, Geotechnical Engineer		
Samuel Proskin	Thurber Engineering Ltd.	Senior Geotechnical Engineer		
Trempess Moore	Thurber Engineering Ltd.	Principal		
Reza Moussavi Nik	Imperial	COSIA Project Steward		
Adedeji Dunmola	Syncrude	COSIA Project Steward		
Rick Chalaturnyk	University of Alberta	Professor		
Gonzalo Zambrano	University of Alberta	Research Director		
Nicholas Beier	University of Alberta	Associate Professor		
Ahlam Abdulnabi	Thurber Engineering Ltd. (Formerly University of Alberta)	Geotechnical Engineer		

esNST Geo-Column and Large Strain Consolidation Test and Simulation

COSIA Project Number: TJ0145

Research Provider: PI (Processing Innovation)

Industry Champion: Canadian Natural

Status: Complete

PROJECT SUMMARY

The test program is intended to repeat two geo-column and large strain consolidation tests for enhanced-spiked non-segregating tailings (esNST) with sands to fines ratio (SFR) at about 3.5 (fines content of 22%) and 4.5 (fines content of 18%) with a polymer dosage of 70 g/tonne.

The key objectives of the test program are:

- To study the consolidation behaviour of these NST products,
- To obtain consolidation parameters (compressibility and hydraulic conductivity) for two esNST products (targeted SFR 3.5 and 4.5) by using laboratory test results from geo-column and large strain consolidation test program,
- To evaluate the consolidation performance of selected tailings products using the derived consolidation parameters and a one-dimensional finite strain consolidation numerical analysis for a hypothetical DDA (Dedicated Disposal Area), and
- To compare and confirm findings with the previous geo-column and large strain consolidation test program.

The following key performance indicators were used to evaluate the comparison of consolidation performance for these esNST products for a hypothetical deposition analysis.

1. Maximum mudline elevation: It implies the volume required to store tailings. The lower the maximum mudline elevation the better the storage performance.

2. Total mass of fines storage: The total mass of fines storage is the mass of fines sent to the DDA at the end of filling. The higher the mass of fines storage the better the storage performance.

3. Post deposition settlement: The post deposition settlement is the settlement occurring between the end of deposition and the end of consolidation. The smaller the post deposition settlement the more favorable for reclamation purposes.

PROGRESS AND ACHIEVEMENTS

The parameters for compressibility and hydraulic conductivity for esNST SFR 3.5 and 4.5 with 55 g/tonne flocculation dosages were developed in the 2019 geo-column and large strain consolidation test program and compared with the results from this study. The outcomes of this projects are:

1. Compressibility and hydraulic conductivity of esNST SFR 4.5 are similar to those of the 2019 esNST results. It confirmed that the esNST SFR 4.5 when sufficiently flocculated has favourable hydraulic conductivity properties as previously found in the 2019 study.

2. Compressibility and hydraulic conductivity of esNST SFR 3.5 are similar to those of the 2019 esNST and 2017 sNST (Spiked Non-Segregation Tailings).

3. The elevated fines and clay in esNST SFR 3.5 option require additional polymer to enhance the consolidation properties.

4. The current chemical with the specified dosage does not provide enhanced consolidation properties for esNST SFR 3.5.

LESSONS LEARNED

The right flocculant dosage has a significant impact on the consolidation behaviour of esNST. The polymer dosage is currently based on total solids. Flocculation of tailings with variable SFR will require different dosages depending on fines and clay contents.

After the accomplishment of this project, a suite of NST (Non-Segregating Tailings), eNST (Enhanced Non-Segregating Tailings) and esNST are now available and they can be shared with the industry for tailings planning and management purposes.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Bruce Li

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Bruce Li	Canadian Natural	Senior Tailings Geotechnical Engineer		

Rapid Assessment of Tailings Settlement Using a Benchtop Geotechnical Centrifuge

COSIA Project Number: TJ0148

Research Provider: Suncor., Coanda Research and Development Corporation

Industry Champion: Suncor

Status: Year 4 of 4

PROJECT SUMMARY

Oil sands fluid fine tailings have very poor water release characteristics. Tailings treatments are generally required to improve the consolidation behaviour and manage the tailings in an economical and environmentally acceptable manner. The effect of each treatment method is commonly evaluated, in part, by measuring the short- and long-term consolidation behaviour of treated samples. Geotechnical beam centrifuges, large strain consolidation (LSC) apparatus, and geocolumns are normally used to measure the consolidation properties. However, these methods require many months to complete or are expensive and difficult to deploy in the field.

The objective of this project is to develop a small-scale geotechnical centrifuge that can rapidly assess tailings settlement and disposal options and is suitable for use in both research environments and laboratories at industrial sites. The settlement data enables short- to long-term volume reduction predictions and mine planning, while the sample itself is sized to support follow-up analyses on the consolidated tailings and/or release water. With a relatively fast turnaround, the benchtop centrifuge can be used as a tool to evaluate the consolidation performance of treated tailings on an ongoing basis, provide feedback on the process, and identify anomalies in field tailings treatment operations.

Both beam and benchtop centrifuges have been used for geotechnical testing. Beam centrifuges provide a more theoretically ideal setup for geotechnical experiments and monitoring but are relatively complicated and costly to operate, time-consuming to load and set up, and are typically not readily available for industry use or field “deployment”. On the other hand, benchtop centrifuges are well suited for field and in-laboratory use but are not commonly instrumented with in-flight devices to monitor the consolidation progress. Modifying off-the-shelf benchtop centrifuge to add in-flight measurements would become costly due to the required body alterations to fit in the in-flight instrumentation and integrating these instruments with the existing electronics for operation and timing. The latter item could result in various challenges as off-the-shelf units are not designed with “open” electronics. A more reliable and cost-effective alternative was constructing a custom centrifuge with integrated instrumentation for the necessary in-flight measurements.

This project developed a benchtop geotechnical centrifuge with accompanying software to facilitate the operations, and data collection and analysis. The design and build of the centrifuge accounts for size, robustness, simplicity, functionality, safety, and sample height and volume. The unit spins four samples simultaneously while monitoring the interface settlement of each sample during the flight.

Treated tailings samples were prepared and tested in the benchtop centrifuge, large strain consolidation (LSC) apparatus, and 5 m tall geocolumns for comparison and validation purposes. Additional samples were used to establish operational limits and confirm consistency of the benchtop centrifuge.

PROGRESS AND ACHIEVEMENTS

Custom-designed benchtop centrifuge units were built and commissioned, and validations tests were completed in 2018 in the field. Validation testing performed at multiple relative accelerations produced self-consistent results. The benchtop centrifuge results closely match the outcomes from 5 m geo-columns and numerical modelling using material parameters measured from LSC. Additionally, the impact of a non-linear stress profile from the small centrifuge radius and possible wall effects from the small radius container were separately assessed and determined to be small, consistent with the positive validation results. The validation tests indicate that the benchtop centrifuge is suitable for consolidation modelling and provides a quick and economical way to evaluate tailings samples.

Since 2018, the centrifuge units have been deployed in the field and research laboratories to assess the short - and longer-term settling performance of treated tailings, and to evaluate the effect of the tailings process and material conditions on tailings settlement. These centrifuges enable the analysis of a greater number of samples than would be feasible using conventional techniques, allowing geotechnical engineers, research scientists, and commercial operators to make more informed tailings management decisions. The sample volume is sufficient for evaluating additional characteristics post-flight, such as but not limited to, the following:

- Consolidated sample shear strength, sensitivity, plasticity, BMW (Bitumen, Minerals, Water), clay content via MBI (Methylene Blue Index) or XRD (X-Ray Diffraction), and density.
- Release water trace metals, main ions, TSS, DOC, residual polymer, turbidity, and naphthenic acid.

LESSONS LEARNED

The motivation for developing a small-scale geotechnical centrifuge (benchtop centrifuge) is to address issues related to the cost, time, and infrastructure requirements of existing consolidation test methods. The small radius of the centrifuge is commonly a concern; however, the validation tests results show that the differences between benchtop centrifuge predictions and conventional testing methods are relatively low, indicating that the benchtop centrifuge is suitable for consolidation modelling and provides an economical way to evaluate various tailings treatment options.

Additional consolidation information can be extracted from benchtop centrifuge data with refinement to procedures, control software and analyses. Moving forward, development efforts will aim to enable this, as well as improve the limitations on the types of samples and conditions the benchtop centrifuge is able to support. For instance, samples with low strength (untreated or dilute tailings) can exhibit segregation at moderate accelerations; therefore, require more complex testing and analysis methods to be applied.

PRESENTATIONS AND PUBLICATIONS

Omotoso, O., Melanson, A., Webster, S.E., Dubash, N., Sorta, A.R., Johnson, G.W., Depew, T.A., Mottershead, J., Roy, S.G., Veenstra, C.N., & Mars, E. (2018). *Tailings Centrifugation for Accelerated Assessment of Tailings Treatments and Dewatering* (Canada Patent No. 03014373). Canadian Intellectual Property Office.

RESEARCH TEAM AND COLLABORATORS

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Principal Investigators: Oladipo Omotoso

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Alan Melanson	Suncor	Engineering Advisor, Tailings		
Benny Moyls	Coanda Research & Development Corporation	Research Engineer, Project Manager		

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Neville Dubash	Coanda Research & Development Corporation	Research Scientist, Applied Mathematics and Modelling		
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Alexandre Mars	Coanda Research & Development Corporation	Research Engineer, Mechanical Design Lead		

Large Strain Consolidation Test and Simulation for Weak Tailings in ETF At Horizon

COSIA Project Number: TJ0149

Research Provider: PI (Processing Innovation)

Industry Champion: Canadian Natural

Status: Complete

PROJECT SUMMARY

Results from the 2019 fall pond investigation at the Horizon External Tailings Facility (ETF) indicate that there is a weak NST (Non-segregating tailings) unit in the beach below water (BBW) zone. This weak NST has a fines content roughly between 23% and 43% (sands to fines ratio, SFR between 1.3 and 3.3), solids content between 65% and 78% and peak shear strengths of less than 5 kPa based on Ball Penetration Test. The scope of the project includes laboratory test program to obtain consolidation parameters from the field samples collected from the May 2020 pond investigation. The parameters of large strain consolidation model were used to simulate the consolidation trajectory and identify potential solutions for these tailings under 15 hypothetical tailings treatment scenarios.

The objective of this project is to assess the consolidation trajectory for the weak NST unit at selected location under 15 hypothetical tailings treatment scenarios in the ETF at Horizon site.

The compressibility and hydraulic conductivity parameters for weak tailings at three sands to fines ratios were determined by the large strain consolidation tests. One-dimensional finite strain consolidation analyses were conducted to improve the understanding of relative impacts of selected hypothetical scenarios on the rate of consolidation. The simulation indicates that the deep treatment scenarios (below the weak tailings surface) with drain are most effective followed by the granular cap (shallow treatment) and self-weight consolidation (no treatment). The weak tailings consolidate slowly even with a granular cap load, and some form of internal drainage is essential to increase the rate and amount of consolidation within a short time frame.

Three key performance indicators were used to evaluate the consolidation performance of the treatment strategies:

- Remaining weak tailings thickness at 1, 5 and 10 years. It is to assess how fast the weak tailings (with projected peak undrained shear strength < 5 kPa) are eliminated with time. The lower the remaining weak tailings thickness the better the dewatering performance of strategy;

- Time when 90% of the weak tailings layer is eliminated. It is to assess the total amount of time required to eliminate 90% of weak tailings. The 90% is based on the initial weak tailings thickness and is evaluated using projected peak undrained shear strength. The shorter the time when 90% of the weak tailings is eliminated, the better the dewatering performance of a strategy; and

- Technology readiness level (TRL) rating. Three levels of TRL are used. The higher the TRL rating the closer a technology is to commercial use in the oil sands industry.

PROGRESS AND ACHIEVEMENTS

Large strain consolidation models were developed for weak tailings at three SFR. The consolidation trajectory of weak tailings under 15 hypothetical tailings treatment scenarios were simulated.

The parameters of compressibility and hydraulic conductivity of large strain consolidation models for weak tailings at three SFR have been obtained. These weak tailings parameters did not exist previously but are now available for tailings planning and management purposes for the Horizon ETF.

LESSONS LEARNED

The natural formation of weak tailings is unique, and large strain consolidation parameters for these tailings are now available which can be shared with the industry for tailings planning and management purposes.

The consolidation parameters of weak tailings are available and ready to be shared with the industry.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Bruce LI

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Bruce Li	Canadian Natural	Senior Tailings Geotechnical Engineer		

Froth Tailings Treatment

Minimization Of Greenhouse Gas Emissions in Froth Treatment Tailings by Manipulation of Electron Acceptors

COSIA Project Number: TE0055 (IOSI2017-06)

Research Provider: Queen's University

Industry Champion: Suncor

Status: Year 4 of 3 (one year extension)

PROJECT SUMMARY

The main sources of carbon dioxide (CO_2) and methane (CH_4) emissions in tailings ponds are from the biodegradation of diluent (naphthenic or paraffinic solvents) used in froth treatment, and to a lesser extent from residual bitumen. However, different types of tailings can be mixed in the same tailing pond and can influence the composition of the microbial community involved in degradation. Differences in diluent composition and deposition practices make it difficult to extrapolate the relationship between microbial activity and CO_2 and CH_4 emissions from one tailings pond to another. CH_4 has a global warming potential (GWP) of 28-36 times that of CO_2, therefore reducing or eliminating CH_4 emissions can be of significant environmental and economic benefit under Alberta's Technology Innovation and Emissions Reduction (TIER) Regulation and must be addressed. In the tailings ponds, CH_4 production is due to the bio-oxidation of hydrocarbons coupled to the reduction of terminal electron acceptors (TEAs) such as acetic acid or CO_2 at low redox conditions (~ -250 mV) when other TEAs are absent. When other TEAs are present, the redox potential increases and methanogenesis is inhibited.

The key research objectives/milestones of this program are to:

1. Evaluate the impact of the concentration of different TEAs (such as sulphate and nitrate), diluent (e.g., naphtha), and of nutrients such as phosphate (PO_4^{3-}) and ammonium (NH_4^+), on biogenic gas production from tailings. The tailings samples were obtained from different types of tailing ponds impacted by froth treatment tailings (FTT), with samples from varying depths and locations.

2. Evaluate the effect of bitumen aggregates on biodegradation rates in static microcosm studies and whether residual solvent trapped inside bitumen aggregates offers a mass transfer resistance that may limit biodegradation rates.

3. Develop a first-generation model coupling mass transfer and reaction rates to provide basic information on CO_2 and CH_4 emissions based on pond chemistry, and to use the model to potentially identify dominant mechanisms which may aid in developing strategies for minimizing CH_4 emissions *in situ* or for manipulating the biodegradation rate of the diluent (naphtha).

PROGRESS AND ACHIEVEMENTS

Objective 1 – Effect of TEAs, phosphate, ammonium, etc., on Greenhouse Gas production:

Initial experiments were primarily done on MFT from Pond 7, followed by Pond 2/3 at 5 m, and lastly Pond 2/3 at 15 m. Based on earlier results, later experiments were modified to probe trends observed with Pond 7 MFT so experimental conditions are not identical for all ponds.

A disappearance of phosphate and ammonium (approximately 40%-75% depending on the amount added) was previously reported when these nutrients were supplemented to MFT samples to evaluate microbial activity. The solids in the MFT from Pond 7 have a composition that includes kaolinite (~43 wt%), illite/muscovite (~20 wt%), quartz (20 wt%), siderite (3.7 wt%), calcite (~0.5%) and pyrite (0.3 wt%) (pers. comm. Suncor). Some of these, especially the clays like kaolinite, illite and iron-containing minerals can adsorb these ions (Gerard 2016, Mazloomi and Jalali 2017). The sorption isotherm experiments found that kaolinite KGa-2 could remove 0.58 mg P/g of kaolinite while illite ISCz-1 could sorb 2 mg P/g of illite. Pond 7 MFT was able to remove 0.4 mg P/g of MFT while both Pond 2/3 samples removed about 0.9 g P/g of MFT. When Pond 7 MFT was rigorously extracted with toluene to remove bitumen, it was found to remove significantly more, 2.24 mg P/g of cleaned MFT, compared to only 0.43 mg P/g of MFT for the non-cleaned Pond 7 MFT. This indicates that the presence of bitumen and other organic matter may block adsorption sites on MFT. Additional data is being collected to conduct a phosphate balance to determine whether phosphate removal was primarily by sorption and/or whether other mechanisms may be involved.

From independent experiments, an intrinsic rate of methane and carbon dioxide production was established for each Pond sample without any nutrient amendment. The rate of methane production was similar for Pond 2/3 at 5 m and Pond 7 at 12.5 m with a value of ~ 0.65 ± 0.17 µmol CH_4/100 mL/MFT/day and both had a CH_4:CO_2 ratio of ~3 which is indicative of a multiple methanogenic pathway with a dominance of H_2-independent methylotrophy (Colosimo et al 2016). However, the methanogenic population in Pond 2/3 at 15 m differed in having an intrinsic rate of methane production of 0.20 ± 0.04 µmol CH_4/100 mL/MFT/day with a significantly different

CH_4:CO_2 ratio of 1.0 which is indicative of acetoclastic methanogenesis (Colosimo et al. 2016). When only naphtha (0.2 to 1.0% wt/vol) was added to the MFT samples under methanogenic conditions at concentrations consistent with those discharged into the tailing ponds, the results were similar for all pond samples. With the addition of 0.2% (wt/vol) naphtha, CH_4 production increased above the intrinsic rate. However, adding more naphtha (0.5 and 1.0% (wt/vol)) did not substantially increase methane production. Since there was no correlation with the amount of naphtha, one possible explanation is that nutrients such as a NH_4^+ or PO_4^{3-} may be limiting the rate of methane production with increasing naphtha since phosphate was below detectable levels and ammonium was low in the “as received” pore water from the MFT samples. Another mechanism which may be limiting the biodegradation of naphtha is its bioavailability when solubilized in bitumen. Objectives 2 and 3 are intended to provide more insight into this phenomenon.

To assess the effect of ammonium and phosphate in a reasonable timeframe, a small amount of naphtha (0.2% wt/vol) was added to enhance methanogenic activity. With the addition of 0.2% naphtha alone (biotic control), methane production was significantly higher than when nothing was added using one-way ANOVA with Dunn’s post hoc test ($p < 0.05$). However, adding NH_4^+ or PO_4^{3-} alone or in combination at low or high concentrations resulted in similar methane production as when only naphtha was added.

Sulfidogenic conditions were created by adding sulphate and sulphate reduction was confirmed by H_2S production in the gas phase. Although the experiments were set up slightly differently for the different pond samples, the data consistently showed that there was some enhancement in terms of sulphate reduction with the addition of ammonium and/or phosphate. Methane production was inhibited for approximately the first 20 weeks, regardless of the amount of sulphate, ammonium, or phosphate that was added and remained inhibited at sulphate concentrations greater than 1000 mg/L for experiments conducted for at least 110 days.

The pore water of the MFT samples (as received in the laboratory) had no detectable levels of nitrate. Similar to the studies conducted under sulphate-reducing conditions, either 0.6% or 1% (wt/vol) naphtha was added with ammonium and the increasing concentrations of phosphate. Methanogenesis was inhibited, and nitrate-reducing conditions were achieved by adding NO_3^-. Nitrate can be reduced through a series of intermediates (nitrate (NO_3^-) → nitrite (NO_2^-) → nitric oxide NO → nitrous oxide N_2O → nitrogen gas (N_2)) to nitrogen gas. Nitrate reduction was confirmed by the gas-phase evolution of N_2O, with the amount of N_2O produced increasing with the increasing phosphate. Furthermore, it was found that at low phosphate levels and increasing ammonium concentrations that N_2O production can decrease to non-detectable levels if ammonium was present. The release of N_2O from tailings ponds is not desirable, as it is a more potent greenhouse gas than methane. Methane has a global warming potential (GWP) of 28–36 over the next 100 years, while the GWP of N_2O has a global warming potential of 265–298 over the next 100 years (USEPA https://www.epa.gov/ghgemissions/understanding-global-warming-potentials). In our studies, which were conducted in a closed environment, the N_2O was eventually totally consumed and was reduced to nitrogen gas, and we found that nitrate-reduction can be enhanced at low phosphate concentrations and high ammonium concentrations without, or minimal, N_2O produced.

Objective 2 – Effect of bitumen on naphtha biodegradation:

Previous experiments looked at the abiotic diffusion of the naphtha surrogates (i.e., o-xylene and 1-methylnaphthalene) out of a bitumen "droplet" measured by fluorescence using a very sensitive ross fluorescence imaging centre - PTI QuantaMaster 1. These results were applied to the model developed in Objective 3. The abiotic work was extended to evaluate how biodegradation of o-xylene in a similar system would be affected with and without the diffusion component. After developing MFT enrichment cultures on o-xylene with nitrate or sulphate as the terminal electron acceptor, the nitrate enrichment was selected because it is easier to track biodegradation through nitrate-reduction via the generation of N_2O than through the disappearance of o-xylene. This experiment is in progress.

Objective 3 – First generation model:

A mass transfer model for light hydrocarbon components in bitumen droplets has been developed. The model accounts for diffusion within the bitumen, bitumen-water partitioning, rate-limited mass transfer to the aqueous phase, and reaction in the aqueous phase. It is based on the model developed by Shafieiyoun and Thomson (2018). The model has been applied to a series of 60-day laboratory experiments conducted using bitumen spiked with xylene and 1-methylnaphthalene to determine model parameters and was able to reproduce equilibrium concentrations and the rate of concentration increase in the aqueous phase. Using those parameters, a series of simulations was conducted to investigate the sensitivity of light hydrocarbon release (i.e., depletion from inside a bitumen droplet) to bitumen viscosity and droplet size assuming rapid degradation in the aqueous phase. Simulation results showed that light hydrocarbon release over a 2-year period was limited by diffusion within the bitumen for many of the conditions considered, including those of the bench-scale experiments, for 1-cm diameter droplets. Simulated light hydrocarbons were removed rapidly from the bitumen-water interface, resulting in concentration gradients from the center of the droplet to the interface and lower mass transfer rates to the aqueous phase. Diffusion rates through the bitumen differed between light hydrocarbon compounds, resulting in viscosity and composition that were a function of time and radial distance through the droplet. Additional simulations are underway to investigate light hydrocarbon release over a longer (~20 year) time period, additional droplet sizes, and a variety of degradation rates in the aqueous phase.

LESSONS LEARNED

1. The disappearance of phosphate and ammonium could be due to sorption onto MFT components like kaolinite and illite components. Using standard clays it was found that kaolinite KGa-2 removed 0.58 mg P/g of kaolinite while illite ISCz-1 could sorb 2 mg P/g of illite. While Pond 2/3 samples removed about 0.9 g P/g of MFT and Pond 7 MFT removed 0.4 mg P/g of MFT, Pond 7 MFT cleaned to remove bitumen was able to remove significantly more (2.24 mg P/g of cleaned MFT). This indicates the ability of bitumen to block adsorption sites.

2. The intrinsic rate of methane production was similar in Pond 2/3 at 5 m and in Pond 7 at 12.5 m at ~ 0.65 ± 0.17 µmol CH_4/100 mL/MFT/day with a CH_4:CO_2 ratio of ~3, indicative of a H_2-independent methylotrophic pathway of methanogenesis. However, Pond 2/3 at 15 m had a lower intrinsic rate of methane production (0.20 ± 0.04 µmol CH_4/100 mL/MFT/day) and a CH_4:CO_2 ratio of 1.0, indicative of acetoclastic methanogenesis.

3. Addition of terminal electron acceptors, e.g., NO_3 and SO_4, effectively suppressed CH_4 production. Although N_2O was produced under nitrate-reducing conditions and increased with increasing phosphate, its production was minimized or stopped at low phosphate and high ammonium concentrations.

4. Simulation of the mass transfer model for light hydrocarbon components in bitumen droplets showed that light hydrocarbon released over a 2-year period was limited by diffusion within the bitumen for many of the conditions considered, including those of the bench-scale experiments for 1-cm diameter droplets.

5. Simulation of the mass transfer model for light hydrocarbon components in bitumen droplets showed that light hydrocarbons were removed rapidly from the bitumen-water interface, resulting in concentration gradients from the center of the droplet to the interface and lower mass transfer rates to the aqueous phase.

6. Simulation of the mass transfer model for light hydrocarbon components in bitumen droplets showed that diffusion rates through the bitumen differed between light hydrocarbon compounds, resulting in viscosity and composition that were a function of time and radial distance through the droplet.

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PRESENTATIONS AND PUBLICATIONS

Ramsay, J.A., de Lima e Silva, M.R., Tawadrous, M.A.R., and Ramsay, B.A. 2021. Does Addition of Phosphate and Ammonium Nutrients Affect Microbial Activity in Froth Treatment Affected Tailings? *Microorganisms 9*, 2224. https://doi.org/10.3390/microorganisms9112224

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Rheology Of Froth Treatment Tailings

COSIA Project Number: TE0070

Research Provider: University of British Columbia

Industry Champion: Suncor

Status: Year 2+6 months

PROJECT SUMMARY

Executive summary

The residual light hydrocarbons in froth treatment tailings (FTT) result in generation of a range of biogases in tailings ponds. Upon formation, bubbles would either escape or remain trapped depending on their size and local deposit yield stress characteristics. FTT affected tailings will have to be dredged from the ponds for further processing and treatment using a range of available technologies. Designing such treatment systems and estimating the size of processing units (pumps, pipes etc.) require knowledge of flow behavior (rheology) of the samples. While rheology of tailings has been studied extensively in the past, one aspect that has received little attention is the impact of biogas on their flow behavior at different shearing conditions. This project aims at closing such gaps through performing experimental testing with model and real samples as well as development of models for prediction of their rheology.

