

COSIA Tailings EPA

2022 – 2023 TAILINGS RESEARCH REPORT



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**A worker on the Wapisiw Lookout observation deck at sunrise*

Introduction

This report is funded by members of the COSIA Tailings EPA:

This is the fifth summary report from the Canada's Oil Sands Innovation Alliance (COSIA) Tailings Environmental Priority Area (EPA). This report highlights research and technology development in tailings management at various stages of research over 2022-2023: 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, containment, 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:

- Manage the accumulation of fluid tailings (FT) within tailings ponds through development of new and continuous improvement of current tailings technologies.
- Minimize net environmental effects from tailings treatment and deposits.
- Accelerate the pace of 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 five principal research areas: tailings treatment technologies, tailings capping, froth treatment tailings, tailings characterization, tailings deposition and monitoring. Each research project seeks to advance the understanding of the risks and uncertainties associated with tailings management, with the goal of designing appropriate mitigation strategies.

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, design, 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. Permission for non-commercial use, publication or presentation of excerpts or figures is granted, provided appropriate attribution is cited. Commercial reproduction, in whole or in part, is not permitted. The use of these materials by the end user is done without any affiliation with, or endorsement by, any COSIA member, and is at the sole risk of the user.

This report is funded by members of the COSIA Tailings EPA:

- Canadian Natural Resources Limited (Canadian Natural)
- Imperial Oil Limited (Imperial)
- Suncor Energy Inc. (Suncor)*
- Syncrude Canada Ltd. (Syncrude)**

* Teck Resources sold its stake in the Fort Hills project to Suncor Energy in October 2022 and exited the oil sands business and its COSIA membership.

** Suncor Energy assumed operatorship of the Syncrude Joint Venture in September of 2021, however Syncrude Canada Ltd. remains a full member of COSIA.

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COSIA PROJECT NUMBER AND TITLE

COSIA Project Number	Project Title
Tailings Treatment Technologies	
TE0065	Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria
TE0075	NAIT Industrial Research Chair for Colleges in Oil Sands Tailings Management
TE0093	Mitigating the Adverse Effect of Ultrafine Particles in Pressure Filtration of MFT
TJ0086	CST Enhanced Fines Beach Capture
TJ0117	Co-Deposition of Enhanced In-line Flocculated Fluid Tailings and Thickened Tailings
TJ0128	Physically Upgraded Trafficable Tailings Innovation (PUTTI)
TJ0151	Co-processing of Fresh Tailings and FFT
TJ0153	Fluid Tailings Thickening Pilot
Tailings Capping	
TE0084	Constitutive Model Development and Experiment Scale-Up for Fines-Dominated Tailings Deposit Capping
TJ0141	Hydraulic Coke Capping of Tailings Ponds
Froth Tailings Treatment	
TJ0130	NSERC-Syncrude IRC in Mine Closure Geochemistry
TJ0158	MRM TSRU Gas Generation Testing
Tailings Characterization	
TJ0138	Environmental Fate and Implications of Polyacrylamide Addition to Oil Sands Tailings
Tailings Deposition and Monitoring	
TE0054	Physical and Numerical Modeling of Progradation of Segregating Tailing Beaches into MFT and associated depositional mechanisms.
TE0088	Managing Long-Term Settlement of Deep Cohesive Tailings Deposits
TJ0059	Tailings Consolidation Casing Experimental Pilot Project (TCCEPP) and Other Consolidation Studies
TJ0104	Co-Deposition
TJ0105	Measuring CO ₂ at Inlet to ETF

COSIA Project Number	Project Title
TJ0152	Modified Atmospheric Fines Drying (MAFD) Pilot
TJ0154	Inline Flocculated Fluid Tailings and Coarse Sand Tailings Mixing Pilot
TJ0155	NSERC-Syncrude IRC in Mine Closure Pressuremeter

Tailings Treatment Technologies

Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria

COSIA Project Number: TE0065 (IOSI19)

Research Provider: University of Alberta

Industry Champion: Syncrude

Status: Year 4 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 already native to tailings ponds be engineered to actively cause the 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, these self-replicating bacteria are expected to 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, a more compact mature fine tailings is expected to be formed. Finally, safety through genetic engineering has been considered using best practice principles to ensure no environmental harm occurs through these bacteria.

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 can lead to a self-sustaining, environmentally safe, in situ solution for MFT.

PROGRESS AND ACHIEVEMENTS

By the end of year 3, the team was able to incorporate engineered DNA so that bacteria could produce the biopolymers of choice. Moreover, this proved that these biopolymers could be localized on the outer membrane of the bacteria. Preliminary results showed that settling times using 5wt% MFT solutions were affected by the initial concentration of bacteria used and the engineered biopolymer present. Further, a more comprehensive range of bacterial concentrations was used last year to optimize the settling results. This work identified a minimum bacterial load that led to enhanced settling of the MFT solutions. Moreover, these results were comparable to the already used polymer flocculants.

Several questions remained about the applicability of engineered bacteria to higher concentrations of MFTs: i. will bacteria survive a 35wt% MFT solution; ii. are they able to migrate through this solution to any appreciable extent; iii. can they propagate in a 35wt% MFT solution; and iv. do they require nutrient addition to achieve these results? This strategic shift from 5wt% to 35wt% MFT solutions allows researchers to consider the usefulness of these bacteria for consolidating 35wt% MFTs to achieve a higher MFT density, recalling that the major advantages of engineered bacteria are that they are large, their surface properties can be tailored to act as a flocculant, they self-replicate *in situ* (cheap, as low amounts can be seeded in the tailings environment), and they are mobile without the need for industrial mixing. Thus, the focus was on answering these questions as they directly applied to engineered bacteria's usefulness in these environments.

In this last year, the team was able to show that the engineered bacteria with the best settling results from the 5wt% MFT experiments not only survived in the 35wt% MFT solution but that they traveled remarkably up to 2 cm (~1,000x the length of a bacterium) through this solution in 24 hrs (~80 $\mu\text{m}/\text{h}$). Supplemental addition of nutrients was not required to achieve this milestone. However, it should be stated that in some cases, nutrient addition did lead to a faster outcome. It was further observed that two things were occurring in the 35wt% MFT solution to achieve these rates: motility and propagation. This is crucial, as it is not enough to have bacteria move in solution, they need to propagate as well to reach local concentrations that have been shown to lead to enhanced settling.

Critically, the focus on the biochemistry involved in the engineering of the bacteria can now shift towards investigating these bacteria within scaled-up MFT experiments. The goal is to elucidate the penetration and propagation rates in temperature-controlled and larger volume reservoirs of MFT solution. Information that can move this biotechnology from the bench closer to the field.

LESSONS LEARNED

1. Developed set points for bacteria concentrations required for enhanced settling.
2. Showed that engineered bacteria survive 35wt% MFT solutions.

3. Showed that engineered bacteria were able to move through 35wt% MFT.
4. Engineered bacteria could propagate without nutrient supplements.
5. Preliminary OPEX and CAPEX for industrial manufacturing of bacteria were evaluated.
6. Questions requiring further work:
 - a. Penetration distance in scaled-up MFT reservoirs.
 - b. Environmental temperature effects on bacterial mobility in 35wt% MFT.
 - c. Evidence for localized flocculation in 35wt% MFTs within scaled-up volumes.

PRESENTATIONS AND PUBLICATIONS

Journal Publications

Bahniuk, M.S, Alidina. F., Tan. X., & Unsworth. LD. (2022). The last 25 years of research on bioflocculants for kaolin flocculation with recent trends and technical challenges for the future. *Front. Bioeng. Biotechnol.* 10:1048755. doi: 10.3389/fbioe.2022.1048755.

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	Synchrude	Senior Associate – Chemical		
Tyler Colberg	Imperial	Research Advisor – Environmental		

Research Collaborators:

Institute for Oilsands Innovation (University of Alberta)

NAIT Industrial Research Chair for Colleges in Oil Sands Tailings Management

COSIA Project Number: TE0075

Research Provider: NAIT – Heather Kaminsky

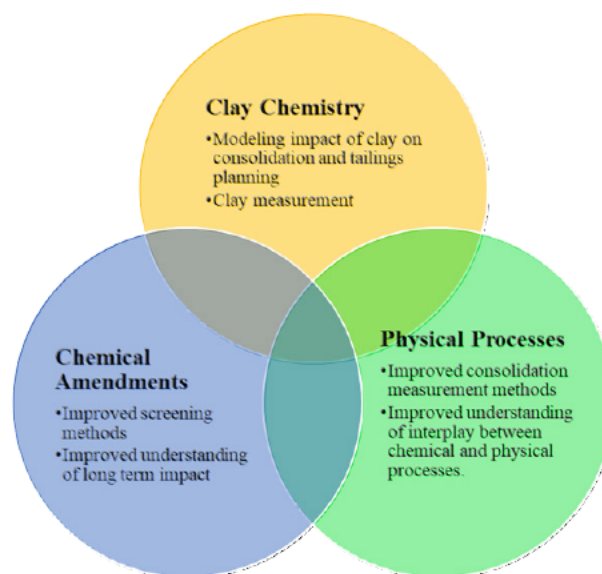
Industry Champion: Imperial Oil

Status: Year 3.5 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 oil sands tailings waste treatment methods. The IRCC in oil sands tailings is dedicated to seeking tailings remediation strategies 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 themes are: Clay Chemistry, Chemical Amendments, and Physical Processes.

The theme of clay chemistry focuses 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 focuses 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



targets 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 experiment scope led by three PhD students at the university by conducting the characterization of their samples, preparing treated tailings materials for the PhD students and performing other 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 in Figure 1.

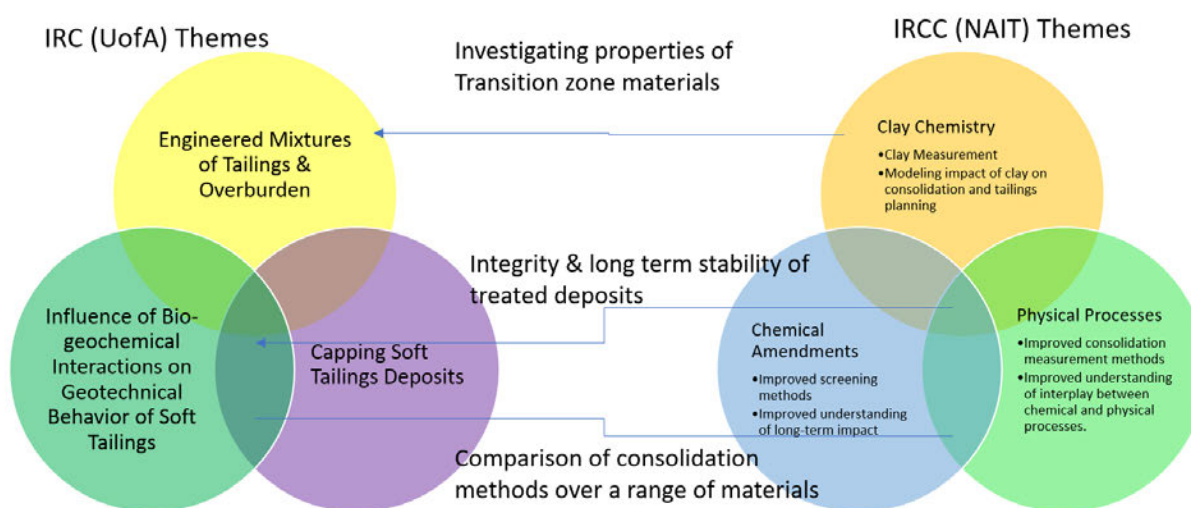


Figure 1: Connections between IRCC and IRC programs

PROGRESS AND ACHIEVEMENTS

Clay Chemistry – Impact of Clay

Reviewing “Fundamentals of Soil Behavior 3rd Edition, by Mitchell and Sogi”, highlights that in practice non-swelling/well behaved clays can dominate behavior of soils if present in quantities of more than a third but that as little as 1% of bentonite can significantly impact the behavior of soil. This is due to the way that clay surface area captures the water, and the combination of water and clay that fills voids of granular material. This rule of thumb therefore boils down to typical surface areas of these materials – typical water active surface areas for a well behaving clay like kaolinite is $\sim 25\text{m}^2/\text{g}$ for kaolinite, whereas the surface area including internal surfaces is $\sim 800\text{m}^2/\text{g}$. A soil having either $\sim 33\%$ kaolinite or one percent bentonite will have a surface area of $\sim 8\text{m}^2/\text{g}$ which is equivalent

to a Methylene Blue Index (MBI) of 1 meq/100g. This suggests that using a surface area rule of thumb vs a % clay rule of thumb is a better predictor of when clay behavior may dominate sample behavior from a geotechnical perspective. Also interesting is the finding that low grade poor processing ore tends to occur at an MBI >1.5 meq/100g with some challenges occurring at an MBI >0.9meq/100g depending on water chemistry. These two observations indicate that an MBI of ~1meq/100g may be an important cut off for paying attention to clay behavior in a deposit. For reference, the average MBI of FFT is around a value of 7, which is about twice that for a typical pure kaolinite deposit. Higher MBI values are associated with increased challenges to remediation, which explains why kaolinite frequently outperforms FFT in consolidation and settling tests.

Deposit	Typical MBI (meq/100g)	Surface area (m2/g)
High Grade/Good processing ore	0.5	4
Low grade/reasonable processing ore	0.9	7
Low grade very poor processing ore	1.5	12
Pure kaolinite clay deposit	3.0	23
Typical FFT (Average)	7.0	55
Pure Bentonite Deposit	102	799
Soil with 33% kaolinite	1.0	8
Soil with 1% bentonite	1.0	8

Table 1: Typical MBI results for different ores, clays and soils

Collaborator Andrew Vietti of Vietti SlurryTech in South Africa has compiled the ranges of MBIs typically found in different tailings around the world that he has dealt with (Figure 2). As expected, the typical range of MBI for FFT in oil sands is comparable to that of diamond tailings and mineral sands tailings, which have also been noted for challenges with solid-liquid separation processes.

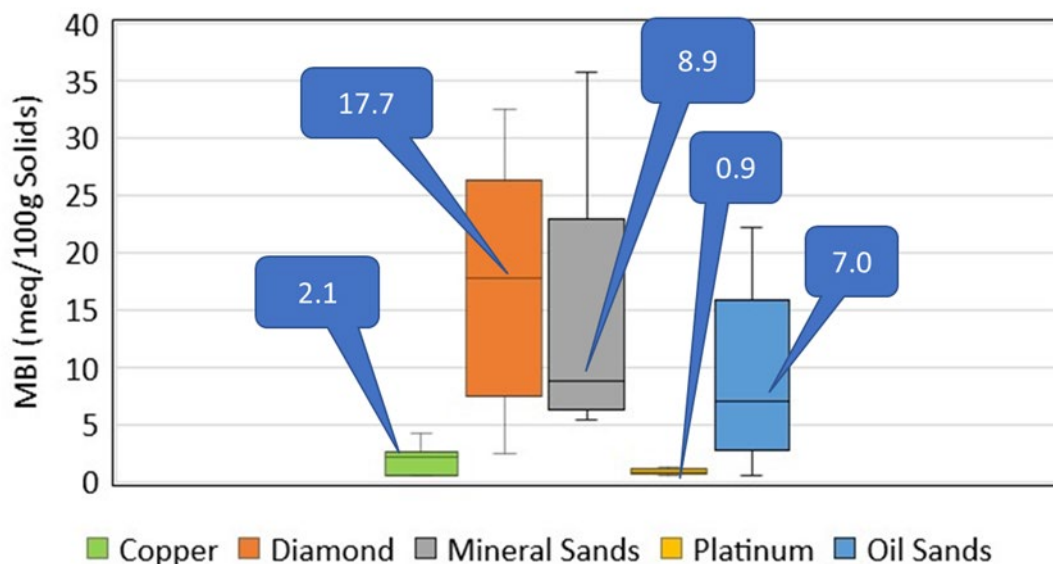


Figure 2: Typical MBI ranges observed for tailings samples, courtesy of Andrew Vietti, Vietti Slurry Tech.

Clay Chemistry – Better measurements

In the theme of better measurements, the chair conducted a round robin assessment of the MBI test. Two samples were prepared 1) a sample of kaolinite (polygloss 90) from the Kamin company and 2) a sample of Dean & Stark (D&S) solids compiled from hundreds of D&S tests conducted at NAIT over the past 5 years. Since the kaolinite samples were processed to a uniform size and had previously been used as a QC standard at NAIT, they were subsampled directly into 2g samples for use. The D&S solids were combined and homogenized using hand mixing and cone & quartering to create a ~4kg sample that was then split using a large splitter, recombined, and riffled into over two thousand, 2g samples. The mass of each sample was weighed to verify a consistent mass split and 172 of the samples were selected across the created subsamples for measurement of MBI by NAIT personnel.

As shown in Figure 3, the solids content and MBI were consistent across the sets created with no bias observed in riffled set number. The average mass for the samples created was 2.11g with a standard deviation of 0.05g. The average end point for MBI titration was 20mL with a standard deviation of 1mL. The average MBI was therefore 5.7meq/100g with a standard deviation of 0.2 meq/100g.

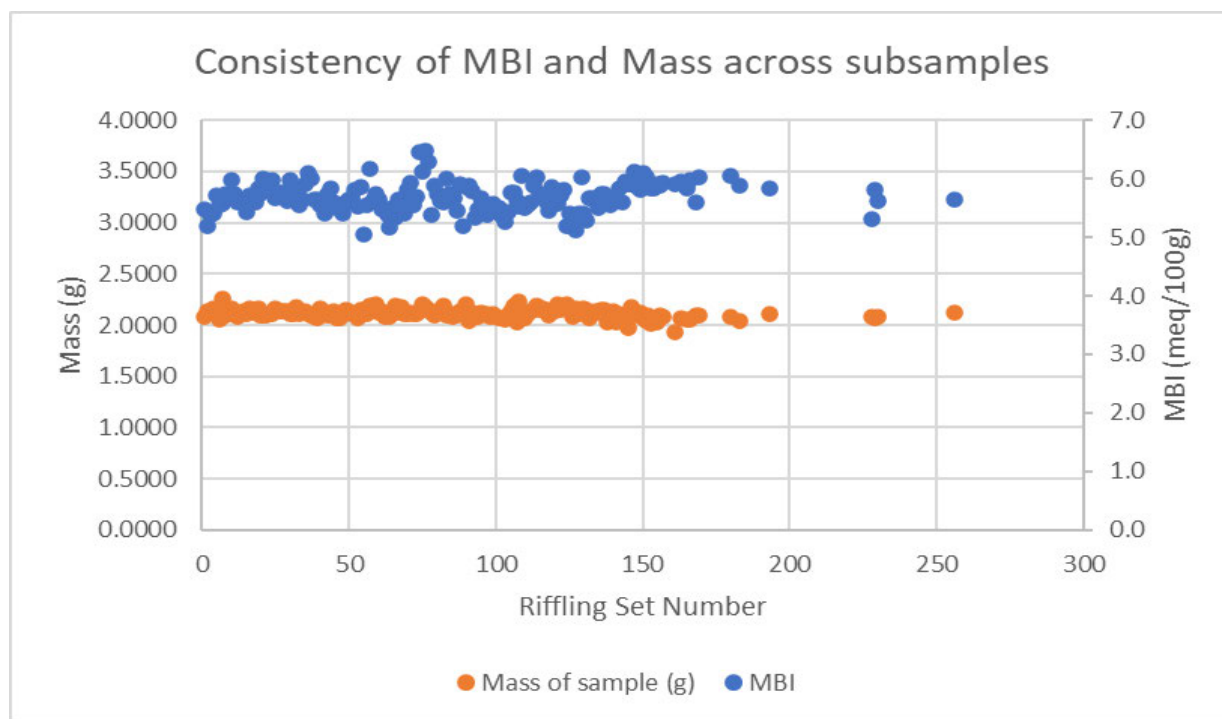


Figure 3- Consistency of results across subsamples

11 different trained laboratory technologists contributed to measuring the samples, and while a range of observations were noted, the results were consistent technologist to technologist (Figure 4).

