



COSIA TAILINGS EPA

2020 Tailings Research Report

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*Bugs and Veggies Project, page 28

Introduction

This is the third summary report from the Canada's Oil Sands Innovation Alliance (COSIA) Tailings Environmental Priority Area (EPA). It highlights just some of the recent progress and research work in tailings management at various stages of research—from literature reviews, laboratory projects, pilot trials and to large, field-scale demonstration and commercialization programs. The COSIA 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.

The *COSIA Tailings EPA 2020 Tailings Research Report* summarizes 40 active research projects, a few less than the first two summary reports. Several projects were completed, while others were put on hold. The COVID-19 pandemic presented unforeseen and unprecedented challenges for all involved in tailings research. COSIA member companies, universities, and other research collaborators faced challenges to advance the research projects as planned, while ensuring the health and safety of all involved and adhering to public health measures.

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 COSIA Tailings EPA, member companies are focused on improving the management of oil sands tailings throughout their production and treatment, storage, reclamation and closurephases.

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

- minimizing the accumulation of fluid tailings (FT) within tailings ponds;
- advancing treatment of process-affected water, the water which remains once the FT are removed; and
- accelerating reclamation of tailings deposits so that they can be incorporated into the final closure landscape.

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

Tailings deposits can have very different properties: from sand-dominated deposits to thin and thick lift fines-dominated deposits; deposits that will underlie the water column 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 closure planning and implementation.



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.

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

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COSIA Project Number and Title

COSIA Project Number	Project Title
Tailings Treatment Technologies	
TE0040 RWG (IOSI)	Optimizing the Usage of <i>Lumbriculus variegatus</i>
TE0053 RWG (IOSI18)	Maintaining Permeability for Continuous Mature Fine Tailings Dewatering
TE0056 RWG (IOSI18)	Partially Hydrophobic and Natural Graft Polymers for the Efficient Treatment of Mature Fine Tailings
TE0063	Pit Lakes: A Surface Mining Perspective
TE0065 (IOSI19)	Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria
TE0066 (IOSI19)	Pipeline Transport of Flocculated Tailings Materials
TE0067 (IOSI19)	Combining Worms and Vegetation to Enhance Tailings Dewatering – Building with Nature on Successfully Tested Methods
TE0068 (IOSI19)	Effect of Dispersants on Dispersion and Flocculation of Oil Sands Tailings
TE0069 (IOSI19)	Mechanics of Methane Bubbles in Tailings Ponds
TE0075	NAIT Chair in Applied Tailings Processes
TE0080	Tailings Fines Measurement Using a Wet Method by Laser Diffraction-Particle Size Distribution Analyzer
TE0083	The Role of Bubble Ebullition on the Vertical Transport of Fine Solids in End Pit Lakes
TJ0031	Clay Removal from Fluid Tailings
TJ0033	Engineered Tailings Research
TJ0073	Tailings Surveillance Technologies
TJ0082	Permanent Aquatic Storage Structure for Fluid Tailings
TJ0108	Fluid Tailings In-line Flocculation and Co-deposition
TJ0109	Accelerated Dewatering and Deposit Monitoring
TJ0117	In-line Flocculation of Fluid Tailings Field Pilot
TJ0118	Enhanced In-line Flocculation of Fluid Tailings Field Pilot
TJ0128	Physically Upgraded Trafficable Tailings Innovation (PUTTI)
TJ0129	Enhanced Fines Beach Capture Using Carbon Dioxide in Coarse Sand Tailings
TJ0130	NSERC-Syncrude Industrial Research Chair in Mine Closure Geochemistry (Term 2)
TJ0131	Optimized Seasonal Mature Fine Tailings Dewatering
Froth Treatment Tailings	
TE0035 RWG (IOSI)	Laboratory Investigation of Transport, Segregation and Deposition of Tailings Solvent Recovery Unit Tailings
TE0050 and TJ0110	Froth Treatment Tailings Evaluation
TE0055 RWG (IOSI18)	Minimization of Greenhouse Gas Emissions in Froth Treatment Tailings by Manipulation of Electron Acceptors
TJ0134	Investigations into the Biogenic Methane Potential of Diluent Containing Tailings: In-depth Microbiological and Chemical Analysis of Microcosms
TJ0136	Naphtha Recovery Unit Tailings – Preliminary Biogeochemical Conceptual Model

COSIA Project Number	Project Title
Tailings Capping	
TE0046	Planning and Design of Deep Cohesive Tailings Deposit Guide
TE0073 (IOSI 19)	Modelling the Cap Placement with Tailings Deformation and Consolidation
Consolidation Modelling	
TE0010	NSERC-COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique
TE0036	Long-term Dewatering of Amended Oil Sands Tailings: Co-funded by COSIA and NSERC (an NSERC Collaborative Research and Development Grant)
TE0041 RWG (IOSI)	In-situ Real Time Measurements of Solids Content in Settling Tailings
TE0071 (IOSI19)	Assessment of Liquefaction Potential of Unsaturated Tailings Subjected to Future Saturation
TE0072 (IOSI19)	Comparison of Rapid Centrifuge Test, Geotechnical Beam Centrifuge Test and Large Strain Consolidation Test
TE0074 (IOSI19)	Geotechnical Modelling of Surface Strengthening for Soft Tailings Capping
TJ0045	Deep Cohesive Deposit Modelling
TJ0072	Deep Deposit Filling, Monitoring and Modelling
TJ0132	Seepage Induced Consolidation Testing for Permanent Aquatic Storage Structure