The flow properties of FTT affected tailings will be studied at a fundamental level as a function of composition (solids content), biogas content, pressure, and temperature at conditions relevant to industrial process. Of special interest is to understand the impact of biogas volume fraction, bubble shape and other gas-phase characteristics on flow behavior of tailings under shear conditions relevant to the industry. The knowledge generated from this work is expected to support development of more efficient tailings processing units leading to enhanced tailings treatment and dewatering technologies.

Key research objectives

To assist with development of a fundamental knowledge of tailings flow behavior in the laboratory, a model fluid will be developed based on Kaolinite powder mixed with deionized water. The rheology of this model fluid will be matched with oilsands tailings collected from tailings ponds in Alberta. Gas will be injected into the samples at various quantities followed by rigorous agitation to form bubbles of various sizes. To generate bubbles in a controlled fashion, a microfluidics device will be implemented to generate bubbles of different sizes for further testing under a pressure-controlled rheometer. Using a model fluid enables controlling the variables of interest in a systematic manner and facilitates the measurement of bubble size and morphology with respect to suspension characteristics and flow field.

Rheological experiments will be performed using the developed model fluid (Year 1 – Completed) and the tailings from the field (Year 2 – Completed) to identify the properties as a function of gas concentration, temperature, and pressure in the cell.

Rheological experiments will be performed using the parallel-plate geometry and concentric-cylinder geometry as well as a vane geometry to prevent slip effects during testing (Year 2 – Completed). The parallel plates are made of glass for online monitoring of bubble size microscopically during testing (in progress).

Rheological data will include linear viscoelasticity, steady shear to determine the flow curves, thixotropic loops to examine thixotropy effects and yield stress measurements (Year 2-3, completed to large extent).

The rheological properties will be related to morphology (structure-property relationships).

Methodology

This project is purely rheological to develop a fluid based on kaolinite particles to mimic the rheological behaviour of oil sand tailings. Such fluids will be essential to be used to generate bubbles to understand the presence of bubbles on the rheological behaviour of oil sand tailings.

To form bubbles, a microfluidics device has been set up and it is currently used to complete the last part of this work (Year – 3). The rheological methods include steady shear (low to high shear rates and high to low shear rates to understand thixotropy in both kaolinite suspensions and oil sand tailings. Complimentary to these studies, creep testing is used to determine the yield stresses and how these are affected by the presence of bubbles. Complications at the interfaces such as slip are essential to be studied to extract the correct rheological parameters.

The significance of this study is to understand how yield stress and other rheological parameters affect the yielding and therefore dewatering and settling. The methodology has been extended to consider different surfactants to alter the yield stress for easier dewatering and settling. Two such surfactants have been used and the types of surfactants that can lower yield stresses have been understood.

PROGRESS AND ACHIEVEMENTS

Kaolinite suspensions – a model fluid to mimic flow behavior of oilsands tailings: Three different samples of kaolinite particles were used to study the rheology and slip behaviour of suspensions at several concentrations. It was observed that kaolinite suspensions follow a Herschel-Bulkley model with power-law exponents in the range of 0.2-1 (shear thinning to Bingham fluid), depending on the concentration and type of kaolinite particles. The geometry of kaolinite particles was analyzed in detail using Atomic Force Microscopy (AFM). The results, in addition to showing typical morphology of kaolinite particles, revealed unique information about their structure in terms of surface asperity and overall aspect ratio. Comparing the aspect ratios of particles used in the study, particles with large sizes (>1 µm), were found to reach percolation faster than their counterparts. Therefore, at equal volume fractions, they have higher yield stress in comparison to other particles. The true yield stress was determined with the help of the Mooney equation and sandpaper.

Three flow regimes were identified that were associated with type of slip and critical shear stresses, namely (i) an initial elastic regime where the applied shear stress simply causes solid-like deformation (ii) a plug slip flow regime for shear stresses higher than a critical “slip” yield stress but less than the true yield stress of the fluid and (iii) a yield flow regime where the fluids slip and flow. The relationships between “slip” yield stress, true yield stress and slip with the type of kaolinite particles (size, aspect ratio and polydispersity) and concentration were discussed qualitatively using nonlinear rheological characterization.

Based on the experimental findings, the following generalizations can be made for the apparent slip behaviour of the kaolinite suspensions: Upon the progressive increase of the applied wall shear stress, all suspensions initially exhibit plug flow (interfacial yielding). The interfacial yielding stress decreases with decrease of concentration (expected as interfacial strength is a function of concentration). The wall slip in this regime can be suppressed by use of sandpaper of optimum grit size. The thickness of the interfacial layer appears to vary over a narrow range, as it can be judged by the variation of interfacial strength, and it appears to increase with shear stress. At the wall, shear stress is greater than the yield stress, and slip increases further. It appears that the slip in this regime increases with the decrease of concentration. Kaolinite possessing the lowest asperity, average particle equivalent radius, and the highest aspect ratio exhibited the highest slip due to the weak network formation (lowest “slip” yield stress and true yield stress for flow).

Regarding the rheology of the kaolinite particles, the following observations can be made. The yield stress increases with concentration as expected and depends on the geometrical characteristics of particles. Kaolinite samples possessing the lowest asperity and despite having the reported highest aspect ratio resulted the lowest yield stress and the lowest shear thinning although a mild shear-thickening appeared at higher concentration. These conclusions were based on yield stresses obtained independently from various methods. (i) correcting the flow curves for slip effects using the Mooney method, (ii) use of sandpaper of optimum grit size (iii) use the Herschel-Bulkley equation to fit the experimental results and (iv) creep tests for selected suspensions.

Effects of surfactants on the rheology of kaolinite suspensions: The properties of kaolinite suspensions in the presence of Sodium Dodecyl Sulfate (SDS) using zeta potential measurements, confocal laser scanning microscopy, and rheometry were examined. The real yield stress of kaolinite suspension was tuned using SDS by adjusting interactions between particles and SDS molecules at the nanoscale through SDS content variation. Initially, SDS molecules are believed to behave as hydrophobic entities that adsorb on the kaolinite surface and boost particle adhesion (seen mostly in 31wt% only). However, as the SDS concentration grew, micelles developed and acted as steric barriers, pushing particles away and thus weakening the network. The formation of micelles reduced the yield stress of the suspension.

Slip effects, a common phenomenon in kaolinite networks and other colloidal suspensions were also investigated to add to the rheological characterization. The results demonstrated that sonication, concentration, and SDS molecules all influenced slip. Steady shear experiments demonstrated that the slip and real yield stress, as well as the slip velocity of the suspensions, decrease with an increase of SDS. As a final remark, we note that a simple relationship exists between the strength of the network and the apparent slip i.e., apparent slip increases with network weakening that implies easier particle migration from the interface and easier formation of the depletion layer. On the other hand, a strong network implies relatively immobilization of the particles at the interface and thus, less particle migration. Weakening can be achieved by the addition of a surfactant, a reduction in concentration, or sonication.

Rheology of MFT (mature fine tailings): The rheological characteristics of mature fine tailings (MFT) were examined in both the linear and non-linear viscoelastic regimes. The yield stress of MFT with shear thinning behaviour was retrieved by using various methods (i) fitting a Herschel-Bulkley equation to flow curves obtained by shearing the samples from high-to-low shear and from low-to-high shear rate (ii) creep tests (iii) strain sweep experiments in oscillatory mode by exploring the Payne effect. The results were consistent, demonstrating that a single yield stress value cannot characterize the yielding process.

The presence of bitumen in the MFT (up to 2 wt%) suppressed the apparent slip to a large extent likely due to the immobilization of the particles at the interface. On the other hand, simple kaolinite suspensions at similar solid loadings clearly exhibited apparent slip effects, particularly at low shear rates. The effect of temperature on MFT rheology was also studied in detail over the range of 0 °C to 50 °C showing a minimum viscosity and yield stress at about 20 °C (non-monotonic viscosity behaviour). These unexpected results were confirmed using various methods (i) independent flow curve measurements at various temperatures (ii) temperature sweep tests at various shear rates (iii) temperature sweep tests in oscillatory mode in the linear viscoelastic regime. It was concluded that this surprising behaviour is due to the increase of surface charge of particles with increase in temperature. Increase of particle surface charge increases the repulsive forces between particles, improving network strength and thus increases the yield stress with temperature.

MFT samples exhibited thixotropic behaviour higher than simple kaolinite suspensions. Moderate sonication helped with homogenization of samples and thus reduced thixotropic effects helping samples to recover their structure faster and more consistently. Evidence for the thixotropic behavior of MFT is the reduction of viscosity at constant shear rate (typical time scales for thixotropy elimination on the order of 30-50 s). On the other hand, recovery takes longer times (over one hour) due to reduced Brownian motion. Reduction of thixotropic effects will help to improve dewatering of the samples (i.e.; particles would settle faster).

LESSONS LEARNED

As discussed above, yield stress is an important parameter for dewatering and settling of particles. This has been addressed in all our work and the three publications so far in detail. Use of small amounts of SDS surfactants may decrease the yield stress of MFT by a factor of over 10 and thus, are expected to speed up dewatering and settling of particles in MFT. This has already been demonstrated in published papers. It should be noted, however, that the impacts of SDS on the subsequent processing of tailings e.g., flocculation or coagulation have not been studied in this work. Such effects should be considered before making conclusions on using surfactants for rheology reduction.

The effect of the presence of bubbles on the rheological behaviour of these tailings is currently being completed. A microfluidics device has been setup and fluids with various amounts of gas, bubbles of different sizes, and distributions have been prepared to examine their effect on the rheological behaviour of kaolinite and MFT.

PRESENTATIONS AND PUBLICATIONS

Journal Publications

Moud, A.A., Poisson, J., Hudson, Z.M., and Hatzikiriakos, S.G. (2021). Yield stress and wall slip of kaolinite networks. *Physics of Fluids*, *33*, 053105.

Moud, A.A., and Hatzikiriakos, S.G. (2022). Kaolinite Colloidal Suspensions under the Influence of Sodium Dodecyl Sulfate. *Physics of Fluids*, *34*, 013107.

Moud, A.A., Piette, J., Danesh, M., Georgiou, G.C., and Hatzikiriakos, S.G. (2022). Apparent Slip in Colloidal Suspensions. *J. Rheology*, *66*, 79-90.

Piette, J., Moud, A.A., Poisson, J., Derakhshandeh, B., Hudson, Z.M., and Hatzikiriakos, S.G. (2022). Rheology of mature fine tailings. *Physics of Fluids, 34,* 063104.

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Parya Keyvani	University of British Columbia	Postdoctoral	03/2022	-

NSERC-Syncrude IRC in Mine Closure Geochemistry

COSIA Project Number: TJ0130

Research Provider: University of Saskatchewan

Industry Champion: Syncrude

Status: Year 2 of 5 (Term 2 of IRC)

PROJECT SUMMARY

Led by Dr. Matthew Lindsay in the Department of Geological Sciences at USask, the overall IRC goal is to generate scientific knowledge and tools to mitigate geochemical risks to mine closure.

Mine closure research has traditionally focused on improving our understanding of the chemical, biological and physical aspects of individual mine waste deposits, and developing strategies for managing and reclaiming these deposits. Although deposit-focused research is important, a more integrated and interdisciplinary approach is critical for understanding the geochemical evolution of mine wastes and associated waters within closure landscapes at oil sands mines in northern Alberta, and, more generally, at mine sites globally. Insights gained from the first IRC term, which examined the geochemical characteristics of individual mine wastes, form the foundation for this second IRC term. Ongoing research focuses on the evolution of reactive mine wastes, both within individual landforms and, more broadly, mine closure landscapes.

The overarching goal for the second IRC term is to improve estimates of contaminant source terms for reactive mine wastes, and to develop strategies for decreasing chemical mass loading from the closure landscape to the receiving environment. These strategies have the potential to improve environmental outcomes and to minimize mine closure costs for industry. This research focuses on the geochemistry of reactive wastes, with an emphasis on froth treatment tailings (FTT), and how they interact with other mine materials in closure landscapes. Specific research activities fall under four interrelated themes:

Theme 1: Mineralogy and geochemistry of mine materials.

Theme 2: Geochemical evolution of closure landforms.

Theme 3: Geochemical stabilization of reactive wastes.

Theme 4: Passive water treatment in closure landscapes.

These research themes incorporate complementary field, laboratory and modelling approaches that collectively increase knowledge of the geochemical characteristics and evolution of mine waste materials in both individual mine waste deposits and across the closure landscape. Comprehensive chemical and physical characterization focus on understanding the geochemical, mineralogical, and hydrogeological properties of oil sands mine materials. Field sampling, field and laboratory experiments, and numerical modelling examine the geochemical evolution of FTT deposits and evaluate potential geochemical stabilization methods including application of reclamation soil covers. Finally, laboratory experiments evaluate passive water treatment strategies that could be integrated into the mine closure landscape.

This research is generating critical new information to support long-range mine closure and reclamation planning. Key information includes improved contaminant source term estimates for reactive mine wastes, insights into positive and negative implications of mine reclamation strategies, and identification of new opportunities for integrated mine waste management and reclamation. Overall, information generated through this IRC program will offer new strategies to decrease environmental impacts and financial liability of oil sands mining operations.

PROGRESS AND ACHIEVEMENTS

Following unanticipated delays related to the COVID-19 pandemic during 2020, research activities ramped up again in 2021. Progress made toward research objectives are detailed below for each theme.

Theme 1: Mineralogy and geochemistry of solid waste materials

This theme encompasses two research activities focused on the mineralogy of a commercial-scale FTT deposit, examining geochemical and mineralogical compositions, spatial and temporal variability in geochemical, mineralogical, and physical characteristics, and associated variability of acid generation, acid neutralization, and metal(loid) release. Research conducted under Theme 1 focuses on core samples obtained in late 2019 from a commercial scale FTT deposit, known as the Plant 6 FTT beach, shortly before the COVID-19 pandemic (additional details are provided below under Theme 2).

Activity 1.1 - Characterize process mineralogy and geochemistry

MSc-1 continued geochemical and mineralogical analysis of core samples ($n > 150$) obtained during the 2019 drilling program (see Theme 2 below). Substantial progress was made during 2021 and all geochemical and mineralogical analyses were completed by December 2021. Corresponding data analysis and interpretation are nearing completion.

Activity 1.2 - Assess potential impacts of mineral-water interactions on water chemistry

MSc-5 initiated research in September 2021 that builds upon previous research conducted by BSc-1, UG-4 on the geochemical response (i.e., acid generation, acid neutralization, metal(loid) release) between September 2020 and August 2021. Subsequent research has examined acid neutralization and associated metal(loid) release to improve understanding of the geochemical evolution of FTT deposits during oxidative weathering. Laboratory batch experiments are nearing completion and subsequent column experiments are planned for summer 2022.

Theme 2: Geochemical evolution of closure landforms

Continuous sonic core samples extending from surface to > 40 m below surface were collected at eight locations along a 1.6-km transect of the Plant 6 FTT beach deposit. This drilling program produced ~200 discrete samples that directly support Activities 2.1 and 1.1.

Activity 2.1 - Examine the long-term geochemical evolution of FTT deposits

MSc-2 and PDF-1 continued their research on the geochemical evolution of the Plant 6 FTT beach deposit. Sample collection and analysis was completed by December 2021, and ongoing data analysis and interpretation, including geochemical modelling, will be completed by August 2022. This research has demonstrated potential for acidification and metal(loid) release under field conditions within sub-aerial FTT beach deposits. These findings are directly supporting research being carried out under Themes 3 and 4.

Activity 2.2 - Assess geochemical evolution of drainage derived from adjacent FTT and fluid coke deposits

MSc-4 is conducting research into geochemical controls on metal(loid) mobility in landforms that may contain both FTT and fluid coke. Recent efforts have focused on the development of field-scale experiments, which were constructed in November 2021 with instrumentation to be completed in May 2022. Corresponding laboratory column experiments are being initiated to examine controls on metal(loid) transport and attenuation under controlled conditions representative of field settings. This research greatly improves the understanding of the geochemical controls on metal transport and attenuation in mine closure landscapes.

Theme 3: Geochemical stabilization of reactive wastes

Research under this theme was delayed due to field access restrictions and supply chain issues associated with the COVID-19 pandemic. Nevertheless, progress was made on preliminary model development and associated material characterization. Results from Activity 2.1 have directly informed this research theme. Recent efforts have emphasized establishment of field experiments and complementary laboratory studies.

Activity 3.1 - Evaluate the geochemical implications of soil covers for FTT deposits

PhD-1 has focused efforts on experimental design, materials testing, and numerical modelling during 2021. Field-scale lysimeter experiments were constructed in November 2021, with instrumentation to be completed in May 2022 due to supply chain delays. Materials stockpiled during lysimeter installation were sub-sampled to support detailed geochemical, mineralogical, and hydrogeological testing. The bulk geochemical and mineralogical composition of these samples has been determined, and hydrogeological testing has included measurement of particle size distributions, particle densities, and soil water characteristic curves. Resulting data have enabled refinement of preliminary groundwater flow models and supported development of reactive transport models of the lysimeter experiments. Laboratory experiments are underway to quantify oxygen consumption rates during FTT weathering, and additional experiments are planned to examine the implications of reclamation soil covers on the geochemical evolution of FTT under controlled laboratory conditions. This activity will continue through 2024.

Activity 3.2 - Evaluate the geochemical implications of FTT co-disposal

Student recruiting for this activity was postponed due to COVID-19 related laboratory access restrictions. Associated delays were deemed workable as other activities are not directly dependent upon results from this activity. In addition, retrospectively, initiating this project after gaining insight into the geochemical characteristics of FTT through Activities 1.1 and 2.1 was beneficial. A MSc student (MSc-6) is being recruited to initiate this research in September 2022.

Theme 4: Passive water treatment in closure landscapes

Research under this theme has evolved and expanded in response to evolving industry needs. Although specific changes are described below, principal changes involve a shift toward understanding reactive transport along groundwater flow paths within varied mine closure landscape scenarios.

Activity 4.1 - Examine potential for integrated water treatment

This revised activity examines opportunities for integrated passive water treatment of various mine materials used to construct closure landforms. PhD-2 joined this IRC program in September 2020, but COVID-19 related travel restrictions forced remote study until summer 2021. PhD-2 is conducting laboratory experiments and numerical modeling to assess acid neutralization and metal attenuation by various mine materials (i.e., overburden, extraction wastes, upgrading by-products) that may be used during construction of closure landforms. Laboratory batch experiments are underway and column experiments are expected to start during summer 2022. This research activity will continue through 2024.

Activity 4.2 - Evaluate passive treatment options for FTT drainage

Through discussions with the Syncrude MCR team, this activity has shifted to focus on contaminant attenuation via microbial sulfate reduction within FTT deposits and, more broadly, oil sands mine closure landscapes. This decision was supported by preliminary findings from Activity 2.1 and related research on oil sands pit lakes. MSc-3 carried out laboratory batch experiments from August to December 2021 and initiated complementary laboratory column experiments in March 2022. This research activity should be completed by December 2022.

LESSONS LEARNED

Research conducted over the past year offers new insight into the geochemical characteristics and evolution of commercial-scale FTT deposits. These findings will support ongoing mine closure and reclamation planning and, more generally, contribute new information to the field of environmental geochemistry. The potential significance of key contributions is described below.

Geochemical and mineralogical composition of FTT deposits

Information on the geochemical and mineralogical composition of FTT deposits was previously based on end-of-pipe sampling and cursory field campaigns. Research conducted under Activities 1.1 and 2.1 have contributed large amounts of new information that: (i) further constrains the mineralogical and geochemical composition of FTT solids and identifies new relationships between metal(loid) and mineral contents; (ii) identifies relationships between particle-size distributions and FTT mineralogy that develop during post-depositional hydraulic segregation; and (iii) establishes relationships between FTT mineralogy and passive gamma counts to support FTT delineation within tailings ponds.

Geochemical evolution of FTT deposits during oxidative weathering

Research conducted under Activity 2.1 clearly demonstrates that sulfide-mineral oxidation can lead to localized acidification and metal(loid) release within the vadose zone of commercial-scale FTT deposits. Moreover, this research offers the first field-based insight into acid neutralization and microbial sulfate reduction, and their influence on metal(loid) mobility within these siderite-dominated, hydrocarbon-bearing tailings. These results also suggest that chemical reactions (i.e., methane oxidation) and gas transport (i.e., upward advective gradients) within methanogenic FTT deposits influences in situ sulfide-mineral oxidation rates and associated metal(loid) mobility. These new field-based results significantly advance understanding of the geochemical evolution of FTT deposits and, therefore, conceptual models upon which reactive transport models will be developed.

Metal(loid)-mineral interactions in FTT deposits

Understanding metal-mineral interactions has been an important component of research associated with Activities 2.1 and 3.1. Detailed mineralogical and geochemical investigations reveal that metastable secondary phases are important sinks for various metal(loid)s within weathered zones of FTT deposits. For example, synchrotron-based microanalyses (i.e., µXRF, µXRD, µXAS) show substantial accumulation of arsenic(V) with iron(III) phases within these zones. Selective chemical extractions reveal strong potential for metal(loid) mobilization during pH changes and redox transitions that could arise during mine closure and reclamation.

Controls on metal release from fluid petroleum coke and subsequent metal mobility in closure landscapes

Research into geochemical controls on metal(loid) mobility in fluid petroleum coke deposits initiated during the first IRC term continued through 2021. This research revealed strong relationships between geochemical conditions and metal release over time. Related studies have further probed geochemical processes affecting vanadium and molybdenum mobility (key metals released from fluid petroleum coke) in mine closure landscapes. Overall, this research demonstrates that elevated metal concentrations can occur in fluid coke pore water and leachates despite a very low leachable portion of total metals. Additionally, this research demonstrates that development of acidic conditions (e.g., due to potential ARD generation in FTT deposits) could enhance the release of some metal(loid)s from fluid petroleum coke.

PRESENTATIONS AND PUBLICATIONS

The following includes presentations and publications since the start of IRC Term 2 on April 1, 2019. Some of these outputs, therefore, describe research results related to IRC Term 1 that ended on March 31, 2019.

Published Theses

Cowell, M.L. (2021). Geochemical implications of gypsum addition to oil sands fluid fine tailings: Laboratory batch and column experiments. MSc Thesis, University of Saskatchewan, Saskatoon, Canada, 87 pp.

Abdolahnezhad, M. (2020). Metal leaching from oil sands fluid petroleum coke under different geochemical conditions. MSc Thesis, University of Saskatchewan, Saskatoon, Canada, 196 pp.

Journal Publications

Abdolahnezhad, M., Lindsay, M. B.J. (2022). Geochemical conditions influence vanadium, nickel, and molybdenum release from oil sands fluid petroleum coke. *Journal of Contaminant Hydrology*, *245*, 103955–103955. DOI:10.1016/j.jconhyd.2022.103955

Schoepfer, V.A., Lum, J.E., Lindsay, M.B.J. (2021). Molybdenum(VI) sequestration mechanisms during iron(II)-induced ferrihydrite transformation. *ACS Earth and Space Chemistry*, *5*, 2094–2104. DOI:10.1021/acsearthspacechem.1c00152

Schoepfer, V.A., Qin, K., Robertson, J. M., Das, S., Lindsay, M.B.J. (2020). Structural Incorporation of Sorbed Molybdate during Iron(II)-Induced Transformation of Ferrihydrite and Goethite under Advective Flow Conditions. *ACS Earth and Space Chemistry*, *4*(7), 1114–1126. DOI:10.1021/acsearthspacechem.0c00099

Vessey, C.J., Schmidt, M. P., Abdolahnezhad, M., Peak, D., Lindsay, M. B. J. (2020). Adsorption of (Poly)vanadate onto Ferrihydrite and Hematite: An In Situ ATR–FTIR Study. *ACS Earth and Space Chemistry*, *4*(4), 641–649. DOI:10.1021/acsearthspacechem.0c00027

Vessey, C.J., Lindsay, M.B.J. (2020). Aqueous vanadate removal by iron(II)-bearing phases under anoxic conditions. Environmental Science & Technology, *54*(7), 4006–4015. DOI:10.1021/acs.est.9b06250

Lindsay, M.B.J., Vessey, C.J., Robertson, J.M. (2019). Mineralogy and geochemistry of oil sands froth treatment tailings: Implications for acid generation and metal(loid) release. *Applied Geochemistry*, 102, 186–196. DOI:10.1016/j.apgeochem.2019.02.001

Robertson, J.M., Nesbitt, J.A., Lindsay, M.B.J. (2019). Aqueous- and solid-phase molybdenum geochemistry of oil sands fluid petroleum coke deposits, Alberta, Canada. *Chemosphere (Oxford),* 217, 715–723. DOI:10.1016/j.chemosphere.2018.11.064

Vessey, C.J., Lindsay, M.B.J., Barbour, S.L. (2019). Sodium transport and attenuation in soil cover materials for oil sands mine reclamation. *Applied Geochemistry*, 100, 42–54. DOI:10.1016/j.apgeochem.2018.10.023

Conference Presentations/Posters

Schoepfer, V.A., Lum J.E., Lindsay, M.B.J. (2021). Bamfordite precipitation contributes to Mo(VI) coordination changes during Fe(II)-induced ferrihydrite transformation. Goldschmidt Conference, July 4 – 9, Virtual Conference. [Poster]

Schoepfer, V.A., Lindsay, M.B.J. (2020). Mo(VI) incorporation into products of Fe(II)-induced Fe(III) (oxyhydr)oxide transformation. Goldschmidt Conference, June 21 – 26, Virtual Conference. [Poster]

Vessey, C.J., Schmidt, M.P., Abdolahnezhad, M., Peak, D., Lindsay, M.B.J. (2020). Formation of vanadium polymers at ferrihydrite and hematite surfaces. Goldschmidt Conference, June 21-26, Virtual Conference. [Oral]

Schoepfer, V.A., Lindsay, M.B.J. (2020). Structural incorporation of adsorbed Mo(VI) during Fe(II)-induced ferrihydrite transformation. American Chemical Society Spring 2020 National Meeting, March 22 – 26, Virtual Conference. [Poster]

Lindsay, M.B.J. (2019). Acid generation and metal release in oil sands froth treatment tailings. 26th Annual BC/MEND Metal Leaching/Acid Rock Drainage Workshop, December 4 – 5, Vancouver, Canada. [Oral]

Lindsay, M.B.J., Moncur, M.C. (2019). Geochemical considerations for improved management of sulfide mine tailings. *In:* Proceedings of 15th Biennial Meeting of the Society for Geology Applied to Mineral Deposits (SGA), August 27 – 30, Glasgow, Scotland, 4: 1597–1600. [Oral]

Vessey, C.J., Lindsay, M.B.J. (2019). Vanadate attenuation by iron(II)-bearing phases. Goldschmidt Conference, August 18 – 23, Barcelona, Spain. [Oral]

Lindsay, M.B.J. (2019). Acid generation and metal(loid) release in froth treatment tailings. 2019 Canada's Oil Sands Innovation Alliance – Oil Sands Innovation Summit, June 2 – 4, Calgary, Canada. [Oral]

Reports & Other Publications

Lindsay, M.B.J., Bews. B.E. (2021). Industrial Research Chair in Mine Closure Geochemistry: 30 Month Research Progress Report (April 1, 2019 to October 1, 2021). Prepared for NSERC, (File No: 463568 – 18), November 15, 28 pp.