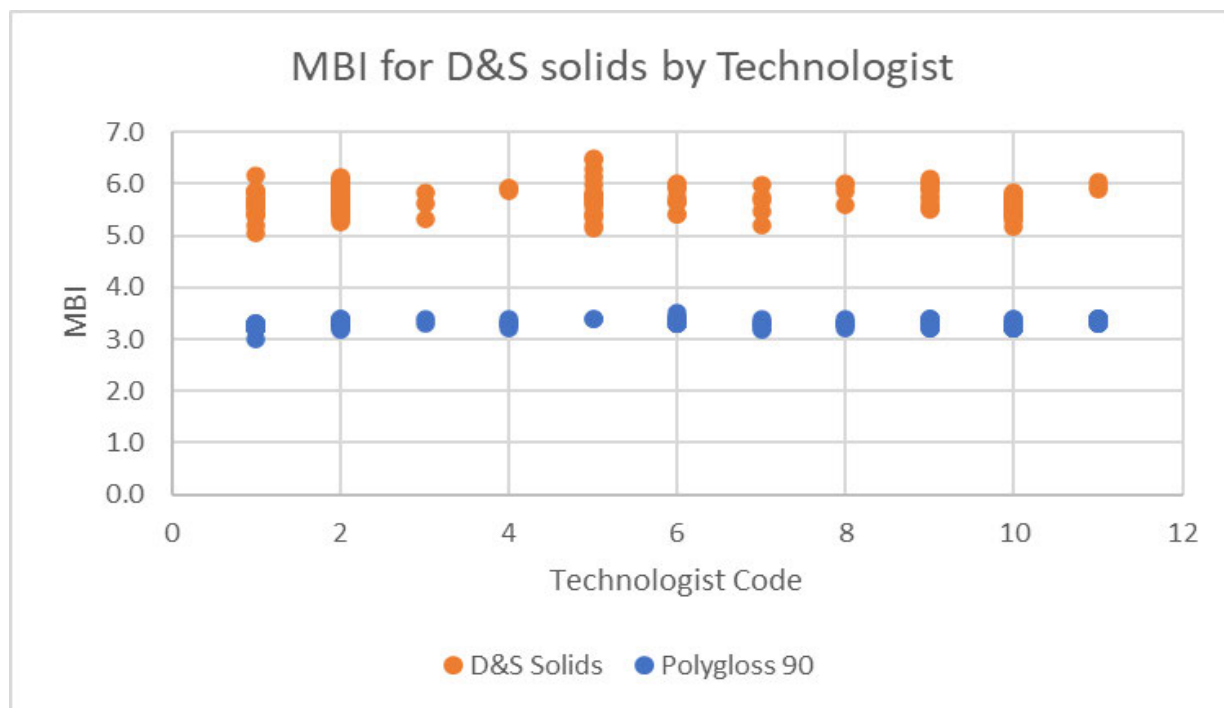


Figure 4- MBI Results for Kaolinite Polygloss 90 and D&S solids sample by technologist.

Data on the D&S solids samples were collected over a year while the data on the Polygloss 90 covered just under 2 years. No significant change in MBI with time was noted (Figure 5). For the 122 data points measured on Polygloss 90 over this time period the average was 3.3 meq/100g and the standard deviation was 0.07 meq/100g.

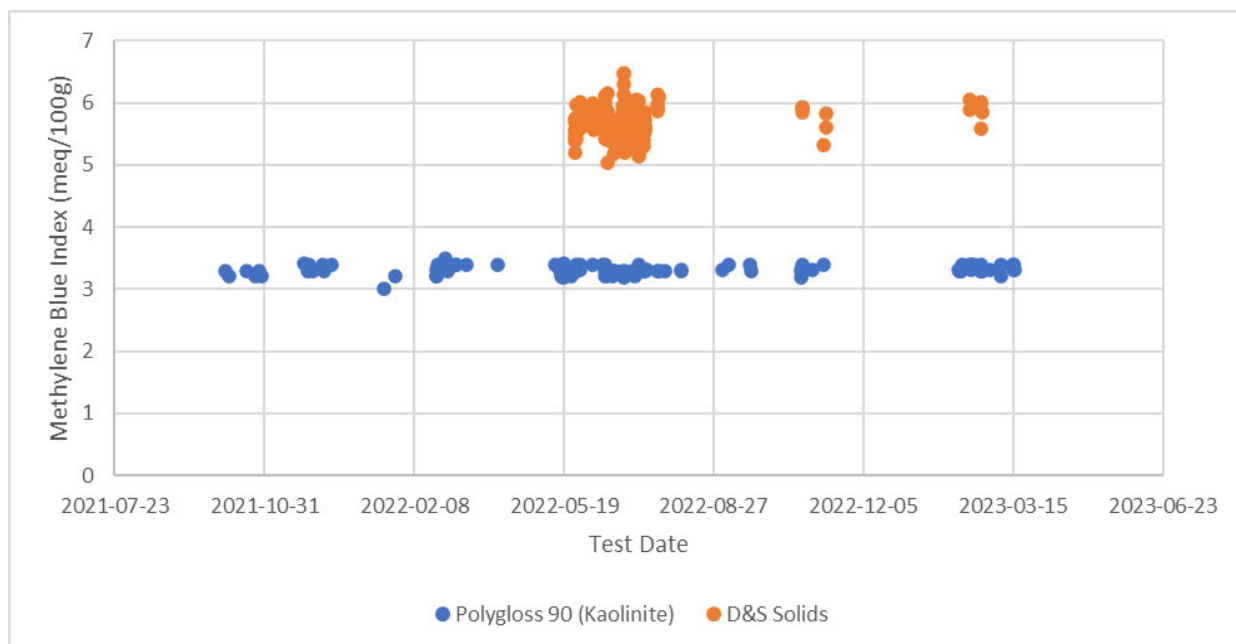


Figure 5 MBI results with time for Kaolinite Polygloss 90 and D&S solids sample.

The next stage of the test was to check the reproducibility of the results between laboratories. 5 samples of the D&S solids and 2 samples of Kaolinite Polygloss 90 were sent to 3 commercial labs and to 2 research labs who commonly conduct the MBI test on oil sands samples. Samples sent to commercial labs were treated as typical fee-for-service characterization analysis tests. Research labs participated on a voluntary basis and were not paid for their analysis. For consistency, one technologist from NAIT analyzed the 5 D&S and 2 Kaolinite samples and the results were compared with the results from the participating third-party labs.

As shown in Figure 6, there was a significant difference between the 6 labs but the trends in the samples were somewhat consistent -i.e. if a lab measured high on one sample it measured high on the other.

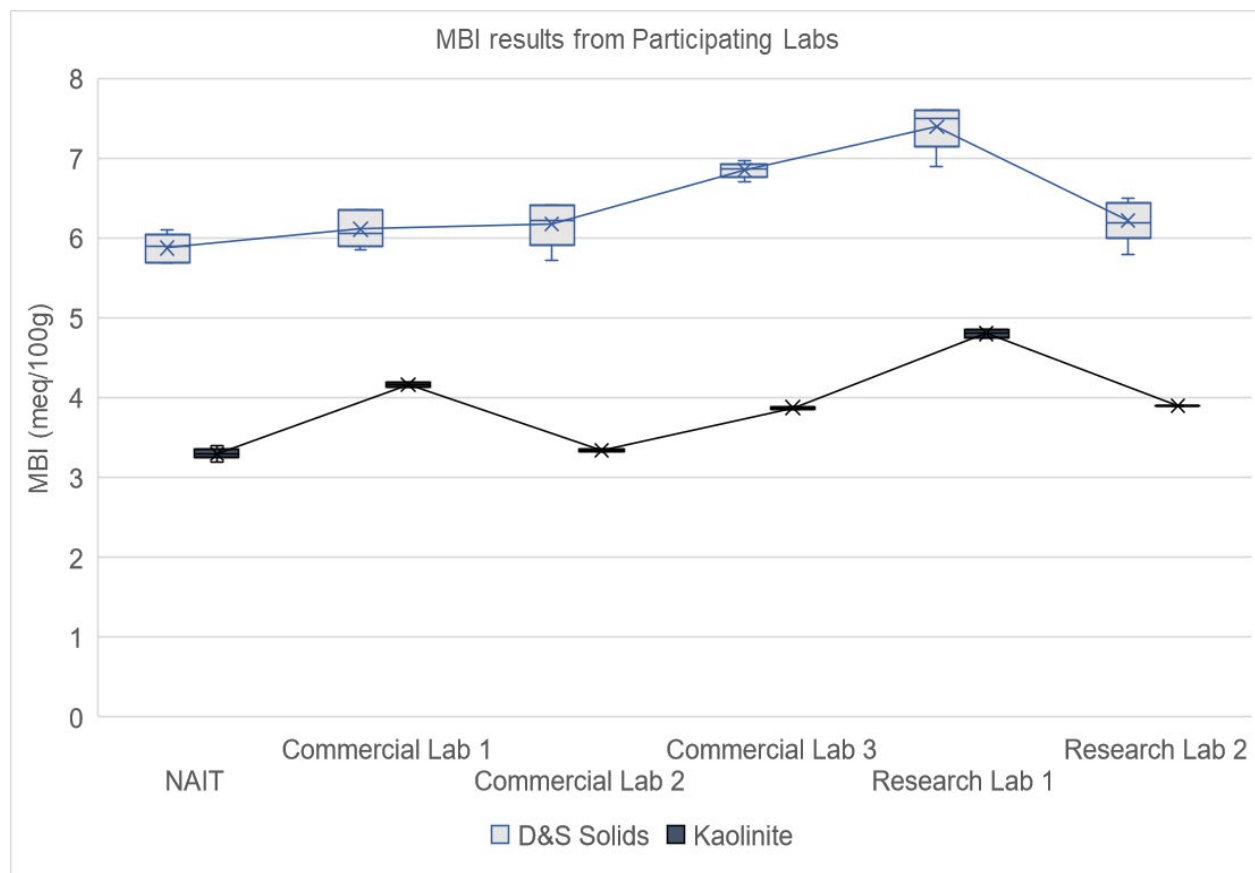


Figure 6- Box & Whisker plot of test results from participating labs

The repeatability of the MBI test was relatively consistent between labs. Defining relative uncertainty as the standard deviation divided by the average (as per John R. Taylor –An Introduction to Error Analysis), the relative uncertainty was just under 5% for all participating labs ranging from a low of 1.4% for commercial lab 3 to a high of 4.6% for commercial lab 2 for the D&S solids. This repeatability is within the range expected for a MBI titration with an end point of around 20mL, consistent with the samples tested. The smallest titration step size used in MBI testing is 0.5mL and the end point can only be defined by comparing at least two titration points. Thus, an uncertainty of 1mL in a ~20 mL titration is expected to give a ~5% relative uncertainty. These results indicate that within each lab QC procedures are sufficient to give consistent results.

Consistent reproducibility in MBI test results between different labs remains a challenge to be surmounted. A collection of results from all laboratories gives an average MBI value of 6.4, and standard deviation of 0.57, representing a relative uncertainty of 9%. However, the absolute range of MBI values between the labs was 1.5, with NAIT having the lowest average measured MBI of 5.7 and Research Lab 1 having the highest, at 7.4. Since a difference in MBI value of just 1 can imply a significant difference in expected behaviour, a wide range of reported MBI values on the same

sample from different labs is not acceptable. Therefore, in the current state, it is not possible to directly compare results between labs unless a standard QC sample is used to normalize the results. Just as importantly, the experimental method for MBI must also be meticulously standardized between labs.

Since the QC samples used in this study eliminated differences in subsampling between labs, these results provide a good assessment of the difference reported between labs for the methylene blue index method itself. For true samples, differences in subsampling methodology and mass of sample used will likely increase the differences between labs in reported data.

Further analysis in collaboration with one of the commercial labs in the study demonstrated that the biggest difference between NAIT and the other commercial lab is endpoint determination. NAIT procedure determines the endpoint as the point where there is a small continuous halo around the titrated aliquot and where subsequent addition of MB dye will lead to a significant expansion of the halo (illustrated in Figure 7). The ability to detect this point is significantly influenced by the type of filter paper used. Following work done with COSIA in 2018, NAIT switched to a nylon filter paper which makes the end point easier to detect. Subsequently, the detected endpoint is shifted ~2mL earlier, and corresponds to a shift in MBI value of ~0.6 for a 2g sample. A manuscript summarizing all the research done at NAIT on the MBI method is planned for 2023.

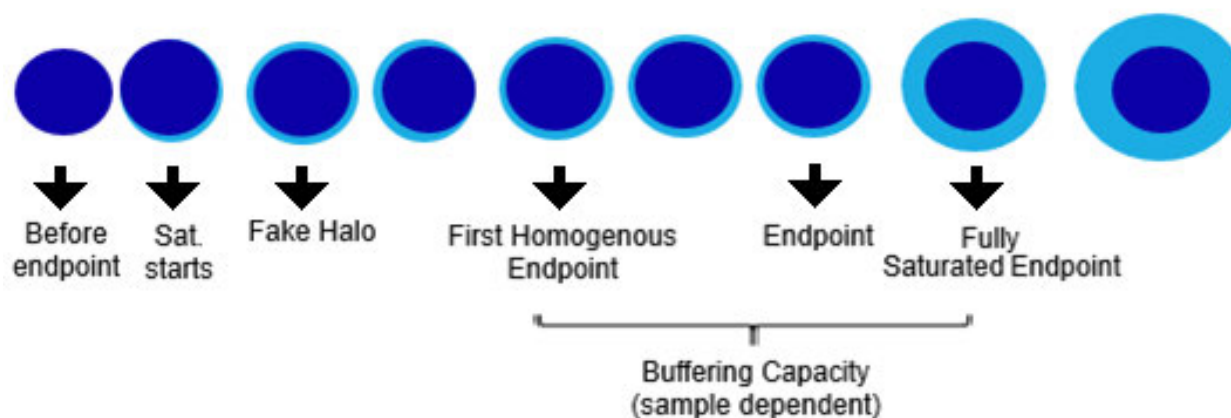


Figure 7: Illustration of endpoint determination in a MBI test.

Chemical Amendments

The study evaluating High-Fines Sand Tailings (HFST) as a novel oil sand tailings treatment technology was published in 2022 at the International Oil Sands Tailings Conference (IOSTC). Key findings include that the HFST technology at the targeted sand-to-fines ratio (SFR of 2 was able to achieve 80% solids content in 15 minutes of pressure filtration at 30psi, compared to the over 500 minutes to achieve the similar 80% solids in the filter cake for the same sand and FFT blend with no

HFST treatment. This demonstrates that chemical amendment to capture clays and fines can be highly effective at increasing the rate of filtration and deposit dewatering. The study also highlighted that some sand sourced from the oil sands region may contain small quantities of pyrite which can cause the sand to be acid generating and therefore significantly impact flocculation behavior.

It is recognized that while the HFST technology is not currently deployed commercially, the flocculation of tailings streams with higher sands is an area of active research and deployment at Canadian Natural Horizon (enhanced Non-segregating tailings (esNST)), Syncrude (Co-processing) and Imperial (co-deposition with enhanced inline flocculation (eILF)), it is expected that some of the learnings in the HFST assessment will be relevant to development and understanding of these technologies.

LESSONS LEARNED

1. Methylene Blue Index is a useful metric for difficulty likely to be encountered when processing an ore, flocculating a tailings stream or remediating a deposit and an MBI >1meq/100g indicates that clay will likely impact soil/tailings/ore behavior from a process and a geotechnical perspective and should be considered in planning.
2. Methylene Blue Index has good repeatability within a given lab, but poor inter-lab repeatability, primarily owing (within the context of the oil sands industry) to endpoint detection methodology.
3. The use of a quality control standard is recommended to calibrate MBI results over time and over providers.
4. Sand addition up to a sand to fines ratio of 3 in a flocculated mixture can be effective in increasing permeability of the mixture while maintaining clay capture.
5. The presence of pyrite and other hydrophobic minerals such as rutile, anatase, and siderite in sand can significantly impact flocculation of high sand mixtures and is something that should be evaluated in ongoing work.

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.

To receive copies of previous book club slides please contact Vicky Qualie (vqualie@nait.ca). To register for future book club presentations visit www.nait.ca/tbc2023

In addition to the 11 Tailings book club presentations given in 2022, Dr Kaminsky also provided keynote presentations on the State of Fluid Fine Tailings to the 2022 APEGA Nexus conference and International Oil Sands Tailings Conference, 2022.

Short Courses

Three short courses have been developed and were offered in 2022 to help mobilize knowledge on oil sands tailings management.

- **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. For information on the course see: <https://www.nait.ca/applied-research/research-support-services/training-courses/oil-sands-tailings-101>
- **Flocculation & Thickening** – This short course is offered in collaboration with CSIRO with a focus on thickener operation and flocculation.
- **From Geology to Closure How Clays Influence Mining** is offered in collaboration with Andrew Vietti and Lois Boxil. This course focuses on how clay minerals found in an ore and waste sections (overburden/interburden) within a deposit impacts extraction of valuable products, solid liquid-separation in tailings processing, tailings volumes, geotechnical properties of the created tailings deposits and finally the challenges and opportunities in reclaiming/closing the created tailings deposits.

Journal Publications

Ahmed, M., Beier N., & Kaminsky, H. (2023). A Comprehensive Review of Large Strain Consolidation Testing for Application in Oil Sands Mine Tailings. *Mining* 2023. 3(1), 121-150. <https://doi.org/10.3390/mining3010008>.

Conference Presentations/Posters

Li, Y., Kaminsky, H., Revington, A., & A, Sadighian. (2022, December 4-7). A protocol to assess and screen new flocculant for Suncor's PASS program Planning. Proceedings of the Seventh

International Oil Sands Tailings Conference, Edmonton, Alberta, Canada. University of Alberta Geotechnical Centre.

Sun, S., Devereux, E., Kaminsky, H., & M.L. Catling (2022, December 4-7) High-Fines Sand Tailings as a Novel Oil Sands Tailings Treatment Technology. Proceedings of the Seventh International Oil Sands Tailings Conference, Edmonton, Alberta, Canada. University of Alberta Geotechnical Centre.