TAILINGS TREATMENT TECHNOLOGIES

Optimizing the Usage of *Lumbriculus variegatus*

COSIA Project Number: TE0040 RWG (IOSI)

Research Provider: Deltares and University of Alberta

Industry Champion: Suncor

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 3 of 3

PROJECT SUMMARY

Oligochaete worms are (generally) anaerobic earthworms with the capability to live under numerous chemical, biological, and soil environments. For example, they can survive in adverse environmental conditions. When added to sediment, Oligochaete worms “travel up and down the bed” and create a network of small channels. Accordingly, the hydraulic conductivity of the sediment increases leading to enhancement of the self-weight consolidation rate and the shear strength. While proven to be effective in accelerating the consolidation of loose deltaic and coastal sediments in Europe, the effectiveness of Oligochaete worms in consolidation of oil sands tailings had not been tested until 2014. Preliminary proof-of-concept experiments conducted in 100 mL beakers by Deltares in 2014, the first testing of Oligochaete worms on oil sands tailings, indicated that *Tubifex* (the species of worms with which this research started; other species were introduced later) could survive for a long enough amount of time in the tailings environment and that it was capable of substantially enhancing consolidation and dewatering rate of tailings. This initial finding warranted further analysis of the performance of *Tubifex* at larger scale columns and under variable conditions as part of the current phase of work. The ultimate objectives of this scope of work were to:

1. Optimize the survival and reproduction of Oligochaete worms in tailings environment;
2. Quantify the ultimate solids content and shear strengths achieved by adding Oligochaete worms to tailings;
3. Gather critical information about feasibility and scale-up to operational conditions.

Deltares (Netherlands) and University of Alberta (Canada) are the joint technical team for delivering these objectives through the following tasks:

Task 1 (Deltares): Perform small-scale tests to evaluate the effects of temperature, tailings type, and solids content on dewatering and strength gain of tailings mixed with Oligochaete worms.

Task 2 (Deltares): Perform a series of beaker tests with different biological parameters (i.e., nutrients and organic matter) for exploring optimization/survival of Oligochaete worms’ reproduction in oil sands tailings.

Task 3 (Deltares): Perform a second series of small-scale column tests, similar to Task 1, with different densities of Oligochaete worms and at optimized conditions established in Task 2.



Task 4 (University of Alberta): Perform large-scale column tests with optimal parameters from Tasks 1 to 3 to evaluate the consolidation and dewatering of tailings. These data will provide a basis for future pilot implementation if necessary.

PROGRESS AND ACHIEVEMENTS

The following describes the achievements made to date in this project for each task discussed above.

Task 1: Complete – Small-scale column tests were conducted to study the effects of Oligochaete worms on dewatering and consolidation in fluid tailings (FT) and thickened tailings (TT) at 10 °C and 22 °C. For a layer of 30 cm of tailings consolidating over three months, worms resulted in a factor 2 relative increase in equilibrium solids content (which was reached over half of the time only). In the same layer, worms resulted in factor 1.5 to 3 larger strengths, particularly near the bed's surface. These were consistently found for both FT and TT.

Task 2: Complete – A series of beaker tests were conducted to study the effects of several “feeding strategies” on reproduction and survival of Oligochaete worms. These included low quality organic matter, high quality organic matter, and inorganic nutrients (two concentrations). Low quality organic matter applied at a 3% of the dry weight of tailings resulted in a factor 3 reproduction after four months. In all other cases population of worms slowly decayed with time, reaching zero at approximately four months as well.

Experiments in tasks 1 and 2 were repeated for the new worm species after the project’s scope change (when the former species was substituted by a new one), obtaining consistent but less impactful results.

Task 3: When added in combination with low quality organic matter (see Task 2 results), Oligochaete worms initially produced the largest dewatering rates measured in the project. Later, the dewatering rates with worms and low quality organic matter became similar to those for worms in the absence of low quality organic matter, resulting in a final equilibrium solids content. Addition of low quality organic matter therefore results in worms’ survival over the long-term and in initial dewatering rates. However, the final equilibrium solid contents remains unaltered with respect to using worms only with no organic matter. In general, the new species of worm did not perform as well the former one, but the effects of both types remain relevant. In the case that exhibited the lowest performance of the new worm species, a factor of 1.5 larger equilibrium solids content was achieved compared with the case where no worm was used. Results also showed better reproduction rates of worms for TT than for FT.

Task 4: In progress - Ten acrylic columns with 12 cm ID, 1.85 m tall, equipped with 10 ports for pH and redox potential monitoring and 3 ports for pore pressure monitoring were established on November 9, 2020 (TT) and November 16, 2020 (FT). Experimental analyses and monitoring include: interface level of water and tailings deposit; geotechnical characterization (solids content, hydraulic conductivity, undrained shear strength (peak and residual), Atterberg limits, particle size distribution); pore water pressure; *Lumbriculus variegatus* (LV) worms’ survival; microbial community characterization through 16S rDNA pyrosequencing; overlying water and pore water characterization (redox, pH, alkalinity, chemical oxidation demand, biochemical oxygen demand, naphthenic acids, dissolved organic compounds, MicroToxR).