Lindsay, M.B.J., Bews. B.E. (2021). Industrial Research Chair in Mine Closure Geochemistry: Research Progress Report for 2020 (Y1 of 5, Term 2). Annual report prepared for Syncrude Canada Ltd. and Canada's Oil Sands Innovation Alliance (COSIA), COSIA Proj.No. TJ0130, February 25, 7 pp.

Lindsay, M.B.J. & Moncur, M.C. (2019). Geochemical considerations for improved management of sulfide mine tailings. In: Proceedings of 15th Biennial Meeting of the Society for Geology Applied to Mineral Deposits (SGA), August 27 – 30, Glasgow, Scotland, 4: 1597–1600.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Saskatchewan

Principal Investigators: Dr. Matthew Lindsay

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Matthew Lindsay	USask	Principal Investigator		
Emily Champion	USask	BSc – Summer Student	2019	2019
Drake Meili	USask	BSc – Summer Student	2019	2019
Josh Paulsen	USask	BSc – Summer Student	2019	2019
Matthew Fellwock	USask	BSc – Research Student	2020	2021
Mojtaba Abdolahnezhad	USask	MSc	2016*	2020
Mattea Cowell	USask	MSc	2016*	2021
James Schulte	USask	MSc	2018	2022
Drake Meili	USask	MSc	2019	2022
Josh Paulsen	USask	MSc	2019	2022
Jake Marchi	USask	MSc	2020	2023
Julia MacGillivray	USask	MSc	2021	2023
Stuart Ferry	USask	MSc	2021	2023
Eduardo Marquez	USask	PhD	2020	2024
Sanaz Hasani	USask	PhD	2020	2024
Valerie Schoepfer	USask	PDF	2019	2022
Mohamed Edahbi	USask	PDF	2019	2020
Noel Galuschik	USask	Research Assistant		
Brenda Bews	USask	Research Engineer		
Mattea Cowell	USask	Research Assistant		

*Research projects initiated during IRC Term 1.

Research Collaborators:

Name	Institution or Company	Title
Dr. Lee Barbour	USask	Professor Emeritus
Dr. Lesley Warren	University of Toronto	Professor
Dr. Rich Amos	Carleton University	Associate Professor
Dr. Michael Wieser	University of Calgary	Professor
Dr. Jordan Hamilton	Syncrude	Project Steward

On-Line Measurement of Naphtha

COSIA Project Number: TJ0142

Research Provider: Suncor, Coanda Research and Development Corp.

Industry Champion: Suncor

Status: Year 3 of 4

PROJECT SUMMARY

The naphtha content in oil sands tailings is an important process parameter that influences the long-term behaviour of tailings systems. Due to the complex nature of the tailings matrix, coupled with the low levels of naphtha contained therein, there is currently no available solution for live measurement of naphtha in tailings. The current project was focused on enabling a methodology for quantifying naphtha levels in oil sands tailings.

The objectives of the work were to: a) Screen possible platforms upon which to base the measurement, b) Develop a commercial concept based upon the selected platform, c) Demonstrate a 'proof-of-concept' by showing the concept could address the key risk factors associated with implementation, and d) Develop a commercial prototype, leveraging the learnings from the proof-of-concept work.

To de-risk and accelerate the development, a primary strategy applied to the project was to leverage expertise, knowledge and infrastructure gained through the execution of other programs completed on tailings materials. This included analytical methods, and laboratory platforms developed to study tailings systems.

Enabling an instrument that provides an on-line quantitative measure of naphtha in tailings may add significant value to the oilsands industry. The measurement will enable process control of tailings treatment processes, ensuring that material is below target naphtha levels prior to final placement.

PROGRESS AND ACHIEVEMENTS

After a screening of various possible approaches to measuring naphtha, a methodology based upon air stripping was selected as the base platform. The use of air stripping had several advantages over other concepts, providing a simple means of removing the complexities of the sample matrix from the analysis. The approach leveraged know-how and expertise that was gained through previous development work focused on treating naphtha-affected tailings through air sparging. This included kinetic models and lab equipment that could then be tailored and re-purposed to the current project.

The basic analyzer concept consisted of:

- Removing a sub-sample from the process stream;
- Introducing a fixed rate of air through the sample;
- Measuring the transient concentration in the air stream using a photoionization detector (PID); and
- Integrating the transient signal.

Results from the apparatus built to test the proof-of-concept demonstrated:

- A linear response between the analyzer output and the naphtha concentration in the sample;
- Reproducibility of the results;
- Sufficiently short measurement time; and
- Instrument operability.

As part of the concept, a methodology was developed for converting the raw transient signal into a naphtha reading. Using dimensional analysis, a means of integrating only a fraction of the transient signal was developed and tested. Using this methodology, it was found that the concentration in the sample could be estimated by only integrating a fraction of the transient signal, significantly decreasing the time required between samples.

Following the proof-of-concept, a commercial prototype was designed, fabricated, and tested. Although many aspects of this first generation (Gen I) commercial concept performed adequately, upon testing others were found to be lacking. Therefore, a Gen II design was completed that addressed these shortcomings.

LESSONS LEARNED

The work completed to date demonstrates that the on-line analysis of naphtha by air stripping is indeed feasible, as supported by the proof-of-concept results.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corp., Suncor

Principal Investigators: Wayne Brown, Cedric-Laborde-Boutet

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Babak Derakhshandeh	Suncor	Lead-Technology Development		
Elco Hollander	Suncor	Lead-Technology Development		
Wayne Brown	Coanda Research & Development Corp.	Principal Investigator Research Scientist		
Cedric Laborde-Boutet	Coanda Research & Development Corp.	Principle Investigator Research Scientist		
William McCaffrey	Coanda Research & Development Corp.	Principle Investigator Research Scientist		
Derek Hood	Coanda Research & Development Corp.	Engineer in Training (EIT)		
Stephen Roberts	Coanda Research & Development Corp.	Research Scientist		
Andrew Mezzo	Coanda Research & Development Corp.	Research Scientist		
Jeff Mottershead	Coanda Research & Development Corp.	Research Scientist		

Research Collaborators: Benchmark Instruments (Edmonton, AB)

Aerobic Biodegradation Within FTT Affected MFT

COSIA Project Number: TJ0147

Research Provider: Suncor, Coanda Research, and Development Corporation, Innotech Alberta

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

Froth treatment tailings (FTT) refers to the tailings stream that originates from the secondary extraction process step in mineable oil sands processing. This material primarily consists of water and a mineral solids phase, as well as some unrecovered bitumen and trace light hydrocarbons. Depending on the operator, the light hydrocarbons can be paraffinic or naphthenic in nature. During placement of the stream in the tailings containment, the material tends to segregate into a beach portion near the deposition point and a runoff portion that combines with the fluid tailings inventory in the pond. This fluid inventory can be considered FTT-affected Mature Fine Tailings (MFT) if the concentration of FTT markers in the mixture is sufficiently high. The light hydrocarbons originating from the FTT runoff are known to be bio-available and have been linked to microbial processes like sulfate reduction and methanogenesis in some oil sands tailings ponds.

Biodegradation of residual light hydrocarbons have been investigated for several years. Those studies primarily focused on degradation processes within the sediment layer, *i.e.*, under low oxygen conditions. This project considered an alternative approach to light hydrocarbon management, by making use of aerobic degradation processes. Aerobic degradation tends to be much faster than anaerobic processes, and the operational complexity of air introduction into a fluid tailings stream could be justified if the bioreaction time scale could be reduced materially. In this project, scouting level biodegradation experiments were run to test whether there was technical merit to an aerobic degradation approach. Two microbial sources were used in the study: 1) the microbiology naturally present in the fluid tailings inventory, and 2) dedicated biosolids used for refinery wastewater treatment.

PROGRESS AND ACHIEVEMENTS

Experimental findings can be summarized with the following highlights:

- Both the native microbiology and the refinery wastewater treatment biosolids are capable of biodegrading the residual light hydrocarbons from the fluid tailings samples. No obvious initial nutrient restrictions were identified if the fluid tailings are diluted with process water, some indications of nitrogen limitations were observed near the end of the experiments.

- Characteristic times for complete conversion are in the order of 50 to 100 days.

- Degradation rates were compatible with constant biomass concentrations within the reaction medium. This suggests some form of transport limitation for the light hydrocarbons. Reaction rates did not increase with increased initial biomass concentration.

The finding that native microbiology was capable of aerobically degrading light hydrocarbons was of particular interest. Practical deployment of this mechanism may be challenging, however, as outlines below.

LESSONS LEARNED

Two key learnings followed from this work.

First, it was found that great experimental care needs to be taken to ensure that the method of oxygen introduction into the samples does not lead to a loss of volatile organics. Evaporative losses will be indistinguishable from biodegradation and would lead to an overestimation of the bioconversion rates. This is mitigated relatively easily by the addition of pure O_2 to sealed reaction vessels, but periodic checks for the remaining O_2 pressure in the head space will be required to ensure oxygen is not limited.

The second finding, related to the potential for commercial deployment, is that significant scale-up aspects would need to be addressed for this concept to be viable. One complication is the likely need for seasonal operation of this type of bioreactor. To treat meaningful quantities of fluid tailings, reactor scales of the order of 1-10 Mm^3 in volume may be required. This far exceeds practical process equipment scales, and lagoon style systems would be required. Climatic conditions in the region are such that the system would have to go through a cold start-up cycle every year. Biological systems are typically not robust to major transients, and it will require significant operational effort to guarantee acceptable annual efficiency for such a system.

When considering the added complexity of managing the flow distribution of a fluid tailings slurry through the reactor system and the potential for floating bitumen because of slurry aeration, the practicality of active aerobic diluent degradation for fluid tailings is somewhat in question.

PRESENTATIONS AND PUBLICATIONS

Hollander, E., Gharabegian, V., Brown, W., & Derakhshandeh, B. (2019). *Active Biodegration of Light Hydrocarbons from Fluid Tailings* (Canada Patent No. CA3059673A1). Canadian Intellectual Property Office.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor, Coanda Research and Development Corporation, Innotech Alberta

Principal Investigators: Elco Hollander

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Elco Hollander	Suncor	Engineering Specialist		
Wayne Brown	Coanda R&D	Chief Technology Officer		
Karen Budwill	Innotech Alberta	Research Scientist		

Tailings Characterization

Long-Term Dewatering of Amended Oil Sands Tailings: Co-Funded by COSIA And NSERC (An NSERC Collaborative Research and Development Grant)

COSIA Project Number: TE0036

Research Provider: Carleton University

Industry Champion: Syncrude

Status: Year 4 of 4 plus 1-year extension

PROJECT SUMMARY

The project aims to reduce dewatering performance uncertainty in oil sands tailings deposits through:

- Increasing reliability of predictions of long-term settlement and dewatering; and
- Improving understanding of how pipeline transport modifies subsequent dewatering behaviour.

The specific objectives and deliverables to achieve these goals include:

1. Improving methods and experimental techniques to rapidly estimate consolidation properties, namely the compressibility and hydraulic conductivity functions;
2. Investigating time-dependent behaviours in polymer-amended fluid fine tailings (fFFT) (creep and thixotropy/structuration) that potentially influence long-term consolidation predictions;
3. Incorporating such behaviours into our research group's consolidation-desiccation model UNSATCON;
4. Extending UNSATCON from a one-dimensional (1D) to two-dimensional (2D) model;

5. Evaluating long-term dewatering potential for a range of polymer types, and providing feedback to polymer developers on how to optimize polymers for long-term tailings dewatering; and

6. Studying changes in pipeline rheology and linking to post-pipe dewatering behaviour to optimize polymer dosage and to assist operators developing improved technologies for on-spec and off-spec detection.

7. The methodologies employed include a spectrum of experimental and theoretical work. Experimental work includes i) standard large strain consolidation testing to provide benchmarks for new consolidation estimation methods, ii) Construction of a new apparatus for measuring consolidation parameters at high void ratios / low effective stress iii) Consolidation, rheology, and shear strength testing on multiple small samples (10 cm high, 20 cm diameter) aged in sealed conditions up to a year, iv) Simulating flocculation.

Numerical work involved theoretical development, tested against laboratory but also data from field pilot tests on fFFT deposition conducted by member companies.

PROGRESS AND ACHIEVEMENTS

The research found that structuration/aging is an important phenomenon in at least some kinds of polymer-amended FFT (fFFT). Structuration means the compressibility of the material decreases (the material stiffness increases) over time, independent of density. The consequence is that current predictions of long-term dewatering in deep deposits of tailings may over-predict long-term dewatering if compressibility measured over a short duration is used in the predictions (which it usually is) Specifically, structuration generated pre-consolidation pressures over 50 kPa, over a period of 100 days. The samples of FFT were 10 cm thick, submerged and mixed with standard anionic high molecular weight polymers. The mixing procedures were designed to simulate short pipeline transport such as the Atmospheric Fines Drying (AFD) technology. Structuration did not appear to progress beyond 100 days.

The database expanded on structuration tests to different kinds of FFT and centrifuge cake. Tests were also conducted on a sensitive natural clay, to check the methodology and to examine the generality in the results. The results show the magnitude of structuration varies with polymer dose. To date, polymer doses that result in high short-term dewatering manifests the largest degree of structuration. The effect is significant enough that, for example, for one FFT, the final state of hypothetical 50 m deposit (as estimated using the compressibility curve to predict the end of consolidation state) can go from a relatively weak deposit (at 1000 ppm dose) with a residual undrained shear strength less than 5 kPa throughout most of the depth, to one where the residual undrained shear strength is greater than 20 kPa (at 600 ppm dose). In this example, structuration in the 1000 ppm samples is high, while lowest is the 600 ppm sample. Also, for this example, 1000 ppm would be the optimal dose based on short-term dewatering. The findings show centrifuge cake does manifest some structuration, but the magnitude is lower than in the fFFT samples studied to date, with the pre-consolidation pressure being in the order of 10 kPa. However, this effect is still strong enough to influence accurate extrapolation from pilot studies.

Three candidate methods were developed were developed to rapidly estimate the hydraulic conductivity-void ratio (or k-e) relationship. These methods are described in a number of papers, particularly a paper presented at the International Oil Sands Tailings Conference (IOSTC) 2018 (Babaoglu, Y., Qi, S., Simms, P, 2018). These methods range in time and cost from single point measurement of hydraulic conductivity coupled with database learning, to column tests involving *ex-situ* measurement of density using non-gamma ray techniques. Using data from large strain consolidation (LCS) tests at the University of Alberta (UA) (co-principal investigator (co-PI), Beier), the three methods to rapidly estimate k-e have been further verified. These tests include data on novel polymer fFFT mixtures, the new polymers created in co-PI Soares (UA Chemical Engineering) laboratory. A column test was developed to rapidly estimate the k-e function using a combination of the three methods previously documented in IOSTC 2018. The column test uses a high rate of non-destructive measurement of density and pore-water pressure measurements to directly calculate fluxes and gradients in pressure, therefore allowing for a high density of direct k-e measurements. The column test can be designed to measure k-e in the high range of void ratio, where the greatest uncertainty lies, in less than two weeks. This can be combined with other methods to estimate the full k-e function. Preliminary comparisons with the UA LSC data using replicate samples are very good to date.

These techniques are sufficient to be used as screening tools to evaluate proposed changes to current technologies, such as the development and assessment of new polymers.

The findings show that high-powered optical microscopy coupled with digital image analysis is a powerful tool for studying floc evolution during short-term dewatering (two to three days) or for studying the effects of shearing and floc recovery during pipeline transportation and deposition. Flocs are clumps of fine particulates formed during flocculation. The results demonstrated that in certain types of flocculated FFT, flocs continue to grow for at least a 48-hour period. Flocs initially approaching maximum diameters of 200 microns are reduced by shearing but recover through aging to flocs up to 60 microns in diameter.

The work linking pipeline transport to dewatering replicated earlier work performed by industry using a large Couette rheometer to simulate pipeline transport. Further work is now progressing to understand how material changes and recovers after shearing during pipeline transport, using optical microscopy and advanced rheometry. Plans are in place to generate tailings exposed to different flow regimes and test them in our specialized column experiment to measure consolidation properties.

Advancements have been made in the use of the torque rheometer to optimize mixing and to simulate pipeline shear, to the point where it can optimize short-term dewatering based on the torque measurements during mixing, for different polymers, different fluid fine tailings (FFT), at different solids contents. Knowledge has been gained on how the rate of polymer injection affects optimization. Work is progressing correlating polymer mixing and pipeline transport to long-term dewatering. The tests conducted to date show that in most cases, while short-term dewatering may be reduced due to pipeline transport, long-term dewatering is similar or slightly enhanced compared to the non-sheared samples.

A 2D version of the UNSATCON model was developed. This 2D model has capabilities for large strain consolidation and quasi-unsaturated desiccation.

The use of coupled creep-consolidation models embedded in UNSATCON are being used to analyze pilot data provided by COSIA's Tailings Environmental Priority Area (EPA) members. Results to date suggest that this type of model can be used to credibly extrapolate from these pilot tests, as they are able to match both density profiles and pore-water pressure measurements. In general, for a realistic range of parameters, the difference in settlement predictions between consolidation only models and consolidation-creep models is less than 10% (for example, a spread of final heights between 23 and 19 m, for an initially 50 m high deposit), but the difference in pore-water pressure and therefore effective stress predictions is much greater. Modelling of these pilot studies that also accounts for structuration was initiated.

Ageing was studied in a different fFFT (different FFT, different polymers). A sandier (SFR 0.6) FFT showed less ageing, with maximum pre-consolidation pressures of 10-20 kPa, rather than 50 plus kPa observed in a lower SFR ~0.4) FFT.

PhD student Arazoo Patel is investigating ageing using soils and material other than FFT. For example, tests were run on Leda Clay; which has somewhat similar mineralogy and Atterberg limits to FFT and is also easier to reuse in tests. The research discovered that for a wide range of fFFT, FFT, and natural clays, both the rate and maximum extent of ageing are relatively well-bounded, when the increase in strength is normalized with the strength developed after consolidation, which generally conforms to an initial plateau in the ageing data. To pick a rough estimate, the maximum extent of ageing seems to be 5 times this initial strength; termed EES for early equilibrium strength (shown in Figure 9 below) Likewise, the rate of ageing can be well-bounded using the equation shown.

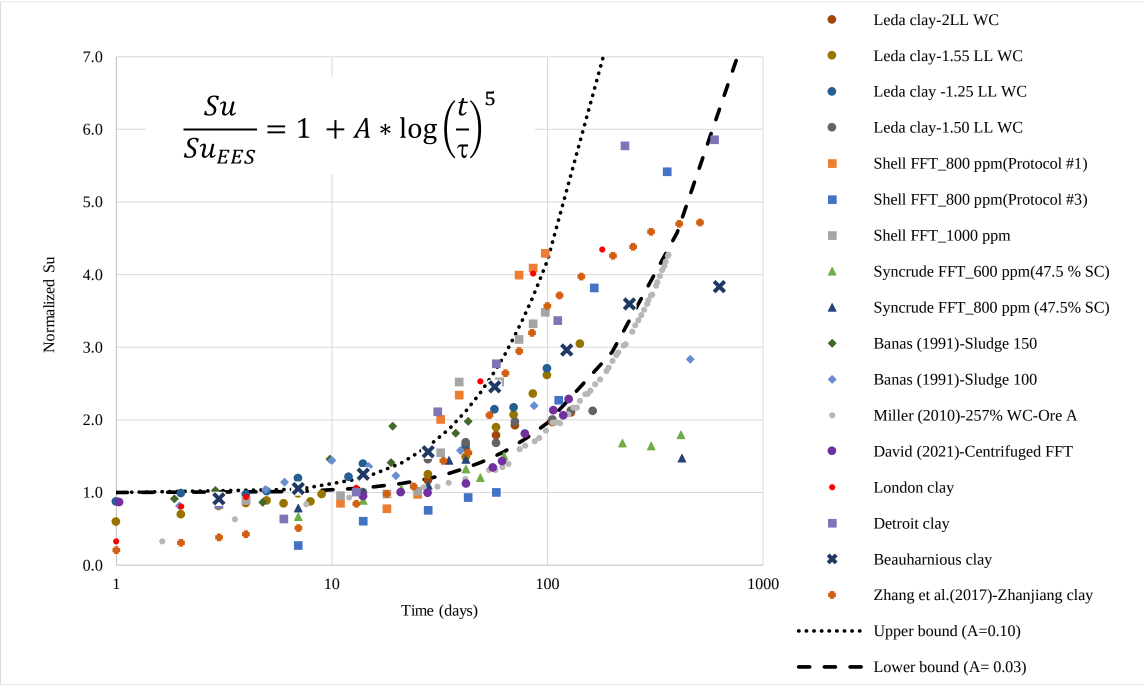


Figure 9. Rate and magnitude of ageing as indicated by measurements of strength relative to post-consolidation strength.

A large consolidation test (0.3 m by 0.3 m by 0.7 m tall steel box) was completed on centrifuge cake tailings. This last test was performed to examine consolidation at a large enough scale, such that the test cell could be instrumented with multiple porewater pressure sensors and water content sensors. The test show: quite clearly how creep and ageing affect the consolidation process of centrifuge cake tailings, pre-consolidation pressure can develop in a more realistic physical simulation than a simple oedometer test, how creep suppresses pore-water pressure dissipation after the pre-consolidation pressure is exceeded. An example of the results is shown in Figure 10 below; where the settlement predicted from a large strain consolidation model is compared with the measured settlement. The effect of the pre-consolidation pressure, developed sometime before the end of the initial self-consolidation phase, is clear. More details can be found in Igbinedion (2020).