Patarachao, B., Way, R., Zbrowski, A., Kung, J., Couillard, M., Tyo, D., Li, Y., & H. Kaminsky. (2022, December 4-7). Influence of Clays and Organic Rich Solids on Tailings Behavior. Proceedings of the Seventh International Oil Sands Tailings Conference, Edmonton, Alberta, Canada., University of Alberta Geotechnical Centre.

Cossey, H., Ulrich, A., & Kaminsky, H. (2022, November 26-28). Evaluating the long-term behaviour and viability of an oil sands tailings management and reclamation strategy. Mine Closure 2022 - M Tibbett, AB Fourie & G Boggs (eds) © 2022 Australian Centre for Geomechanics, Perth, ISBN 978-0-6450938-4-1. doi:10.36487/ACG_repo/2215_19.

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)
Simon Sun	NAIT	Research Associate		
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Mitigating the Adverse Effects of Ultrafines in Pressure Filtration of Oil Sands Tailings

COSIA Project Number: TE0093

Research Provider: University of Alberta

Industry Champion: Syncrude, Canadian Natural, Imperial

Status: Year 1 of 2

PROJECT SUMMARY

The scope of the project

This project was jointly sponsored by COSIA (TE0093) and IOSI (IOSI2020-03) and built on the knowledge of previous COSIA and IOSI research projects, particularly COSIA TE0053 (IOSI2017-04). It was identified that the presence of swelling clays and a patchy and thick* coating of residual bitumen on clay surfaces were the two reasons for the poor filtration dewatering of oil sands tailings. Based on that knowledge, the objective of this project was to find mitigation measures to counter the slow filtration caused by swelling clays and bitumen coating.

Rationale

It was previously reported that the swelling clays were concentrated in the ultrafine ($<0.2\ \mu\text{m}$) fraction, and bitumen content was higher in the finer size fraction of the Alberta oil sands (Osacky et al. 2013). Therefore, to alleviate the detrimental effects of swelling clays and patchy bitumen coating, the ultrafine fraction of oil sands tailings was the primary target, and the project objective was to assess chemical amendment schemes to target the ultrafine fraction.

In COSIA project TE0053 (IOSI2017-04), it was observed that swelling clays had very high specific surface areas, which significantly increased the solid phase “effective volume fraction”, leading to slow filtration (Wang et al. 2022). A practical solution to counter this challenge was to reduce the thickness of the hydration layer (or electrical double layer) by adding coagulants, which effectively

* A patchy bitumen coating on clay surfaces affects filtration because it can form an interlocking structure and block water flow, even when the average coating thickness is low. A very thin layer of bitumen coating on clay surfaces is actually found to benefit filtration due to the induced surface hydrophobicity.

reduced the effective volume fraction of the solids. COSIA's site pilot (TJ0113) showed that the use of coagulant was indeed effective in pressure filtration using a commercial filter press (Freeman, 2020). Coagulant dosage should be minimized while maintaining the filtration performance, and the detrimental effect of patchy and thick bitumen coating on clay surfaces also needs to be dealt with.

The hypotheses to be tested are: (1) Coagulants such as alum are needed to target swelling clays. (2) Coagulant dosages may be reduced without affecting its efficiency when the tailings were previously flocculated by polymer flocculant since the coagulant would only need to function on the outer surface of the flocs. If this is the case, prior flocculation of the tailings is logical because removing the ultrafine fraction from the oil sands tailings to treat it separately is out of the question. (3) Proper use of a dispersant (type and dosage) may be able to thin the bitumen coating on clays, thus improving filtration.

Experimental design and methodology

Laboratory filtration tests are the main type of test work to assess filtration performance after the various treatment schemes. Vacuum filtration using a $\phi 35$ mm filter funnel, pressure filtration by compressed air in a $\phi 142$ mm Millipore filter, and pressure filtration by a 275 cm³ laboratory filter press (Model SERFILCO 0.02-7PPHM) were used.

Fluid fine tailings were treated with different chemicals at different dosages. When two chemicals or more were used, the sequence of their additions was also tested. The polymers included SNF A3335, SNF A3370, Kemira PAM, BASF Alcomer 7115, PEO, and the chemicals included alum, ferric chloride, lignosulfonate, and tannic acid.

Performance criteria included filtration rates and cake solid content after the different chemical amendments.

The untreated tailings samples, chemically amended tailings samples, and filtered tailings samples were characterized by CST, particle size (both off-line Malvern particle size analyzer and on-line FBRM real-time in-situ particle size measurement), MBI, SEM, and XRM (X-ray microscope, or micro-CT). Some filter cake samples were tested in a Fall Cone Apparatus to measure their shear strength.

Why does it matter?

Typical hard rock mine tailings can be relatively easily filtered to ≥ 85 wt% solids ready for reclamation by pressure filtration (Amoah, 2019., Goldup et al. 2019., Moreno et al. 2018), and there is an increasing trend in the mining industry to adopt filter presses to dewater tailings (Leonida, 2020., Leonida, 2021., Carter, 2022., Morton, 2023).

COSIA's site pilot (TJ0113) demonstrated that commercial filter presses could rapidly dewater oil sands fluid fine tailings, and the generated filter cakes were ready for reclamation. The challenge was to reduce coagulant dosages to make it more economical. This project was aimed at studying the filtration responses of oil sands tailings, particularly the ultrafine fractions, which contain most of the swelling clays and residual bitumen, under different chemical amendment conditions. The results are expected to guide the research and development effort to lower reagent dosages and make pressure filtration of oil sands tailings economically as well as technically feasible.

How does the research project build upon existing knowledge and incorporate existing research results?

This research project was built on existing knowledge developed from previous research on dewatering Alberta oil sands tailings, particularly COSIA projects TE0053 and TJ0113.

How does the research project advance the understanding of, and improve upon, the risks and uncertainties with tailings management?

The risks and uncertainties associated with oil sands tailings management primarily originate from the extremely slow dewatering behavior of the tailings. The industry has shown that chemical amendment followed by mechanical treatment is one of the promising approaches to mitigate these risks and uncertainties. This project helps provide a better understanding of the oil sands tailings under various chemical amendment conditions and the corresponding filtration performance and assists the development of rapid dewatering technologies that are economically and technically feasible.

Identify milestones that will ensure research results can be incorporated into mine and tailings management plans

The project may demonstrate that desirable filtration dewatering performance could be achieved at lower and potentially economical chemical dosages. This could be a step forward towards incorporating pressure filtration into the oil sands tailings management plan.

PROGRESS AND ACHIEVEMENTS

In 2022, a series of jar tests were used to quickly screen many different chemicals and polymers to examine their effects on oil sands tailings dewatering and bitumen removal. Over 50 Millipore pressure filtration tests were performed on 250-g batches of FFT samples (28.7 wt% solids) to examine their filtration behavior. Many tests were repeated multiple times due to issues with crack formation when using compressed air in pressure filtration.

- It was observed that PEO, N-carboxymethyl chitosan (N-CMC), turpentine, Solvay 13105737, and lignosulfonate was able to break bitumen emulsion and/or remove bitumen from clay surface.
- Adding an anionic flocculant first (A3335) followed by a cationic coagulant (alum) performed better in the pressure filtration of FFT than adding the cationic coagulant first followed by the anionic flocculant.
- For instance, adding 1 kg/t A3335 and 10 kg/t alum, a 25-min filtration of 250 g FFT (28.7 wt% solids) in the $\phi 142$ mm Millipore filter under 600 kPa generated a cake with 54-59 wt% solids (multiple repeat tests). There was a clear synergy between A3335 and alum, because adding 1 kg/t A3335 alone did not cause dewatering and did not form a filter cake and adding 10 kg/t alum alone led to a cake with only 47 wt% solids.
- The different filtration performances were mainly reflected by the different initial filtration rates. Filtration was much faster when A3335 was added prior to alum than when alum was added prior to A3335. However, when filtration time was extended, the total amount of removed water from the FFT became similar no matter the reagent addition sequence, so the final cake solid content tended to be the same when filtration was carried out for longer than about 30 minutes.
- The anionic flocculant A3335 formed large flocs, which seemed to be the reason for the fast filtration rate when coupled with alum. When the polymer flocculant is non-ionic, such as PEO, the sequence of reagent addition did not seem to make a difference.
- For instance, adding 1 kg/t PEO and 10 kg/t alum, a 25-min filtration of 250 g FFT (28.7 wt% solids) in the $\phi 142$ mm Millipore filter under 600 kPa generated a cake with 58 wt% solids. Reversing the order of reagent to alum followed by PEO gave similar results. There was again, a clear synergy between PEO and alum, because adding 1 kg/t PEO alone did not cause dewatering and did not form a filter cake.
- Interestingly, PEO did not form large flocs when added at 1 kg/t dosage to the FFT sample. The floc size was much smaller than A3335, which could be due to the different charges (PEO is non-ionic and A3335 is anionic) but could also be because of the molecular weight (PEO is 8M and A3335 is 17M). Overall, PEO+alum caused a slower but nearly constant filtration rate, and A3335+alum caused a very fast initial filtration rate which levelled off. When the filtration time was extended to more than about 30 minutes, the total amount of water removed became similar.

- Therefore, it seems that the study on the type, dosage and addition sequence of flocculants and coagulants in FFT filtration is mainly aimed at faster filtration rate and shorter filtration cycles.
- Adding tannic acid prior to PEO and alum improved filtration. But adding tannic acid after PEO or after alum impeded filtration. This phenomenon is being further investigated.

LESSONS LEARNED

The effects of flocculant + coagulant addition sequence, and the difference of such effects between anionic (A3335) and non-ionic (PEO) flocculants are of interest*. While the mechanism behind the reagent sequence effect is being investigated, it points to a way to reduce coagulant dosages. It is possible that after flocculating the tailings and then adding the coagulant, the coagulant only needs to interact with the “outer shell” of the flocs and would thus be more effective and can achieve the desired effect at lower dosages.

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RESEARCH TEAM AND COLLABORATORS

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CST Enhanced Fines Beach Capture

COSIA Project Number: TJ0086

Research Provider: Imperial

Industry Champion: Imperial

Status: Ongoing – Year 2 of 3

PROJECT SUMMARY

The Enhanced Fines Capture Study is intended to improve Kears's ability to forecast Fluid Fine Tailings (FFT) volumes and tailings treatment requirements by studying CST beach fines capture in various depositional environments related to tailings area geometry.

FFT is primarily stored within the West & East External Tailings Areas (WETA & EETA) and in 2023 began accumulating in In-Pit Tailings Area 1 (ITA1). The WETA is the primary fluid storage facility; all other tailings facilities have relatively smaller fluid inventories and pump continuously back to WETA. Kears's current mine plan does not include construction of significant additional fluid capacity in the form of external tailings areas or internal tailings areas for the remainder of the life of the mine driving the critical importance of fluid management and tailings treatment.

Forecasting of future FFT volumes ultimately informs resource allocation and planning for tailings treatment. Accurate forecasting is essential when the mine plan is fluid capacity constrained as increasing treatment capacity above plan can take years of research, development, construction, and operational ramp-up. While Kears recalibrates its tailings mass balance annually to improve forecasting performance, FFT volume predictions far exceeded actuals in 2021 & 2022. An explanation for these results could not be developed within the set of assumptions included in the mass balance. A hypothesis was developed based on the "Prospects for Enhancing Fines Capture in Conventional Tailings Facilities" report completed by BGC Engineering for COSIA in 2017. This hypothesis stated that lower than expected FFT accumulation rates from 2019-2022 could be attributed to the geometry of the WETA; higher relative fines capture could be expected as it is a mature tailings facility with a deep, dense inventory of FFT. The hypothesis also stated that, when Coarse Sand Tailings (CST) deposition was moved to ITA1 in 2023, which more resembles a 'sand dump' and is expected to have relatively lower fines capture, rates of FFT accumulation would increase significantly. The specific risk that this study is intended to mitigate is that plans for future tailings treatment could be based on the temporarily low FFT accumulation rates experienced in the

2021 & 2022 rather than potential higher FFT generation that could be seen in 2023 and beyond. Sufficient tailings treatment is essential for effective fluid inventory management within available capacity.

The scope of this project included:

- Completing a qualitative study on available data in 2022 to test the hypothesis.
- Gather sufficient beach fines capture data to test the hypothesis.
- Complete a quantitative study based on the new data gathered in 2022.
- Upgrade Kearl's tailings mass balance to consider tailings area geometry when defining CST beach fines capture, improving FFT volume forecasting accuracy.

This work builds upon the work undertaken by COSIA's Enhanced Fines Capture Working Group, including the "Beach Fines Capture Study" completed by AMEC in 2013 as well as the study completed by BGC Engineering in 2017 previously mentioned.

PROGRESS AND ACHIEVEMENTS

A qualitative study was completed by McKenna Geotechnical in 2022 using data available at the time, including annual pond investigation data from Kearl and relevant industry experience. This study was intended to test the validity of the hypothesis as sufficient CST beach sampling had not been conducted to date. The study directionally supported the hypothesis and recommended further work that would ultimately allow the tailings mass balance to better account for variable fines capture in the CST beaches.

Approximately 400 beach samples were collected via sonic sampling across 5 cross-sections in the WETA & EETA and tested for solids content and fines content via Dean Stark and Laser Diffraction. Other lab tests such as MBI, Atterberg Limits, Sieve & Hydrometer, and XRD were also conducted on a subset of samples. Six Shelby tube samples were also collected. Samples were collected in 2022 and testing was completed in 2023.

A quantitative study by BGC Engineering was ongoing in 2023

LESSONS LEARNED

Early results from the 2022 beach sampling campaign appear to support the hypothesis, but detailed work to confirm is underway and is expected to continue into 2024. Conversations undertaken

through COSIA with other operators also anecdotally support the hypothesis; the phenomenon of temporary reduced FFT generation rates followed by a sudden increase has been experienced at other sites.

The lessons from this study are expected to improve Kearl's ability to manage fluid inventories and tailings treatment, reducing the risk of higher fluid inventories than plan through the life of the mine.

REFERENCES

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Canada's Oil Sands Innovation Alliance (COSIA). (2017). *Prospects for Enhancing Fines Capture in Conventional Tailings Facilities*

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

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Co-Deposition of Enhanced In-line Flocculated Fluid Tailings and Thickened Tailings

COSIA Project Number: TJ0117

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 1 of 3

PROJECT SUMMARY

Imperial's long-term tailings deposition strategy for the East External Tailings Area (EETA) at Kearl is co-deposition of in-line flocculated (ILF) or enhanced in-line flocculated FFT (eILF) with thickened tailings (TT) and coarse sand tailings (CST). In 2022, a field pilot was initiated at EETA which focused on evaluating eILF treatment of fluid tailings from West ETA and its co-deposition with TT from KFTT plant. The eILF process utilizes three chemicals for treatment of fluid tailings: a flocculant (polyacrylamide), a binder (colloidal silica) and a coagulant (aluminum sulphate).

The objective of the pilot is to assess performance of eILF treated FFT that is co-deposited with TT, either simultaneously or interlayered in the deposition area. Figure 1 shows the pilot location and layout of separate pipelines directing eILF treated FFT and TT streams towards the southern boundary of TT deposition area. Five distinct discharge locations were devised, each purposed for creation of a specific deposit composition as listed below:

- Discharge Location OB-A; for co-deposition of eILF and TT (i.e., simultaneous pour of both streams).
- Discharge Location OB-B; for intermittent deposition of eILF and TT (i.e., consecutive eILF and TT layers).
- Discharge Location OB-C; for pouring eILF only during the first few months of pilot to create a thick (~4 m) layer of eILF treated FFT; and then will be used for co-deposition of TT and eILF treated FFT. The objective of creating a relatively thick eILF layer is to evaluate its strength and dewatering characteristics for closure planning.

- Discharge location OB-D; to direct off-spec eILF treated FFT and to deposit TT when TT is not in the pour plan for locations OB-A, OB-B and OB-C.
- Discharge location OB-E; to direct TT stream when it is not in the pour plan for locations OB-A, OB-B and OB-C.

The volumetric proportion of eILF and TT streams and their duration of pour at locations OB-A and OB-B was managed by targeting an average SFR of 1 for the resultant deposit. The co-deposition and inter-layering of eILF and TT at an average SFR of 1 is expected to follow a relatively similar trajectory of strength gain as TT.

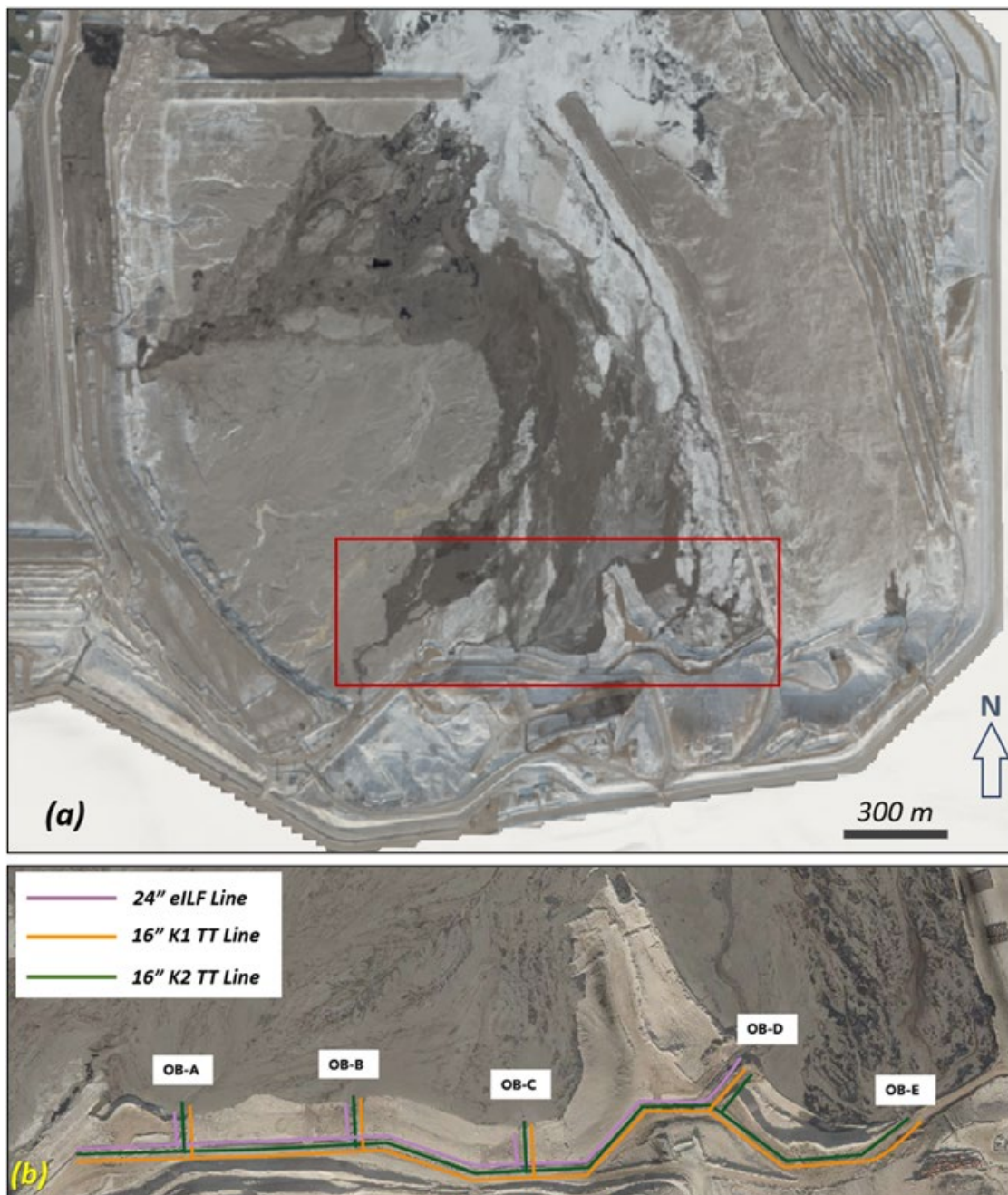


Figure 1 - (a): Co-deposition pilot location. (b): Layout of eILF and TT pipelines

PROGRESS AND ACHIEVEMENTS

Co-deposition of the eILF treated FFT and TT started in September 2022 followed by more co-deposition during October and November 2022. The eILF pour was temporarily paused due to operational challenges after November 26, 2022 and was resumed in 2023.