LESSONS LEARNED

The results of the project show that Oligochaete worms improve dewatering properties of oil sands tailings in a laboratory environment to a very competitive range (factor 2 relative increase in solid contents, factor 1.5 to 3 higher strengths), and that Oligochaete worms can live and reproduce in oil sands tailings when combined with the correct amendment. Finally, it appears that adding the amendment to provide worms survival also has a positive initial effect in the enhancement of the dewatering properties, with the equilibrium solid content being equivalent to these without amendment. The project has also provided practical knowledge that needs to be considered when designing a follow-up pilot. Deltares is currently preparing an infographic to synthesize all lessons learned and milestones obtained throughout all worm dewatering projects in Canada and Europe, and with the objective of informing expected performances in a potential follow-up or pilot.

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Principal Investigator: Miguel de Lucas Pardo, Deltares

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Maintaining Permeability for Continuous Mature Fine Tailings Dewatering

COSIA Project Number: TE0053 RWG (IOSI18)

Research Provider: University of Alberta

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 2 of 3

PROJECT SUMMARY

Large quantities of tailings are deposited in on-site tailings ponds during the mining and bitumen extraction process in the mineable Athabasca oil sands region. Over the many decades of oil sands production more than 800 million m³ of mature fine tailings (MFT), a fine-grained, slow settling portion of the deposited tailings, have accumulated in the tailing ponds. The other components of oil sands tailings include water, which is recycled for use in the bitumen extraction process, and coarse sands, which settle quickly in the tailings pond. The slow settling MFT presents issues to the oil sands industry such as the need for long-term containment and delayed reclamation.

Over the last few decades the oil sands industry has developed several dewatering technologies such as: composite/consolidated tailings; thickened tailings; in-line thickening with thin lift; centrifugation; filtration, to accelerate the separation of liquid from solids and consolidation of the MFT. Generally, however, these dewatering technologies have not resulted in a tailings stream that is ready for land-based reclamation activities. Of note is the observed phenomenon that the dewatering of MFT is extremely slow after reaching around 50-60 wt% solids even after treatment with chemical amendments such as flocculants and coagulants.

Our recent study results show that the difficulty of dewatering oil sands tailings could be attributable to the residual bitumen in MFT, which resulted in reduced permeability during the dewatering (filtration) process. Test work has shown that an ultrafine kaolinite (0.6 μ m) slurry with 35 wt% solids could filter to ~70 wt% solids using 150 g/t polyacrylamide under 6 bar (600 kilopascal) pressure. After blending in 3 wt% of an ultrafine fraction obtained from MFT by high speed centrifugation, which contained residual bitumen and ultrafine clay particles, the kaolinite slurry could only be filtered to ~60 wt% solids at an order of magnitude higher polyacrylamide (chemical amendment) dosages⁵. In other words, the kaolinite slurry now behaves exactly like MFT even when only 3 wt% of this ultrafine fraction was blended in.

The purpose of the project is to identify appropriate substances or chemicals/polymers to alleviate the effect of the residual bitumen and maintain the permeability of the pores, allowing the tailings to continuously dewater at a reasonable rate. Several research techniques will be used. These include:

- 1) jar tests to evaluate the interaction of potential bitumen binders/flocculants with residual bitumen isolated from MFT by centrifugation;



- 2) an isothermal titration calorimetric (ITC) study to investigate the binding strength between residual bitumen and bitumen binders/flocculants, and between fine solids and bitumen binders/flocculants;
- 3) filter press filtration tests of the MFT after treatment by the bitumen binders/flocculants to observe the dewatering effect and the achieved filter cake % solids content; and
- 4) micro computed tomography (micro-CT) and cryogenic scanning electron microscopy (cryo-SEM) techniques to study the pore structures of the filter cake after the treatment and to investigate the reasons for the poor, as well as improved, dewatering performance.

PROGRESS AND ACHIEVEMENTS

The project began in May 2019, and continued through 2020. This summary includes the progress made since projection inception in 2019. The major findings include:

- 1) Bitumen in the “bulk” form, such as bitumen from bitumen froth samples (versus bitumen in the MFT samples), had a much less detrimental effect on the pressure filtration of either the pure kaolinite slurry or the MFT. After blending in a bitumen froth sample to kaolinite to achieve 10.2 wt% bitumen, the 37 wt% solids kaolinite slurry could still be pressure filtered to form filter cake with greater than 65 wt% solids using 1000 g/t A3335 and 3000 g/t Alcomer 7115, two chemical amendments. However, when blending in only 3.4 wt% of the ultrafine fraction centrifuged from MFT, the kaolinite slurry could only be filtered to less than 60 wt% solids under the same test conditions.
- 2) The above results prompted us to re-examine the composition of the ultrafine fraction centrifuged from MFT. Our centrifuge had a relative centrifugal force (RCF) of 17,340, and the centrifugation was carried out for three hours. It was found that the ultrafine fraction (called “middle layer”) obtained after the centrifugation had a yield of 13.5%, and it contained 12 wt% bitumen and 42.6 wt% ultrafine solids (particle size predominately less than 450 nm), the remainder being water. This ultrafine fraction recovered 45% of the bitumen and 18% of the solids from the MFT. An X-ray Diffraction (XRD) analysis of the fine solids in the “middle layer” showed that it was mainly composed of montmorillonite and kaolinite. The bitumen in the “middle layer” was found to be an oil-in-water emulsion (as it dispersed readily in water, but not in toluene). The predominant size of the bitumen emulsion was about 2-4 μm .
- 3) Our subsequent research work was divided into two parts: (A) to examine the roles of different fine solids on filtration, and (B) to examine the roles of the fine bitumen emulsion on filtration, with or without coating on the ultrafine solids. While (B) is ongoing, (A) is essentially complete. We examined six different fine solids: rutile ($d_{50} = 0.7 \mu\text{m}$), quartz ($d_{50} = 3.6 \mu\text{m}$), kaolinite ($d_{50} = 4.1 \mu\text{m}$), illite ($d_{50} = 2.8 \mu\text{m}$), illite-smectite ($d_{50} = 2.7 \mu\text{m}$), and montmorillonite ($d_{50} = 2.8 \mu\text{m}$). Our conclusion was that the swelling clays such as montmorillonite and illite-smectite were extremely difficult to filter, much more difficult than the non-swelling clays such as kaolinite or illite, which in turn was more difficult to filter than the non-clay solids such as quartz and rutile. Since the particle sizes were all similar, these conclusions were robust. In fact, the tested rutile had a sub- μm mean size of 700 nm, the finest of all 6 tested solid samples, and yet it was the easiest to filter.