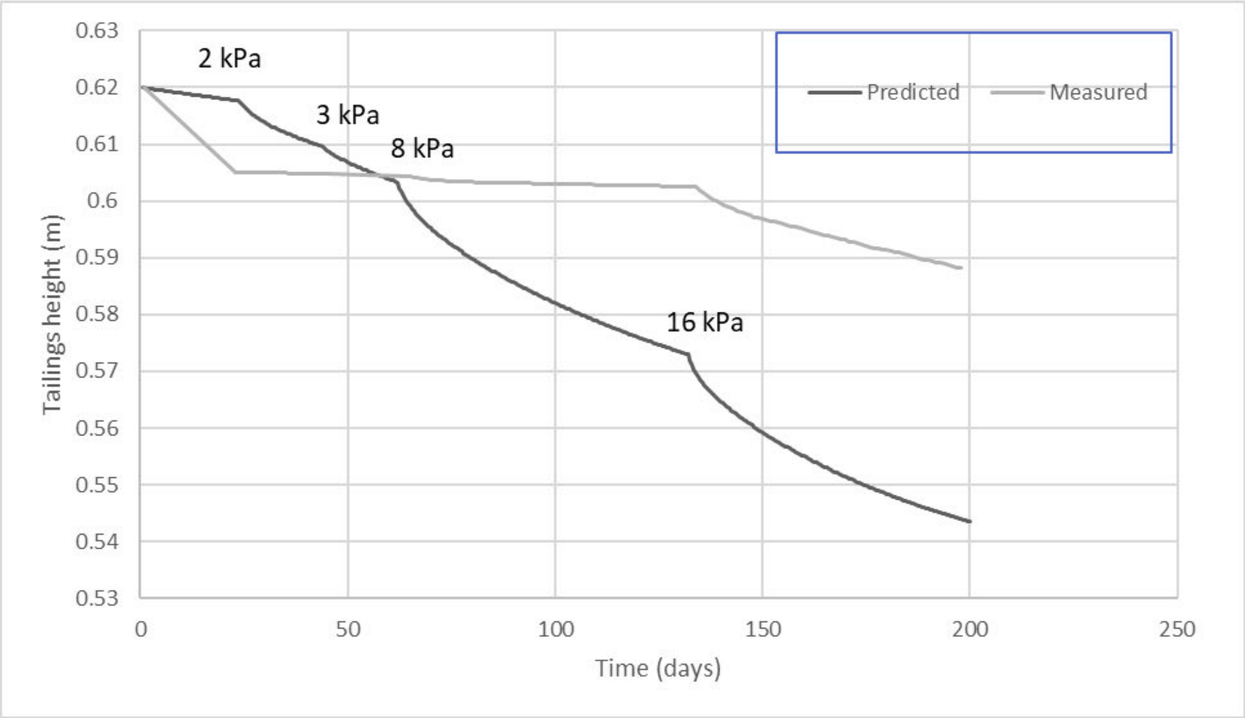
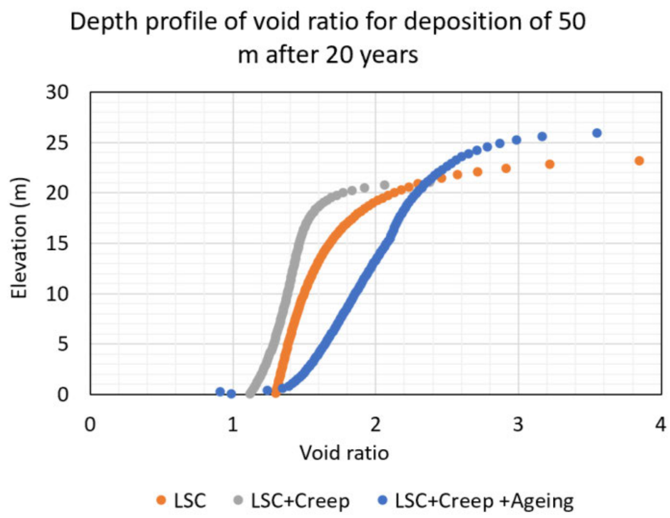


Figure 10. Measured settlement and settlements predicted by a large strain consolidation model in a large consolidation test on centrifuge cake tailings (Igbinedion 2020).

On the modelling side, PhD student Narges Gheisari has developed a large stain consolidation model that incorporates creep and structuration. This model seems to work well, but unlike the previously developed creep-consolidation models, it has several novel elements, that we are endeavoring to test rigorously. The model uses both experimental and pilot data from tailings, and the much larger dataset from soft soils to validate and develop the model. Part of the dataset to be used for model validation is the large consolidation test discuses above.

Gheisari has also published a paper (Gheisari et al. 2020) that describes a methodology for calibrating creep-consolidation models to pilot data; despite significant uncertainties in the input parameters. This paper uses calibrated conventional large-strain consolidation and the creep-consolidation models to generate predictions of consolidation in a hypothetical deep deposit. The analyses show that, while different models are employed, the predictions of all the models fall within a reasonable range: for a 50 m deposit (Figure 11) the difference in predicted settlements at any time is less than 5 m between the models. For the creep models, the dissipation of pore-water pressure is slower, and the settlements over the long term will be larger.

Gheisari has continued this analysis to include the model with ageing, which was presented at the COSIA's industry student-interaction day event in December 2020. The ageing model resulted in less settlement, higher void ratios (lower density), but also higher effective stress than the other models. As stated above, because of several novel additions to this model, there is still uncertainty that the ageing model is the best that can be done and continues to be tested against other tailings data and soft soil data from around the world.



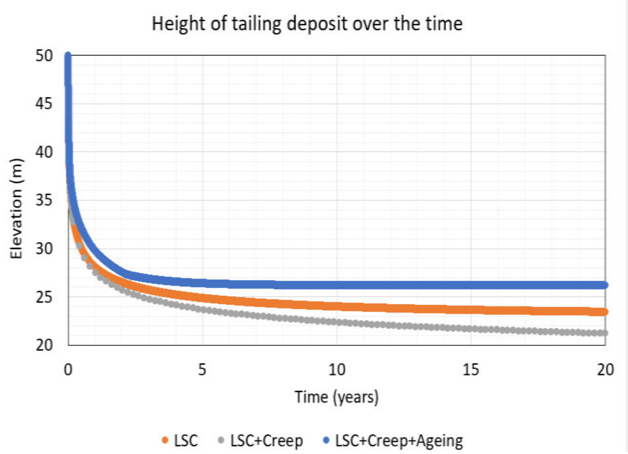


Figure 11. Output from different models used to analyze a hypothetical deposition scenario; all models calibrated to the same data set from a pilot of fFFT deposition.

LESSONS LEARNED

The change in the compressibility curve due to structuration potentially has great significance to the anticipated rate of settlement and strength gain in deep deposits. If structuration occurs in field deposits, then the rates of settlement and strength gain in the long-term may be less than currently anticipated. However, with respect to strength, it may be more correct to say ageing increases peak strength for a given void ratio. Work continues on examining the generality of the results, in other words, what type of tailings deposits would be subject to this behaviour. Additionally, through the ongoing modelling work of COSIA member pilots and field trials, results will determine if creep and structuration are net positives or negatives to the performance of their deposits. If negative, there are ways of depositing tailings that would minimize the negative aspects of structuration, and the research can assist member companies with those decisions. For some reclamation strategies, such as water-capped tailings, structuration may be positive, as it will affect consolidation and therefore reduce contaminant flux to the overlying water body. The results that indicate a lower polymer dose is more optimal for long-term dewatering in the field has the potential for large financial implications. Even for terrestrial reclamation, ageing may be net positive, as evidence in somewhat analogous soils suggest that at least part of the peak strength attributed to ageing reliably contributes to deposit or landform stability; and the magnitude of long-term settlement would be reduced by ageing, allowing for quicker reclamation.

The methods proposed at the COSIA student-interaction day and in conference papers (Babaoglu et al. 2018 & Babaoglu & Simms 2020, 2018, 2017), and in journal papers (Baboaglu & Simms 2020, Qi & Simms 2019, Qi et al. 2020), to rapidly estimate the consolidation properties, are sufficiently accurate to be used at least as screening tools. Industry can adopt these methods as tests for key performance indicators, if convenient. There is increased confidence now that these methods can be used by industry to rapidly estimate k-e, removing either slow or expensive consolidation testing as a barrier to innovation. A summary paper, comparing these methods, has been accepted in Tailings and Mine Waste 2022.

Feedback from mechanical devices interacting with the tailings seems to be an excellent means to optimize flocculation, and to monitor tailings during pipeline transport. The research group is moving towards testing an application in a small pipeline, where a series of mixers, with torque measurements and feedback control, will be used to control and optimize polymer mixing in real time. There are plans to conduct experiments where the properties of the feed are varied with time to challenge the optimization system. Initial findings from this line of work have been final published in Minerals Engineering (Aldaeef et al. 2021).

Following research from a previous grant from COSIA, there is now the ability to simulate channel formation during tailings deposition in computational fluid dynamics (CFD) simulations of non-Newtonian flow. The work has been extended to simulate 3D Dam breach; this will be used in the next project on tailings flowability (Figure 12).

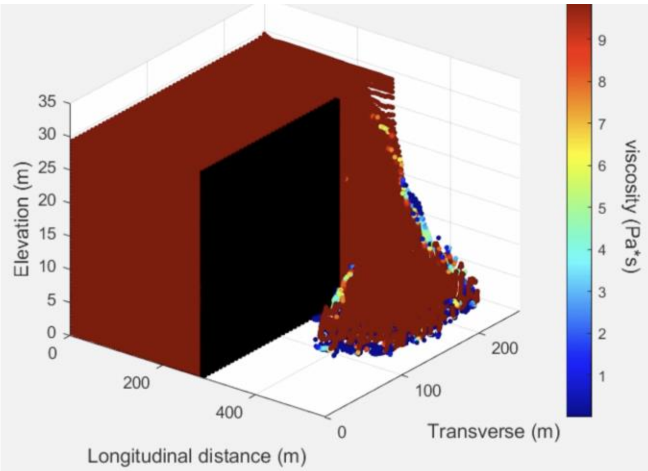


Figure 12. Simulation of 3D Dam breach using thixotropic rheology in a CFD model

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RESEARCH TEAM AND COLLABORATORS

Institution: Carleton University, University of Alberta

Principal Investigators: Paul Simms, P.Eng.

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Paul Simms	Carleton University	Principal Investigator		
Nick Beier	University of Alberta	Assistant Professor		
Joao Soares	University of Alberta	Professor		
Sunchao Qi	Carleton University / Sichuan University China	Postdoctoral Fellow/ Professor at Sichuan University	2017	Completed PostDoc December 2018
Amin Esmaelizadeh	Carleton University	Postdoctoral Fellow	2019	2022
Abdulghader Adulrahmna	Carleton University	Research Engineer / PhD	2018	2021
Yagmur Baoaboglu	Carleton University	PhD Candidate	2016	Defended March 2021
Muhammad Asif Salam	Carleton University	PhD Candidate	2015	2020 (completed)
Narges Gheisari	Carleton University	PhD Candidate	2018	2022
Arazooben Patel	Carleton University	PhD Candidate	2019	2023
Oswaldo Hurtado	Carleton University	MSc Candidate	2016	2018 (complete)
David Ignaebion	Carleton University	MSc Candidate	2018	2020 (complete)

Hissan Khattack	Carleton University	MSc Candidate	2017	2018 (complete)
Hirlatu Peruga	Carleton University	MSc Candidate	2018	2021
Nadine Salam	Carleton University	MSc Candidate	2019	2021
Linda Botha	University of Alberta	Postdoctoral Fellow	2017	2017 (complete)
Sarang Gumfekar	University of Alberta	PhD Candidate	2018	2021
Vahid Vajinejad	University of Alberta	Postdoctoral Fellow	2017	2019 (complete)
Yunhai Zhang	University of Alberta	PhD Candidate	2019	2023
Kwaku Amoako	University of Alberta	M.A.Sc. Candidate	2018	2020 (complete)

Insitu Real Time Measurement of Solids Content

COSIA Project Number: TE0041 – RWG (IOSI 2016-10)

Research Provider: University of Alberta, Northern Alberta Institute of Technology /Ying Tsui

Industry Champion: Canadian Natural

Status: Complete (final report under review)

PROJECT SUMMARY

The objective of this project is to develop a subsurface solids content analyzer based on hybrid optical and safe X-ray methods. Various options are being explored for both techniques, including different wavelength lasers and detection geometries for the optical technique and different sources and geometries for the low-level X-ray detector. The X-ray technique is used as the calibration standard for the optical sensors. The technology is being validated in laboratory scale systems. Numerical models are being developed for both the scattering and X-ray measurement techniques to allow easy extension to systems with different material constituents. The technology is being developed in such a way that it can be potentially implemented at remote oil sands tailing ponds to measure settling of tailings in situ in real time with lateral and depth spatial resolutions. This technology can be used by the oil sands industry to incorporate into the design of their oil sands projects to deliver a more effective process and improved environmental performance.

Milestones include:

1. Testing of scattering techniques with simple clays in suspension such as kaolinite.
2. Testing of scattering techniques with Fluid Fine Tailings (FFT) samples.
3. Development of a low activity X-ray source and demonstration of ability to measure solids contents.
4. Implementation of a low activity X-ray source in a geometry and detector system suitable for installation in test columns.
5. Investigation of window fouling and development of strategies to mitigate effects on scattering measurements.
6. Optimization and demonstration of optical measurements of settling using an array of scattered light detectors in test columns with FFT samples.

7. Demonstration of low-level X-ray measurements in test columns with FFT samples.

8. Demonstration of calibration of optical scattering detectors with low-level X-ray detectors in test columns.

9. Development of a modelling code for light scattering from kaolinite and FFT.

10. Development of a modelling code for X-ray transmission through kaolinite and FFT.

PROGRESS AND ACHIEVEMENTS

The project has been completed on July 31, 2021. The results include:

Progress made in 2018

1. Lab bench measurements of the scattering of laser light at various angles and at various wavelengths were completed.

2. A test column and detector mounting tube was developed.

3. Scattering measurements of the settling of tailings in a test column began over periods of up to one month.

4. Fouling tests were carried out on various plastic and glass windows.

5. The ability to measure inorganic solids content in test samples of kaolinite and FFT was demonstrated using a low level X-ray source.

6. The development of a first principles modelling code began using 3D Finite Difference Time Domain (FDTD) Electromagnetic Scattering calculations to model the scattered light from one to a few irregular shaped particles.

7. A first principle modelling code based on GEANT4 (**GE**ometry **AN**d **T**racking) was developed for the low level X-ray scattering measurements and compared to the measurements obtained in kaolinite and FFT.

Progress made in 2019

Building on the 2018 activities:

1. Lab bench measurements of the scattering of laser light at various angles and at various wavelengths were completed and an optimum wavelength for measuring solids content was determined.

2. Fouling tests were completed on various plastic and glass windows and the best “anti-fouling” optical material was determined.
3. The ability to measure inorganic solids content at few percent accuracy in test samples of kaolinite and FFT was demonstrated using two low-level X-ray sources.
4. A specially designed compact, portable, and economical gamma ray detector was fabricated. The custom-made gamma ray detector can be fabricated at a significantly lower cost than a typical commercial gamma ray detector.
5. A first principal modelling code based on GEANT4 was developed for the low-level X-ray scattering measurements and compared to the measurements obtained in kaolinite and FFT for different setups. The calculations accurately model the X-ray source and measurement system giving good agreement with the experimental results to within a few percent.
6. Scattering and low-level X-ray measurements were used to track the temporal change of solids content in a settling column filled with a kaolin and water mixture and showed consistent results.

Progress made in 2020

Building on the 2019 activities:

1. The solids content measurement precision at the optimum wavelength was determined based on the lab bench measurements.
2. As a result of finding “anti-fouling” optical materials, water contact angles, bitumen-in-water contact angle and fouling tests were carried out using various optical windows and coatings.
3. The inorganic solids content detection ability of the compact low-cost gamma ray detector was demonstrated with high accuracy (within a few percent) in kaolinite and FFT test samples using a low-level X-ray source.
4. Progress on the first principle GEANT 4 modelling of the low-level X-ray scattering measurements enabled comparison of the simulation results to actual measurements using kaolinite and FFT in different experimental setups. The calculations were found to accurately model the X-ray source and were in good agreement (within a few percent) with the experimental results.

5. Experimental results demonstrated that both the optical and low-level X-ray techniques provide consistent results for temporal change of the solids content at varying depths within the settling column.

Progress made in 2021

Building on the 2020 activities:

1. Conversion of optical scattering signals to FFT solids content (in wt.%) was confirmed with two different lab calibration set ups.
2. Conversion of gamma ray signals to FFT solids content (in wt.%) was confirmed with a lab calibration set up and the first principle GEANT 4 modelling.
3. The agreement between the optical and low-level X-ray techniques was established from settling column experimental results on solids content measurements at several depths.
4. Optical materials with bitumen fouling resistant properties were investigated to extend the duration of the optical analyzer before it needs maintenance.

LESSONS LEARNED

The lessons learned from the previous and current reporting activities are:

1. Long wavelength near infrared (NIR) laser sources are advantageous for solids content detection.
2. Accurate absolute measurement of solids content can be made with low-level X-ray transmission diagnostics.
3. Compact, portable and high accuracy custom-designed gamma ray detectors can be fabricated economically.
4. Accurate modelling of X-ray diagnostic response requires incorporation of both absorption and scattering in the X-ray model.
5. Use of low-cost widely available fouling resistant optical materials can extend the duration of the optical analyzer substantially before maintenance will be required.
6. Optical and gamma ray techniques can be used simultaneously to measure the solids content at different depths with excellent agreement.
7. Gamma ray technique can be used as in-situ calibration method for the relatively low-cost optical system.

PRESENTATIONS AND PUBLICATIONS

Journal Publications

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RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigators: Ying Tsui

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Robert Fedosejevs	University of Alberta	Professor		
Manisha Gupta	University of Alberta	Assistant Professor		
Andrea Sedgwick	Northern Alberta Institute of Technology	Applied Research Chair		
Md Zahurul Islam	University of Alberta	Visiting Professor		
Nathaniel Zirk	University of Alberta	Technician		
Felipe Goncalves	University of Alberta	BSc Co-op student	2015	2020
HaMy Dong	University of Alberta	BSc Co-op student	2015	2020
Wendy Wan	University of Alberta	MSc student	2016	2018
Priyesh Dhandharia	University of Alberta	Postdoctoral Fellow		
Bo Yu	University of Alberta	MSc student	2017	2020
Wei Wang	University of Alberta	MSc student	2017	2021
Tulika Srivastava	University of Alberta	Postdoctoral Fellow		
Talwinder Kaur Sraw	University of Alberta	Postdoctoral Fellow		
Channprit Kaur	University of Alberta	Postdoctoral Fellow		
Jiangwen Zhang	University of Alberta	MSc student	2019	2022

Allen Feng	University of Alberta	BSc Co-op student	2016	2021
Bo Yu	University of Alberta	Research Assistant		
Xiaoxuan Liu	University of Alberta	PhD student	2020	2023

State Of Knowledge of Environmental and Human Health Impacts of The Use of Anionic Polyacrylamides in Oil Sands

COSIA Project Number: TE0086

Research Provider: Intrinsik Corp. (with Vandenberg Water Science)

Industry Champion: Syncrude

Status: Year 1 of 1

PROJECT SUMMARY

Anionic polyacrylamide (PAM) compounds are polymeric flocculants that are applied in many industries, including oil sands mines, for the purification and management of water and solids, among other uses. At oil sands mines, PAM flocculants are applied to fluid tailings to accelerate and improve consolidation and to clarify supernatant water processes that are important for water recycling and reclamation. As part of mine reclamation, treated tailings pore water and supernatant water will be actively or passively transported to the receiving environment. Therefore, the environmental transport and transformation mechanisms of PAM, including degradation to daughter products and release of residual acrylamide, must be understood to manage the materials during operations and closure.

Historically, the environmental risk of PAM has been thought to be relatively low because the polymer is very large and non-toxic and would be strongly bound to soil particles, while the residual monomer and other degradation products are highly biodegradable and unlikely to persist in the environment. Abundant literature suggests that PAM itself poses little to no toxicological risk as an amendment in oil sands tailings. PAM sorbs strongly to soil and is unlikely to be transported to human or ecological receptors. Even if PAM were transported, it is not bioavailable or toxic. It is widely applied in many industrial and personal products with no apparent adverse effects.

To test these assumptions, this literature review compiled the state of knowledge regarding the use of anionic PAM in tailings management at Alberta oil sands mines and the potential environmental consequences of PAM and its by-products.

PROGRESS AND ACHIEVEMENTS

PAM Degradation

Biodegradation of PAM may occur within the tailings matrix where PAM is abundant and stably bound until degraded. Long-term storage of PAM may present opportunities for microbial communities to adapt to metabolize the molecule after other sources of carbon or nitrogen are depleted.

Studies generally suggest that while nitrogen appears to be readily metabolized from PAM under a wide range of conditions, carbon tends to be used only when labile carbon sources have been depleted. This suggests that PAM degradation in oil sands tailings may be incomplete or absent in fresher tailings where labile sources of carbon (such as solvents) are present but could become more pronounced in the future as these compounds are depleted.

The literature from many non-oil sands applications and three oil sands tailings ponds suggests the following:

- Microbes are able to degrade PAM to use nitrogen under anaerobic and aerobic environments. While they are able to use PAM as a nitrogen source in oil sands tailings ponds, they do not always do so. The reasons for microbes using PAM as a nitrogen source in one pond but not another remain unknown but are generally thought to be driven by nitrogen-limited conditions.

- Microbes are able to degrade PAM to use carbon under limited circumstances. The PAM backbone is relatively recalcitrant, and microbes are expected to use more available electron donors that may be present before they adapt to using PAM. Therefore, carbon enrichment from PAM degradation is unlikely in the short-term, though the long-term fate of the carbon is not known.

- Acrylamide is not a measurable by-product of PAM degradation, and residual acrylamide is consistently and rapidly removed through biodegradation.

Biodegradation is the most common mechanism of PAM degradation. Mechanical, thermal and photodegradation may be relevant for short periods during handling and placement but are not likely to persist after tailings have been placed and covered with soil or water.

Several factors can affect the rate and degree of PAM degradation. The degree of hydrolyzation can influence degradation, especially regarding deamination. Molecular weight affects degradation, with higher molecular weight being less degradable. Microbial communities and oxidation-reduction potential of tailings deposits, factors that interdependent, will affect degradation, with aerobic environments typically promoting faster degradation. Degradation is also increased under neutral pH and high temperatures. Considering these factors, PAM degradation in oil sands tailings is likely to be slow in most of the deposit but may be more prominent in geochemically active zones such as near the surface of the deposit.

Degradation Rates and Products

During biodegradation of PAM, deamination of acrylamide subunits within PAM results in the release of nitrogen in the form of ammonia or ammonium and the conversion of acrylamide subunits in PAM to acrylic acid subunits. Once PAM has become completely deaminated, the remaining carbon backbone is polyacrylic acid or polyacrylate, depending on environmental pH. Thus, degradation products formed via deamination are polyacrylate and ammonium or polyacrylic acid and ammonia.

Although numerous studies report on the degree of PAM or polyacrylate removal in laboratory testing or bioreactor studies, the test conditions are generally not representative of environmental conditions. Furthermore, different analytical methods may produce different degradation rates estimates or measure different degrees of degradation. Thus, the literature is often not clear about whether reported polymer degradation leads to size reduction of the polymer, intermediate compounds, or mineralization. Degradation of PAM is often incomplete, with partial degradation occurring over weeks to months.

On the other hand, degradation rates for acrylamide and acrylic acid are well known from many years of study in different settings. Half-lives for acrylamide vary depending on ambient conditions but may be on the order of hours to days. Despite uncertainty in the PAM degradation rates, it is well established that PAM degrades much more slowly than acrylamide.

Based on laboratory studies and information derived from other industries, PAM degradation products arising from chain scission are generally limited to lower molecular weight polymers, and volatile fatty acids and their intermediates. No compelling evidence exists to indicate that acrylamide or acrylic acid would accumulate as a degradation product of PAM in oil sands treated tailings.

Environmental Transport and Exposure

Due to the characteristics that lend PAM its flocculating properties, anionic PAM is strongly adsorbed to soil and clay mineral surfaces, which limits its mobility in soil and leaching potential to groundwater. Anionic PAM adsorption to soil is rapid and irreversible. Therefore, PAM is not expected to migrate from tailings to groundwater or surface water systems.

Fugitive dust from dry tailings is a documented issue in mine waste management at oil sands and other mines. The application of PAM to tailings is expected to reduce the amount of fugitive dust from a dry tailings deposit compared to a deposit that has not been amended with PAM, as PAM has been used in other applications to control dust. Based on findings from several agricultural studies, deposition of dust is not considered to be a significant health risk. Site-specific data from dry tailings applications would be required to confirm these findings.

Based on its solubility, acrylamide contained in leachate from tailings could be transported by aqueous phase migration to groundwater and then downgradient via advective groundwater flow to a receiving waterbody. However, this transport would likely be mitigated by two factors:

- The degradation rate of acrylamide is high, so acrylamide is likely to be degraded before reaching environmental receptors.
- The hydraulic conductivity of PAM-amended tailings is very low, so the total mass load associated with the leachate is also expected to be very low.

Based on these considerations, acrylamide is unlikely to be detected along surface or groundwater pathways downgradient of tailings deposits.

Environmental (non-toxicological) implications of PAM deposition and degradation were considered in terms of nutrient enrichment, change in pH and generation of greenhouse gases. None of these processes were deemed to pose significant environmental risks.

LESSONS LEARNED

Challenges associated with analyzing PAM are well documented. While there may be good reasons to measure PAM from a geotechnical or economical perspective, the low environmental risk of PAM itself suggests that developing methods to analyze PAM in oil sands tailings would be a low priority. Instead, future efforts should be focussed on three potential pathways where the risk is thought to be low but uncertain: (1) PAM exposure through fugitive dust; (2) release of acrylamide from the initial deposit; and (3) release of ammonia from long-term deposits. Future tests can be considered to confirm the conclusion of the report.

Although the risk of PAM exposure through fugitive dust is considered low, testing dust, including whether PAM is a component of dust, from drying tailings may be warranted to confirm this. Based on the results from similar applications, it is likely to show that PAM provides a net benefit for dust control.

Acrylamide is not likely to be produced through PAM degradation, but it may be present as a residual monomer in commercial formulations. In addition, PAM-treated tailings are likely to have initially higher hydraulic conductivity and pore water release. Therefore, sampling and analysis for acrylamide in groundwater or surface waters should focus on the initial deposit. If significant quantities of acrylamide are not detected in the initial release of water, they are unlikely to be detected thereafter. Conversely, ammonia is more likely to be generated over the long term through deamination of PAM. Therefore, ammonia should be monitored in seepage waters or tailings release waters until it can be shown that degradation is not occurring or that insignificant quantities of water are seeping from tailings deposits. Ammonia may serve as an early indicator of PAM degradation.