A surveillance plan was developed to monitor the KPIs of the treated slurry during the pilot and leveraged readily available inline instrumentation combined with laboratory testing of samples collected from the pipeline. Geotechnical investigation of the deposit was postponed to 2023; as duration of the pour was limited in 2022 and the resultant eILF/TT deposit was not thick enough to allow collection of representative samples and in-situ strength measurements.

The KPIs that were monitored during the commissioning and operations include:

- Untreated FFT flowrate, density/solids content, average SFR and MBI
- Dosage of chemical additives
- Capillary suction time (CST) of treated FFT and release water
- 24 hour and 7-day solids content of treated FFT

During 2022, eILF-TT co-deposition pilot produced 0.89 Mm³ of eILF treated tailings. The targeted flocculant dosage was 1500 g/t and fluctuated due to variation in FFT density. The targeted dosage for Alum and Colloidal Silica were 200 ppm and 40 ppm respectively. Based on the limited samples that were collected during the trial, Figure 2 illustrates variations of solids content after one day and 7 days, also variations of yield stress at 1 hour, 1 day and 7 days for the eILF treated samples. For on-spec samples (i.e., CST < 60 seconds), the average yield stress increased from ~400 Pa to >1500 Pa after 7 days, and the average solids content increased to ~42% from the initial FFT slurry (~20% solids content), indicating good dewatering.

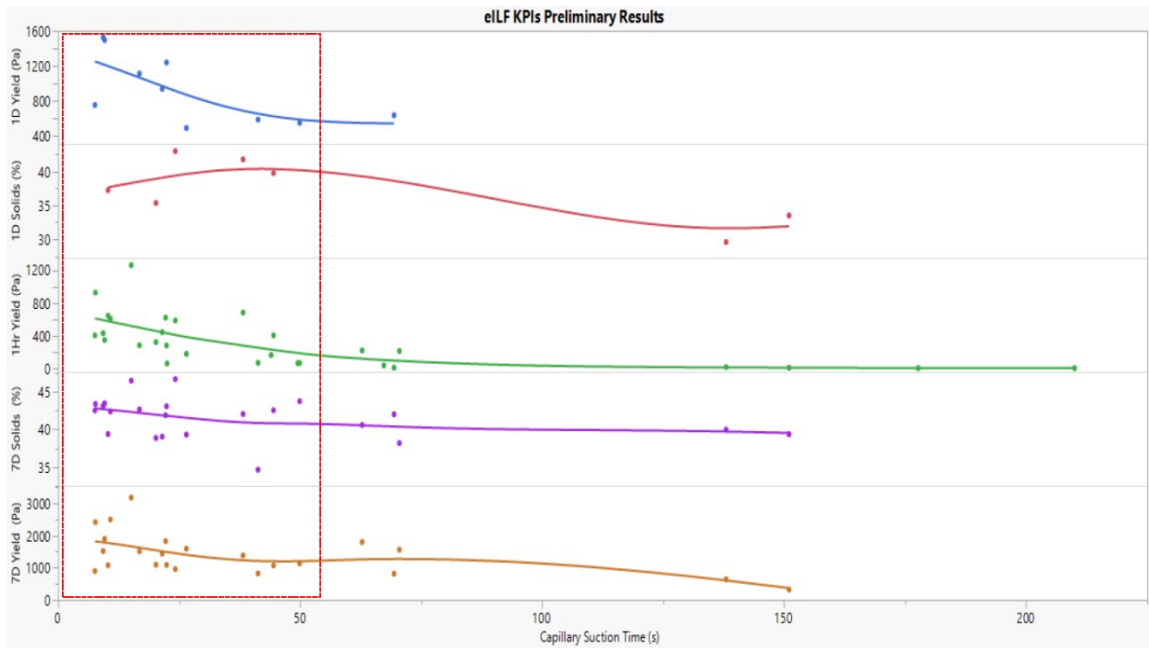


Figure 2 - Variations of Solids Content, Yield Stress and Capillary Suction Time

LESSONS LEARNED

A site investigation program was conducted in Q3 2023 to collect samples from the eILF-TT deposit for laboratory characterization tests, also to conduct in-situ strength measurements. A summary of the learnings will be provided in the next Tailings Research Report after analysis of the test results is complete.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigators: Reza Moussavi Nik and Givemore Sakuhuni

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Physically Upgraded Trafficable Tailings Innovation (PUTTI)

COSIA Project Number: TJ0128

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 3 of 4

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. The PUTTI work is now being progressed through an IOSI funded project titled: Dewatering of oil sands fluid fine tailings with a combination of enhanced flocculation chemistry and volute screw press.

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.
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.
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/m²/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 enhanced inline flocculated fluid tailings for both batch and continuous mechanical dewatering was evaluated. The effect of

higher SFR on mechanical dewatering efficiency for enhanced inline flocculated fluid tailings was also evaluated. Further optimization studies for continuous mechanical dewatering continue to be progressed with the objective of determining a suitable combination of fluid tailings properties, chemical treatment, and equipment variables to maximize throughput and cake solids content.

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. Whilst enhanced inline flocculation treatment yielded better performance for batch mechanical dewatering, a single polymer treatment yielded better performance for the volute screw press (continuous mechanical dewatering) application.

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

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Co-processing of Fresh Tailings and FFT

COSIA Project Number: TJ0151

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Year 2 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 sand to fines ratio (SFR) could increase hydraulic conductivity of co-processed deposit. Compared to Composite Tailings (CT) 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.

The technical gap assessment for co-processing recommended that the following technical uncertainties needed to be resolved in Stage B before considering field-scale pilot.

- 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.

In order to close the technological uncertainties identified above, a test plan was developed to be executed 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, FGDS + 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 2022, below is a preliminary summary of the test results:

Phase 1: Lab tests.

As reported in 2021 COSIA Research Report, most of the technological uncertainties in Phase 1 were resolved and the relevant technical gaps in Phase 1 were closed. In 2022, test continued to

close the rest of the gaps in Phase 1 that included the tests of sensitivity of feed mineralogy and water chemistry, and the effect of release water on bitumen extraction.

It was found that the feed mineralogy may have a slight effect on flocculation performance, but it was not significant, especially when the flocculant + coagulant (alum) + flocculant (FC or FCF [1]) recipe was used. Water chemistry concentrations were compared in the expressed water from the untreated feed and with each respective co-processing treatment. It was found that all treatments reduced naphthenic acid (NA) concentrations relative to the feed water by ~20-30 mg/L. This is a positive effect. Data suggested it was primarily a polymer driving treatment effect. The test data showed that there were no impacts of release water on bitumen extraction for the recipes of polymer only, polymer + alum, and gypsum + polymer, but a slight effect of release water for the FGDS + polymer recipe.

Phase 2: Small pilot tests

The co-processing material was successfully flocculated during the continuous pilot testing using an inline dynamic mixer. The treated materials rapidly released water and gained strength. The inline dynamic mixer scale-up model $K_c = N^2 D^4 / Q$ was validated. It is applicable to co-processing of fresh tailings and FFT at SFR of 2.0. The optimal K_c is approximately 10 m/s for polymer only, FGDS + polymer and gypsum + polymer recipes, which is similar to that for flocculated tailings (Floc-T) for the same type of impeller. For polymer + alum recipe, smaller K_c for polymer/alum mixing of 10/5 m/s was required. Pipeline shear should be considered together with the inline mixer K_c to reduce the risk of segregation in pipeline and deposition in flume. As expected, the deposit slopes in the flume increased with increase in yield stress of flocculated materials. In general, there was no significant sand segregation in the flume deposition.

The LSC (large strain consolidation) and beam centrifuge test results for the deposits produced from the small pilot tests with four recipes demonstrated that:

- Compared with the cohesive tailings (i.e., flocculated FFT with 0~0.1 SFR), the co-processed deposits with SFR of about 2 for four recipes have 2~3 orders of magnitude higher hydraulic conductivity.
- Co-processed deposits settle less than cohesive deposits post deposition, which reduces the cost for reclamation.
- The LSC data and the beam centrifuge test results are generally consistent in terms of compressibility and hydraulic conductivity.

- For 50m deep co-processed deposit, the consolidation could complete in less than 10 years, resulting in 83~85% average solids content deposits.
- For 25m deep co-processed deposit, the consolidation could complete in less than 3-5 years, resulting in 83-85% average solids content deposit.
- Compared to fines-dominated cohesive tailings deposits, co-processed deposits can be capped and reclaimed to create a terrestrial landform at a faster pace.

LESSONS LEARNED

Based on the test results to date, the co-processing technology produces treated tailings that can be successfully integrated into a terrestrial closure landform.

REFERENCES

Yuan, X.S. & 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

Institution: Syncrude Canada Ltd.

Principal Investigators: Simon Yuan

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Fluid Tailings Thickening Project

COSIA Project Number: TJ0153

Research Provider:

Industry Champion: Canadian Natural

Status: Year 2 of 2

PROJECT SUMMARY

Increasing the fines over fines plus water (FOFW) content of a Non-Segregating Tailings (NST) mixture results in stronger NST receipt and thus higher fines capture. In 2021 and 2022, a pilot study at Horizon was designed and operated to test the feasibility of dewatering FT with a thickener. Mixing the dewatered FT with Canadian Natural's NST would result in increased fines capture compared to a mixture of the original FT and NST (a product known as esNST).

The three main objectives of the pilot study were:

1. Quantify the dewatering capability of a thickener on Horizon FT.
2. Test the geotechnical properties of thickened tailings with various SFRs.
3. Create a large test deposit with a co-mix of thickened FT and NST to demonstrate incremental increase in NST fines capture.

In 2021 the focus was on testing the feasibility of using a thickener to dewater FT and the fines capture when co-deposited with NST. In 2022, the focus was on determining the robustness of the process under different operating conditions as well as the optimal conditions for producing thickened FT.

PROGRESS AND ACHIEVEMENTS

Modifications were made to the plant in 2022 to ensure consistent feed to the thickener through the use of a screen tank and a different polymer flocculant. These two changes combined with a change in operating philosophy to keep the plant running 24/7 helped to provide steady and reliable operation of the thickener.

The FT Thickener pilot ran for approximately 3 months from July to September 2022 under a range of conditions including feed density, solids flux, retention time, rake speed, thickener bed height, and polymer dosage.

The average solids content of the thickened FT was 43 wt%, which was approximately 20 wt% higher than the FT feed.

A deposition cells was used to observe the slope of the thickened FT deposit as well as flow parameters, strength, and consolidation.

LESSONS LEARNED

The thickener was able to successfully operate with FT feed, in the range of conditions tested and performance improved compared to 2021. As expected, underflow solids content was strongly correlated with polymer dosage, rake speed, solids flux, and retention time.

Overflow water quality was lower than observed in 2021, though overflow quality was only monitored, and no adjustments were made to improve it in 2022. It is expected that overflow quality could be improved with the use of a coagulant and modifications to the thickener design to consider both overflow and underflow quality.

The deposit densified due to self-consolidated and evaporation. The shrinkage rate was dependent on the deposit thickness, with lower rates and lower average solids content in thicker areas of the deposit.

Though debris was a problem in the 2021 pilot and a screen tank was added for 2022 it is not expected that it would be a significant issue in a commercial scale operation. In the pilot operation, the debris was large relative to the piping and instrument diameter. At a commercial scale, the equipment would be much larger in diameter compared to the debris from Horizon's FT system.

Canadian Natural is evaluating the viability of this technology at Horizon within the family of NST technologies. The envisioned usage would be via co-deposition with NST/eNST or replacing FT with thickened FT in esNST.

PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

2021 Canadian Natural Tailings Management Report

2022 Canadian Natural Tailings Management Report

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Jiangying Wu

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Jorge Gomez	Canadian Natural	Pilot Operator		
Shawn Dirk	Canadian Natural	Pilot Operator		
Jamie Smith	Canadian Natural	Pilot Operator		
Armand Marchand	Canadian Natural	Pilot Operator		
Peter Stapleton	Canadian Natural	Advisor		

Tailings Capping

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 & 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: 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 conduct large-strain numerical simulations of a bench-scale test of sand capping. The bench-scale test had been completed as part of COSIA project number TE0059. The data from the bench-scale test was revisited to provide more detail 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

The paper was presented by Mario Martinelli at the International Oil Sands Tailings Conference 2022 (IOSTC '22). This conference was held in Edmonton on December 4-7, 2022.

RESEARCH TEAM AND COLLABORATORS

Institution: Barr Engineering and Environmental Science Canada Ltd.

Principal Investigators: Jed Greenwood, Dirk Luger

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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		
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Mario Martinelli	Deltares	Co-Principal Investigator, Strategic Adviser, Soil and Structure Department		

Research Collaborators: Deltares, University of Perugia

Hydraulic Coke Capping of Tailings Ponds

COSIA Project Number: TJ0141

Research Provider: Suncor

Industry Champion: Suncor

Status: Active

PROJECT SUMMARY

Hydraulic coke placement is being evaluated as an alternative to mechanical coke placement as a necessary step to creation of trafficable terrestrial surfaces on existing tailings deposits. As demonstrated in Pond 5, the Semi-Anchored Floating Experimental (SAFE) cover showed the ability to terrestrially close Composite Tailings (CT) deposits like Pond 5 with a combination of coke, geosynthetics, wick drains and time. However, in completing the SAFE cover for Pond 5, it became apparent that air quality emissions for future pond closures may result from an initial water cap removal and the resultant depressurization of the tailings. As a result, the principal of an initial hydraulically placed coke layer was developed to manage the coke depressurization and create stable coke cap which can be transitioned from a sub-aqueous deposit to a sub-aerial deposit capable of supporting vehicular traffic.

PROGRESS AND ACHIEVEMENTS

The technology development scopes were broadly separated into two separate area (i) coke placement and (ii) subsequent geotechnical performance of the hydraulically placed coke layer. Thus, the majority of the work has been separated into these two streams with lab work, numerical studies and ultimately field trials being used to validate the assumptions and expectations of the coke placement and geotechnical performance of the coke capped tailings.

For the coke placement, the theoretical (Technology Innovation Management System, TIMS Stage 1), lab and numerical (TIMS Stage 2) and field trial (TIMS Stage 3) scopes were completed in 2020, 2021 and 2022 respectively. The culmination of this work to date has been the completion of the beaching trial during which 6,000 tonnes of coke was slurried and deposited on the shoreline of Pond 6 over soft tailings. Four objectives were set to de-risk the assumptions and validate numerical models. These included:

1. Validate hydraulic coke capping is a “no planned GLC” (ground level exceedances for air quality emissions) approach.
2. Correlate the relationship between coke slurry solids content and coke beaching angle.
3. Collect tailings and cap performance data to validate the hydraulic coke placement models.
4. Create a coke beach for future geotechnical assessment.

Next steps for the technology de-risking are to advance to Stage 3B and look at the 2nd placement methodology, Coke Raining-in. This method will account for >80% of the coke placed in Pond 6, with the raining-in trial expected to leverage the learnings on coke slurring operation and placement modeling from the beaching trial. Supporting activities for this trial and technology will include sloped mudline simulations for raining-in for pre- and post-trial simulations to provide guidance on trial operation and success respectively. This trial is expected to be operated in the summer of 2024.

For the geotechnical performance to date, there have been two broad initiatives in the lab and numerical scopes to evaluate the expected conditions a hydraulically placed coke cap can be trafficked and an investigation of the beached deposit, placed by the beaching trial.

LESSONS LEARNED

With respect to the coke beaching trial objectives, it was found that (i) beaching didn’t result in GLCs exceedances above background levels, (ii) there was a strong correlation between slurry solids and beaching angles, and (iv) a coke beach suitable for future investigation was created. The main investigative and analytical effort was employed in the (iii) validation of the hydraulic coke beaching models, the summary for which is as follows:

- The beaching was able to advance ~100 m from the spigot without failure of the tailings substrate.
- Simulations were successful in representing the trial conditions in steady state but were unable to do so for dynamic placement.
- The main learning appears to be that the model representation of the trial area is too simplified, compared or the complex nature of the depositional environment.
- Additional supporting analysis have been completed to assess how much tailings could have been displaced in 3D. It was estimated that several times less upward displacement than

downward displacement was measured, suggesting that the coke cap was not solely displacing an incompressible fluid outward (which would imply an inability to cap the soft substrate).

For the geotechnical performance scope, a lab scope of work was executed with the aim of closing gaps related to physical properties of low-density coke layers. Experimental results for parameters such as particle size distribution, hydraulic conductivity and strength of (partially saturated) frozen materials were largely in line with literature values. The data are available to serve as input for future modeling activities. Some of these parameters which were determined in the lab were then further validated at the field scale for coke beaching with as-placed dry densities and freezing rates being measured.

The numerical scope was targeted with the aim at assessing options for converting a hydraulically placed coke layer into a deposit trafficable with progressively higher ground pressure equipment. A parametric study was conducted that considered aspects like initial MFT strength, hydraulically placed coke thickness, type of equipment accessing the deposit and surface preparation options (e.g. frozen surface, geotextiles, etc.). Both limit equilibrium and 2D and 3D finite element techniques were deployed. The original intent of the numerical study was to determine whether there was *any* viable path from hydraulically placed coke to a trafficable surface. Exploration of the parameter space has shown that a variety of options are available. The generic numerical framework is now available for further assessment. However, future development activity would heavily benefit from project execution and design input. If the desired stages of construction can be defined (e.g. the sequence of placement by raining in vs. beaching), then specific numerical analysis could be used to optimize material placement rates, etc.

The numerical scope of work has flagged a relevant constraint for further technology development work. While it is in principle possible to validate the results by geotechnical assessment of the coke deposits from the hydraulic coke capping trial, validating all test cases would be time and cost prohibitive. Validation cases will need to be chosen such that maximum confidence is gained from the tests. The cost of test deposits significantly larger than the 6,000 tonne deposit completed in October 2021 would likely be comparable to the cost of commercial deployment.