The realization of the different effects of the different “forms” of bitumen on tailings filtration, and the subsequent work and findings on the very different filtration behaviours of the mineral solids on filtration caused the project to deviate slightly from the original objective. Rather than screening different flocculants and chemicals to identify ones that target “residual bitumen” (the original scope), we identified one of the main reasons contributing to poor filtration: the presence of swelling clays. We are currently studying the effects of bitumen emulsion and bitumen coated on the clays in MFT on filtration. And we are also investigating ways to mitigate the detrimental effects of the swelling clays. Even with the slight deviation the overall goal is still in line with the original objective.

We would also like to acknowledge that the COVID-19 pandemic has had a significant impact on the progress of the project.

LESSONS LEARNED

It is generally recognized that oil sands tailings need to be dewatered to below or close to the plastic limit so that the tailings deposit is strong enough to commence reclamation. Pressure filtration is one of the potential promising technologies to achieve terrestrial reclamation of tailings deposits.

It has been reported recently that typical mine tailings could be filtered to =>85 wt% solids using commercial filter presses^{1, 3-4, 6}, well below the plastic limit. However, Loerke⁵ observed that a MFT sample could only be filtered to ~60 wt% solids at 1000 g/t A3335 and 3000 g/t Alcomer 7115 using a laboratory filter press. COSIA Tailings EPA² reported a pilot filter press test campaign conducted in 2019. They reported the range of achieved filter cake solid content of 50-70 wt% with an average at 63 wt%. The use of coagulant was mentioned but the type of coagulant and its dosage were not disclosed². The results show that oil sands tailings are clearly more difficult to filter than non-oil sands mining operations.

This research could reveal the root causes and mitigation measures for the difficulties encountered during pressure filtration of oil sands tailings when compared to non-oil sands mining ventures.

Lessons learned to-date include:

- 1) The identification of the detrimental roles of swelling clays on MFT filtration can partially explain the difficulties associated with fine oil sands tailings filtration, and provide the industry with information about what to focus on.
- 2) The ongoing work on the effects of bitumen emulsion and bitumen coated on the fine clays would further illustrate the reasons for the difficulties in fine oil sands tailings filtration.
- 3) The ongoing work on ways to overcome the difficulties in swelling clay filtration would help improve filtration performance and reduce coagulant and flocculant dosages and costs.

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PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Wang D., Tao H., Wang K., Tan X., Liu Q. 2020. Decoupling the effects of ultrafine solids and residual bitumen on the filterability of oil sands tailings. Proceedings of the 2020 Tailings and Mine Waste Conference, November 14-17, Keystone, CO. https://www.engr.colostate.edu/ce/wp-content/uploads/2020/11/TMW2020_V3.pdf



RESEARCH TEAM AND COLLABORATORS

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Principal Investigators: Qi Liu and Xiaoli Tan

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Xiaoli Tan	University of Alberta	Principal Investigator Research Associate, Adjunct Professor		
Hongbiao Tao	University of Alberta	Postdoctoral Fellow	September 2019	
Dong Wang	University of Alberta	PhD student	January 2018	April 2022
Simon Yuan	Syncrude	COSIA Project Steward		

Partially Hydrophobic and Natural Graft Polymers for the Efficient Treatment of Mature Fine Tailings

COSIA Project Number: TE0056 RWG (IOSI18)

Research Provider: University of Alberta

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 1 of 3

PROJECT SUMMARY

Today, more than 50 years after the Clark Hot Water Extraction Process was first used to extract bitumen from oil sands, the oil sands industry is still dealing with vast volumes of water trapped in tailing ponds. Polyacrylamide (PAM) flocculants are typically used to treat tailings, but their application is limited by the high viscosity of PAM solutions, which makes them difficult to dose and handle. Flocs, the groups or clusters of fine particles bound together generated with PAM, are also shear sensitive and may break when they are pumped through pipelines from the treatment station to the deposition site. In addition, PAM is hydrophilic, which creates two main limitations when treating mature fine tailings (MFT): 1) PAM does not absorb onto the organic coating typically found on the surface of MFT clays, and 2) the low-density flocs generated by PAM retain water in the sediments, slowing down the long-term dewatering and consolidation of the treated tailings.

It is clear that minor tweaks in PAM composition are insufficient, and that a step change in technology is required to deal with this problem. For this reason, our group is developing alternative polymer platforms such as grafted and partially hydrophobic polymers. These novel polymers have already demonstrated good potential in treating MFT, but their compositions and molecular structures need to be further tuned to optimize their behaviour as flocculation and dewatering aids for different types of oil sands tailings. This is the main objective of this project.