In summary, the literature review confirmed that the risk to the environment, including toxicological and non-toxicological risks, posed by PAM are low. PAM is expected to be strongly retained within the soil matrix. Degradation is likely to be very slow, on the order of decades, and will primarily entail deamination. If chain scission occurs to the carbon backbone, it will also be very slow and only generate fragment carbon chains or fatty acids with low toxicity.

Despite these risks being low, future tests can be considered to investigate: (1) PAM release through fugitive dust; (2) residual acrylamide release from an initial deposit; and (3) ammonia release through long-term deamination.

RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Jerry Vandenberg	Vandenberg Water Science Ltd.	Environmental Chemist		
Daniel Smith	Intrinsik Corp.	Environmental Scientist		
Bart Koppe	Intrinsik Corp.	Senior Environmental Health Scientist		

Environmental Fate and Implications of Polyacrylamide Addition to Oil Sands Tailings

COSIA Project Number: TJ0138

Research Provider: University of Saskatchewan, University of Alberta

Industry Champion: Imperial and Syncrude

Status: Year 1 of 3

PROJECT SUMMARY

The oil sands industry is increasingly using flocculants to produce thickened tailings suitable for deposition in terrestrial dedicated disposal areas. The most widely used flocculant, polyacrylamide (PAM), contributes organic carbon and nitrogen that past studies have suggested may stimulate microbial activity in thickened tailings. However, the environmental fate of PAM and its implications for water quality are not fully understood.

This research examines the implications of PAM addition on water chemistry and assesses PAM biodegradation rates and pathways. Additionally, impacts of PAM addition on biogenic gas production (i.e., carbon dioxide, methane) and the biodegradation of other organics (e.g., petroleum hydrocarbons, naphthenic acids) present in thickened tailings are being studied.

The specific objectives defined for this project are to:

- examine the impacts of PAM on water chemistry;
- assess influence of PAM addition on biogenic gas concentrations;
- evaluate temporal and spatial changes in microbial communities;
- explore PAM degradation rates and pathways;
- assess potential impacts of PAM on degradation of other organics; and
- develop conceptual models of biogeochemical processes in thickened tailings.

Complementary and collaborative field and laboratory research activities are being conducted to realize these objectives. Research activities are divided among the following two research themes:

- Theme 1 (USask): Examining biogeochemistry of treated tailings deposits; and
- Theme 2 (UAlberta): Investigating polyacrylamide (PAM) biodegradation in treated tailings deposits using microcosms.

PROGRESS AND ACHIEVEMENTS

Research activities were initially delayed due to university restrictions on laboratory access during the COVID-19 pandemic. However, easing of these restrictions during 2021 allowed our teams to make progress toward stated research objectives. Nevertheless, project timelines have been revised to accommodate these unforeseen delays.

THEME 1: University of Saskatchewan

Research activities under this theme are being conducted by Emily Champion (MSc student) under the supervision of Dr. Lindsay. Additional support from research technicians at USask has helped ensure progress on this research during COVID-19 restrictions.

Activity 1.1: Collect core samples of treated tailings and subsample for analysis

Imperial collected 109 thickened tailings samples from Kearl in October 2019. These included 59 fluid samples in 5 L pails, and 50 core samples in Shelby tubes. All samples were stored at −20 °C until sub-sampling and analysis was complete. Sub-sampling of the 59 fluid samples was completed on February 26, 2021. Core sample extrusions and subsampling began mid-February 2021 and was completed in October 2021.

Syncrude postponed sample collection originally planned for 2020 due to the COVID-19 pandemic. Collection of thickened tailings samples at Mildred Lake occurred in the winter of 2022. Sub-sampling will be completed at USask.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2019-10-09	2020-10-31	2020-09-01	2021-10-24
Mildred Lake	2021-01-01	2021-04-30	TBD	TBD

Activity 1.2: Analyze pore-water chemistry of treated tailings sub-samples

Analysis of pore-water chemistry is nearing completion. All water samples obtained from the Kearl samples have been submitted to internal and external labs for analysis. Time-sensitive geochemical parameters (e.g., pH, redox potential, electrical conductivity, alkalinity, ammonium, nitrate, nitrite, hydrogen sulfide) were measured immediately, whereas other samples were preserved according to standard methods.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2020-07-01	2020-12-31	2021-01-01	2022-03-31

Mildred Lake	2021-03-01	2021-08-31	TBD	TBD

Activity 1.3: Conduct chemical analysis and mineral identification for treated tailings sub-samples

Sub-sampling is now complete, and samples are being stored frozen. Geochemical and mineralogical analysis of thickened tailings solids will be conducted in the next few months.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2020-11-01	2020-04-30	2021-06-01	2022-03-31
Mildred Lake	2021-07-01	2021-12-31	TBD	TBD

Activity 1.4: Conduct DNA extractions, sequencing, and bioinformatics on tailings sub-samples

DNA extraction for Kearl samples is underway and we anticipate submitting samples for 16S sequencing by February 28, 2022. Associated bioinformatics will be performed immediately upon receiving these data. Although we had originally planned to perform bioinformatics for Kearl and Mildred Lake samples together, we have elected to proceed with the Kearl data to avoid additional delays.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2021-07-01	2022-02-28	2021-09-01	2022-12-31

THEME 2: University of Alberta

Research activities under this theme are being carried out by Anya Batycky (MSc student) under the supervision of Dr. Ulrich.

Activity 2.1: Initial screening of PAM-degrading microcosms

A treatment plan has been developed for PAM degrading microcosms under methanogenic, sulfate-reducing, and oxic conditions. FFT have been shipped from Kearl to the UAlberta, which will then be dosed with PAM (provided by Imperial) at the UAlberta. The methanogenic microcosms are in the process of being setup, and once those have been established, the sulfate-reducing and oxic microcosms will be setup as well. Thickened tailings samples from Kearl have been shipped from USask to the UAlberta and these experiments will be initiated shortly.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2020-09-01	2023-02-28	2022-02-01	2023-02-01

Activity 2.2: Detailed analysis of PAM-degrading microcosms

This activity is dependent upon preliminary results from Activity 2.1; the start and end dates have been revised accordingly.

Samples	Proposed Start	Proposed End	Revised Start	Revised End

Kearl	2020-10-01	2023-06-30	2022-03-01	2023-03-01

Activity 2.3: Enrichment culture establishment

This activity is dependent upon preliminary results from Activities 2.1 and 2.2; the start and end dates have been revised accordingly.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2021-01-01	2023-06-30	2023-05-01	2025-05-01

Activity 2.4: Substrate study in enrichment cultures and elucidation of PAM biodegradation pathway

This activity is dependent upon preliminary results from Activities 2.1, 2.2 and 2.3; the start and end dates have been revised accordingly.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2021-02-01	2023-06-30	2023-05-01	2025-05-01

Activity 2.5: Method development

Dr. Ulrich's group has finalized the methodology for quantifying PAM in tailings pore water using Size Exclusion Chromatography with only a few tests remaining. PAM will be quantified using the Agilent PL Aquagel-OH Mixed-H column with a mobile phase of 0.01 M NaH_2PO_4 and 0.1 M NaCl at a pH of 7. PAM is detectable from 10 ppm to 450 ppm; however, lower concentrations will be investigated to determine the detection limit. Further test for this method includes determining: (1) the detection limit for PAM, (2) if filter types influence PAM detection, (3) if decreasing the HPLC flow rate influences peak resolution.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2020-09-01	2022-08-31	2021-04-01	2022-08-31

LESSONS LEARNED

University of Saskatchewan:

- Our results indicate that pore water chemistry within these treated tailings is generally consistent with fluid tailings deposits, including:
- Mildly alkaline pH and anoxic conditions;
- Moderate electrical conductivity values;
- Slightly elevated sodium, chloride, sulfate, and bicarbonate concentrations.
- Dissolved CH_4 concentrations were generally low, while H_2S was detected at very low concentrations.

- Aqueous-phase PAM concentrations were consistently below method detection limits.

University of Alberta:

- A method for quantifying PAM and its metabolites using SEC-HPLC in pore water and release water has been developed.
- For the qualification of PAM metabolites additional methods of analysis may be necessary such as FTIR and GC-MS of acrylic acid and acrylamide monomers. Methods for qualifying polymers are limited.
- We have found that PAM strongly binds to MFT solids, and aqueous concentrations for certain PAM doses are consistently below detection. We have attempted to extract PAM bound to the solids, but these attempts were unsuccessful.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Saskatchewan, and University of Alberta

Principal Investigators: Dr. Matthew Lindsay, and Dr. Ania Ulrich

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Matthew Lindsay	USask	Principal Investigator		
Emily Champion	USask	MSc	Sep.1/2019	Aug. 31/2023
Ania Ulrich	UAlberta	Principal Investigator		
Anya Batycky	UAlberta	MSc	Jan. 1/2021	Apr. 30/2023

Offline Measurement of Clay Activity Using X-Ray Diffraction Methods

COSIA Project Number: TJ0146

Research Provider: Suncor, Coanda Research & Development Corporation

Industry Champion: Suncor

Status: Year 2 of 2

PROJECT SUMMARY

An x-ray diffraction method is described for quantifying clay minerals in fluid fine tailings streams and a correlation developed for converting the clay mineral weight percentages to “wt% clay” measured by methylene blue. The methylene blue Index (MBI) test is a titration method for measuring clay activity, and it has been a workhorse for understanding fluid tailings and bitumen extraction behavior. It is demonstratively cheap and when diligently conducted, is superior to most off-line variants of particle size distribution methods for understanding process behavior limited by fine particles in the ore.

The main drawback of the MBI is the poor reproducibility between different labs or even within the same laboratory over time. Coupled with the lack of a commercially available independent method to determine the true accuracy of the methylene blue test, its use has been largely restricted to index testing for clay activity (expressed as *“wt% clay”*). X-ray diffraction (XRD) measures the crystalline phases in a solid sample and the instrument has been around for more than a century. The method is ubiquitous in the mineral industry where clay minerals are not significant contributors to the process or to tailings behavior. The clay minerals in oil sands influencing tailings behavior are poorly crystalline and difficult to quantify with XRD without some expertise in clay mineralogy. This has largely limited its application to research because the required expertise is not commonly available in commercial laboratories or amenable to high throughput analysis.

Leveraging advances in structure analysis of poorly crystalline clay minerals was investigated in this project, a routine method was developed for quantifying clay minerals with XRD without the need for mineralogy expertise and converting the clay minerals wt% to “clay activity” or wt% “clay” measured by MBI (termed MBX to differentiate from the titration based MBI).

PROGRESS AND ACHIEVEMENTS

Different clay minerals have different activities that vary with the specific surface area of the clay mineral. Therefore, while the clay mineral wt% in MFT is sufficient to describe tailings behaviour or flocculation efficiency in broad strokes, there often is a potential for clay mineral segregation in a pond or a treated tailings deposit that requires knowing the activity contributed by different clay minerals. The specific surface area (SSA) for each clay mineral can also be estimated from the crystallite size (coherent scattering domains) measured from x-ray diffraction ((Omotoso, Mikula, & Stephens, 2002)). So, for a sample, x-ray diffraction data can be converted to MBI using the following equation:

$$Surface\ area\ from\ MBI\ \left(\frac{m2}{g}\right) = SSA_{kaolinite} * wt\%kaolinite + SSA_{illite} * wt\%illite$$

The specific surface area is ideally determined from the diffraction patterns generated for each sample and has been reported by several authors. However, the analysis method requires significant expertise which may not be easily available in a process laboratory. To circumvent this problem, an average SSA is determined for the kaolinite and illite minerals in Suncor fluid fine tailings. The average then forms the basis for the conversion of clay minerals to MBI in the equation above.

In order to measure the SSA of the clay minerals in Suncor's Base Plant operations, extensive sampling of the ponds was performed over a number of years followed by the measurement of their diffraction patterns by XRD. It was found that the variation in the specific surface area for a specific clay is low indicating that clay mineral percentages can be converted to MBI using a direct calibration without a significant increase in the measurement uncertainty.

Using data collected from various ponds, a partial least squares regression was used to calibrate MBI measured by external laboratories between 2016 and 2018 and methylene blue from x-ray diffraction (MBX) as shown in Figure 13. A good correlation exists between the two measurements indicating that MBX could be used as a tool to measure clay content of tailings on a process stream once such calibration curves are developed.

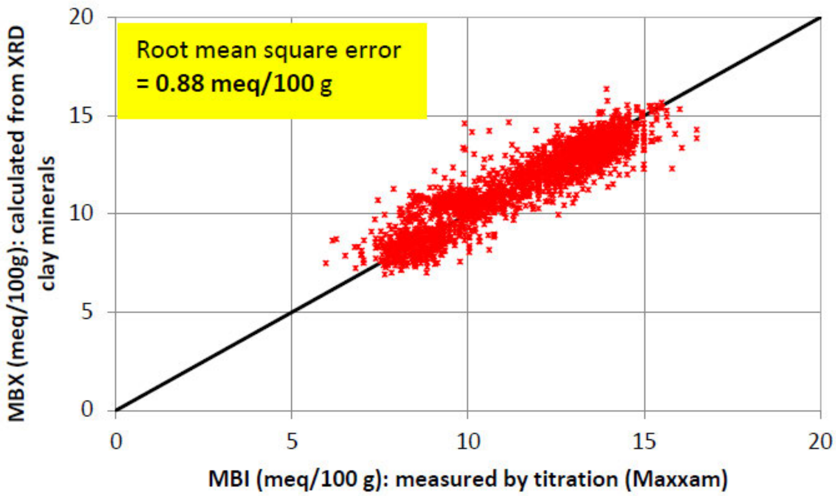

Figure 13 – Calibration curve for converting clay minerals measured by x-ray diffraction to methylene blue index (MBI) measured by titration.

LESSONS LEARNED

Successful implementation of this MBX measurement technique requires that the laboratory maintains some level of expertise in x-ray diffraction measurement and analysis. This risk is mitigated by encouraging diffraction analysts to attend regular meetings and workshops on the use of x-ray diffraction techniques for clay mineral analysis.

Also, the equation used for converting the clay mineral composition to the equivalent methylene blue adsorption clay activity is solely for fluid fine tails and should not be used for secondary extraction tails. For tailings other than those evaluated as part of this program a new calibration curve may be required for accurate conversion of clay minerals to clay activity.

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RESEARCH TEAM AND COLLABORATORS

Institution: Suncor, Coanda Research and Development Corporation

Principal Investigators: Oladipo Omotoso

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Greg Fulton	Suncor	Lab Specialist-Ph.D. Chem		
Alan Melanson	Suncor	Tailings Advisor-P.Eng		
Chelsey Goodwin	Suncor	ADW Fine Tailings-EIT		
Benny Moyls	Coanda Research	Senior Engineer, P.Eng		
Mark Olson	Coanda Research	Lab Technologist, CET		

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Tailings Deposition and Monitoring

NSERC/COSIA Industrial Research Chair In Oil Sands Tailings Geotechnique

COSIA Project Number: TE0010

Research Provider: University of Alberta (UAlberta)

Industry Champion: Imperial, Canadian Natural, Suncor, Syncrude, Teck

Status: Year 3 of 5

PROJECT SUMMARY

COSIA, in collaboration with The University of Alberta (UAlberta), is undertaking research into the development and application of new and innovative approaches to design dry stacked deposits, geotechnical and bio-geochemical aspects of tailings management and reclamation strategies. The research is focused on three themes:

Theme 1: Engineered Mixtures of Tailings and Overburden for Dry Stacked Deposits

Theme 2: Influence of Bio-geo-chemical Interactions on the Geotechnical Behaviour of Soft Tailings

Theme 3: Capping Soft Tailings Deposits

These complementary themes will look to the future of tailings deposits as well as immediate or interim challenges. It is anticipated that 15 highly qualified personnel will be trained in state-of-the-art reclamation techniques through the research program. [redacted]

PROGRESS AND ACHIEVEMENTS

The NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique began September 1, 2019. The research team has participated in knowledge sharing activities between COSIA, UAlberta, NAIT and Carleton University. Between March 15, 2020, and July 1, 2021, there were various levels of restrictions on in-person research activities due to COVID-19, impacting the research progress (e.g., For extended periods of time, the research team did not have access to laboratories due to provincially mandated closures. The University authorized limited access to laboratories in between lockdowns. Fieldwork access has not been possible; however, COSIA facilitated the delivery of tailings samples to assist the highly qualified personnel (HQP) with their research.). Note: In the research summaries below, HQP have made changes in project titles and objectives based on consultations with COSIA member companies.

Project 1-1: The influence of clay content on mixtures of Clearwater Shales and Fluid Fine Tailings (FFT)

Objective: Understand the relative influence of high and low plastic clay, and no clay, on the blending of various treated and untreated MFT with Clearwater Shale.

Recruitment is ongoing for a suitable graduate student to undertake this research. Recruitment efforts have been impacted by COVID-19.

Project 1-2: Assessment of the Physical Stability of the Tailings and Overburden Mixture for Dry Stacking

Objective: Evaluate the use of alternative overburden materials for blending with various types of FFT to form suitable materials for dry stacking.

Field conditions were experimentally simulated by applying CRL (controlled rate of loading) on a mixture of overburden with filtered tailings in a series of consolidometer tests. In these tests, the applied load on the samples was incrementally increased to account for the increase in drainage path length in the field as the tailings stack rises. The mixture of tailings and overburden was stacked at the naturally blended moisture contents in a loose and unsaturated state. When the material was subjected to stress, it initially underwent compaction. Upon the development of positive pore pressure in the mixture, the volume change is a function of the coupled compaction-consolidation process. Once the mixture became fully saturated, the volume change was a function of the consolidation.

Project 1-3: Geotechnical and rheological correlations applied to run out analysis and tailings facility breach analysis

Objective: Develop new methodologies for run-out analysis to be included in the risk assessment of tailings storage facilities to aid in the understanding of the risk associated with mining.

This research is in its early stages and the PhD student recently completed mandatory coursework. The correlation of the geotechnical and rheological parameters of tailings can be complex due to several factors related to tailings sampling and testing methods. Historical cases were evaluated to create a database of tailings facility failures. The next step will be to gather geotechnical and rheological test data from mining sites to analyze and build the correlations. Then, physical testing of some of the tailings at the laboratory, as a control variable, will be conducted. The last stage will be to develop a methodology to correlate and incorporate the geotechnical and rheological parameters into the run-out analysis.

Project 1-4: Investigating the properties of transition zone materials

Objective: Investigate the properties of the fines fraction and its influence on the behaviour of tailings mixtures in the transition zone of the tailings classification chart.

Experiments were designed to determine the characteristics of the transition zone materials' characteristics in relation to characteristics of tailings for other zones of the Ternary diagram. Large strain consolidation, vane shear and Atterberg Limits index tests will be done to determine consolidation and hydraulic conductivity parameters and the correlations between the parameters and the plasticity Index (Ip). Specific Resistance to Filtration (SRF) and Soil Water Characteristic Curve (SWCC) tests are designed to examine the relationship between the fines and solids contents with filterability, settlement and consolidation behaviour of materials in the transition zone. Scanning Electron Microscope (SEM), X-Ray Diffraction (XRD) and Ion Chromatography (IC) tests will be done to determine the influence of pore water chemistry, fabric and structure on engineering properties of the tailings in the transition zone.

Project 2-1: Geotechnical optimization of treated tailings systems for aqueous covers

Objective: To develop design criteria from optimized geotechnical properties (coupled with biogeochemical properties) for an engineered deep deposit that sequesters constituents of potential concern to transition to a natural ecosystem (pit lake).

Preliminary bench-scale experiments were started at the end of 2019 to estimate if FFT would hold 50 cm of sand or 50 cm of petroleum coke. Due to COVID-19 restrictions and subsequent delays in receiving FFT and coke samples, 11 settlement columns were established in February 2022, and there are currently no results to report. The planned experiment duration is 6 months; after that, the columns will be decommissioned and replaced with the next series of columns, which will be designed based on the results of the first experiment.

Project 2-2: Integrity and long-term stability of treated tailings systems

Objective: To assess the long-term stability and performance of chemically amended deposits.

This research project evaluates the long-term biogeochemical and geotechnical behaviour of end pit lakes and attempts to fill some of the knowledge gaps that exist surrounding the use of end pit lakes for tailings reclamation, such as water cap quality. Further, this work will compare the behaviour of untreated and polymer-treated tailings deposited in end pit lakes. This project comprises two parts: Part 1 evaluates the behavior of shallow deposits of EPL tailings and the overlying water cap; and Part 2 evaluates the behavior of deep (>10 m) deposits of EPL tailings. The first step in this project was to develop a method that mimics and accelerates the natural aging process in EPLs. Three aging methods are being examined in this work: elevated temperatures; carbon amendments; and gas ebullition. All of these methods accelerate microbially-derived biogeochemical cycling and consolidation processes that naturally occur in tailings as they age. Columns were then designed to mimic EPL aging at the laboratory-scale.

Project 2-3: Comparison of consolidation methods over a range of materials

Objective: Compare the consolidation parameters measured by the different consolidation tests used in the industry over a range of different materials.

This research is in its early stages. The PhD student is completing mandatory coursework this semester. This research will focus on comparing the results for a variety of tailings (clay-rich fines dominated sample, clay-poor fines dominated sample, and a transition zone sample) using: Large Strain Consolidation; Seepage Induced Consolidation Testing; Beam Centrifuge; Column Testing; and Modified Resistance to Filtration. Sensitivity and repeatability of the methods will be examined and compared.

Project 3-1: Optimization of capping soft tailings deposits

Objective: Determine the effect of strength and density of underlying tailings and cap configurations (thickness, slope, composition, etc.) on the deformation response and failure modes of the cap and tailings system.

Laboratory characterization of centrifuge cake tailings. Fall cone and vane shear tests were conducted on samples prepared under the following stress paths: a) Tempe cell at target matric suctions to simulate different degrees of desiccation; b) different durations of rewetting of the Tempe cell samples using de-ionized water with various levels of salinity; c) consolidated samples to various consolidation pressure under fully saturated conditions; and d) air-dried and rewetted samples under a relatively constant temperature and relative humidity.

Centrifuge experiment. A new GeoEnvironmental centrifuge strongbox has been designed with fabrication completed in late February 2022. Parts have arrived in the GeoCERF facility awaiting assembly and commissioning. Procurement of additional load cells and pore pressure sensors is expected to occur during the summer.

Recipe development for synthetic tailings material. Synthetic material has been used in physical modelling and centrifuge experiments due to repeatability and controllability of their mechanical properties and cost-effectiveness. The use of synthetic material is even more important due to disruptions in logistics of obtaining samples during COVID-19. The purpose of this task is to develop a range of recipes to mimic some aspects of mechanical behaviour in desiccated rewetted TT.

Project 3-2: Deformation behaviour of crusted tailings

Objective: Investigate the bearing capacity and deformation response of caps placed on tailings deposits with a thinner, stronger surface layer overlying a weaker foundation material.

The objective of this project was to investigate the mechanisms driving the dewatering and strength behaviour of two types of treated deep tailings deposits (centrifuged tailings and in-line thickened tailings (ILTT)) undergoing seasonal weathering dominated by a) freeze-thaw cycles and b) alternating freeze-thaw and drying-wetting cycles using controlled laboratory experiments under three temperature gradients. The laboratory testing carried out on the ILTT samples were further compared to the ILTT pilot scale field deposit, while a coupling numerical approach was developed to simulate the laboratory testing performed on the centrifuged tailings samples. Hence, laboratory testing was validated by simulating field conditions and the efficacy of coupled model was validated by simulating the laboratory testing conditions.

LESSONS LEARNED

Notwithstanding the schedule and productivity being materially disrupted by COVID 19 impacts, important learnings were realized:

Project 1-2

The consolidometer test results demonstrated the addition of a small amount of rock to the filtered tailings could significantly reduce the build-up of excess pore pressure at the base of the stack. Therefore, deformation and pore pressure should be modelled using a representative model like FLAC3D. By using such a model, density under self-weight consolidation can be predicted. Additionally, the pore pressure response at the base of the mixture can be characterized. Unequal distribution of the load within the samples was observed due to wall friction loss.

Project 1-3

This new methodology will aid in the understanding of the risk associated with mining. However, it will be applied to any kind of deposition, not just for dams. The development of this methodology is intended to help the mining sector, regulators, and society, by facilitating proper risk management. The importance of including dry deposition waste dumps, such as filtered tailings, is because there are no guidelines for the dry deposition run out analysis that could occur once the dump becomes saturated, and dry deposition is increasingly being used in the mining sector.

Project 1-4

The research is expected to advance the understanding of dewatering characteristics and the rates and magnitudes of self-weight consolidation in transition zone materials. Findings from this research will also support the design of mixtures of FFT and overburden.

Project 2-1

These properties (pH, EC, turbidity) plateaued at 4-6 months. Proposed treatments (permeable reactive barrier + sand layer) worked at the beginning (control vs capped MFT), but in 6 months the measured parameters became identical; therefore, other capping layers or/and larger thickness needed to be explored.

Project 2-2

Part 1 of this research project required the design and construction of 64 columns, each containing a layer of untreated or treated tailings and a water cap. Monitoring of these columns is ongoing and requires weekly assessment of the water chemistry of the water cap and tailings (which includes measuring parameters such as pH and ion concentrations) and monthly assessment of geotechnical and microbial behavior of the tailings. Preliminary results of Part 1 of this project were presented at the Tailings and Mine Waste Conference in 2021. Briefly, sulfate reduction and subsequent generation of reduced sulfur species is expected to be an important biogeochemical process in polymer and alum treated tailings. Final results are expected in late 2022.