Future investigation of the rained-in coke cap as placed by the 2024 trial will also validate additional assumptions on that placement method as well as tailings-coke interface thicknesses to inform the wick drain design.

REFERENCES

This research primarily references internal Suncor work on the TRO and PASS technology development scopes.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor Energy Inc. developed and lead this technology development but leveraged numerous internal and external professionals

Principal Investigators: Fergus Murphy, Elco Hollander

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- Thurber: Sam Proskin, Josh Wu
- WSP (formerly Golder): Jason Stianson
- Bentley: Murray Fredlund
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Froth Tailings Treatment

NSERC-Syncrude IRC in Mine Closure Geochemistry

COSIA Project Number: TJ0130

Research Provider: University of Saskatchewan (USask)

Industry Champion: Syncrude

Status: Year 3 and 4 of 5 (Team 2 of IRC)

PROJECT SUMMARY

Led by Dr. Matthew Lindsay in the Department of Geological Sciences at USask, the overall Industrial Research Chair (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 potential 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 new information to support long-range mine closure and reclamation planning. Key information includes improved 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.

PROGRESS AND ACHIEVEMENTS

Following the unanticipated delays related to the COVID-19 pandemic during 2020, research activities ramped up again in 2021. Considerable progress was made during 2022 and 2023 toward accomplishing the original research objectives. However, the delays associated with the COVID-19 pandemic, coupled with significant demand for geochemical expertise in the mining sector, has led several students to begin working before completing their degrees. Although all students are committed to completing their degree requirements, their timelines for degree completion have been extended as a direct result of their work obligations. Details on recent progress and remaining work are provided 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 (additional details are provided below under Theme 2).

Activity 1.1 - Characterize process mineralogy and geochemistry

Masters of Science student #1 (MSc-1) continued geochemical and mineralogical analysis of core samples ($n > 150$) obtained during the 2019 drilling program (see Theme 2 below). Although geochemical and mineralogical analyses were completed, the quantitative X-ray diffraction results were revisited following initial data analysis in early 2022. Statistical analysis has revealed relationships between bulk mineralogy, geochemistry, and passive gamma readings that support delineation of FTT within tailings storage facilities. MSc-1 is expected to defend their thesis in 2024.

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 Bachelors of Science student #1 (BSc-1), Undergraduate student #4 (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. This research has considered the influence of FTT weathering history (i.e., non-weathered, partially weathered, highly weathered) and residual hydrocarbons (i.e., solvent washed, non-solvent washed) on acid neutralization and metal(Loid) release. Laboratory batch experiments were completed in early 2022 and subsequent column experiments were completed in early 2023. Data analysis and interpretation is ongoing, and MSc-5 is expected to defend their thesis in 2024.

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 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, was completed in 2022. This research has revealed potential for acidification and metal(loid) release under field conditions within sub-aerial FTT beach deposits. Observed trends in pore-water pH and metal(loid) release are generally consistent with

recent results from Activity 1.2 and have directly informed research being carried out under Themes 3 and 4. MSc-2 is expected to defend their thesis in 2024.

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

MSc-4 continued their research into geochemical controls on metal(loid) mobility in landforms that may contain both FTT and fluid coke. Two field-scale lysimeters were constructed in November 2021 and instrumented in May 2022, with core sampling was carried out in October 2022 and 2023. Geochemical analysis of water and solids from these cores was completed in late 2022 and results informed column experiments established in early 2023. This research greatly improves the understanding of the geochemical controls on metal transport and attenuation in mine closure landscapes. Data analysis is ongoing, and MSc-4 is expected to defend their thesis in 2024.

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

Doctor of Philosophy student #1 (PhD-1) continued their research into the geochemical implications of reclamation soil covers on underlying FTT exhibiting different weathering extents (i.e., non-weathered, partially weathered, highly weathered). Six field-scale lysimeters were constructed in November 2021, instrumented in June 2022, and sampled in late 2022 and 2023. Data logging sensors collected data through 2022 and 2023, the associated data processing and analysis is ongoing. Various measurements (e.g., soil water characteristic curves, oxygen consumption tests) and analysis (e.g., geochemistry, mineralogy, acid-base accounting) were performed in 2022 to support preliminary model development. Corresponding laboratory column experiments were initiated in 2023 to further constrain field observations. PhD-1 is expected to complete their degree requirements by early 2025.

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 is performing laboratory experiments and numerical modelling to assess acid neutralization and metal(loid) attenuation by various mine materials (i.e, overburden, extraction wastes, upgrading by-products) that may be used during construction of closure landforms. PhD-2 made excellent progress through 2022 and 2023, including completion of laboratory batch experiments and subsequent laboratory column experiments. Data analysis and interpretation for the batch experiment is ongoing and will be completed in 2023. Laboratory column experiments will continue through 2023 and corresponding data analysis and interpretation will be completed in 2024. PhD-2 is expected to complete their degree requirements by early 2025.

Activity 4.2 - Evaluate passive treatment options for FTT drainage

Through discussions with the Syncrude MCR team, this activity was revised to assess influences of microbial sulfate reduction on pore-water chemistry within FTT deposits. 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 completed complimentary column experiments in October 2022. Subsequent data analysis and interpretation was completed in early 2023, MSc-3 completed their thesis in the Fall 2023.

LESSONS LEARNED

Research conducted over the past year expands our understanding of the geochemical evolution of FTT beach deposits under different conditions. 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 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-rich, hydrocarbon-bearing tailings.

Field data and laboratory experiments reveal strong relationships between acid-neutralization reactions, corresponding pH conditions, and associated metal(loid) mobility within Plant 6 FTT beach material. Although carbonate-mineral dissolution may delay the onset of acidic conditions, pore-water pH dropped to between 5 and 6 when siderite dissolution was the dominant acid neutralizing

reaction. Following depletion of carbonate minerals, abrupt decreases in pore-water pH to below 3 generally corresponded to large increases in dissolved metal(loid) concentrations. Acidic conditions developed more rapidly in partially weathered FTT samples compared to non-weathered FTT samples, reflecting depletion of carbonate-minerals over time. Finally, laboratory results indicate that residual hydrocarbons may suppress the intrinsic acid neutralization capacity of FTT solids.

Field data and laboratory results indicate that microbial sulfate reduction promotes attenuation of sulfide-mineral oxidation products below the sulfide-mineral oxidation zone. Stable isotopes of sulfur revealed that microbial sulfate reduction drives large decreases in pore-water sulfate concentrations below the oxidation zone. Low concentrations of dissolved hydrogen sulfide gas are consistent with the precipitation of insoluble metal-sulfide minerals. Laboratory experiments have produced similar results, suggesting that microbial sulfate reduction and metal-sulfide precipitation can limit transport of sulfide-mineral oxidation products within FTT deposits.

Laboratory experiments have shown that various oil sands mine materials, including overburden (i.e., peat, till, shale) and tailings (i.e., fluid fine tailings, sand tailings), can contribute to acid neutralization and metal(loid) attenuation. For many of these materials, observed pH increases and metal(loid) concentration decreases are comparable to those observed for reactive materials (i.e., zero-valent iron, zeolite) commonly used for mine water treatment.

The combined results of this research continue to advance understanding of the geochemical evolution of FTT deposits beyond source terms and show considerable potential for attenuation of sulfide-mineral oxidation products within FTT deposits and, more broadly, oil sands mine closure landscapes.

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(loid) release, with the largest cumulative mass release observed under acidic conditions. Related studies have further probed geochemical processes affecting vanadium and molybdenum mobility – key metals released from fluid petroleum coke. Results obtained during 2022 and 2023 indicate that dissolved organic carbon, and both inorganic and organic colloids, in leachates derived from reclamation soil covers can enhance metal(loid) release from fluid petroleum coke. 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.

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

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

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.

Marchi, J.A. (2024) Influence of microbial sulfate reduction on pore-water chemistry in oil sands froth treatment tailings. M.Sc. Thesis, University of Saskatchewan, Saskatoon, Canada, 77 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

Albakistani, E.A., Nwosu, F.C., Furgason, C., Haupt, E.S., Smirnova, A.V., Verbeke, T.J., Lee, E.-S., Kim, J.-J., Chan, A., Ruhl, I.A., Sheremet, A., Rudderham, S.B., Lindsay, M.B.J., & Dunfield, P.F. (2022) Seasonal dynamics of methanotrophic bacteria in a boreal oil sands end-pit lake. *Applied and Environmental Microbiology*, 88: e01455-21. <https://doi.org/10.1128/AEM.01455-21>

Craig, A.T., Shkarupin, A., Amos, R.T., Lindsay, M.B.J., Blowes, D.W., & Ptacek, C.J. (2021). Reactive transport modelling of porewater geochemistry and sulfur isotope fractionation in organic carbon amended mine tailings. *Applied Geochemistry*, 127: 104904. <https://doi.org/10.1016/j.apgeochem.2021.104904>

Francis, D.J., Barbour, S.L., & Lindsay, M.B.J. (2022) Ebullition enhances chemical mass transport across the tailings-water interface of oil sands pit lakes. *Journal of Contaminant Hydrology*, 245: 103938. <https://doi.org/10.1016/j.jconhyd.2021.103938>

- Jessen, G.L., Chen, L.-X., Mori, J.F., Colenbrander Nelson, T.E., Slater, G.F., Lindsay, M.B.J., Banfield, J.F., & Warren, L.A. (2022) Alum addition triggers hypoxia in an engineered pit lake. *Microorganisms*, 10: 510. <https://doi.org/10.3390/microorganisms10030510>
- 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
- Mori, J.F., Chen, L.-X., Jessen, G.L., Rudderham, S.B., McBeth, J.M., Lindsay, M.B.J., Slater, G.F., Banfield, J.F., & Warren, L.A. (2019). Putative mixotrophic nitrifying-denitrifying Gammaproteobacteria implicated in nitrogen cycling within the ammonia/oxygen transition zone of an oil sands pit lake. *Frontiers in Microbiology*, 10: 2435. <https://doi.org/10.3389/fmicb.2019.02435>
- 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
- Schoepfer, V.A. & Lindsay, M.B.J. (2022) X-ray absorption spectroscopy and X-ray diffraction data for molybdenum minerals and compounds. *Data in Brief*, 45: 108576. <https://doi.org/10.1016/j.dib.2022.108576>
- Schoepfer, V.A. & Lindsay, M.B.J. (2022) Repartitioning of co-precipitated Mo(VI) during Fe(II) and S(-II) driven ferrihydrite transformation. *Chemical Geology*, 610: 121075. <https://doi.org/10.1016/j.chemgeo.2022.121075>
- 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
- Slater, G.F., Goad, C.A., Lindsay, M.B.J., Mumford, K.G., Colenbrander Nelson, T.E., Brady, A.L., Jessen, G.L. & Warren, L.A. (2021). Isotopic and chemical assessment of the dynamics of methane sources and microbial cycling during early development of an oil sands pit lake. *Microorganisms*, 9: 2509. <https://doi.org/10.3390/microorganisms9122509>

- Vessey, C.J., Schmidt, M. P., Abdollahnezhad, 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
- 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 Papers

- 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.
- Paulsen, J.J., Meili, D.E., Marchi, J.A., Marquez, J.E., Schoepfer, V.A., & Lindsay, M.B.J. (2022) Geochemical evolution of froth treatment tailings at an oil sands mine in northern Alberta, Canada. In: Proceedings of the 12th International Conference on Acid Rock Drainage, September 18–24, Brisbane, Australia, Paper No. 136.

Conference Presentations/Posters

- Ferry, S. & Lindsay, M.B.J. (2023) Acid neutralization and metal(loid) release in oil sands froth treatment tailings. Geological Association of Canada–Mineralogical Association of Canada–Society for Geology Applied to Mineral Deposits (GAC-MAC-SGA) Joint Meeting, May 24 – 29, Sudbury, Canada. [Poster]
- Francis, D.J., Barbour, S.L. & Lindsay, M.B.J. (2019, June 2 – 4). Modelling methane dynamics in fluid fine tailings in an oil sands end pit lake. 2019 Canada's Oil Sands Innovation Alliance – Oil Sands Innovation Summit, Calgary, Canada. [Poster]
- Francis, D.J., Barbour, S.L. & Lindsay, M.B.J. (2019, May 12 – 15). Methane dynamics in fluid fine tailings in an oil sands end pit lake. Geological Association of Canada–Mineralogical Association of Canada–Canadian National Chapter of the International Association of Hydrogeologists (GAC–MAC–IAH) Joint Meeting, Quebec City, Canada. [Oral]

- Francis, D.J., Lindsay, M.B.J. & Barbour, S.L. (2019, September 22 – 25) Methane ebullition can influence internal mass loading in oil sands end pit lakes. Geological Society of America Annual Meeting, Phoenix, USA. [Oral]
- Hasani, S. & Lindsay, M.B.J. (2023) Evaluating reactive materials for passive water treatment in oil sand mine reclamation landscapes. Geological Association of Canada–Mineralogical Association of Canada–Society for Geology Applied to Mineral Deposits (GAC-MAC-SGA) Joint Meeting, May 24 – 29, Sudbury, Canada. [Poster]
- Jessen, G.L., Chen, L.-X., Mori, J.F., Nelson, T.C., Slater, G.F., Rudderham, S.B., Lindsay, M.B.J., Banfield, J.F., Warren, L.A. (2020, June 21 – 26). Insights into biogeochemical cycling and unanticipated geobiological trajectory after alum addition to an engineered lake. Goldschmidt Conference, Virtual Conference. [Oral]
- Lindsay, M.B.J. (2019). Acid generation and metal(loid) release in froth treatment tailings. (2019, June 2 – 4). Canada's Oil Sands Innovation Alliance – Oil Sands Innovation Summit, Calgary, Canada. [Oral, Invited]
- Lindsay, M.B.J. (2019, December 4 – 5). Acid generation and metal release in oil sands froth treatment tailings. 26th Annual BC/MEND Metal Leaching/Acid Rock Drainage Workshop, Vancouver, Canada. [Oral, Invited]
- Lindsay, M.B.J. (2022, February 17) Metal-mineral interactions in dynamic redox environments. Ottawa-Carleton Geoscience Centre–Geoscience Seminars, Ottawa, Canada, Virtual Conference. [Oral, Invited]
- Lindsay, M.B.J., Marquez, J.E., Paulsen, J.J., Meili, D.E., Ferry, S.R., & Marchi, J.A. (2023) Developing Integrated Understanding of the Geochemical Evolution of an Oil Sands Froth Treatment Tailings Deposit. 30th Annual BC/MEND Metal Leaching/Acid Rock Drainage Workshop, December 6–7, Vancouver, Canada. [invited]
- Marquez, E.J., Hamilton, J., & Lindsay, M.B.J. (2023) Influence of tailings weathering history on the hydrogeochemical evolution of oil sands froth treatment tailings under a reclamation soil cover. Geological Association of Canada–Mineralogical Association of Canada–Society for Geology Applied to Mineral Deposits (GAC-MAC-SGA) Joint Meeting, May 24–29, Sudbury, Canada. [Oral]
- Paulsen, J.J., Schoepfer, V.A. & Lindsay, M.B.J. (2022, May 15 – 18). Geochemical controls on acid generation and metal(loid) mobility in froth treatment tailings at an oil sands mine. Geological Association of Canada–Mineralogical Association of Canada–Canadian National Chapter of

the International Association of Hydrogeologists–Canadian Society of Petroleum Geologists (GAC–MAC–IAH–CGPS) Joint Meeting, Halifax, Canada. [Poster]

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

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

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

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

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

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

Wang, Y., Galuschik, N.E., Cowell, M.L., Schulte, J.P., Hayatifar, A., Omotoso, O. & Lindsay, M.B.J. (2022, May 15 – 18). Early biogeochemical development of coagulated-flocculated mature fine tailings for oil sands mine reclamation. Geological Association of Canada–Mineralogical Association of Canada–International Association of Hydrogeologists–Canadian Society of Petroleum Geologists Joint Meeting, Halifax, Canada. [Poster]

Reports & Other Publications

Lindsay, M.B.J., Bews, B.E. (2022). Industrial Research Chair in Mine Closure Geochemistry: Research Progress Report for 2021 (Y2 of 5, Term 2). Annual report prepared for Syncrude Canada Ltd and Canada's Oil Sands Innovation Alliance (COSIA), COSIA Proj.No. TJ0130, April 6, 10.

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.

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.

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 – Summer Student	2020	2021
Scott Churchill	USask	BSc – Summer Student	2022	2023
Mojtaba Abdolhazeh	USask	MSc	2016*	2020
Mattea Cowell	USask	MSc	2016*	2021
James Schulte	USask	MSc	2018	withdrawn
Drake Meili	USask	MSc	2019	2024
Josh Paulsen	USask	MSc	2019	2024
Jake Marchi	USask	MSc	2020	2023
Julia MacGillivray	USask	MSc	2021	2023
Stuart Ferry	USask	MSc	2021	2024
Eduardo Marquez	USask	PhD	2020	2025
Sanaz Hasani	USask	PhD	2020	2025
Philip Adene	USask	PhD	2022	2023
Ardalan Hayatifar	USask	PDF	2021	2024
Valerie Schoepfer	USask	PDF	2019	2024
Mohamed Edahbi	USask	PDF	2019	2020
Noel Galuschik	USask	Research Assistant		
Brenda Bews	USask	Research Engineer		

Mattea Cowell	USask	Research Assistant		
Mojtaba Abdolhnezhad	USask	Research Assistant		

*Research projects initiated during IRC Term 1.

Research Collaborators:

Dr. Lee Barbour	USask	Distinguished 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 R&D	Project Steward

MRM TSRU Gas Generation Testing

COSIA Project Number: TJ0158

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Year 2 of 3

PROJECT SUMMARY

Canadian Natural participated in the regional Froth Treatment Tailings (FTT) evaluation project initiated in 2017 within COSIA to assess the geochemical properties and compositions (gas, water, oil and solid) of FTT at various oil sands tailings storage facilities. In 2022, Canadian Natural started an additional field and laboratory testing program at MRM to further understand the gas generation potential of Tailings Solvent Recovery Unit (TSRU) tailings, a form of FTT.

Key aspects of the 2022 program included analyzing gases generated by the biodegradation of residual solvent in TSRU tailings, assessing their compositions, volumes, and generation rates, and studying the biological, geochemical, and physical properties influencing gas generation. This involved microbiological analysis, organic property assessment to quantify solvent contents and characterize petroleum hydrocarbons, evaluation of inorganic factors such as pore-water and surface water chemistry, and examination of the physical characteristics of the tailings.

The 2022 program milestones include collection of tailings samples (July – August 2022), measurement of free gas within the collected samples, completion of comprehensive analyses to characterize the tailings materials, and establishment of 15 microcosm tests to measure long-term gas generation rates from MRM TSRU tailings deposits. Results from this program are expected to enable Canadian Natural and other stakeholders to assess potential impacts associated with gas generation from TSRU tailings deposits, develop suitable mitigation strategies, and enhance tailings management practices.