The key hypothesis to be tested in this project is whether or not partially hydrophobic polymers, linear or grafted, lead to good flocculation and, more importantly, more efficient dewatering of MFT.

All the novel polymers synthesized in this project are compared with PAM flocculants, either commercial or synthesized in our own labs. The objective of this comparison is to find out whether the new polymers perform at least as well as, and preferably better than, conventional PAM flocculants.

We are measuring the performance of the flocculants using standard methods in tailings dewatering: 1) initial settling rate (ISR), 2) capillary suction time (CST), 3) supernatant turbidity, 4) solids contents in the sediments, 5) specific resistance to filtration (SRF), and 5) net water release. From a more scientific point of view, we are also conducting focused-beam refraction measurements (FBRM) to follow the dynamic formation of flocs when different flocculants are added to dilute MFT suspensions.



The polymer synthesis experiments are designed to find out the effect of changing the polymer microstructure on flocculation performance. For instance, for grafted polymers, such as hydrolyzed poly(methyl acrylate) grafted on ethylene/propylene/diene chains (EPDM-*graft*-HPMA), we varied the length of the EPDM backbone, and the length and frequency of the HPMA grafts to find out how these microstructure parameters affected the effectiveness of these flocculants.

All polymer flocculants considered in this project are made by free-radical polymerization, a low cost, reliable, and widely used industrial polymerization method. Free radical polymerizations are performed in batch autoclave reactors, and do not require very complex installations. Even though, similarly to commercial PAM, the novel polymer flocculants could be purchased as powders from an external supplier, they could also be made already as polymer solutions right at the oil sands mine site, in a dedicated in-situ polymer production facility. The in-situ production of polymer flocculants could become a transformative concept in the oil sands industry, reducing operational costs and adding unforeseen flexibility to the tailings treatment process.

PROGRESS AND ACHIEVEMENTS

This project so far led to the production of several new polymers with promising applications as flocculants for oil sands tailings. Two main families are worth noting: 1) the EPDM-*graft*-HPMA polymers mentioned above, and 2) PAM grafted on amylopectin (AP-*graft*-PAM).

Even though these polymers are different, they share some traits in common: they have hydrophilic grafts (HPMA and PAM) and hydrophobic backbones (amylopectin and EPDM). Because both are graft copolymers, it is relatively easy to study the effect of backbone length, and graft length and frequency, on their performances as flocculants.

We have shown that these graft copolymers perform at least as well as PAM flocculants, and in some cases even outperformed them (Najafabadi and Soares, 2021; S. Davey and Soares, 2020, Aldaeef et al., 2020; Bazoubandi and Soares, 2020).

LESSONS LEARNED

The main outcome of this research is that reducing the hydrophilicity of polymer flocculants can help tailings sediments dewater more rapidly than when PAM is used. A delicate balance is needed to reach this goal, because if the polymer becomes too hydrophobic it cannot be dissolved, or even dispersed, in water and will fail as a flocculant. Using super hydrophilic polymers such as PAM, however, traps too much water in the sediments, which make it very hard to reach a desired solids content, even after mechanical means, such as filtration or centrifugation, are employed after flocculation.

Even though we can make partially hydrophobic flocculants using linear polymers, grafting hydrophilic chains to hydrophobic backbones offers a few advantages. First the polymers have hydrophobic cores (amylopectin or EPDM, in our polymers) that repel water and form less water flocs with low CSTs. Second, the degree of hydrophilicity can be controlled by changing the frequency (average number of grafts per backbone) and length of the hydrophilic grafts, giving enormous flexibility when we try to optimize the polymer structure. Third (an option that we did not test yet in this project), the hydrophilicity of the grafts themselves can be regulated by instead of making them



homopolymers (hydrolyzed PMA or PAM, as we did thus far), making them copolymers of a hydrophilic comonomer and a hydrophobic comonomer. In this way, the affinity of the grafts with water could also be tuned to its optimum degree.

PRESENTATIONS AND PUBLICATIONS

Published Theses

Benjamin Nguyen. Morphological Effects of Water Soluble Polymer Flocculants Synthesized by Controlled Reversible-Deactivation Radical Polymerization for Treatment of Mature Fine Tailings, University of Alberta, 2020.

Stepheney Davey. Amylopectin-*graft*-hydrolyzed-poly(methyl acrylate) (AP-*g*-H-PMA) Flocculants for the Treatment of Oil Sands Tailings, University of Alberta, 2020.

Journal Publications

Z.R. Najafabadi, J.B.P. Soares. Flocculation and dewatering of oil sands tailings with a novel functionalized polyolefin flocculant. *Sep. Purif. Tech.* **2021**, submitted.

S. Davey, J.B.P. Soares. Amylopectin graft copolymers for oil sands tailings treatment. *Sep. Purif. Tech.* **2020**, submitted.

A. Aldaeef, P.H. Simms, J.B.P. Soares. Torque-based evaluation of mixing optimization and shear sensitivity during transport of flocculated tailings. *Minerals Engineering* **2020**, submitted.

B. Bazoubandi, J.B.P. Soares. Amylopectin-*graft*-polyacrylamide for the flocculation and dewatering of oil sands tailings wastewater. *Minerals Engineering* **2020**, 148, 106196.

Conference Presentations/Posters

J.B.P. Soares. Natural and synthetic polymers for environmental remediation. *12th Global Chinese Chemical Engineers Symposium* (Annual Conference of the Global Academy of Chinese Chemical Engineers), October 27 – November 2, 2020 (plenary lecture).