Part 2 of this research project required the design and construction of 12 5 L columns, each containing tailings. The design of these columns was more challenging than that of Part 1 because the columns must be placed under pressure to compress the tailings. Pressure will be applied to the tailings in the columns first through a series of dead loads and then using air pressure. The design and construction of these 12 columns is complete.

Project 2-3

The findings of this project will help to develop a robust understanding of experiment bias by using interlaboratory comparisons, where testing materials are provided to several qualified laboratories. The research findings, in turn, will contribute to new recommendations for improving practice guidelines for obtaining the consolidation behaviour from large strain consolidation tests.

Project 3-1

Outcomes of this research are expected to optimize thin-lift deposition strategies and provide the upper and lower limit of strength profiles that can guide the choice of construction equipment during reclamation.

Project 3-2

The conclusions from the laboratory results and modeling simulation can be summarized as follows:

- The freeze-thaw process has a significant effect on polymer amended treated tailings properties, which enhanced the post-thaw dewatering process. Among different parameters, freezing temperature gradient, freeze-thaw cycles, and the effects of physico-chemical interactions (solids mineralogy and pore water chemistry) contributed predominantly to improving the dewatering and strength performances.

- The freeze-thaw process may seem to achieve lower dewatering enhancement compared to atmospheric drying, the shrinkage and/or cracks developed during the freeze-thaw cycles facilitate greater evaporation and desiccation during the subsequent drying cycle, thereby, contributing to overall higher dewatering. The extent of these cracks was found to be predominantly dependent on the temperature gradient, number of freeze-thaw cycles and the physiochemical interactions among the tailings particles and solutes. A three-fold lower temperature gradient after five freeze-thaw cycles resulted in two times higher surficial strength compared to its higher gradient. When freeze-thaw dewatering was incorporated with a cycle of drying-wetting, this three-fold lower temperature gradient resulted in nearly eight times higher surficial shear strength than the higher gradient tailings. Further, five alternating freeze-thaw and drying-wetting cycles resulted in half an order of magnitude higher surficial strength for the lower gradient tailings, as compared to the higher gradient one.

- Laboratory testing approach was able to bound the expected field response, given the thermal gradients were in the similar range and were able to validate the proposed coupled model. The coupled modeling analysis demonstrated the ability to simulate the coupled processes of freeze-thaw, consolidation, evaporation and desiccation. This can be used in tailings management in the oil sands industry to predict the short-term field response in terms of dewatering. Based on the model prediction, different scenarios incorporating the sequences of freeze-thaw and evaporation can be maximized in the field.

PRESENTATIONS AND PUBLICATIONS

Published Theses

Burden, R. (2021). *Using Co-Disposal Techniques to Achieve Stable "Dry-Stacked" Tailings: Geotechnical Properties of Blended Waste Rock and Tailings in Oil Sands and Metal Mining.* PhD Thesis, University of Alberta, Fall 2021. https://doi.org/10.7939/r3-k6a3-pe41

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Olmedo, N. (2020) *Tailings characterization using an unmanned ground robot*. PhD Thesis, University of Alberta, Spring 2020. (Thesis temporarily embargoed for Intellectual Property).

Stienwand, K. (2021) *Accelerating Polymer Degradation to Explore Potential Long Term Geotechnical Behaviour of Oil Sands Fine Tailings*. MSc Thesis, University of Alberta, Fall 2021. https://doi.org/10.7939/r3-22gg-w411

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Wilson, G.W. (2021). The new expertise required for designing safe tailings storage facilities. *Soils and Rocks, 44*(3), 1-8. https://doi.org/10.28927/SR.2021.067521

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Conference Presentations/Posters

Burden, R.N. and Wilson, G.W. (2019, October 6-10). *Filtered Tailings and Waste Rock Blends: Improving the Stability of Tailings Deposits* [Conference presentation]. Canadian Dam Association Annual Conference, Calgary, AB.

Cossey, H.L., Kuznetsov, P.V. and Ulrich, A.C. (2021). Evaluating the biogeochemical and consolidation behavior of oil sands end pit lakes with accelerated aging. In *Proceedings of the Tailings and Mine Waste Conference*, Banff, AB.

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Kabwe, L.K., Wilson, G.W., Beier, N.A. and Scott, J.D. (2019, September 29- October 2). *Effects of various chemical treatments on consolidation on oil sands fluid fine tailings tailings* [Conference presentation]. GeoStJohns: 72nd Canadian Geotechnical Conference, St. John’s, NF.

Slingerland, N., Sommerville, A., O'Leary, D., Beier, N.A. and Wilson, G.W. (2019, October 6-10). *Erosional processes on an oil sands tailings dam and implications for reclamation* [Conference presentation]. Canadian Dam Association Annual Conference, Calgary, AB.

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Reports & Other Publications

Beier, N. (2021, January 21). *Leveraging Environmental Processes to Dewater Oil Sands Tailings* [Invited presentation]. Canadian Geotechnical Society – Geoenvironmental Speaker Series, Virtual.

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Wilson, G.W. (2021, July 26-28). *The new expertise required for designing safe tailings storage facilities* [Keynote address]. 3rd Pan-American Conference on Unsaturated Soils, Rio de Janeiro.

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RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigators: Dr. G. Ward Wilson, Dr. Nicholas Beier, Dr. Ania Ulrich

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Dr. Ahlam Abdulnabi	University of Alberta	Research Associate		
David Barsi	University of Alberta	Research Technician		
Dr. Louis Kabwe	University of Alberta	Research Associate		
Dr. Petr Kuznetsov	University of Alberta	Research Associate		
Heidi Cossey	University of Alberta	PhD student	2019	2023
Aniseh Dadashi	University of Alberta	PhD student	2017	2023
Peter Kaheshi	University of Alberta	PhD student	2019	2024
Nathalia Machado	University of Alberta	PhD student	2019	2024
Dr. Umme Rima	University of Alberta	PhD Candidate (recently graduated)	2016	2022
Tony Zheng	University of Alberta	PhD Candidate	2019	2024

Research Collaborators:

- Dr. Rick Chalaturnyk, University of Alberta, Professor
- Dr. Heather Kaminsky, NAIT, NSERC Industrial Research Chair for Colleges in Oil Sands Tailings Management
- Dr. Paul Simms, Carleton University, Professor
- Dr. David Williams, University of Queensland, Professor

Modeling of Co-Deposition of Two Tailings Streams in A Pond Environment

COSIA Project Number: TE0054

Original Title: Physical and numerical modeling of progradation of segregating tailing beaches into MFT and associated depositional mechanisms.

Research Provider: University of Minnesota

Industry Champion: Syncrude., Imperial

Status: Ongoing

PROJECT SUMMARY

This project focuses on co-deposition of two tailings streams in a pond environment, towards understanding how their dynamics affect fines entrapment/entrainment. Physical experiments were conducted to explore phenomena with the goal of developing better understanding for how tailings streams of varying characteristics (e.g., rheological characteristics, grainsize, fines content, water content, etc.) interact during transport and affect attributes of the final deposit with the long-term goal of improving the geotechnical stability of the resulting co-deposit.

The key aspects of the project are summarized here:

- The project objectives focus on developing preliminary or "discovery" level insights into physical processes and deposits generated during co-deposition of differing tailing streams in a pond environment toward improved fines entrapment within coarser particles.

- Experiments use surrogate tailings in laboratory experiments, using specially designed facilities at the St. Anthony Falls Laboratory, University of Minnesota.

- The surrogate materials are created to match the rheological, grainsize, and settling behavior of two distinct tailings materials:

- Fine Fluid Tailings (FFT) treated with a flocculent similar to industry standards to promote dewatering. Here it is referred to as "flocculated FFT" or fFFT;

- Coarse Sand Tailings (CST), which is sand captured in primary settling process and combined with process water.

- Depositional conditions are varied to understand how they may be varied to promote more effective fines entrainment/capture.

Motivation

Fine Fluid Tailing deposition presents challenges for tailings pond reclamation:

- Fines are difficult to capture within part of the deposit referred to as "the beach", a region of stable deposit; rather they are transported into the pond.

- Fine grains (silt and clay size) are slow to settle and dewater.

- Segregated, deposited fines have poor geotechnical properties

Co-Deposition of different tailings streams provides an opportunity to capture fines and provide geotechnical stable deposits for post-mine reclamation and closure.

Research questions

- What type of mixing processes and depositional features are observed during co-deposition and which processes look favorable for geotechnical stability?

- How do operational parameters (tailing discharge rate, slurry concentration, location of discharge) impact co-deposition?

Experimental Basin

Physical experiments are being conducted in a medium sized research basin referred to as the Tailings Flume, Figure 14. The objective of these experiments is to assess the types of flow physics and interactions. The facility is an existing flume with an inner dimension of 122 cm wide (4 ft) x 760 cm long (25 ft) and 60 cm deep (2 ft). The mixing tanks for flocculated FFT surrogate are set up with appropriate mixer and internal baffles. CST surrogate is fed into the flume as a well-mixed slurry. Tap water is used as the fluid component. Dry fine sand is fed into the fluid stream using a mechanical volumetric feeder.

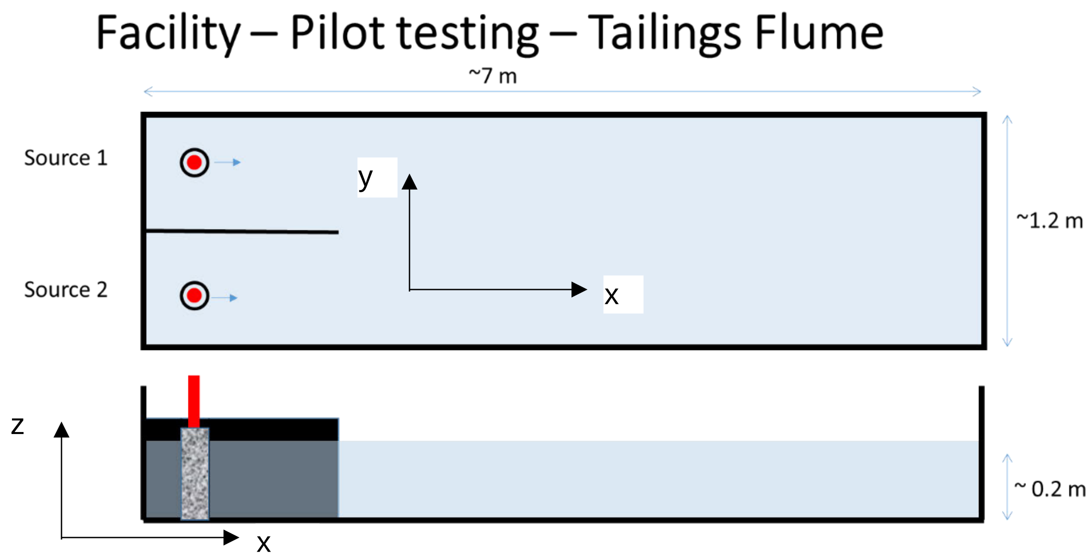

Figure 14. Schematic of the Tailings Flume to be used in experiments. Top view (top) and side view (bottom) Axes (x- y- and z- directions) as noted in the two sketches from different vantage points.

PROGRESS AND ACHIEVEMENTS

Previous Achievements:

The project had made substantial progress through 2020 with surrogate development and through 2021 with the first of two experimental sets. A brief summary of achievements is included here and a full summary of the effort will be provided in a future report. The first phase of the project involved characterizing Fine Fluid Tailings materials.

Surrogate Development

The first phase of the project is complete and involved characterizing real tailings material and developing a surrogate version of this material to use in laboratory experiments. Various facilities were used to develop and characterize surrogates that are being used in the experimental phase of the project. Industry partners supplied the research team with a large sample of FFT material and flocculent chemical, PAM (Polyacrylamide) commonly used by industry.

Rheological Characterization – The team used a Brookfield viscometer, slump tests, and angle of repose tests to characterize the rheological characteristic of flocculated FFT and comparable surrogate material.

Flocculation characterization – The dewatering behavior of flocculated FFT and surrogate was characterized using a bench-top equipment for mixing and measuring properties of the fluids (Figure 15).

The final f-FFT surrogate mixture identified by this phase of the project is a mixture of kaolinite clay and deionized water. The solution is 25%wt solids and flocculant (Poly (diallyldimethylammonium chloride) is added at 843 ppm.

Figure 15. Image of stir tests with FFT material. These tests were used to collect baseline information needed to develop surrogate solutions.

Achievements since 2020:

Experimental Set #1

The first set of laboratory experiments was completed in the Fall of 2021. The experiments used the Tailings Flume (Figure 14) in a multi-stage set of tailings deposition. CST and fFFT were alternately discharged into the flume and observations were made on the transport, segregation and depositional processes.

As shown in Figure 16, the first meter of the flume was segmented into left and right basins by a splitter wall - keeping the CST and FFT tailing separate. Downstream of the splitter wall the deposits were able to interact with one another.

Figure 16 illustrates the three different stages of Experiment 1. The first stage (Experiment 1A) involved discharge of CST material on the right side of the basin. Experiment 1B involved discharge of f-FFT on the left side of the basin. The outlet for fFFT was at the bottom of the flume and was underwater. The final stage (Experiment 1C) was a discharge of CST material on the rights side of the basin. For this stage, a small amount of green tracer sand was added to the CST to help distinguish the deposit from Experiment 1C from Experiment 1A.

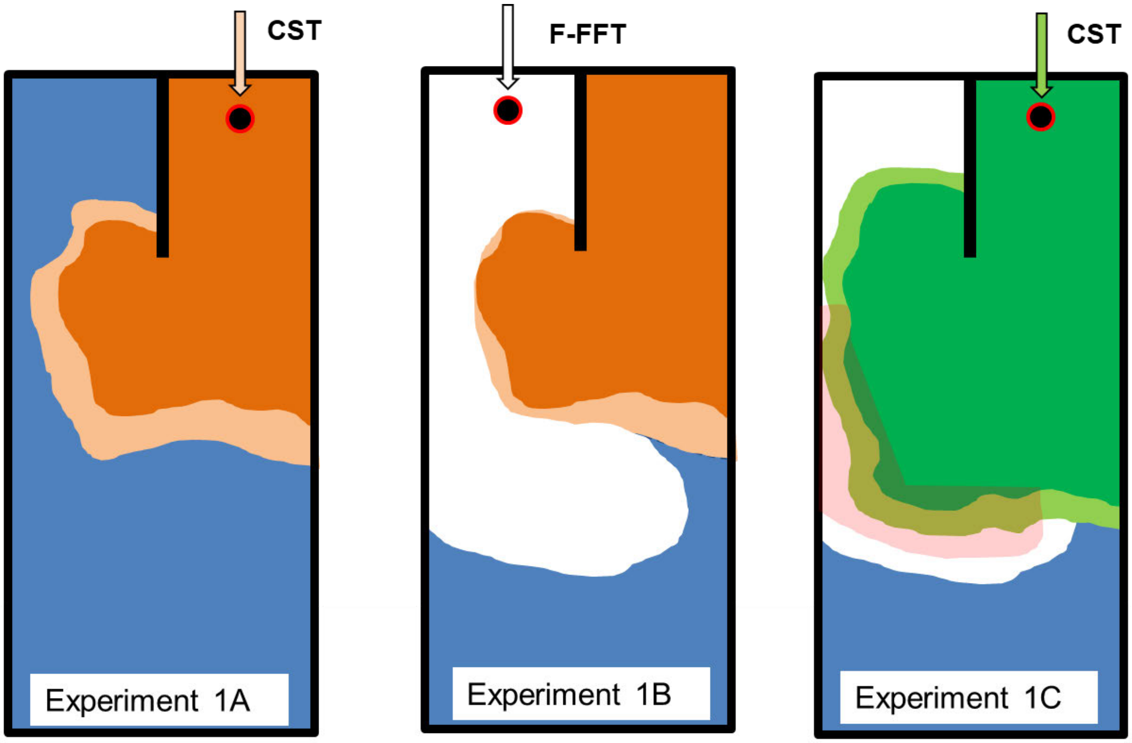

Figure 16. Summary of the three stages of Experiment 1. The tailing materials were alternately discharged and allowed to interact. The FFT was discharged underwater.

Figure 17 shows three images from the three stages and helps illustrate the observations made. In addition to photographs, the surface topography was measured using systematic point gauge technology. Small piston cores were taken from the deposit and analyzed for grainsize; and the whole deposit was dried and sectioned in order to study the internal structure of the deposit (Figure 18). Preliminary observations from the experiment include:

- fFFT (Exp 1B) had little apparent impact on initial CST deposit (Exp 1A). No erosion or reworking observed from pictures or topography measurements.
- Lowering sediment concentration of CST input (Exp 1C) reduced slope of BAW. Rapid remobilization of BAW sand to BBW.
- CST deposited on top of fFFT deposit resulted in:
- Deformation of fFFT deposit.
- CST deposit formed through typical delta growth AND appeared to move as a mass flow, with fFFT serving as a bottom shearing layer. CST lobes appeared to extend into the fFFT deposit.

- Settled CST (sand raining) loaded fFFT, displacing it vertically and laterally.
- Cores suggest various “levels” of mixing of the two tailings streams.

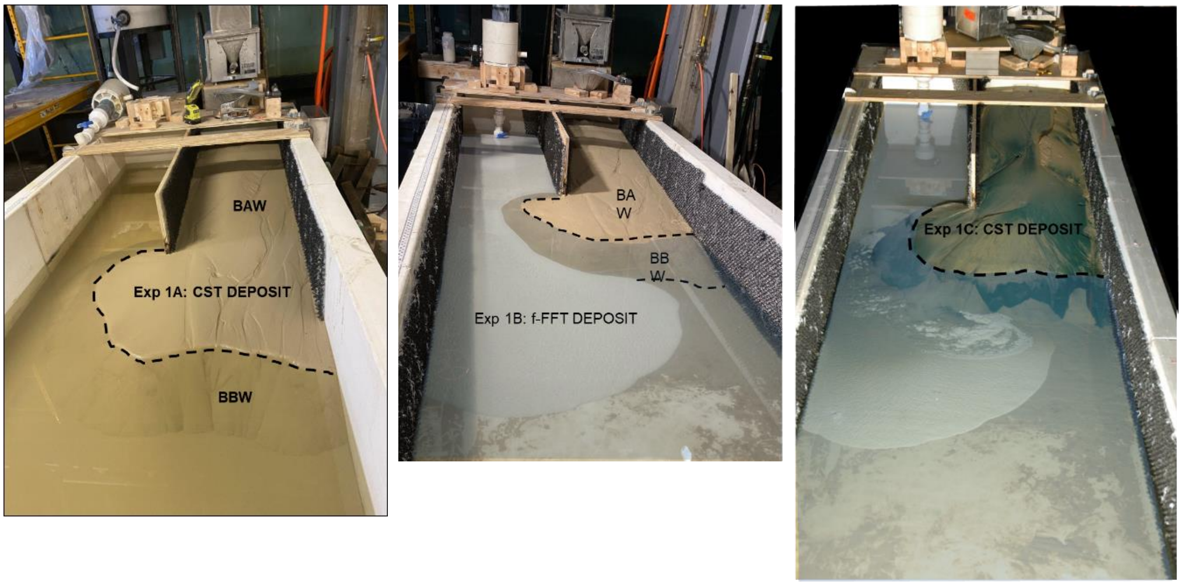

Figure 17. Three images summarizing Experiment 1A (left), Experiment 1B (Middle), and Experiment 1C (Right)

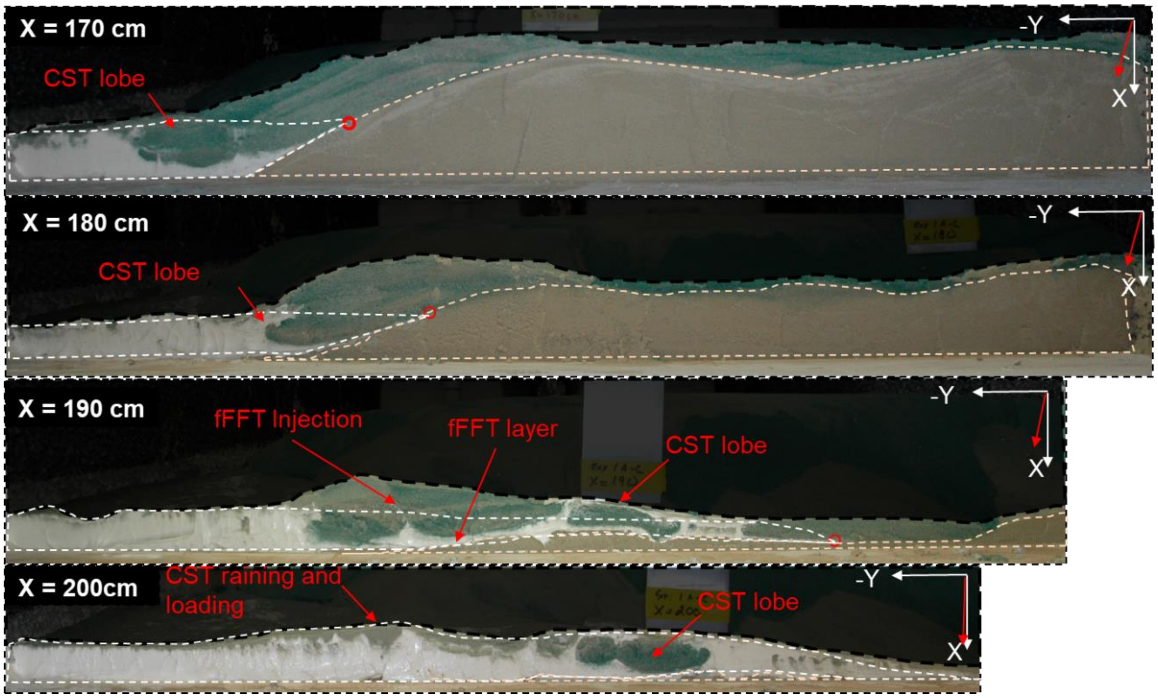

Figure 18. Composite image of four cross section slices taken from the final deposit in Experiment 1 (A-C).

Experimental Set #2

Over the two month period from December 2021 to February 2022, topographic measurements of this basin were substantially improved by developing a computer-controlled scanning system, specifically designed for this basin and these deposits (5 mm x 5 mm spatial resolution).

As of May 2022, the project team has nearly completed Experimental Set #2. The same approach was taken in this four-stage experiment (Figure 19). However, the fFFT tailings was introduced subaerially over an established CST beach rather than underwater as in Experiment 1B.

Similar data collection techniques were used in Experiment #2. Piston cores were taken after all stages and analyzed for grainsize distribution. Topographic scans were completed for all stages. An example of a topographic scan is shown in Figure 20 from Experiment 2C.

Currently, the process of analyzing the data from this experimental setup is underway and is expected to be completed by the end of June 2022.

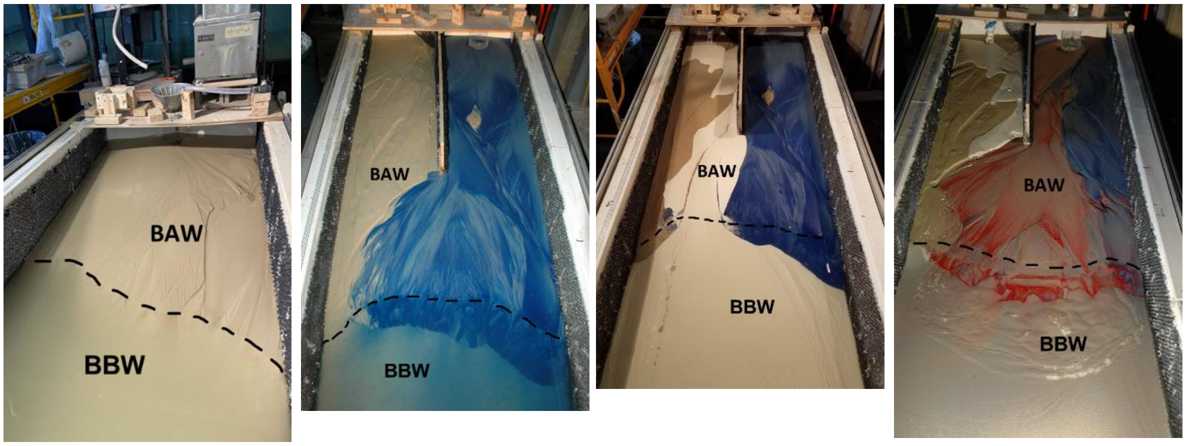

Figure 19. Images from the four stages of Experiment 2. Experiment 2A (Left) and Experiment 2D (Right).