PROGRESS AND ACHIEVEMENTS

In 2022, total of 34 TSRU tailings samples and 5 surface water samples were collected. The primary focus during the sampling process was on gas extraction from the tailings samples, with meticulous measurement of the extracted gas volume. These gas samples were subsequently sent to the

laboratory for in-depth analyses of fixed gases, hydrocarbon gases ranging from C₁ to C₄, and reduced sulphur compounds. In addition to gas analysis, the project adopted a comprehensive approach by collecting additional tailings samples for a suite of organic and inorganic analyses. 15 microcosm tests have been established to measure the rates of methane (CH₄) and carbon dioxide (CO₂) generation in selected tailings samples. These analyses aimed to support the interpretation of gas results, aid in understanding biodegradation reactions, and opportunistically gather other relevant geochemical data. By incorporating organic and inorganic parameters, the project sought to gain a holistic understanding of the TSRU tailings' geochemical properties.

LESSONS LEARNED

Free gas was observed at varying depths within each tested location. The concentrations of free gas exhibit significant variability across different locations. The biodegradation of petroleum hydrocarbons within the TSRU tailings have been identified as the primary source of gas generation. These gases are predominantly derived from residual solvents present in the tailings. However, spatial trends related to gas volumes, gas production rates, microbial populations, and solvent content display high levels of variability, with no discernible patterns at this stage. Correlations between solvent contents, microbial populations, and gases have been observed, albeit with limitations due to the variability and preliminary nature of the microcosms. Further analysis and interpretation are necessary to establish more robust relationships between these variables. The microcosm tests on selected samples will continue into at least 2024 to monitor long term gas generation rates.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Evan Davison

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Evan Davison	Canadian Natural	Supervisor, Tailings Reclamation		
Danuta Sztukowski	Canadian Natural	Engineer, Mine Planning		
Josh Sun	Canadian Natural	Engineer, Tailings Geotechnical		
Skya Fawcett	Ecometrix	Director of Mining West, Senior Geochemist		
Matt Neuner	Ecometrix	Senior Hydrogeochemist		

Tailings Characterization

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 2 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.
- 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.

- 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 and 2022 allowed our teams to make progress toward the stated research objectives. Nevertheless, project timelines have been revised to accommodate unforeseen delays, and the research contract has been officially extended by one year to July 31, 2024.

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 was completed in February 2022. In total, 52 individual core samples were received at USask on March 2, 2022, and stored at 4°C to minimize potential impacts on both biogeochemical characteristics and geotechnical properties. Personnel limitations coupled with the tedious pore-water extraction process means sub-sampling was initiated in November 2022 and will be complete in October 2023.

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	2022-02-02	2023-10-31

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

Chemical and isotopic analysis of pore-water extracted from the Kearl thickened tailings samples is complete and all data has been received from both internal and external laboratories. 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 were typically alkaline at a mean pH of 8.6 (value range: 6.9-10.2, Standard deviation: 0.41). Nitrate and nitrite values were low with most nitrate values below measuring range. Average ammonium levels were 0.7mg/L (value range: 0.2-1.2 mg/L, Standard deviation: 0.2). Hydrogen sulfide read at an average 82 µg/L (value range: 4-349 µg/L, Standard deviation: 64).

For the Mildred Lake samples, time-sensitive parameters are being measured during pore-water extraction and other samples are being preserved for analysis. These samples will be submitted to internal and commercial laboratories for analysis once all pore-water extraction is complete.

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	2022-11-01	2023-12-31

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

Sub-sampling of the Kearl thickened tailings samples is now complete. Samples for geochemical and mineralogical analysis have been submitted to commercial laboratories and these results have been reported. Corresponding samples for the Mildred Lake project will be submitted for analysis once all sample processing is complete.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2020-11-01	2020-04-30	2021-06-01	2022-07-01
Mildred Lake	2021-07-01	2021-12-31	2023-04-01	2024-02-29

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

DNA extraction for Kearl samples has been completed and samples were submitted to an external laboratory for 16S sequencing. Sequencing results were received in January 2023 and, due to personnel constraints, associated bioinformatics are ongoing. Although we had originally planned to perform bioinformatics for Kearl and Mildred Lake samples together, we elected to proceed with the Kearl data separately to avoid additional delays.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2021-07-01	2022-02-28	2022-05-01	2023-04-30
Mildred Lake	2021-07-01	2022-02-28	2023-04-01	2023-08-31

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

Methanogenic, sulfate-reducing, and oxic microcosms were established and monitored for microbial activity. Each microcosm condition was established under four treatments: PAM as a (1) co-metabolite, (2) nitrogen source, (3) carbon source, (4) and nitrogen and carbon source. Microcosms were dosed at 400 mg/L and 1000 mg/L (mg PAM/L tailings). Microbial activity was observed in treatments 1 and 2 for methanogenic and sulfate-reducing conditions, and all treatments for oxic microcosms. Microbial activity was determined by an increase in biogenic gas production, and a decrease in acetate and electron acceptors. These initial observations suggested that the presence of PAM could potentially influence microbial activity, and furthermore could be biodegraded by native tailings microorganisms. Microbial activity was initially observed after 3 months for methanogenic and sulfate-reducing conditions, and 2 weeks for oxic conditions. We continued to monitor active and non-active microcosms, with detailed analysis provided in Activity 2.2.

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

Microcosms studies for the detailed analysis of PAM degradation has been completed. Microcosms were monitored for 374 days for methanogenic, 420 days for sulfate-reducing, and 236 days for oxic experiments. PAM, acetate (supplementary carbon source for treatments 1 and 2), electron acceptors (O_2 , SO_4^{2-}), biogenic gases (CH_4 and CO_2), and ammonium were regularly monitored throughout the duration of the experiments. Final samples have been collected and are in the process of being monitored for petroleum hydrocarbons, naphthenic acids, and microbial community (16S rRNA), and toxicity. The method for measuring acrylamide and acrylic acid using Reverse-Phase Chromatography has been developed and will be used to measure final samples.

Using Size Exclusion Chromatography for measuring PAM molecular weight, PAM experienced a decrease in molecular weight by 60%, 60%, 34%, and 31% in treatments 1, 2, 3, and, 4 for methanogenic microcosms after 374 days. In sulfate-reducing microcosms, PAM experienced a decrease of 22%, 55%, 31%, and 25% for treatments 1, 2, 3, and, 4 after 238 days. Lastly, for oxic

microcosms, PAM experienced a decrease of 99%, 98%, 13%, and 11% for treatments 1, 2, 3, and, 4, respectively after 96 days. The remainder of PAM measurements for sulfate-reducing and oxic microcosms are currently being processed. These findings suggest that PAM may undergo the most biodegradation (measured as relative decreases in PAM molecular weight) when in the presence of additional carbon sources, such as acetate in treatments 1 and 2.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
Kearl	2020-10-01	2023-06-30	2022-03-01	2023-09-01

Activity 2.3: Enrichment culture establishment

PAM degradation and important metabolites were monitored throughout the duration of the microcosm experiments and enriched when necessary to maintain initial conditions. Treatments 1 and 2 received acetate additions, and treatments 1 and 3 received ammonium additions when depleted. Important electron acceptors were maintained in sulfate-reducing (SO_4^{2-}) and oxic (O_2) microcosms. Acetate enrichment was required monthly for methanogenic and sulfate-reducing microcosms, and weekly for oxic microcosms. Ammonium enrichment for treatments 1 and 3 was required monthly only for oxic microcosms.

All microcosm experiments will have been condensed into maintenance cultures by September 1, 2023, and will continue to be monitored for PAM, acetate, electron acceptors, biogenic gases, and ammonium, and enriched when necessary. To date, microbial activity is still being observed in all treatments and conditions, except for treatments 3 and 4 for methanogenic and sulfate-reducing microcosms.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2021-01-01	2023-06-30	2022-03-01	2023-09-01

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 to show the timelines needed if the work were to continue with additional funding.

Samples	Proposed Start	Proposed End	Revised Start	Revised End
N/A	2021-02-01	2023-06-30	2024-08-01	2025-07-31

Activity 2.5: Method development

Dr. Ulrich's group has finalized the methodology for quantifying PAM in tailings pore water using Size Exclusion Chromatography. The molecular weight and concentration of 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. With this method, the limit of detection is 10 ppm.

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

Results for the Kearl thickened tailings samples have not revealed any surprising results. Major and trace element concentrations generally lean toward the lower end of values previously reported for process affected water at oil sands mining operations. Aqueous and gas-phase chemistry results comparing the relationships of sulfur and inorganic carbon isotopes and sulfate, bicarbonate and DOC concentrations suggest rates of microbial sulfate reduction and methanogenesis are currently limited. Biogenic methane production in the samples porewater was low at an average of 0.162 mg/L (range: 0.004-0.646 mg/L, Standard deviation: 0.152). Corresponding carbon and sulfur isotope results are somewhat ambiguous due to the initial composition of organic matter and sulfate present in the ore deposit. Ongoing work focuses on integrating geochemical, mineralogical, and microbiological results to improve understanding of the influence of various microbial respiration pathways on pore-water chemistry.

Results from the Size Exclusion Chromatography analysis suggest that PAM can potentially be biodegraded under methanogenic, sulfate-reducing, and oxic conditions in the presence of acetate. These findings are based on a decrease in molecular weight of the initial PAM polymer, as well as a decrease in PAM concentration in the pore water. Less microbial activity and the least change in PAM molecular weight was observed for treatment where PAM was the sole carbon, or sole carbon and nitrogen source (treatments 3 and 4). This suggests that PAM may not serve as a carbon source to stimulate microbial activity. However, the presence of microbial activity when PAM was provided as the sole nitrogen source (treatment 2), suggests that PAM can potentially serve as a nitrogen source. The biodegradation of PAM in the presence of acetate suggests the potential for PAM biodegradation in tailings ponds, specifically those that receive influxes of carbon from oil sands operations.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Batycky, A.E.; Ulrich, A.C. (2023, June) Methanogenic Biodegradation of Anionic Polyacrylamide in Oil Sands Tailings. 9th International Symposium on Applied Microbiology and Molecular Biology in Oil Systems (ISMO), Edinburgh, Scotland, [Poster Presentation]

Champion E.R., Lindsay M.B., Batycky A.E., Ulrich A.C. (2023, May) Biogeochemical Characteristics of Polyacrylamide-Treated Thickened Tailings at an Oil Sands Mine. GAC–MAC–SGA Joint Annual Meeting, Sudbury, Canada, [Poster Presentation]

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	Dec. 1/2023
Ania Ulrich	UAlberta	Principal Investigator		
Anya Batycky	UAlberta	MSc	Jan. 1/2021	Nov. 30/2023

Tailings Deposition and Monitoring

Physical and Numerical Modeling of Progradation of Segregating Tailing Beaches into MFT and associated depositional mechanisms.

COSIA Project Number: TE0054

Research Provider: University of Minnesota

Industry Champion: Syncrude & Imperial

Status: Complete

PROJECT SUMMARY

This project focuses on co-deposition of two tailings streams in a pond environment, towards understanding how their flow and transport 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:
- Fluid Fine Tailings (FFT) treated with a flocculent similar to industry standards to promote dewatering. Here it is referred to as “floculated 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

Fluid Fine 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 CST deposit; Some fines tend to bypass the beach and are transported into the pond.
- Fine grains (silt and clay size solids, include hydrocarbons) 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 geotechnically 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 were conducted in a medium sized research basin referred to as the Tailings Flume, Figure 1. The objective of the experiments was to assess the types of flow physics and interactions occurring during transport and co-deposition of the tailings material. The facility was 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 were set up with appropriate mixer and internal baffles. CST surrogate was fed into the flume as a well-mixed slurry. Tap water was used as the fluid component. Dry fine sand was fed into the fluid stream using a mechanical volumetric feeder.

Facility – Pilot testing – Tailings Flume

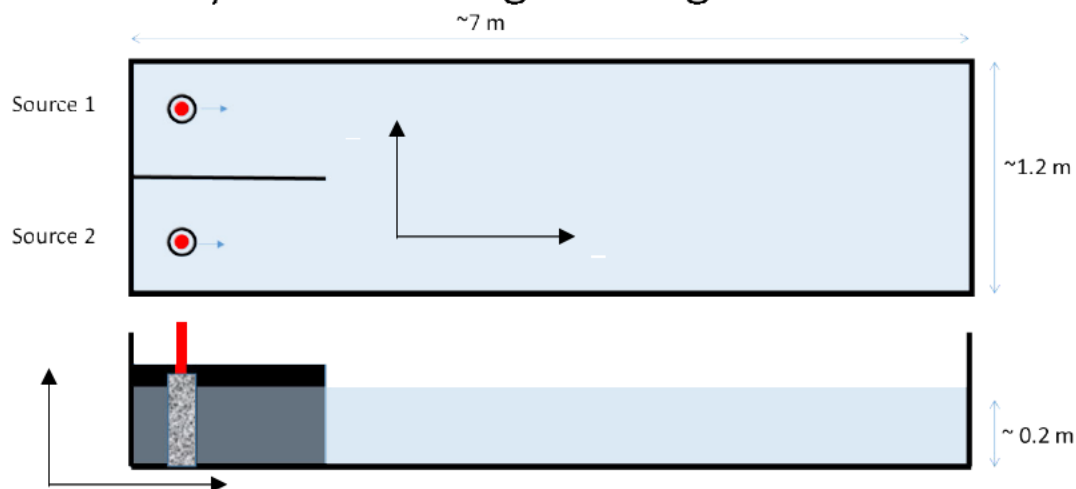


Figure 1. Schematic of the Tailings Flume used in experiments. Top view (top) and side view (bottom). Axes (x- y- and z- directions) as noted in the two sketches from different vantage points.

PROGRESS AND ACHIEVEMENTS

This project was completed and the final report submitted in October 2023. The report is presently in review by COSIA/IOSI.

In the last project update we provided preliminary reporting on Experimental Set#2. Additional information on these experiments are briefly summarized below.

Experimental Set #2

In the spring/summer of 2022, the project team completed Experimental Set #2. The same approach was taken in this four-stage experiment as described in previous report and summarized in Figure 2. The primary different between this set of experiments and Experiments Set #1 is that the fFFT tailings was introduced subaerially over an established CST beach rather than underwater as in Experiment Set #1.

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 3 from Experiment 2C.

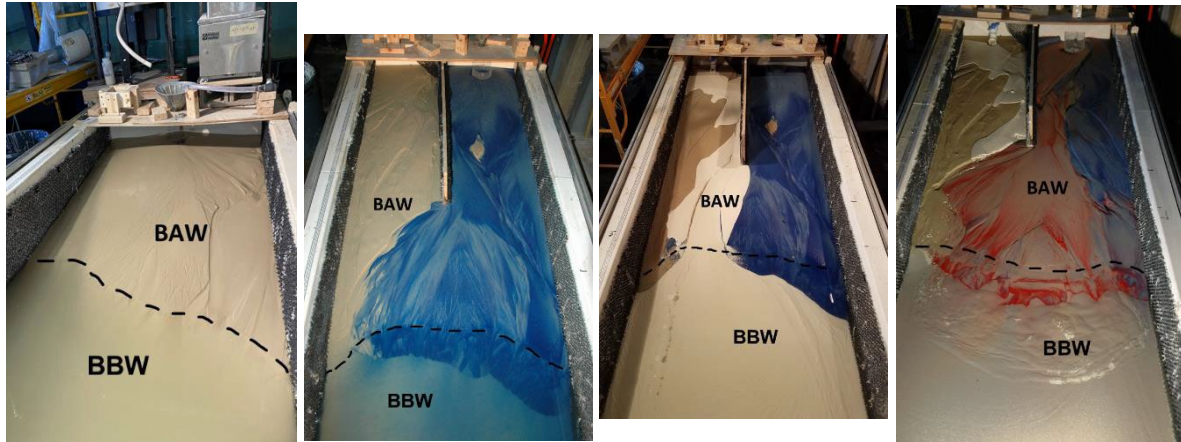


Figure 2. Images from the four stages of Experiment Set #2. Experiment 2A (Left) and Experiment 2D (Right).

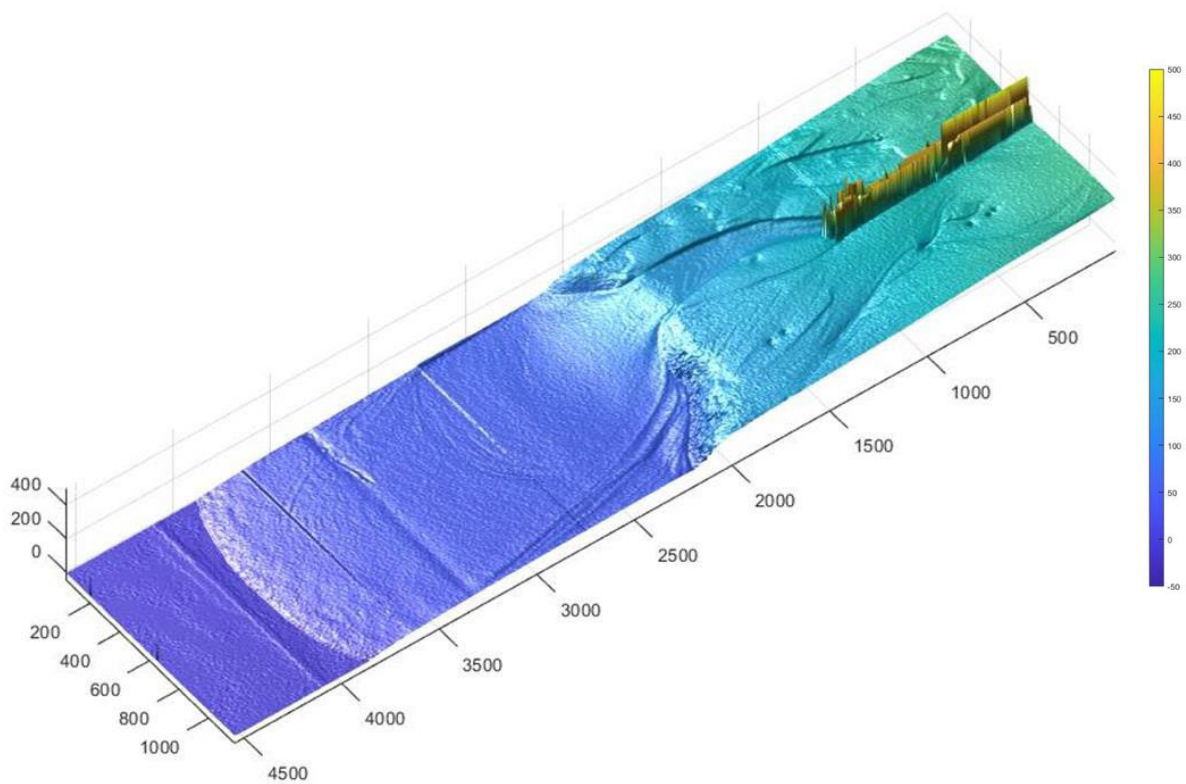


Figure 3. Example of a topographic scan from Experiment 2C.