V. Vajihinejad, J.B.P. Soares. Impact of polymer microstructure on flocculation and dewatering performance: The case of the Canadian oil sands tailings. *ACS Fall 2019 National Meeting*, San Diego, CA, USA, August 25-29, 2019.



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Pit Lakes: A Surface Mining Perspective

COSIA Project Number: TE0063

Research Provider: COSIA

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 3 of 3

PROJECT SUMMARY

Surface mining, which accounts for approximately half of all oil sands production, leaves large pits which must be reclaimed. Mining companies around the world reclaim mine pits as pit lakes by filling them with water, tailings, and other solid mine waste. When properly designed and planned, pit lakes are considered a best practice in global mine reclamation, and there are many successful pit lakes in Canada and around the world.

Oil sands mine reclamation will use a suite of tailings reclamation options, including pit lakes. Pit lakes can serve multiple functions in the reclaimed landscape and will support the overall reclamation of mine sites. As of November 2018, 23 pit lakes were planned in the Alberta oil sands mining region; these lakes will be filled with freshwater or a mixture of freshwater and oil sands process-affected water, and may or may not contain treated or untreated tailings. The proposed oil sands pit lakes vary in size and shape.

The oil sands industry has been conducting research, from laboratory to full scale demonstrations, on pit lakes for over 40 years, and a large body of evidence exists to support the use as features in the closure landscape. Syncrude's Base Mine Lake is the first full scale pit lake in the oil sands industry. There are pilot scale demonstration lakes including Suncor's Lake Miwasin (previously called the Suncor Demonstration Pit Lake), and Syncrude Demonstration Pond. The large body of research to date indicates that pit lakes are a viable strategy to reclaim oil sands mine pits, and that pit lakes will become an integral part of a successful closure landscape.

The document provides information about pit lakes as reclamation features in the closure landscape for oil sands mining, how they are successfully used in other mining industries around the world, and that tailings treatment is only one of many purposes that pit lakes serve.

LESSONS LEARNED

Surface mining leaves large pits, which must be reclaimed, and the global pit lake experience have proven these lakes can be an environmentally sound and economical approach to reclaiming mine pits. They have been used widely in mine reclamation around the world over the last century, and extensive research has been conducted to ensure they are appropriate for the oil sands mining area.

Oil sands mine reclamation will use a suite of tailings reclamation options, including pit lakes. Pit lakes can serve multiple functions in the reclaimed landscape and will support the overall reclamation of mine sites to a locally



common boreal forest environment. Pit lakes planned for the Alberta oil sands mining region could be filled with freshwater, or a mixture of oil sands process-affected water (OSPW) and freshwater, and may or may not contain treated or untreated fluid tailings (FT).

Pit lakes are designed based on decades of research, from small pilots to full-scale demonstrations. Base Mine Lake (Syncrude) is an example of a full-scale pit lake demonstration. Lake Miwasin (Suncor) and the Test Ponds (Syncrude) are two examples of field scale pilot demonstrations.

The size and shape of a lake, the materials placed in and around it, and the resulting physical dynamics will affect the water chemistry of the lake. Deep pit lakes that are influenced by higher density saline water can become permanently stratified, isolating the saline water at the bottom of the lake. If tailings are placed in the lake, porewater release can affect the lake water chemistry, but this effect will be diminished with time. In either case, how the water chemistry changes over time should be considered when predicting biological community development in the lake.

Research, modelling, and monitoring to date, indicates that pit lakes are a viable strategy to reclaim oil sands mine pits and FT, and they will form a part of a successful closure landscape. Using an adaptive management framework will ensure that pit lakes are stewarded to acceptable closure outcomes.

The oil sands industry will continue to work with stakeholders, regulators, and Indigenous groups to ensure that oil sands mine sites are being reclaimed to meet their requirement of creating a self-sustaining, locally-common boreal forest ecosystem, integrated with the surrounding area, and consistent with the values and objectives identified in local, regional, and sub-regional plans. In addition, COSIA continues to engage stakeholders to share information and research on pit lakes around the world, in Canada, and in the oil sands, and to identify and evaluate industry research priorities, and then address them through research and monitoring activities.

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PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

[COSIA] Canada's Oil Sands Innovation Alliance. 2021. Pit Lakes: A Surface Mining Perspective.

<https://cosia.ca/sites/default/files/attachments/Park%20-%20COSIA%20-%20Pit%20Lakes%20-%20Final.pdf>

RESEARCH TEAM AND COLLABORATORS

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Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria

COSIA Project Number: TE0065 (IOSI19)

Research Provider: University of Alberta

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 2 of 3

PROJECT SUMMARY

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

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

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

PROGRESS AND ACHIEVEMENTS

In year 1 of 3 good progress was made preparing the DNA which will direct the biopolymer production and cell surface localization. Anchor system for generating the biopolymers and transporting them to the cell surface of tailings-specific bacterial strains were defined. The DNA sequences for this anchor system and biopolymers to be tested were designed and synthesized. The biopolymer DNA sequences were concatemerized to create numerous highly-repetitive sequences which were then inserted into the anchor/display sequences. DNA sequencing had confirmed the final biopolymer products were correct and ready for production.