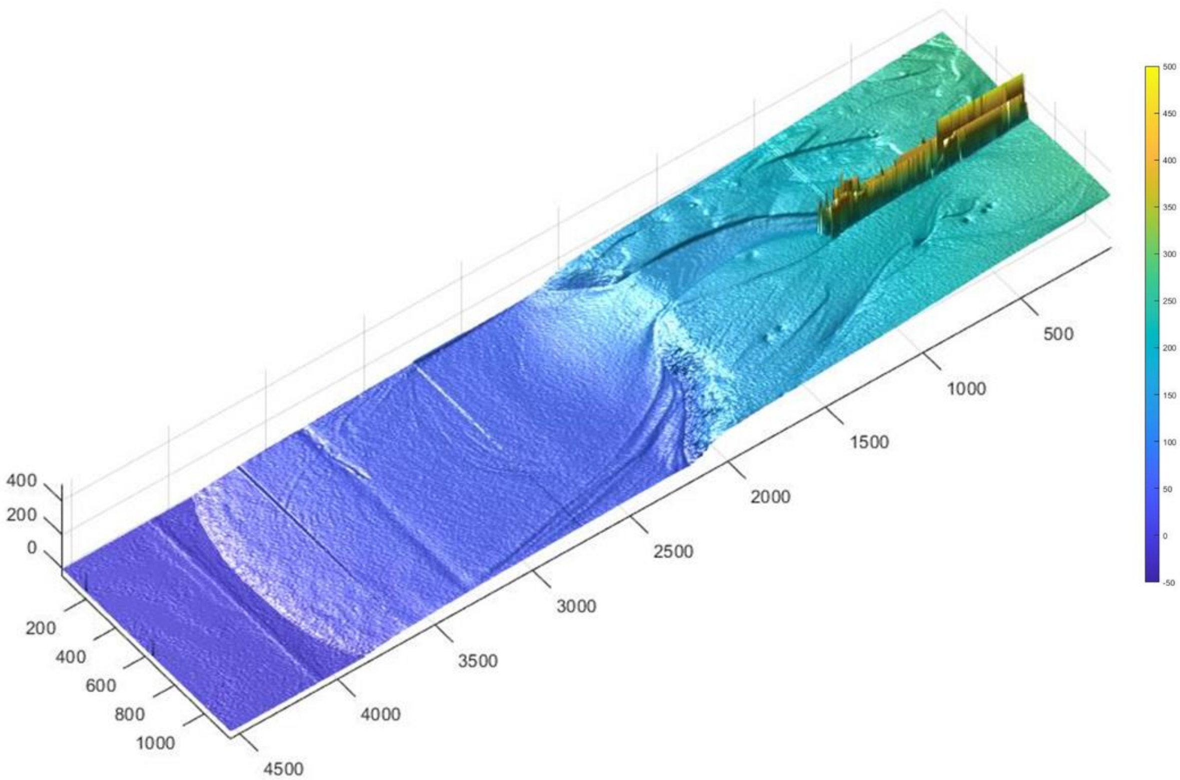

Figure 20. Example of a topographic scan from Experiment 2C.

Next Steps:

The final stage of the project is underway and intended to be completed by September 2022. The remaining work involves the following:

- Complete sectioning of the deposit.
- Final analysis and synthesis of all flume experiment data
- Final report (July/ August)
- September 2022 – project complete.

LESSONS LEARNED

The project is still underway and thus, not prudent to state technical outcomes of the work at this time. Nevertheless, two preliminary lessons learned are: (1) the potential for advection in promoting mixing in parallel streams of coarse and fine materials; and (2) the significance of discharge configuration and sand concentration of the CST stream in promoting improved mixing through erosion of coarse tailings from beach above water to improve geotechnical stability of the fine tailings material with which it is co-deposited.

PRESENTATIONS AND PUBLICATIONS

IOSI Tailings Project Knowledge Dissemination Workshop, November 2021

RESEARCH TEAM AND COLLABORATORS

Institution: University of Minnesota

Principal Investigators: Jeff Marr

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Jeffrey Marr	University of Minnesota, St. Anthony Falls Laboratory	Associate Director of Engineering and Facilities, Project PI		
Kimberly Hill	Department of Civil, Environmental, and Geo-Engineering, University of Minnesota	Associate Professor, Project Co-PI		
Syed Ahmed	Department of Civil, Environmental, and	PhD	June 2021	June 2024

	Geo-Engineering, University of Minnesota			
Amirreza Ghasemi	Department of Civil, Environmental, and Geo-Engineering, University of Minnesota	PhD & Post-doctoral Researcher	July 2020 (Date started with project)	January 2021

Mechanics of Methane Bubbles in Tailings Ponds

COSIA Project Number: TE0069

Research Provider: University of British Columbia

Industry Champion: Suncor

Status: 2 of 4 years

PROJECT SUMMARY

All oil sands tailings ponds produce carbon dioxide (CO_2) (Small *et al.* 2015). In operations where naptha has been used as the diluent, anaerobic biodegradation of naphtha produces methane (CH_4), hydrogen sulphide (H_2S) and CO_2. Similar mechanisms in geological materials, such as shallow marine, terrestrial sediments and some flooded soils, also lead to the formation of CO_2 and CH_4 bubbles. These materials are not all transparent, but evidence of bubbles is found by sampling and acoustic measurements (Boudreau, 2012). It has also been observed that bubbles can escape to the overlying water or the atmosphere (Leifer & Boles 2005; Walter *et al.* 2006). Broadly, the projects scope is to build a mechanical understanding of phenomena relevant to bubble dynamics in tailings ponds; meaning bubble growth, entrapment, and release.

The tailings consist of coarse sands, fine clays, silt, water, residual and unrecovered bitumen, naphtha, naphthenic acids, petroleum hydrocarbons and other extraction by-products. These are deposited in the ponds as they are produced. Coarse sands form beaches upon discharge and some sediment to the pond bottom, then a gradient of mature fine tailings (MFT) to fluid fine tailings (FFT), topped with a clear water zone. Tailings ponds are thus mostly stratified depth wise, with mild lateral variations. This structure evolves over timescales of 1-10 years, if left alone, or more rapidly during processing treatments. The FFT layer has been characterised rheologically as a thixotropic yield stress fluid (Derakhshandeh, 2016). Thus, understanding bubble mechanics is focused on a stratified media that can vary from clear water (top), through gelled suspension layers (FFT/MFT) to a gel-filled porous media at the pond bottom (coarse sand & MFT).

The project is built around three main themes: emissions, risk, and mitigation/control. Regarding emissions, the main objectives here are to provide fundamental quantitative physical understanding of bubble mechanics in yield stress materials. This includes theoretical, computational, and experimental research methodologies. The yield stress of the FFT results in the possibility that bubbles are trapped within the pond and allows for different bubble shapes to be trapped. We start from the basic question of when does a single bubble move or remain trapped, how is this affected by shape and surface tension? Supplementary questions concern multiple bubbles, interactions such as coalescence or the effect of clouds of bubbles on the ability of the material to retain bubbles.

Regarding risk, the main concerns here relate to the possibility of large-scale release of bubble clouds. The evidence suggests that a yield stress fluid such as FFT may hold static a maximal volume fraction of gas, which will depend on the bubble size distribution, the yield stress, surface tension and on how the bubbles are spatially distributed. Ponds are subjected to daily, annual, and seasonal changes in pressure and temperature (including freezing/thawing), as well as local operational events (pond management, tailings deposition). There is strong evidence that these variations are linked to variations in ebullition rates (Natchimuthu et al 2016; Zhao et al 2021). Atmospheric sensitivity of the bubbling suggests that gas generation and bubble trapping in many lakes is close to a critical limit of onset. However, this risk is not yet quantified.

Regarding mitigation, the ideas depend largely on the evolving ideas from the first parts of the project. For example, should one try to “purge” parts of a pond to reduce risk (which may itself be happening naturally with atmospheric fluctuation)? Can one mechanically treat the FFT/MFT layers to mitigate bubble coalescence and increase stability? Can one work directly with aspects of the biodegradation, either chemically or addressing motility to limit bubble production. Can one adjust the rheology of the FFT/MFT in order to trap gas?

The emissions aspects of the project have become a key driver, although not critical at the project start. This is due to Canada’s commitment to GHG emission reduction by 2030.

PROGRESS AND ACHIEVEMENTS

- The theoretical conditions (the critical yield number) have been derived under which a single bubble remains static in a yield stress fluid, correcting some previous errors regarding the role of surface tension.
- Computational codes have been developed and benchmarked that are able to calculate the flow around single bubbles of specified shape, either axisymmetric or 2D, in the limits of low inertia. These codes include the yield stress effects exactly and use adaptive meshing, making them specifically suitable for calculating the critical yield number.
- The above codes have also been used to calculate critical yield numbers for 2D bubbles of cylindrical, elliptical and other shapes, over wide ranges, and including surface tension effects. The latter dominate when the bubbles have high aspect ratio. The theory of perfect plasticity to the 2D bubble shapes have also been partly extended, which exposed some limitations.

- Similar codes have been developed and calculations performed for axisymmetric bubble shapes: basically ellipsoidal shapes. The results presented above are published in Pourzahedi et al, 2022.

- The use of a multi-phase code (Basilisk) for studying transient flows has been developed. This open-source code is specifically targeted at interfacial flows and contains state-of-the-art methods for tracking the interfaces. The yield stress fluid implementation within the code is less exact compared to the developed slow flow codes and this makes it less suitable for computing critical yield numbers. However, the code has been used for 2D bubble computations, that have been described below.

- A bubble column was constructed within which single or multiple bubbles can be injected into laboratory fluids in a regulated way. Initial usage of this apparatus has been to study the effects of injection method on the bubble shape. In most yield stress fluid bubble propagation experiments to date, bubbles develop a pointed tail as they rise. An ongoing debate concerns whether this is an experimental artefact due to injection method or arises from the fluid rheology (specifically viscoelasticity). Evidently, in tailings ponds the bubble formation is not mechanically driven so this is an important aspect of establishing experimental protocols. Using a system of layered fluids, it has been shown that the injection method is not responsible for the later bubble shape (Pourzahedi et al. 2021).

- A second interesting aspect of the reported experiments, as with other earlier observations (e.g., Dubash & Frigaard 2007; Lopez *et al.* 2018), is that after the first bubble enters the bubble column it appears to damage the structured fluid. Whether a viscoelastic or thixotropic mechanism is responsible is unknown. However, the effect is obvious in that subsequent bubbles typically follow the same pathway as the first. This phenomenon is currently being studied using the Basilisk code described above. Here, the damaged channels are modeled as Newtonian fluid channels, constrained by yield stress fluid layers. Bubbles move towards the Newtonian channels, attracted even from many diameters distant, deform and move along the channels. Vertical and angled channels have been studied and experiments in the bubble column have been performed which show similar effects to the computations (Zare *et al*. 2021). Images collected from Base Mine Lake clearly show pockmarks on the interface of the water and FFT layer, providing evidence for associated chimneys below (Zhao *et al*. 2020). A detailed experimental study of the formation of damaged channels, as bubbles cross an interface, was performed collaboratively with Zhao et al. (2021) (project at UBC led by G. Lawrence).

- A second apparatus has been built to address onset of bubble motion. This apparatus consists of a vacuum chamber in which a gelled fluid can be placed and visualised through the sides as the pressure is varied. A bulk measurement of the bubble volume was obtained through the changes in the fluid height as the pressure was lowered. A gradual increase in both bubble size and overall volume was observed. Each step decrease in pressure is followed by an apparently elastic relaxation response as the system attains its new equilibrium. Below a given critical pressure the bubble volume fraction (and bubble size) mobilises en-masse and the fluid sample is degassed in an unstable way. This may mimic the field setting of pond instability, which may indeed be worse in that there can be a larger decrease in static pressure on the larger scale of the pond, rather than in our small apparatus. In Summer 2021, systematic studies were conducted to map out the critical conditions for lab fluids, which show sensitivity to the initial distribution of dissolved gas in the sample. A paper is in the process of being written. Some pond samples were also used for similar studies, but visualization was not possible. In Summer 2022, these studies will be extended to transparent clay-like gels that may be rheologically similar to the pond fluids, but can be transparent.

- Supplementing the above experimental study of bubble cloud stability, we have used our slow flow codes in order to explore critical yield number conditions for clouds of bubbles computationally. This is restricted to 2D flows due to computational resource limitations. The method is to populate a periodic 2D box with cylindrical bubbles randomly positioned. The flow is computed and the mean velocity of the liquid calculated. The yield stress is then increased and the calculation repeated. Eventually the liquid mean velocity decays to zero, thus, giving a critical yield number. The procedure is repeated with a different bubble configuration, i.e. a Monte Carlo approach, and over many calculations, an estimation of the critical yield number and its sensitivity to bubble distribution were built up. This work appeared in Chaparian & Frigaard (2021).

- The vacuum chamber setup has also proven useful for studying the onset of single or pairs of bubbles. Here, the fluid sample is initially degassed completely, and the pressure released. A small bubble (or more) is then placed in the sample using a needle and an experiment is conducted in which the pressure is lowered stepwise. Hence, the bubble size increased until motion started. A paper draft has been written concerning bubble motion onset. The process is very interesting in that elastic creep seems to be responsible for significant changes in bubble shape prior to the actual onset of motion.

- Preliminary experiments on bubble coalescence have been conducted and a simple model for the process has been developed for this purpose. Some preliminary Basilisk computations have been performed.

- Larger scale models of the tailings pond have been proposed, with a view to answering risk-based questions.

LESSONS LEARNED

The single bubble flow onset studies have delivered results that are physically intuitive. For the 1st time (to the knowledge of the authors), these combine the effects of the yield stress in countering both buoyancy and surface tension forces that are promoting bubble deformation, all for different bubble aspect ratios. As well as being physically intuitive, the quantitative limits are quite plausible, e.g., a 5 mm diameter bubble with surface tension $\hat{\gamma} = 50$dyn/cm would be static if spherical and if the yield stress $\hat{\tau}_Y \gtrsim 3.5$Pa. For a more prolate ellipsoid (aspect ratio $\chi = 2$), static stability requires $\hat{\tau}_Y \gtrsim 12$Pa, and if $\chi = 10$, static bubbles require $\hat{\tau}_Y \gtrsim 35$Pa. For a 2 cm diameter bubble with $\hat{\gamma} = 50$dyn/cm, the spherical bubble is static for $\hat{\tau}_Y \gtrsim 14$Pa, whereas $\chi = 2$ & 10 require $\hat{\tau}_Y \gtrsim 28$Pa and $\hat{\tau}_Y \gtrsim 50$Pa, respectively.

It becomes clear that as we go lower in the pond, if the yield stress increases (through aging or increases solids content), then larger and more elongated bubbles can be trapped. Elongation due to elastic creep is also observed experimentally in the flow onset experiments with higher yield stress fluids. It would be of interest to measure both bubble size and fluid rheology, as a function of depth in the ponds.

As with the single bubble experiments, bubble cloud experiments and computations show qualitatively similar effects and point to critical bubble volume fractions of around 15-20% for when the bubble clouds start to move.

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Conference Presentations/Posters

Chaparian, E., and Frigaard, I. (2022, April 26-28). *Rising cloud of bubbles in a yield-stress fluid* [Conference presentation]. AERC2022 - The Annual European Rheology Conference in Seville, Spain.

Daneshi, M., Zare, M., and Frigaard, I. (2022, April 26-28). *Flow onset mechanics of bubbles in yield stress fluids* [Conference presentation]. AERC2022 - The Annual European Rheology Conference in Seville, Spain.

Daneshi, M., Zare, M. and Frigaard, I. (2022, June 5-8). *Flow onset mechanics of bubbles in yield stress fluids* [Conference presentation]. CSME2022 – Canadian Society for Mechanical Engineering International Conference, Edmonton, AB, Canada.

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Frigaard, I. (2021, November 30). *Mechanics of methane bubbles in tailings ponds*. IOSI/COSIA Tailings fundamentals workshop (online).

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Zare, M., Pourzahedi, A. and Frigaard, I.A. (2021, August 22-27). *Constraining the Origin of Fore-Aft Asymmetrical Shape of Bubbles Rising in Yield Stress Fluids* [Extended abstract presentation]. XXV ICTAM.

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RESEARCH TEAM AND COLLABORATORS

Institution: University of British Columbia

Principal Investigators: Ian Frigaard

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Emad Chaparian	UBC	Postdoc		
Tyler Dozzi	UBC	Summer intern	June 2020	August 2020
Miguel Eagleton	UBC	Intern	July 2020	April 2021
Tyler Heim	UBC	Summer intern	May 2021	August 2021
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Omid Hajieghrary	UBC	PhD student	January 2023	Dec 2026

Research Collaborators:

- Dr Marjan Zare, UBC
- Dr Greg Lawrence, UBC
- Dr Ali Roustaei, University of Tehran
- Dr Emad Chaparian, University of Strathclyde (since April 2022)

Assessment of Liquefaction Potential of Unsaturated Tailings Subjected to Future Saturation

COSIA Project Number: TE0071 (IOSI19)

Research Provider: Thurber Engineering Ltd. and Western University

Industry Champion: Imperial

Status: Year 2 of 2

PROJECT SUMMARY

A necessary pre-condition for liquefaction and flow failures in tailings dams is the rapid build-up of pore pressures, which implies that saturation is required for liquefaction to occur, and that subsequent saturation of initially unsaturated tailings may lead to liquefaction and flow failures. This research seeks to investigate the required level of saturation where static liquefaction is no longer likely to occur.

The research aims to develop new insight into liquefaction mechanisms, reduce design uncertainties and minimize the likelihood of catastrophic flow failure of tailings dams.

PROGRESS AND ACHIEVEMENTS

The project was initiated in the summer of 2020 with delivery of oil sands tailings samples to the University of Western Ontario. The laboratory program comprises triaxial, ring shear, compression wave velocity (Vp), and soil-water characteristic curve (SWCC) tests on loose to medium dense tailings sand samples over a range of fines contents (7 % to 25%), confining stresses (100 kPa to 800 kPa) and saturation levels (85 % to 100%). Index tests were also completed, including particle size distribution (PSD), minimum and maximum void ratio assessment and scanning electron microscope (SEM) imaging.

The following works were completed as part of the research work:

- Developed critical state lines (CSL) from a series of drained and undrained triaxial compression tests on saturated tailings with 7% and 25% fines contents.

- Developed the soil water characteristic curve for 7%, 10%, 25% and 50% fines contents.
- Assessed the relationship between compression wave velocity, Skempton's B value and saturation.
- Assessed the stress path behaviour of tailings samples at states loose of the CSL over a range of saturation values.
- Assessed the liquefied shear strength of liquefiable tailings over a range of fines contents and saturation levels.

Extended laboratory closures and the pandemic related restrictions significantly impacted the schedule and scope of the project, which resulted in the final scope being reduced from the original plan.

LESSONS LEARNED

- Reduction of the saturation of the tailings can change contractive materials to dilatant behaviour.
- Measurement of the saturation of unsaturated sand samples during the test requires careful calibration for accurate measurement.
- Adjusting the fines contents through the addition of fluid fine tailings (FFT) to coarse sand tailings (CST) produces gap graded PSDs, that may not be representative of field conditions.
- The sand tailings indicate a semi-logarithmic critical state line.

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PRESENTATIONS AND PUBLICATIONS

There have not been any publications or presentations to date. The work is currently under the review of the project stewards.

RESEARCH TEAM AND COLLABORATORS

Institution: Western University and Thurber Engineering Ltd.

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The Role of Bubble Ebullition on The Vertical Transport of Fine Solids in End-Pit Lakes

COSIA Project Number: TE0083 (IOSI 2019-06)

Research Provider: University of Alberta IOSI

Industry Champion: Suncor

Status: Complete

PROJECT SUMMARY

End-pit lakes offer a cost-effective alternative for tailings disposal and reclamation. Key objectives for pit lakes include effective sequestration of fine solids and meeting water quality targets. In this latter respect, cap water turbidity related to suspended solids is a key consideration. While particles, especially fine particles, may become suspended by a variety of well-documented mechanisms, the possible importance of bubble ebullition has yet to be thoroughly explored. Doing so from the perspective of controlled laboratory experiments is the key objective of this study.

Experiments are run in 2 m tall columns and employ field materials sourced from Base Mine Lake (cap water) and Mildred Lake Settling Basin (fluid fine tailings or FFT). Laboratory experiments are run employing a variety of mud depths and ebullition rates. For this purpose, regular FFT and FFT dosed with an anionic water-soluble polymer flocculant were considered.

An important contribution of this work is to quantify the significant reduction of solids suspension that may be realized by mixing flocculant into the FFT. For example, and considering the most vigorous period of solids suspension, the time rate of change of cap water turbidity may be reduced by up to 85%. More generally, cap water turbidity is found to increase with the depth of FFT and, correspondingly, the number of fine particles available for suspension. While it is also true that the cap water turbidity typically increases with the ebullition rate, important exceptions arise, particularly when considering samples of flocculated FFT. Scenarios were observed where the maximum turbidity is achieved before (sometimes well before) the end of active bubbling. Together, these observations point to the possible formation of stable craters along the mudline and/or sidewall-armored channels within the FFT. In either case, the supply of fine particles able to be suspended is locally depleted. Although the laboratory-based investigation is not specifically tied to a monitoring campaign, the above observations have potentially important consequences for field operations. Whereas one would expect methane production and end-pit lake water

turbidity to correlate in a general sense, the correlation in question may be imprecise and subject to variability quite apart from the role of other mechanisms of fine solids suspension. Indeed, this observation may help to explain the trends noted in Figure 2 of Zhao et al. (2021). Zhao et al. made field measurements of Base Mine Lake that suggest that bubble ebullition events cause cap water turbidity to increase most, but not all, of the time.

Key performance indicators for this study were to gain a better fundamental understanding, from laboratory measurements using real field materials, of the connection between ebullition and solids suspension (and eventual settling). To this end, this study was successful in its ability to highlight the role (sometimes counterintuitive) of relevant factors, i.e., FFT depth, ebullition rate and chemical treatment by flocculant addition. The knowledge gained can be used in both rationalizing monitoring data for existing end-pit lakes such as Base Mine Lake and in planning new tailings repositories. For example, this study quantifies the benefits of chemical treatments and hence, provides helpful cost-benefit guidance when considering such turbidity remediation options as FFT flocculant addition vs. end-pit lake alum addition vs. diluent recovery. An important milestone for the incorporation of conclusions into closure plans would be to have the results directly inform pilot testing meant to assess flocculant efficacy for different FFT types.

PROGRESS AND ACHIEVEMENTS

Representative data sets from this study are exhibited in graphical form below. Measured turbidities are derived using a novel (and non-intrusive) optical technique that, in turn, requires detailed calibration to facilitate estimates of the suspended solids concentration across the entire field of view rather than at one particular point in space.

Figure 21a shows a time series of the column-average turbidity for regular (i.e., non-chemically-treated) FFT. Analogue time series data for the case of flocculated FFT are shown in Figure 21b. Results such as those of Figure 21 are helpful in a number of respects. Firstly, they quantify the significantly lower cap water turbidities that may be realized by flocculation e.g., a nearly 10-fold decrease for the moderate ebullition rate indicated by the blue symbols. Secondly, these data provide insights into mudline processes that impact solids suspension. Most importantly, the black and blue symbols of Figure 21b show an intersection after approximately 10 hours, which supports the hypothesis that larger ebullition rates may be associated with the formation of larger craters within the FFT – see Figure 22.

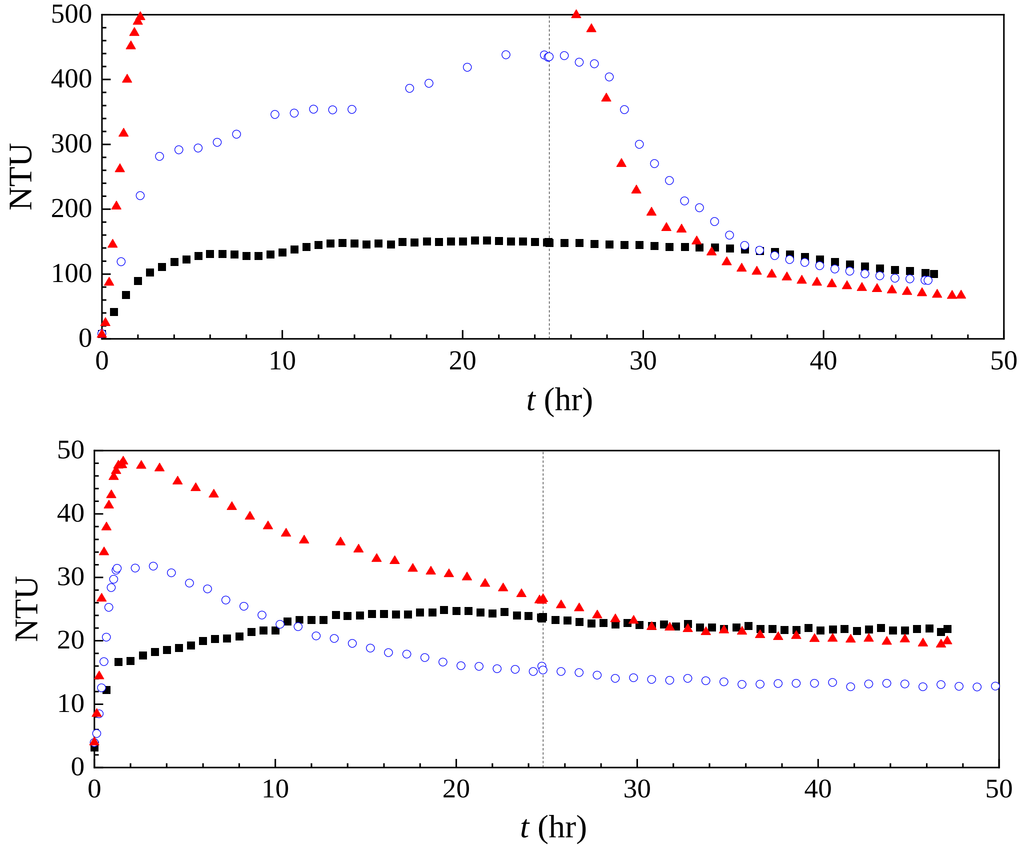

Figure 21. Time series showing the variation of cap water turbidity for (a, top panel) regular (non-chemically treated) FFT, and, (b, bottom panel) flocculated FFT. In both cases, the depth of FFT at the base of the column is initially 3 cm. Three different ebullition rates are considered, i.e., 1 cm^3/min (black symbols), 3 cm^3/min (blue symbols) and 5 cm^3/min (red symbols). Vertical dashed lines indicate the time at which bubbling was terminated.