DEPOSIT SECTIONING

Some of the most interesting data collected in the experiments involved sectioning the deposit after the experiments was completed. Doing so revealed interesting and complex interaction of the two tailings streams during deposition. Figure 4 shows images from four of these sections. More information on the research can be found in the final report.

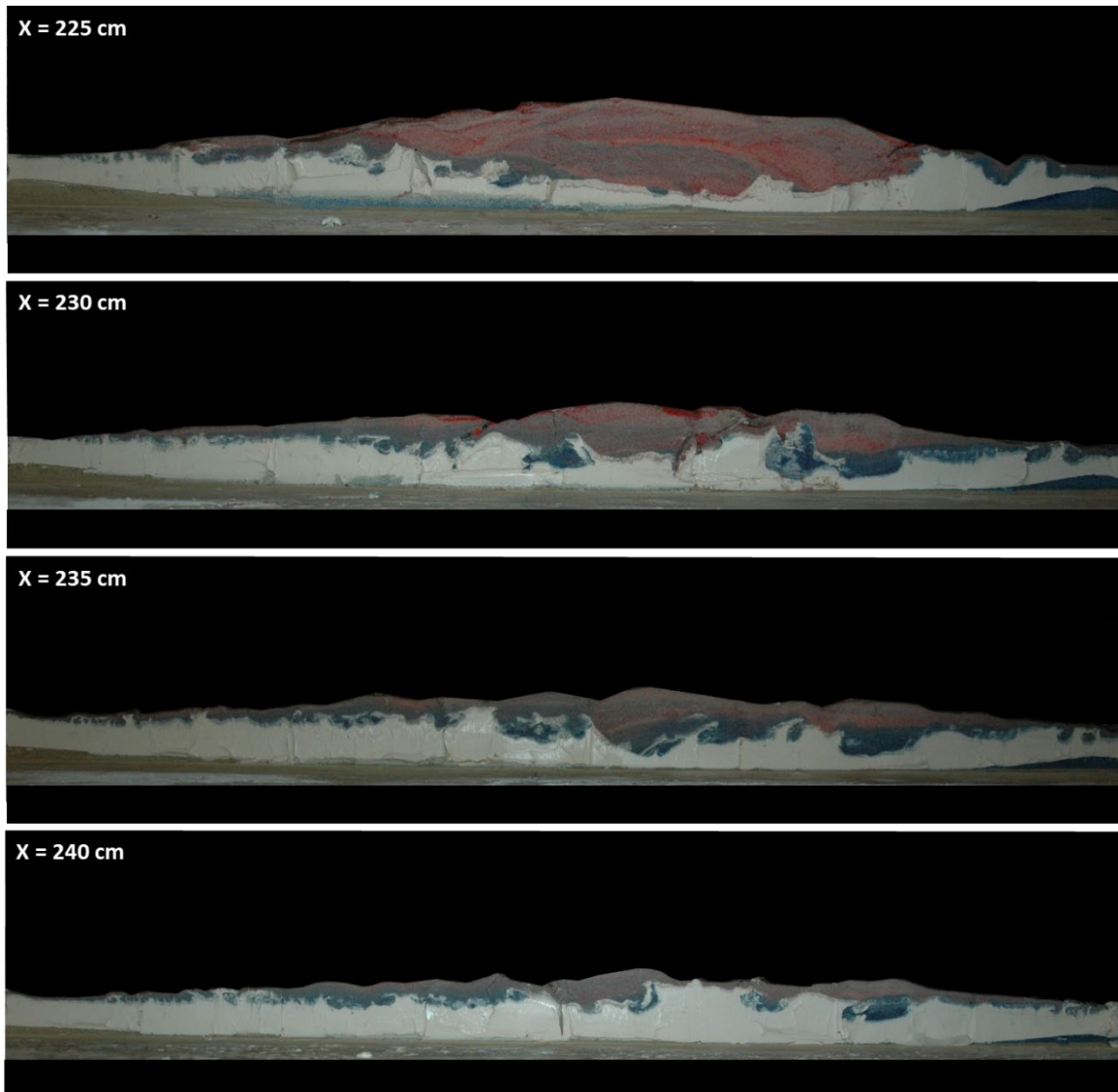


Figure 4. Photographs of the four sections of the deposit taken 225cm to 240cm downstream of the tailings inputs. The images reveal the complex interactions of the CST (tan, red, and blue layers) with the f-FFT (white).

Results from Experiment Set #2

The results of the research provide insights into important linkages between operational control of external tailing facilities and co-depositional interactions and the results serve as a first step in exploring opportunities to improve fines capture within coarse sand tailings and improve geotechnical stability of tailings co-deposits. Key findings from this study are briefly summarized here. Complete details of the study, findings, and recommendations are described in the report.

- Well-designed laboratory experiments are a viable means of exploring operational approaches to managing tailings streams.
- Coarse sand tailings (CST) deposited in the flume in a predictable way by forming a subaerial beach and steep-sloped beach front or foreset.
- Flocculated-Fluid Fine Tailings (f-FFT) was discharged into the flume under subaqueous conditions and flowed as a viscous slurry flow.
- f-FFT was discharged into the flume under subaerial conditions and flowed as a viscous slurry flow and eroded a single channel into the CST beach.
- The sediment concentration of the CST feed was strongly tied to the average beach slope. For example, increasing the CST solids concentration at the feed results in an increase the average beach slope and conversely, reducing the feed concentration will reduce the average beach slope. Varying this sediment concentration is a possible operational mechanism for increasing co-depositional interactions.
- The experiments revealed a range of co-depositional interactions between surrogate f-FFT and CST within the beach margin - the location identified as the primary location for these interactions.
- The project estimated fines capture rates for Experimental Set# 2 and determined that, within the region between the tailings inputs and shoreline (BAW), the deposit contained less than 9%wt. fines. This amount increased to up 85%wt. in the region just downstream of the beach shoreline in a deformation zone at the BAW/BBW transition.

Next Steps

The final report for this project was reviewed by project stewards and finalized. The draft final version was submitted to COSIA/IOSI in October 2023 and is presently in final editorial review.

PRESENTATIONS AND PUBLICATIONS

IOSI Tailings Project Knowledge Dissemination Workshop, November 2021

IOSI Tailings Project Knowledge Dissemination Workshop, November 2022

IOSI Tailings Project Knowledge Dissemination Workshop, November 2023

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 Hills	Department of Civil Environmental and Geo-Engineering, University of Minnesota	Professor, Project Co-PI		
Syed Ahmed	Department of Civil Environmental, and Geo-Engineering, University of Minnesota	PhD	June 2021	June 2022
Amirreza Ghasemi	Department of Civil, Environmental, and Geo-Engineering, University of Minnesota	PhD & Post-doctoral Researcher	July 2020 (Date started with project)	January 2021

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 2 Stage 1

PROJECT SUMMARY

Deep, fines-dominated oil sand tailings deposits (deep cohesive deposits) 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.

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 success criteria:

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/or
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 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 evaluation.

The work scope was split into two phases which are summarized below. This project summary is for the first stage of the Phase 2 scope only (Phase 2 Stage 1). The Phase 1 work was completed in early 2022 and was summarized in the 2021 annual tailings research report summary.

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 began in August 2021 and was completed in February 2022. The Phase 2 Stage 1 Study began in June 2022 and concluded in February 2023.

The Phase 1 work was primarily a technology identification and screening exercise, in which 72 technologies were identified. A suitability assessment was then conducted that consolidated similar or duplicate technologies and rejected technologies unsuitable for achieving the objectives. This resulted in 23 unique technologies that were advanced for further assessment and ultimately culminated in the retention of six technologies warranting further evaluation for potential application in deep cohesive deposits:

- 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 (SCPs).
- Accelerated Dewatering (ADW) – represents a series of horizontal ditches to create a drainage field.

As part of the Phase 1 study, a framework for executing the Phase 2 portion of the project was prepared. The framework provided a recommended path forward for detailed assessment and comparison of the six technologies and for acquiring the data and evidence needed to assess their long-term ability to meet the defined success criteria of accelerating and/or limiting long-term total settlement. The framework was also designed to provide the necessary constraints and definitions such that a single technology (or combination of technologies) could eventually be advanced to a large-scale field trial (Phase 3) after the completion of the Phase 2 scope. A summary of the first stage of the Phase 2 scope (“Phase 2 Stage 1”) is provided below.

The scope of work for the Phase 2 Stage 1 project was to conduct an order-of-magnitude (OoM) techno-economic analysis of the six high-potential technologies from Phase 1 in three different tailings types. The tailings types included fluid fine tailings (FFT), flocculated FFT (fFFT), and thickened tailings (TT). The Phase 2 Stage 1 study was a desktop exercise that involved numerical modelling of tailings consolidation (both with and without technology implementation), technology implementation feasibility, OoM cost estimating, and comparison/evaluation of cost versus performance of the various technology options for managing deep cohesive deposits.

LESSONS LEARNED

A summary of the major conclusions of the Phase 2 Stage 1 study is provided below.

- Managing the long-term settlement of deep cohesive oil sands tailings deposit for terrestrial closure is challenging, expensive, and not without risk.
- The results showed that none of the examined technologies were able to reduce the magnitude of settlement of deep cohesive. The technologies were only able to influence the rate of consolidation. The residual settlement of the deposits is an important consideration for closure landform design. Additionally, results were obtained for technology implementation within a defined generic deposit setting that may not be representative of all planned deposits. Care should be taken to not extrapolate results to basins that significantly vary from those defined in this study.

- The retained technologies included PVDs, SCPs, and ADW, along with mechanical and hydraulic methods for creating a working platform (and some surcharge) on the soft tailings. Based on the experience of our construction partners and the enormous amount of amendment material that would be required for effective implementation, Deep Soil Mixing was deemed impractical for all tailings types and was eliminated for evaluation early in the study.
- PVDs were identified as the most techno-economically feasible approach for meeting the success criteria of accelerating the consolidation (i.e., ability to achieve 90% of total settlement in 50 years) for all three types of deep cohesive deposits examined in this study. The OoM cost for implementation of PVDs in a 4 km x 8 km x 40 m deep deposit is estimated to range from about \$1.2B in TT to \$2.9B in FFT. The primary reason for the large difference in cost between the tailings types is due to the much denser PVD spacing required in the low permeability FFT. A significant portion of the total cost for all tailings types is associated with the construction of a suitable working platform to support the heavy equipment needed for installation. The estimated cost for construction of the required working platform was \$1.15B.
- Subaerial hydraulic capping was evaluated as an alternative to the mechanical approach for preparing the working platform. The cost of this approach was in the same OoM as mechanical capping. However, the time required to achieve required tailings surface strength via self-weight consolidation for hydraulic capping are likely prohibitive (15 to 20 years); future efforts should evaluate options/techniques for accelerating the surface strength of the tailings.
- SCPs were only deemed feasible in TT, and although the technology-only cost appears to be an OoM higher than PVDs (and requires a more robust working platform), the wider spacing achievable with SCPs offsets some of this cost. Key technical uncertainties exist with the application of SCPs in oil sands fine tailings regarding constructability and integrity of the sand pile within the deposit. The significant technical risk and apparently higher cost versus a more proven technology in fine tailings such as PVDs suggests there is little merit in future techno-economic assessment of SCPs.
- It appears that ADW as a stand-alone technology can only be competitive with PVDs if the spacing to achieve the required performance is much greater than the 25 m spacing examined. Several phenomena associated with implementing ADW that likely contribute significantly to the overall settlement of the deposit were not accounted for as they were beyond the scope of the preliminary numerical modelling completed for this work.

- Although the scope of this study was limited to tailings without a water cap, it was recognized that the presence of a water cap could provide a more cost-effective approach for implementing some of the technologies. A water cap would allow for large equipment to operate from a barge, which is a commercially proven approach. Future studies should evaluate and quantify the pros/cons of this approach for comparison with the terrestrial setting examined in this study.

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RESEARCH TEAM AND COLLABORATORS

Institution: Barr Engineering and Environmental Science Canada Ltd.

Principal Investigators: Nav Dhadli, 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)
Nav Dhadli	Barr Engineering and Environmental Science Canada Ltd.	Senior Chemical Engineer, Principal Investigator		
Jed Greenwood	Barr Engineering and Environmental Science Canada Ltd.	Senior Geotechnical Engineer		
Dale Kolstad	Barr Engineering and Environmental Science Canada Ltd.	Senior Environmental Engineer		
Scott Laberge	Barr Engineering and Environmental Science Canada Ltd.	Geoenvironmental Engineer-in-Training		
Arno Talmon	Deltares	Senior Technical Advisor		
Erik Hendricks	Deltares	Senior Technical Advisor		
Hubert Scache	Menard	Senior Technical Advisor		
Dallas McGowan	ConeTec	Senior Technical Advisor		
Bradley Zaworski	Keller	Senior Technical Advisor		
Jeroen Dijkstra	Cofra	Senior Technical Advisor		
Chris Powter	Enviro Q&A Services	Senior Technical Advisor		
Adedeji Dunmola	Syncrude	COSIA Project Steward		

Reza Moussavi Nik	Imperial	COSIA Project Steward		
Paul Cavanagh	Imperial	COSIA Project Steward		
Lucas Barr	COSIA	COSIA Project Steward		

Tailings Consolidation Casing Experimental Pilot Project (TCCEPP) and Other Consolidation Studies

COSIA Project Number: TJ0059

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Phase 2 Stage 1

PROJECT SUMMARY

The objectives of the Tailings Consolidation Casing Experimental Project Pilot (TCCEPP) are to understand the long-term consolidation behaviour of Fluid Fine Tailings (FFT) and to evaluate the performance of various flocculants and process treatments for FFT.

The TCCEPP is a field scale pilot designed to conduct consolidation experiments using eight instrumented columns or casings (3 m wide × 10 m deep) filled with various FFT materials. The casings are at a scale that approaches the expected geotechnical stresses anticipated in field-scale tailings deposits and are considered analogues to deep, fines-dominated tailings deposits. Seven casings were filled in 2015, with the final casing filled in 2016. Casings 1 and 7 were filled with Muskeg River mine (MRM) and Jackpine mine (JPM) untreated FFT, respectively. They serve as the experimental controls for parameters such as settling rates, densification and shear strength. Casings 2 to 4 were filled with MRM FFT treated with various dosages of flocculants added in the inline flocculation process. Casings 5 and 6 were filled with Suncor FFT that were treated with different flocculants at various dosages. Casing 8 was filled with JPM centrifuged fluid fine tailings (CFFT). Once the casings were filled, data collection started, including instrumentation monitoring, sampling, and in situ testing, to determine solids content, water content, shear strength, void ratio and density changes of the FFT. Table 1 summarizes the contents of the casings.

Casing #	FFT source	Amendment/Treatment
1	MRM-ETF ⁽¹⁾	None
2	MRM-ETF	HPAM (SNF A3338) / Inline Flocculated
3	MRM-ETF	XUR / Inline Flocculated
4	MRM-ETF	XUR-4A / Inline Flocculated
5	Suncor South Tailings Pond	HPAM (BASF ETD7010) / Inline Flocculated
6	Suncor South Tailings Pond	HPAM (SNF A3338) / Inline Flocculated
7	JPM-SC1 ⁽²⁾	None
8	JPM-centrifuge plant, Units 1–2	HPAM (SNF) / Centrifugation

Table 2: Casings summary

TABLE NOTES:

1. Albion Sands, Muskeg River Mine, External Tailings Facility
2. Albion Sands, Jackpine Mine, Sand Cell 1

Each casing is monitored to provide the data needed to evaluate consolidation. Key measurements include fluid level, mudline, pore pressure, total pressure and geophysical properties, namely density. The geotechnical information from these projects should assist in planning and scheduling tailings deposition to meet closure landform objectives for deep fines-dominated tailings deposits.

PROGRESS AND ACHIEVEMENTS

Knowledge from this project will help to:

- Enhance the industry's understanding of cohesive deposit consolidation in oil sands;
- Provide confidence in meeting closure and reclamation plans and final landform objectives;
- Provide the industry with the basis for decision-making regarding centrifuged FFT placement, capping and drainage management options to create targeted landforms; and

- Offer insight into fines-dominated deposit performance variables that, in turn, may initiate new fundamental geotechnical research work.

A robust instrumentation plan was implemented in the casings to provide continuous data for the purpose of evaluating the consolidation behaviour of the various tailings and treatments included in the study. Critical measurements included fluid level, mudline, pore water pressure, total pressure, and temperature. Field campaigns were completed yearly until 2018 and included the collection of in situ samples, wireline density profiles, and undrained shear strength measurements. In 2022, a field campaign was completed, including ball penetration testing, vane shear testing, and sampling.

Settlement data were interpreted to assess the relative consolidation performance between the tailings. A thorough analysis of the settlement data using back-analysis modelling (combined with pore-water pressure and solids content data) was conducted to evaluate the consolidation behaviour of the tailings.

LESSONS LEARNED

The following conclusions were made with respect to tailings performance as measured by mudline settlement, increase in measured solids content increase, and the overall degree of consolidation.

- Casings provide a larger scale method to evaluate the comparative performance of various tailings treatments using conventional geotechnical measurement parameters, including initial solids, pore pressure, and mudline data that can then provide calculated solids content over time.
- Inline flocculated FFT settled quicker and contained higher shear strength than untreated FFT or CFFT. Inline flocculation of FFT achieved improved consolidation performance relative to CFFT, i.e., higher deposit permeability at lower void ratios, higher solids content, and further consolidation.
- Material flocculated with HPAM, XUR and XUR-4A all surpassed the Centrifuge Product solids content treated with HPAM less than 30 days from the end of deposition. XUR treated material performed slightly better than XUR-4A-treated material, and both performed better than HPAM-treated material. The XUR, XUR-4A, and HPAM treated material reached 90% consolidation by settlement approximately 1 to 2 years after deposition in the casings.
- After deposition, further dewatering of Centrifuge Product occurred at a very low rate relative to the other tailings treatments that were treated by simple dynamic mixing at a lower initial

solids content. Scale up considerations need to consider if other higher permeability tailings (e.g. sand layers) within a commercial centrifuge deposit could result in improved consolidation behavior when compared to the casing tests, supported by field data.

PRESENTATIONS AND PUBLICATIONS

Stianson, J., Mahood, R., Thomas, D., Li, L., & Song, J. (2016, December 4-7). A Shell Tailings Consolidation Casing Experimental Pilot Project (TCCEPP). IOSTC 2016: Presented at the Fifth International Oil Sands Tailings Conference, Lake Louise, Canada.

Stianson, J., Mahood, R., Fredlund, D., & Sun, J. (2016, December 4-7). Large-strain Consolidation Modelling to Determine Representative Tailings Consolidation Properties from Two Meso-scale Column Tests. IOSTC 2016: Presented at the Fifth International Oil Sands Tailings Conference, Lake Louise, Canada.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Evan Davison

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Josh Sun	Canadian Natural	Engineer, Tailings Geotechnical		
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Co-Deposition

COSIA Project Number: TJ0104

Research Provider: Syncrude Canada Ltd.

Industry Champion: Syncrude Canada Ltd.