Year 2 of 3 built upon the early progress of the project and the focus was able to shift from DNA sequence assembly to biopolymer production and preliminary flocculation testing. The biopolymer DNA sequences were used to transform *Escherichia coli* bacteria in order to assess bacterial survival and biopolymer production. There was no toxicity associated with the introduction of any of the biopolymer DNA sequences to the bacteria. Furthermore, the production of the majority of the biopolymer constructs has been confirmed. The localization of the biopolymers to the bacterial surface is under study, with results indicating ~90% of the lowest molecular weight biopolymers can be properly translocated to the outer membrane. Additional experiments detailed how the temperature of the cultures affected the bacterial growth rate, biopolymer production levels, and localization, with 8°C found to be the best conditions for biopolymer production and localization.

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

Of the objectives listed in the project summary, DNA sequence generation was completed in Year 1. Year 2 progress has allowed for at least partial completion of the creation of all necessary control constructs, confirmation of the production and localization of biopolymers and preliminary settling tests using diluted MFT.

LESSONS LEARNED

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



RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: 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 Bahnuk	University of Alberta	Post-Doctoral Fellow		
Xiaoli Tan	University of Alberta	Research Associate, Adjunct Professor		
Fawad Alidina	University of Alberta	USRA	May 2020	Aug 2020
Simon Yuan	Syncrude	COSIA Project Steward		
Michelle Young	Imperial	COSIA Project Steward		

Pipeline Transport of Flocculated Tailings Materials

COSIA Project Number: TE0066 (IOSI19)

Research Provider: Coanda Research & Development Corporation

Industry Champions: Canadian Natural, Imperial, Suncor

Industry Collaborators: Syncrude, Teck

Status: Year 1 of 1

PROJECT SUMMARY

The goal of many oil sands tailings treatments is to remove water within a reasonable time-frame to reclaim a disposal site. Several technologies have been proposed for dewatering of tailings including flocculation, filtration, centrifugation, and thickening. Once treated, tailings are transported to deposition cells using pipeline systems. During transport and deposition into the cells, treated tailings experience a range of different shear rates for different durations. It is often presumed that shearing adversely affects the water release of treated tailings and therefore shear rate is considered as a constraint in designing processing equipment and deposition methodologies used in the tailings treatment facilities.

A previous project between Coanda, the Institute for Oil Sands Innovation (IOSI) and COSIA member companies explored the effects of shearing on the dewatering and compressibility of treated tailings (COSIA TEPA, 2020). Flocculated fluid tailings (FT) and re-flocculated thickened tailings (TT) tailings were produced using an inline dynamic mixer, and a large-scale Couette device was used to shear the samples. The material rheology, dewatering, and consolidation performance characteristics were measured before and after the shearing. Geotechnical measurements were conducted using seepage induced consolidometers (SICT), a beam centrifuge, and large strain consolidometers (LSC) on identical samples that only differed in the level of shear experienced. The project found that low levels of shear sometimes had beneficial effects for dewatering and consolidation, and that higher levels of shear degraded immediate performance, and possibly had a minor negative influence for long term geotechnical performance.

The current project aims to address how to adequately relate the findings from the previous study to pipeline design and ultimate tailings treatment plant layout for the range of materials and shear rates of interest. The focus is to provide adequate links between the findings from the bench top shear device and the pipeline design criteria required to predict and control the impact of pipeline shear on the ultimate flocculated material performance.

PROGRESS AND ACHIEVEMENTS

Following a planning period, a 5 cm (2") diameter tailings flow loop was constructed at Coanda's Burnaby laboratory, leveraging existing tailings treatment infrastructure co-owned by several COSIA member companies. A series of experiments were performed by treating FT and TT with two polymer types and recirculating the material around a closed pipe loop. Samples of the same material were collected prior to entering the pipe loop and sheared in the

shear device used in the previous project described above. The pipe flow and shear device conditions were determined based on expected field pipeline transport parameters, in particular by matching a nominal laminar flow wall shear rate of $8U/D$, where U is the fluid velocity and D is the pipe diameter. In these experiments we observed significant settling at the selected conditions for the materials treated with partially hydrolyzed polyacrylamide (HPAM) flocculant, but not for materials treated with the Dow XUR polymer.

A 10 cm (4") diameter pipe flow loop was subsequently constructed, and a similar set of experiments was conducted to explore scaling relationships and to provide conditions less prone to the settling behaviour, while maintaining commercially relevant shear rates. Settling was significantly reduced for these tests, though one experiment with HPAM-treated TT was still substantially affected.

During the experiments, data were collected from a variety of instruments, including differential pressure transducers, video via transparent pipe sections, a PVM in-situ microscope, and an FBRM in-situ particle size analyzer. Samples collected before and after shearing were evaluated with index tests for dewatering and material strength, i.e., capillary suction time, yield stress, permeability by vacuum filtration, net water release, and geotechnical column settling.

When we ignored the data from the tests that were affected by settling, we found relatively good agreement between the characterization data for the pipeline-sheared samples and those from the shear device, suggesting that the shear device can emulate the effects of pipeline transport. We compared the shear stress calculated from the shear device torque data and the wall stress from the pipeline pressure gradient measurements. In some cases, the agreement between the device and pipeline was very good. In other cases, the data matched well initially, but then the shear-device values steadily increased, deviating from the pipeline results. We attributed the later behaviour to relatively minor settling at the bottom of the shear cell causing inaccurate torque readings, or other problems with the torque measurement system.