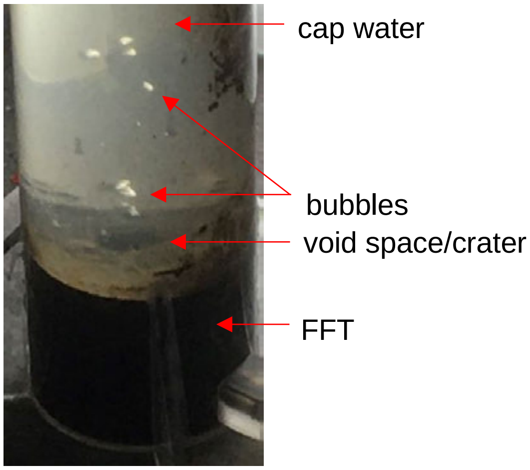

Figure 22. Experimental photograph showing bubble ebullition and a crater along the FFT mudline.

Once craters form, the local supply of solid material available for suspension becomes depleted and so the cap water turbidity typically decreases even as ebullition continues. The behavior just described is apparent for flocculated FFT but less so for regular mud: without the addition of flocculant, it can be speculated that FFT may lack the cohesive strength to avoid crater wall collapse. As a result, and for the data of Figure 21, cap water turbidities achieve their maximum values at about the time when bubbling is arrested.

Synthesizing results such as those exhibited in Figure 21 leads to a number of pertinent observations. As regards the initial rate of turbidity increases with time, it is found that this rate generally increases with the ebullition rate irrespective of FFT depth/type. As ebullition continues, however, this initial rate of turbidity increase cannot be maintained; indeed, and for flocculated FFT, the maximum turbidity may be realized in as little as ~2 hours from the start of the experiment. Since the initial rate of turbidity increases is likewise smaller for chemically-treated FFT, flocculation leads to a substantial reduction in the longer term cap-water turbidity with the data of Figure 21 being representative. Thus, it can be concluded that flocculation has a generally more significant impact on cap water turbidity compared to the ebullition rate, particularly, for larger times where, in the case of flocculated FFT, crater formation leads to a decorrelation between ebullition rate and turbidity.

LESSONS LEARNED

In considering the role of rising bubbles on cap water turbidity, FFT flocculation has a substantial impact compared to the ebullition rate. Flocculation supports the appearance of craters along the mudline, which, once formed represent regions having comparatively little solids material that can be transported into the overlying water column in the wake of rising bubbles. Therefore, and from the point of view of end-pit lake turbidity mitigation, an equal emphasis should be placed on tailings flocculation vs., say, diluent recovery. Of course, bubbles rising through the tailings may transport other constituents rather than fine solids. To this end, the role of rising bubbles on bitumen flotation or salt transport, though outside of the scope of the present study, merits further investigation.

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PRESENTATIONS AND PUBLICATION

Conference Presentations/Posters

Flynn, M.R. (2020, August 13). *Ebullition, mudline destabilization and turbidity*. Syncrude Canada Ltd., Base Mine Lake Sharing Session 3: Transport mechanisms from FFT to water column.

Flynn, M.R. (2021, November 30). *The role of bubble ebullition on the vertical transport of fine solids in end-pit lakes.* IOSI/COSIA Tailings Project Knowledge Dissemination Workshop.

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Rahman, M.S. and Flynn, M.R. (2021). *The role of bubble ebullition on the vertical transport of fine solids in end-pit lakes.* IOSI project final technical report.

RESEARCH TEAM AND COLLABORATORS

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Principal Investigator: Morris R. Flynn

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Deposit Instabilities in Subaqueous and Terrestrial Tailings Landscapes

COSIA Project Number: TE0085

Research Provider: Thurber Engineering Ltd.

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

The presence of gassy soils has been identified as a potential cause or escalator of geotechnical risk in closure landscapes. Gassy soils, resulting from biogenic processes or exsolution, represent partially saturated soils whose pore space is occupied by a continuous water phase and a discontinuous (entrapped) gas phase (usually attached to soil particles), which are typically located below the water table.

This project aimed to guide practitioners in assessing the failure risk of subaqueous and terrestrial closure landscapes influenced by gassy soils. The intent was to give the practitioner insight into the science governing gassy soils and how their presence can impact potential failure of a closure landscape - specifically mechanisms, modes, consequences and likelihood of occurrence. It attempts to synthesize the state of knowledge on gassy soils and identify potential gaps for each of the contributing factors leading to geotechnical failure within them. The guidelines were developed through workshops with industry collaborators and a comprehensive literature review and application of gassy soil mechanics to geotechnical failure event trees.

PROGRESS AND ACHIEVEMENTS

The project was completed in 2021. The final guideline provides a detailed discussion on the process of gas formation within tailings deposits, how that gas affects soil behaviour and the process of gas migration. The guideline assumes that the practitioner will use a risk assessment framework similar to a Failure Mode and Effects Analysis (FMEA). Utilizing this framework, the guideline comments on the role of gas in each step of the risk assessment process, namely, identifying potential paths to failure and the impact of gas on the consequences and likelihood of failure. Various recommendations will be provided to improve the current understanding of the extent of gassy soils within tailings deposits and to close research gaps that were identified during the project.

LESSONS LEARNED

Guidance for practitioners performing risk assessments in the presence of gassy soils is included within the guideline. The guideline summarizes the current state of knowledge with regards to gassy soils within tailings deposits and identifies areas where further research could be conducted to improve the understanding of gassy soils on closure schemes.

PRESENTATIONS AND PUBLICATIONS

The guideline provides numerous references to published and unpublished literature concerning gassy soils in tailings deposits as well as within similar subaqueous environments.

RESEARCH TEAM AND COLLABORATORS

Institution: Thurber Engineering Ltd.

Principal Investigators: Iain Gidley

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Babak Derakhshandeh	Suncor	Project Steward		
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Managing Long-Term Settlement of Deep Cohesive Tailings Deposits

COSIA Project Number: TE0088

Research Provider: Barr Engineering and Environmental Science Canada Ltd., Deltares, Cofra, Keller, Menard, ConeTec, Enviro Q&A

Industry Champion: Syncrude

Status: Phase 1 Completed

PROJECT SUMMARY

Oil sands producers are committed to reclaiming all lands affected by their mining operations. The regulatory framework in Alberta requires Industry to minimize fluid tailings accumulation by ensuring that such fluid tailings are treated and reclaimed progressively during the life of a project, and that all fluid tailings associated with a project are “Ready to Reclaim” (RTR) 10 years after the end of mine life of that project.

Deep, fines-dominated oil sand tailings deposits (deep cohesive deposits) are anticipated to comprise an important and ongoing component of a producer’s mine, tailings, and long-term reclamation and closure plans. Depending on the deposit geometry and material properties, without intervention, current modelling (numerical and physical) indicates that deep cohesive deposits could take decades to centuries to fully consolidate. This may result in a delay in the reclamation of the deposit to a terrestrial closure landform. For the purposes of this project, deep, fines-dominated oil sands tailings deposits were defined as having the following characteristics:

- Greater than 2 m deep at the end of deposition, though more commonly 20 m or deeper
- Encompass an area on the order of several square kilometres.
- Consist primarily of treated fluid fine tailings and have a sand-to-fines ratio (SFR) less or equal to 1; though in some cases may include transition tailings with SFR up to 1.5.
- Solids content is greater than 30% by weight.
- Dewatering and densification occurs primarily by self-weight consolidation.
- No water cap is present on the surface of the deposit at the time of technology application.

- The base and sidewalls of the basin are assumed to be relatively impermeable, and therefore two-way drainage does not occur.
- Potential off-gassing from the deposit does not pose a challenge to technology implementation or effectiveness.

This project aimed to address the challenge presented by these deep, fine-dominated deposits by identifying and evaluating technologies that could be implemented in the oil sands and meet the following specific objectives:

1. Reduce the time for expected long-term settlement of deep cohesive deposits, such that most of the settlement occurs during deposit construction or soon after completion; and
2. Reduce the amount of expected long-term settlement of deep cohesive deposits to a magnitude consistent with long-term closure requirements.

The study focused on 'post-filling' conditions, i.e., tailings deposits that were fully formed and not in the process of being created. "Upstream" technologies, i.e., those that affect tailings properties prior to deposition were considered out of scope. Likewise, technologies that were considered at research or early development stage or those that may aid in reducing settlement *during* deposit placement were identified for further study but were excluded from the Phase 1 evaluation.

The work scope was split into two phases which are summarized below. This project summary is for the Phase 1 scope only.

Phase 1 – Desktop Study: Completion of a literature review of relevant technologies currently in use at large or commercial scale operations in relevant industries or projects. These industries or project examples were both local and global. In parallel, a conceptual model was developed utilizing industry best-practices and geotechnical engineering principles that were used to describe how the technologies identified in the literature review may be used to achieve the specific project objectives. The potential technologies identified during this literature review were then run through primary and secondary screening exercises to evaluate and compare them using pertinent criteria. Finally, a framework for the detailed assessment of the technologies against specific success criteria in Phase 2 of the project was developed.

Phase 2 – Detailed Analysis and/or Bench Scale Testing: As part of the Phase 1 work, a framework for the future Phase 2 work was prepared to guide the next steps of the project. The framework outlined a series of development steps (technical and economic) that should be undertaken to deliver a set of design conditions and performance parameters for a particular technology. Once these design conditions and parameters are established, the suitability of the potential technologies to meet the success criteria will be assessed. This information would then be available to allow recommendations for a scale-up field pilot/demonstration of the most promising technology (or combination of technologies).

PROGRESS AND ACHIEVEMENTS

The Phase 1 Desktop Study project began in August 2021 and was completed in February 2022. A summary of the Phase 1 work is provided below.

The literature review identified 72 relevant technologies. This list was refined by reconciling similar or duplicated technologies, as well as rejecting technologies that were determined to not be suitable for achieving the project objectives (primarily due to their inapplicability to the defined deposit setting). This refinement produced a list of 23 unique technologies (see table below) that were advanced to primary screening for further assessment. Primary screening consisted of predominantly qualitative assessments of each technology based on their perceived technical and operational feasibility. Further rejection and consolidation yielded seven technologies that were advanced through a more detailed secondary screening exercise. This secondary screening assessed the seven technologies against the specific criteria of constructability, operability, landform and closure, and environment, health, and safety (EH&S). The result of these screening exercises was six high-priority technologies that have been recommended for further detailed assessment in Phase 2. A framework for the Phase 2 assessment was prepared to guide next steps towards delivery of a set of conditions and performance parameters for each technology to assess the suitability of each to meet the success criteria defined for this work.

Advanced to Secondary Screening	Not Advanced to Secondary Screening	
Applicability to deep cohesive deposits	**Potential novel applicability to deep cohesive deposits**	**Potentially feasible for application during deposit formation (thin lift/cyclic placement)**
• Prefabricated vertical drains (PVD) • Surcharge loading (mechanical placement of sand or coke) • Surcharge loading in combination with PVDs • Vacuum consolidation with PVDs • Accelerated dewatering (Rim-ditching) • Subaerial capping • Electrokinetic sedimentation • Sand compaction piles (with or without geotextile containment) • Deep-soil mixing	• PVDs with water level regulation • Air injection – fracturing • Electrically conductive drain-tube planar geo-composites (eGCP) • Artificial ground freezing (AGF)+Thaw settlement • Bioengineering: dewatering through addition of worms • Bacteria inoculum of tailings	• Drainage systems • Coarse tailings underdrain • Thin layer consolidation/desiccation • Vegetation evapotranspiration (can include wetland creation • Natural freeze-thaw • Bioengineering: dewatering addition of worms • Bacteria inoculum of tailings

LESSONS LEARNED

Phase 1 of the research described above identified and assessed techniques, methods, and/or processes ("technologies") that could help mitigate the expected long-term settlement of deep cohesive deposits on constructed final terrestrial landforms. As a result, six high-potential technologies have been identified through the technology screening process and warrant further consideration in the planned Phase 2 of the project. These technologies would be inputs to the Phase 2 assessment based on the initial framework developed in Phase 1.

The high priority technologies identified were:

- Prefabricated Vertical Drains (PVDs) – including variants related to vacuum consolidation, water level management, with and without surcharge loading
- Subaerial Hydraulic Capping
- Mechanical Surcharge Loading
- Deep-Soil Mixing
- Sand Compaction Piles
- Accelerated Dewatering (Rim-Ditching)

Work planned to be completed in Phase 2 will aim to provide the scientific, engineering, and economic evidence to determine whether these high-potential technologies would indeed be able to meet the specific success criteria defined for this research. This would include detailed technical evaluations and a quantitative assessment of the economic feasibility considering the scale and complexity of the oil sands setting.

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RESEARCH TEAM AND COLLABORATORS

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Co-Deposition

COSIA Project Number: TJ0104

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Ongoing

PROJECT SUMMARY

Conventional practice involves the separation of different tailings streams or products by way of internal dykes, within the tailings containment footprint. This practice is not cost-effective, minimizes the storage efficiency of engineered tailings structures, and complicates mine and tailings planning due to the need to maintain strict hydraulic gradients across the internal dykes. The current project assesses the benefits and limitations of co-depositing multiple tailings products or streams within the same tailings containment structure, without separation by internal dykes. The major portion of the co-deposit would consist of the individual tailings stream or products, in which case the long-term geotechnical trajectory will be dictated by the properties and performance of the individual streams / products. Of particular interest is the properties and performance of the interface where the tailings streams / products interact.

A series of flume tests, involving the co-deposition of various combinations of tailings products and streams (such as fluid fine tailings - FFT, recycle water- RCW, centrifuge cake, composite tailings-CT, straight coarse tailings- SCT and flocculated FFT - fFFT) were completed. The dewatering and shear strength development of the co-deposits were monitored over time. Results showed that for most of the co-deposition cases tested, there was no detrimental impact on the geotechnical performance of the resulting co-deposits. No geotechnical instability or degradation in the properties and performance of the co-deposits was observed in the flume tests. A technical gap analysis showed the need to assess the geotechnical stability of co-deposits especially where a tailings stream / product of higher density is co-deposited on top of another tailings of lower density. A numerical modeling study aimed at investigating the geometric configurations of such co-deposited tailings that will ensure its overall geotechnical stability is on-going. The results of the numerical modeling study are intended to provide the field-level guidance required for tailings placement during co-deposition operations. Future commercial-scale co-deposition trials are being planned for future implementation at the Syncrude Mildred Lake and Aurora Mine sites.

PROGRESS AND ACHIEVEMENTS

The flume tests were successfully designed and completed to understand the benefits and limitations of co-depositing various tailings streams and products. Based on the flume tests , a few co-deposition scenarios involving FFT, RCW, centrifuge cake, CT and fFFT, were identified for more detailed assessment. These candidate co-deposition scenarios were repeated as flume tests, with the resulting co-deposits monitored for a longer time period (~6 months). The initial dewatering and geotechnical performance of these long-term flume tests were similar to the short-term flume tests. The percent solids content and shear strengths of the co-deposits in these long-term flume tests increased over time. No detrimental impact was observed for the individual tailings stream / products, including at the interfaces. The flume tests were able to close several technical gaps identified at the outset of the project. The remaining technical gaps, especially related to the overall geotechnical stability of co-deposits involving tailings streams with different densities, are currently being investigated by means of numerical modeling as well as forensic assessment of analogue co-deposits. The results from the numerical modeling are expected to provide operational guidance for ensuring the geotechnical stability of the co-deposits during placement. This guidance will inform the operations of the commercial-scale co-deposition trials to be implemented at Syncrude mine sites in the future.

LESSONS LEARNED

The flume tests proved to be an important analytical tool to assess the benefits and limitations of co-depositing multiple tailings streams and products. Despite the inherent limitations of flume testing, the tests generally demonstrated the feasibility of co-deposition and advanced the understanding required to conduct field-scale demonstration of the deposition strategy. Further analyses, including numerical modeling and assessment of analogue co-deposits, to de-risk the co-deposition scenarios identified as promising from the flume tests are on-going.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

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Depositional Configurations Impact on NST And eNST Fines Capture in A Flume

COSIA Project Number: TJ0144

Research Provider: Process Innovation/Horizon Bitumen Production

Industry Champion: Canadian Natural

Status: Complete

PROJECT SUMMARY

Canadian Natural's Horizon oil sands operation began transitioning from Whole Tailings (WT) to Non-Segregating Tailings (NST) to reduce environmental impact, as Fines are a major problem in tailings ponds when it comes to tailings management, reclamation, and the environment. NST and Enhanced NST (eNST) are believed to capture more fine particles in the beach rather than WT.

Canadian Natural hypothesised that in an optimized deposition configuration and environment, % fines and % solids captured within the NST/eNST during deposition can be increased. Having limited segregation with a uniform % solids and % fines during deposition would mean more trapping of fines throughout the NST/eNST deposition reducing the amount of fines suspended throughout the tailings pond. This has both environmental and operational benefits in terms of land reclamation and the reduction of Mature Fine Tailings (MFT) production.

Based on these considerations, the objective of this project was to study the deposition configurations of NST and eNST in sub aerial and sub aqueous conditions in a pilot flume of 8 m length by 1 m wide and 1 m deep with a 1% slope to simulate the natural slopes of the beach above water of the Horizon tailings pond.

Flume testing was conducted on the two tailings streams of NST and eNST with the targeted values for sand to fine ratio (SFR) (ranges from 3.5-6.5), polymer dosage, the depositional height, on spec density and the discharge configuration. The preferred depositional environment was chosen as subaerial and subaqueous.

The study investigated the following:

- Effects of NST & eNST deposition methods on subaerial beach fines capture by using the plunge pool and two spigot deposition method; and

- Effects of subaqueous eNST deposition into water and into fluid fine tailings (FFT) on fines capture using direct pipeline discharge and tremie (radial diffuser method).

The outcome of this study was expected to provide qualitative direction on NST tailings deposition configurations and environmental impacts that enhance fines capture

PROGRESS AND ACHIEVEMENTS

This flume pilot study conducted by Canadian Natural at the Advanced Process Innovation Centre (APIC) is a continuation of a previous flume study conducted by Barr Engineering and Deltares, commissioned by Canadian Natural in 2015. This work is a part of Canadian Natural's efforts to maximize fines capture as part of its tailings management program and to meet their commitments to the Alberta Energy Regulator's Directive 085.

Seven flume tests were conducted with base case NST at a Sand to Fines Ratio (SFR) of 4.9 – 5. Deposit performance was tested using various discharge methods and the performance was evaluated in terms of degree of segregation index and fluidity. Segregation was defined as the ratio of the maximum and minimum SFR over the length of the flume and fluidity was the velocity of the tailings flow at various distances from the discharge point over the length of the flume. The main equipment used was a wooden flume of 8 m length by 1 m width by 0.6 m height with a 1% slope to simulate the natural slopes of the beach above water of the whole tailings in the Horizon tailings pond. Test 1 and test 6 had the highest reduction in solids along the length of the flume while test 5 and test 7 had the lowest variation in solids content. Test 5 and test 7 had also the lowest change in FC and SFR values. These tests (5, 7) were the basis of the current flume study.

In this flume study, deposition methods at different heights from the surface including an open plunge pool (OPP) and two spigot (TS) for subaerial tests, and regular spool and tremie for subaqueous tests were used to deposit NST and eNST feeds for a total of eighteen runs. The beach heights were measured at intervals down the length of the flume, and the overall beach length was measured. The outcomes of this study were expected to evaluate the deposition methods that will return 85% or greater fines capture in the beach, to evaluate the beach geometry and compare between the depositional methods, and to evaluate the non-segregation behaviour and compare between the depositional methods.

The high SFR feeds were made synthetically created in APIC due to the difficulty of retrieving an NST sample of SFR greater than 6. It was noted that the high SFR samples presented rheological discrepancies that rendered its results questionable and potentially not representative to the high SFR NST samples sampled from the pipeline.

The fines capture was computed involving different scenarios in Bilmat. For subaerial depositions, minimal differences were found between NST and eNST feeds, however, the effect of SFR showed a dominant effect. For low SFR feeds, the target of 85% fines capture in the beach is met for almost all cases while for high SFR feeds, with the most optimal case reaching at most 75% fines capture. Subaqueous deposition methods did not reach the target of 85% fines capture.

For the subaerial tests with low SFR feeds, the TS had a flatter slope and longer beach length compared to the OPP. This was true for both NST and eNST. NST feeds had an average % slope of 0.75 and average beach length of 6 m, and eNST feeds had an average slope of 1% and average beach length of 5 m. The deposition height was not significant to the beach slope and length. For subaqueous tests, the deposition method had no effect on the beach slope and length. SFR was the dominant factor, as low SFR feeds resulted in shorter and flatter beaches.

In comparison to Barr's model, non-segregation behaviour was found in low SFR feeds if the shear rate was greater than 0.01 s-1. High SFR feeds were found to be segregating. The solids content, fines content, and SFR were measured along the length of the flume. For subaerial tests, the beach deposit was relatively constant along the length of the flume considering the measurements. High SFR feeds experienced a decrease in SFR along the length of the flume. The use of NST/eNST had no apparent effect on the non-segregation behaviour.

LESSONS LEARNED

The lessons learned were observed in mainly two areas:

1. Mass balance uncertainty: compounding errors increase the mass balance inequality for the subaqueous test conditions:

- Measurement uncertainty: feed and beach sampling, subsampling, analytical errors as laboratory MSA for %Solids content and % fines showed weak signal/noise but in acceptable terms;
- Test control uncertainty: errors due to lack of feed flow control, mixing control and access to the beach below water as reaching the beach b/w through pumping out six totes may entrain partially fluidized beach; and
- Reconciliation uncertainty: seepage water mass, solids content and SFR not known with any certainty as seepage water was not possible to completely pump out of flume and leaked in some tests.

2. Feed Sample Rheology uncertainty:

- Mixing for adjustment to pH 7.5 (30 - 60 min) could induce rheology changes of the flocs

- Usage of Synthetic High SFR NST as feed could lead to unrepresentative effects
- No consolidation time allowed for flume: days vs. years in sampling for the field trials

The results support the idea of a plant trial for the two spigots configuration to validate the potential lower slope and longer beach that could promote longer eNST runs per tailing line resultant in potentially increased fine capture.

PRESENTATIONS AND PUBLICATIONS

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RESEARCH TEAM AND COLLABORATORS

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Modified Atmospheric Fines Drying (MAFD) Pilot

COSIA Project Number: TJ0152

Industry Champion: Canadian Natural

Status: Year 1 of 3

PROJECT SUMMARY

In this pilot, thin lifts of flocculated fluid tailings (FT) from the Horizon External Tailings Facility (ETF) were placed on the existing beach above water (BAW) to evaluate the impact of an anionic flocculant on fines drying before and after the freeze-thaw cycle. Similar techniques were piloted at Albian Jackpine Mine (JPM); an objective of the MAFD pilot is to determine if the Horizon feed stock provides the same results as the JPM pilot. This pilot is considered "Modified" AFD because the MAFD material is intended to be left in place, as opposed to other operators running AFD or TRO where the material is removed from the drying area and hauled for permanent storage in waste dumps. Exposure to ambient conditions promote evaporation, further reducing the water content of deposit. This technology is a fair-weather operation due to evaporation step involved in the process.

The primary objective for the MAFD pilot scope in 2021 was to create an on-spec treated FT product defined by the following: achieve a deposit with a solids content of 50 wt% (weight percent) and achieve a deposit with a peak undrained shear strength of 5.0 kPa, both after 30 days. Other objectives of the pilot include determining the impact the MAFD technology has on the existing NST beach, and lastly, to determine the technical feasibility as a secondary fluid tailings treatment alternative at a commercial scale.

PROGRESS AND ACHIEVEMENTS

The construction of the MAFD pilot ran for approximately 2 months, with official start-up and commissioning of the pilot plant on July 11, 2021, including the first pour on the south portion of the beach. The MAFD pilot operated until August 20, 2021. The total operating time during that period was 260 hours and the volume of FT treated was 113,545 m^3. The pilot operation was shortened due to FT feed interruptions; evaluation of additional lifts after the first lift was not completed.

For the area of the pilot that was not impacted by saturation issues, the average day 30 solids content was 56.4 wt%; 13 out of the 15 spigots exceeding the target solids content of greater than

50 wt%, of which two spigots reached a solids content of 65 wt%. The day 30 peak undrained shear strength ranged from 3.9 to 8.4 kPa, which was measured using a hand vane shear apparatus. A total of 6 of the 15 spigots were below the target peak undrained shear strength of 5.0 kPa, although only 2 were below 4.0 kPa.

LESSONS LEARNED

A main parameter that impacted results was saturation problems from low spots containing water runoff and initial release water. The variance in process feed conditions was small, so the difference in performance at individual spigots has been attributed to be the result of saturation of the beach in the associated location, prior to deposition. A more comprehensive analysis will be initiated once freeze-thaw cycle data is collected in 2022. Further deposit testing will occur in 2022 to target the technical uncertainties that were not addressed in 2021.

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PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

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RESEARCH TEAM AND COLLABORATORS

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