Status: Phase 2 Stage 1

PROJECT SUMMARY

Conventional practice involves separating different tailings streams or products by internal dykes, within the overall tailings containment footprint. This practice is not cost-effective, reduces 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, 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 at the interface where the tailings streams / products interact or mix.

A series of flume tests co-depositing various tailings streams and products (recycle water-RCW, fluid fine tailings-FFT, centrifuge cake, flocculated FFT, straight coarse tailings-SCT, Composite tailings-CT etc.) were previously completed. The flume tests showed no detrimental impacts on the geotechnical properties and performance of the resulting co-deposits. The flume tests revealed there was no geotechnical instability or degradation in the properties and performance of the co-deposits.

To further assess co-deposition, a technical gap assessment was completed. The gap assessment highlighted the need to assess the geotechnical stability of co-deposits especially where a tailings stream / product of higher density (such as CT or SCT) is co-deposited on top of a lower density tailings (such as flocculated FFT or centrifuge cake). Hence, a numerical modeling study aimed at investigating the geometric configurations of such co-deposited tailings that will ensure its overall geotechnical stability was completed. Insights from the numerical modeling study were intended to provide field-level guidance required for tailings placement during co-deposition operations. The study identified that the undrained shear strength of underlying fine-

grained deposit and the slope of the overlying sand-dominated tailings were the primary drivers for the overall geotechnical stability of the co-deposit.

To validate the findings of the flume tests and numerical modeling, an assessment of commercial analogues of co-deposits at Syncrude sites was completed. Commercial-scale co-deposition operations are either recently started or planned for implementation at the Syncrude Mildred Lake and Aurora North mine sites.

PROGRESS AND ACHIEVEMENTS

The previously completed 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 were assessed with the numerical modeling study. The numerical modeling showed that the overall geotechnical stability of the co-deposit is primarily driven by the undrained shear strength of the underlying fine-grained tailings deposit. Also, the slope of the overlying sand-dominated deposit is another key driver for the overall geotechnical stability of the co-deposit. An assessment of analogue commercial co-deposits was completed and validated the findings from the flume tests and the numerical modeling study. The goal of this project is to de-risk co-deposition and provide operational guidance for ensuring the geotechnical stability of the co-deposits during operations, reclamation and closure. This will inform the operations and closure of commercial-scale tailings co-deposition being implemented at the Syncrude mine sites.

LESSONS LEARNED

The flume tests generally demonstrated the feasibility of co-deposition and advanced the understanding required to conduct field-scale demonstration of the depositional strategy. When a denser sand-dominated tailings (such as CT or SCT) is co-deposited on top of a less dense fines-dominated tailings, the shear strength of the underlying fines-dominated deposit is critical for the overall geotechnical stability of the co-deposit. Another key driver of the overall geotechnical stability of a co-deposit is the slope of the overlying sand-dominated tailings. A mixed deposit resulting from the co-deposition of fines-dominated and sand-dominated tailings improves the overall stability and its potential for supporting subsequent layer of sand-dominated tailings. Based on the experimental and numerical modeling studies completed to date, a field-level guidance of co-deposition that can ensure the stability of co-deposits during operations and closure is currently being developed. An assessment of analogue commercial-scale co-deposits at Syncrude was completed and validated the learning to date. The ultimate goal of the project is to de-risk the operations, reclamation and closure of co-deposits at the Syncrude mine sites.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigator: Adedeji Dunmola

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Vanessa Warren	Barr Engineering	Consultant		
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Measuring CO₂ at Inlet to ETF

COSIA Project Number: TJ0105

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Year 1 of 2

PROJECT SUMMARY

Canadian Natural has been using CO₂ in the tailings stream since 2009* and has been shown to improve the segregation boundaries with Non-Segregating Tailings (NST). Canadian Natural engaged the University of Alberta to assess the CO₂ mineralization potential of Horizon's tailings via:

1. Accelerating carbonation of dissolved calcium (Ca) and magnesium (Mg) in mine waters.
2. Carbonating any Ca- and Mg-bearing minerals in tailings (if present at sufficient abundance).
3. Addition of solid lime (CaO) or brucite [Mg(OH)₂] during CO₂ addition to tailings.

Samples of NST, fluid tailings (FT), naphtha recovery unit (NRU) tailings, cold recycle water, warm process water, hydrotransport slurry, and basal water were collected and a quantitative estimate of the maximum potential for CO₂ mineralization was done using water chemistry analyses.

Alkalinity trapping is the primary mechanism of CO₂ storage at Horizon and the alkalinity of the process and tailings water at Horizon is approximately 10x that of seawater. The minerals in Horizon tailings are not a suitable source of divalent metals (Ca and Mg) for carbon mineralization and no newly formed carbonate minerals were detected in Horizon tailings. Precipitation of carbonate minerals is unlikely due to the low concentration of Ca and Mg in solution in the tailings water.

Horizon's Basal water has approximately 25x higher alkalinity compared to seawater and could be used to mineralize carbon with changes to the microbial activity of the pond.

Portlandite $[Ca(OH)_2]$, also known as hydrated lime] and brucite $[Mg(OH)_2]$ were added to filtered recycle process water from Horizon and XRD was used to determine the conversion of hydroxide minerals to carbonate minerals. Brucite addition was found to have a greater CO_2 sequestration potential than portlandite though it is a much slower reaction compared.

LESSONS LEARNED

The University of Alberta concluded that alkalinity is the primary store for CO_2 at Horizon and the mineralogy of Horizon tailings is not suitable for accelerated mineral carbonation. Mg-hydroxide mineral, brucite, could be used to improve settling and would act as a sink for CO_2 , though it is rare and other Ca and Mg minerals that can be carbonates should be considered.

Further work is planned to quantify CO_2 sequestration in the form of alkalinity in the tailings beach at Horizon.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Will Richardson

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Will Richardson	Canadian Natural	Development Engineer		
Sasha Wilson	University of Alberta	Associate Professor, Canada Research Chair		
Maija Raudsepp	University of Alberta	Postdoctoral Research Fellow		

Modified Atmospheric Fines Drying (MAFD) Pilot

COSIA Project Number: TJ0152

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Year 2 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 Albion 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 operation in 2022 was similar to 2021, creating 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. A secondary objective was to evaluate the impact the MAFD technology has on the existing NST beach, such as the impact of environmental conditions, the impact of drainage below the deposit, and lastly, to determine the technical feasibility as a secondary fluid tailings treatment alternative at a commercial scale.

Unplanned downtime due to multiple factors led to a shortened pilot season for 2021, only achieving a single lift at each designated spigot. Additional test work in 2022 focused on the operation of multiple thin lifts, while meeting the on-spec treated FT product. A total of 40 spigots were utilized to deposit the treated FT product in 2022, with spigots 3-16 on the south side of the injection infrastructure and spigots 17-43 on the north side. Spigot 1 was unavailable for the 2022 pilot, and spigots 2 and 44 were designated for plant startup and shutdown purposes.

PROGRESS AND ACHIEVEMENTS

Based on the 2021 pilot, evaporation and freeze-thaw compression effects led to improved deposit solids content after one season of approximately 15 wt% and the clay mineral fraction did not vary significantly, irrespective of the deposit location.

The 2022 MAFD pilot operated for approximately 367 hours in July through September, processing 182,500 m³ of FT. Material was placed in two lifts with approximately 30 days of drying between the lifts.

In the first lift, the average day 30 Dean Stark solids content was 53.6 wt% with 31 out of the 40 spigots exceeding the target solids content of greater than 50 wt%. The day 30 peak undrained shear strength had a wide range, with 39 out of 40 spigots exceeding the 5.0 kPa target, which was measured using a hand vane shear apparatus.

The second lift average day 30 solids content was 54.5 wt%; 18 out of the 20 spigots exceeding the target solids content of greater than 50 wt%. The day 30 peak undrained shear strength results for all 20 spigots exceeded the 5.0 kPa target.

Weekly MAFD release water samples were taken throughout the pilot and water chemistry results were comparable to Horizon's recycle water samples. The average MAFD release water results had lower ion concentration in majority of test results, and no statistical difference in total alkalinity, pH and total dissolved solids to the average recycle water quality.

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. Freeze-thaw cycle data from the 2022 pilot program will be collected and analyzed in 2023.

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PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

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Canadian Natural. (2022). Jackpine Mine 2021 Fluid Tailings Management Report. Submitted to Alberta Energy Regulator.

Canadian Natural. (2022). Muskeg River Mine 2021 Fluid Tailings Management Report. Submitted to Alberta Energy Regulator.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Colin Szpecht

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Colin Szpecht	Canadian Natural	Process Engineering Lead		
Armand Marchand	Canadian Natural	Pilot Operator		
Calvin Kiehn	Canadian Natural	Pilot Operator		
Christian Lofstrom	Canadian Natural	Pilot Operator		
Jamie Smith	Canadian Natural	Pilot Operator		
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Inline Flocculated Fluid Tailings and Coarse Sand Tailings Mixing Pilot

COSIA Project Number: TJ0154

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Year 3 of 8

PROJECT SUMMARY

In-line flocculated (ILF) fluid tailings (FT) co-deposited with coarse sand tailings (CST) has been identified as a potential means of producing a sandy-fines mixed deposit. It was hypothesized that introducing CST to dewatered ILF FT would result in mixing and the formation of an ILF FT/CST mixed deposit. The ILF FT/CST Mixing Pilot program has been developed to test this hypothesis. To date, two field pilots have been executed to test alternate deposition strategies.

In 2020, an ILF FT/CST co-deposition pilot was executed in which ILF FT were deposited in close proximity to a high-solids content slipstream taken from the CST line. The two streams mixed on the beach above water (BAW) and formed a BAW deposit. The BAW deposit showed evidence of limited fines and coarse mixing, but the composition of the deposit did not meet the fines capture target established for the pilot. Furthermore, the beach below water (BBW) deposit formed during the pilot was not large enough to be identified in the pond. It was determined during the 2020 pilot that the end-of-pipe ILF FT solids content was not sufficient to enable effective mixing with the CST slipstream in this deposition configuration.

In 2022, the phase 2 ILF FT/CST mixing pilot was executed in a different tailings storage pond, leveraging the learnings from the 2020 pilot. The ILF FT were deposited into the test area and allowed to release water and increase in solids content prior to the introduction of CST. The introduction of CST from two locations into the dewatered ILF FT deposit resulted in the formation of a sandy-fines mixed deposit. It was learnt from the 2022 pilot that in addition to the ILF FT properties, cell geometry and deposition conditions play key roles in the formation of a mixed deposit.

PROGRESS AND ACHIEVEMENTS

The activities associated with the 2020 field pilot included bench-scale feasibility testing, system design, equipment procurement, and the setup of the field pilot itself. Before the pilot commenced, a comprehensive BBW baseline site investigation was carried out. During the pilot, ILF FT and the slipstream CST were deposited side by side (co-deposition) for five days. Throughout the pilot, various tests were conducted, including passive data collection and real-time measurements to ensure effective process system control. Following the pilot, thorough post-pilot BAW test pitting and BBW pond investigations were conducted.

Planning activities for the 2022 pilot were initiated in late 2021, including initial scoping and location selection, preliminary engineering, detailed engineering, procurement and fabrication of parts, and earthworks for area preparation. The treatment facility was commissioned in late March 2022. During the course of the pilot, over one million cubic metres of FT were treated between March and July 2022 prior to CST addition. Coarse Sand Tailings were deposited from two discharge locations, namely the north and the south CST pours. The north CST pour was completed in a total of thirteen days in August and September 2023, and subsequently, the south CST pour took approximately ten days in September 2023.

Three site investigations were conducted during the 2022 pilot. Investigation A took place in May, as soon as the pond was clear of ice, to characterise the ILF FT deposit and confirm the target operating parameters for the ILF FT production process. Investigation B was performed in August 2022 before CST pours to characterise the final ILF FT deposit. The final investigation (Investigation C) was performed in October 2022, following the completion of CST pours to characterise the ILF FT/CST mixed deposit. The ILF FT deposit was characterised using ball gamma cone penetration tests (GCPTs) and laboratory tests on fluid samples. The ILF FT/CST mixed deposit was characterised using GCPTs and laboratory tests on sonic samples. The mixed deposit samples were sent to laboratories for index testing and advanced testing, including consolidation testing.

LESSONS LEARNED

The 2020 pilot laid the foundation for the 2022 pilot by establishing crucial design elements, such as treatment volume, location selection, and mixing strategies. For successful tailings field pilots, it is essential to plan for a relatively large volume compared to the deposition pond. Consequently, locations with a straightforward deposition history should be the preferred choice. Moreover, the efficiency of mixing is greatly improved when there is a minimal difference in density between the tailings streams/deposits to be mixed.

The estimated volume of the mixed deposit produced during the 2022 pilot was over one million cubic metres, not including clean CST present on top of the mixed deposit. The modelled average solids content of the mixed deposits was greater than 70% and the modelled average sand to fines ratio (SFR) was 3.4. At the time of sampling, the ILF FT/CST mixed deposit was less than two months old, depending on the location.

During the 2022 pilot, high-energy deposition of CST off the high wall at the north pour location resulted in displacement of the pre-existing ILF FT in the pond. Portions of the CST BBW formed during the north pour also did not have any opportunity to mix with ILF FT because of the geometry of both the CST and ILF FT deposits. The north CST pour formed a BBW deposit that confined the ILF FT deposit, potentially assisting in the formation of the mixed deposit during sand deposition from the south.

The lower energy CST pour from the south across the pre-existing beach resulted in the formation of an ILF FT/CST mixed deposit up to 15 metres thick in the pond. The role of the north CST pour in confining the ILF FT to improve mixing requires more testing and interpretation.

The ILF FT/CST mixing pilot is being continued in 2023.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigators: Evan Davison

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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Paul Korba	Canadian Natural	Supervisor, Site Services		

NSERC-Syncrude Industrial Research Chair (IRC) In Mine Closure Pressuremeter

COSIA Project Number: TJ0155

Research Provider: University of Saskatchewan, University of Alberta

Industry Champion: Syncrude Canada Ltd.

Status: Active

PROJECT SUMMARY

The goal of this research is to develop a new test method for geomaterials that are difficult to accurately characterize using conventional laboratory methods by experimenting with pressuremeters (RPM – reaming pressuremeter, SBPM – self-boring pressuremeter, HPD – high pressure dilatometer). The in-situ test results can then be incorporated into constitutive models that will help inform designers as well as other oil sands operators on best practices for pit wall stability and use of the observational method going forward.

Achieving this goal requires several advancements including the ability to evaluate the stiffness and strength of the materials; the development and implementation of complex constitutive models to capture the behaviour of intermediate geomaterials; deformation modelling; and quantification of the impact of exsolution of gases on the operational strength of the oil sands.

Material parameters have historically been derived from advanced laboratory testing conducted on recovered samples. Strength and stiffness parameters obtained from conventional lab testing are used in advanced geotechnical models needed to assess the nature and extent of slope movements when implementing the observational method. The results of laboratory test data of heavily overconsolidated materials (HOC) are currently used cautiously as they are extremely difficult to sample and test (Morgenstern & Thomson, 1971; Medieros, 1979; Wittlebolle, 1983; Gasparre et al. 2007; Elwood, 2015). This disturbance also strongly reduces the stiffness of these materials (DeJong & Morgenstern, 1971; DeJong & Morgenstern, 1973; Medieros, 1979; Wittlebolle, 1983; Gasparre et al. 2007; Elwood, 2015).

An alternative method for determining the stress-strain response of these materials, and thus the modulus, while limiting sample disturbance is through the use of pressuremeters with a focus on

the data gathered by the self-boring pressuremeter. This method provides a stress-strain curve during cycles of loading and unloading (Wroth & Hughes, 1973). The unique construction of the Cambridge SBPM also allows for testing of consolidation parameters (Clarke et al. 1979; Randolph et al. 1979.; Fahey & Carter, 1986; Lie et al. 2017) ; the coefficient of lateral earth pressure at rest (Lacasse & Lunne, 1982; Hoops & Hughes, 2013); and the permeability of the formation (Ratman et al. 2005.; Liu et al. 2017).

The project's specific objectives are:

1. Evaluate the suitability of pressuremeters to determine the input parameters for the Hardening Soil (HS) and Small Strain Hardening Soil (ssHS) constitutive models in HOC soils.
2. Evaluate the change to the shear strength and modulus of the stiff, pre-sheared, HOC sediments following excavation of the pit wall.
3. Develop an operational strength model for these problematic materials.
4. Determine the effectiveness of using the pressuremeters to determine the shear strength loss and change in hydraulic conductivity in situ of the rich feed oil sands following a change in in situ pore-water pressure.

The proposed research will examine the use of an SBPM to test the strength, stiffness, and permeability of the NWMC sediments (Clearwater and upper McMurray Formations) and rich feed oil sands. The research program consists of the following projects:

- Project 1: Developing parameters for the HS model from pressuremeter testing (MSc 1).
- Project 2: Evaluating the operational strength of the HOC clays (PhD 1).
- Project 3: Using pressuremeter testing to evaluate the response of gassy soils (PhD 2).

The research will require field and laboratory work, as well as 2D and 3D numerical modelling. The collaborations with SCL, ConeTec, Cambridge In-situ, and both the Universities of Saskatchewan and Alberta will be paramount to achieving the specific and overall objectives.

The outcomes of this research will include improved characterization of material properties that will benefit all oil sands operators in Western Canada as well as mine operators in other sectors where shales are the primary overburden. The improvement of mining techniques and monitoring methods will allow the oil industry to minimize the risk of slope failure. The above tools will indicate negative trends in ground movement prior to slope movements becoming unmanageable. This

research will ensure that Canadian owners and operators throughout the mining industry remain competitive globally.

Moving forward, with validation of practice, the pressuremeter and the methodology of use and interpretation will be leveraged to explore and characterize treated tailings deposits. The information will feed into projected closure landform performance.

PROGRESS AND ACHIEVEMENTS

Field work was completed at six drill locations with 37 pressuremeter tests in total along with vertical seismic profiling. Core was gathered in between test locations for later logging and sampling. Vibrating wire piezometers were installed along with a weather station for measuring the barometric efficiency response to evaluate the small strain shear moduli (Dourado, 2018; Hendry et Al. 2017; Smith et al. 2018).

LESSONS LEARNED

Work is on-going to process the data gathered.

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PRESENTATIONS AND PUBLICATIONS

Work is on-going to process the data gathered.

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)
Dr. David Elwood	University of Saskatchewan	Associated Professor Civil, Geological, and Environmental Engineering Principal Investigator		
Dr. Micheal Hendry	University of Alberta	Professor Civil and Environmental Engineering Principle Investigator		
Ana Manderson	Syncrude Canada Ltd.	Geotechnical Associate MSc student	September 2019	May 2024

Research Collaborators:

Syncrude Canada Ltd. has committed to the project through funding and in-kind investments, including access to an active mine site; historical laboratory test; and monitoring data and staff time for field organization and consultation.

ConeTec Investigations has committed to the work by providing in-kind contributions of staff time, drilling, testing equipment and materials.

Cambridge In-situ is contributing to the work by providing field and office staff as well as access to testing equipment.