LESSONS LEARNED

- The laboratory shear device provides useful information on the effects of shearing for homogenous materials despite their non-Newtonian nature. This means that industry could use the shear device to predict pipeline shear effects for flocculated oil sands tailings materials and employ this knowledge to design their treatment facilities; for example, to determine the distance between the flocculation location and the deposition site.
- Similarly, oil sands operators could use the shear stress calculated from the torque data from the shear device to predict the pressure gradient in pipelines which could aid in pipeline design.
- The utility of the shear device is highly dependent on the nature of the material and shear conditions, which limits the range of commercial scenarios that can be simulated.
- While the shear device results have been compared with two scales of pipelines in the laboratory, the technique would benefit from validation with full scale commercial data.

LITERATURE CITED

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PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

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

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigators: Scott Webster and Clara Gomez

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Scott Webster	Coanda Research & Development Corporation	Principal Investigator Research Scientist		
Clara Gomez	Coanda Research & Development Corporation	Principal Investigator Research Scientist		
Tayfun Aydin	Coanda Research & Development Corporation	Research Scientist		
Imran Shah	Coanda Research & Development Corporation	Research Scientist		
Pravik Komal	Coanda Research & Development Corporation	Laboratory Technician		
Abu Junaid	Canadian Natural	COSIA Project Steward		

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

COSIA Project Number: TE0067 (IOSI19)

Research Provider: Northern Alberta Institute of Technology (NAIT) & Deltares

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 1 of 2

PROJECT SUMMARY

Accelerating the dewatering and consolidation process of Fluid Tailings (FT) is a major challenge to the oil sands industry in Canada. Significant technology development efforts have focused on engineered solutions, with less attention granted to biological options. The present study combines and builds upon previous NAIT research into wetland plants and Deltares research into aquatic and terrestrial worms, which have been independently shown to facilitate the densification of oil sand tailings. The project work was divided into three phases:

1. A pilot study of the interactions between *Lumbriculus variegatus* (LV) and *Enchytraeidae* worms and *Carex aquatilis* (wetland grass) and *Salix interior* (willow);
2. A screening assessment of worm survival when combined with straw, alfalfa, and hydrochar; and
3. A larger-scale study combining plants and worms in columns (8 L) and barrels (100 L) with oil sand tailings for an extended growth period.

The intent of the initial two phases was to determine a set of conditions most conducive to worm and plant cohabitation, while the purpose of the third phase examines the ability for plants and worms to provide shear strength gain to tailings over a 6 month growth phase.

PROGRESS AND ACHIEVEMENTS

The project is currently in the third and final phase, with final harvest of plants planned for mid-March, 2021.

Key progress milestones from the first two phases are as follows:

1. Upland worm species *Enchytraeidae* was determined to be a potentially invasive species following consultation with the Canadian Food Inspection Agency (CFIA) and therefore deemed inappropriate for

further consideration as a tailings treatment option. *Enchytraeidae* was subsequently replaced in this study with an earthworm species native to the Peace River region in northern Alberta (*Lumbricus terrestris*).

2. In phase 1, two species (willow and sedge) were co-planted in columns filled with thickened tailings, amended with alfalfa or straw, and incorporated with worms (LV and earthworm). Total plant aboveground biomass significantly increased with straw amendment, but not with worm incorporation. Similarly, amending planted columns with straw significantly increased solids content at the top (0-35 cm) and middle (35-65 cm) sampling points. In terms of undrained shear strength, amending planted columns with straw coupled with worm incorporation increased tailings shear strength compared to all treatments. High quartz sand content (sand-to-fines ratio, SFR = 2.65) in thickened tailings was concluded to be harmful for the smaller LV worms. When exposed to this tailings type, LV did not burrow into the substrate and subsequently died on the surface. Benchtop trial with centrifuge cake showed significant improvement to LV worm survival, hence thickened tailings was replaced with centrifuge cake of significantly lower SFR (SFR = 0.03) in subsequent trials.
3. In the phase 2 benchtop screening assessment, LV worm survival was poor in centrifuge cake amended with alfalfa and hydrochar, and only slightly better in the straw-amended containers. Due to this observation, alfalfa and hydrochar amendments were not carried forward to the larger growth trial of phase 3. Earthworm survival proved to be more robust, with over 60% survival of worms in 1 L of tailings over 21 days both with and without straw treatment.
4. Survival tests performed by Deltares revealed that terrestrial *Enchytraeidae* worms die under prolonged saturated conditions. Conversely, the aquatic LV worm did not survive under unsaturated conditions. LV and other Oligochaetes are known for migrating downwards with the water table in partially unsaturated beds undergoing drying. In our tests, water was fully evaporated throughout the entire bed (0.5 L), resulting in the disappearance of LV. Finally, LV survived when tested in saturated tailings amended with straw as a food source, whereas terrestrial *Enchytraeidae* worms survived under unsaturated conditions regardless of the presence of straw.
5. In the 100 L barrel study, the mudline of treatments amended with straw was observed to increase for a period, likely due to gas generation associated with straw decomposition. Data collected as of 110/180 days indicate that conditions which incorporate plants, including plants in conjunction with LV worms and earthworms, are showing better consolidation than raw tailings.
6. In the 8 L column study, conditions which incorporate plants alone, and plants in conjunction with LV worms, are showing more rapid consolidation. However, plant health is observed to suffer in columns relative to barrels, likely due to the physical constraints on plant roots in the narrower columns.

Upon final harvest of the columns and barrels, the tailings will be characterized to determine the gains in shear strength which can be attributed to the plant/worm-based treatment. Plant root mass, leaf size, and total biomass will be assessed to determine which factors were most beneficial to overall plant health.

LESSONS LEARNED

1. High SFR thickened tailings was replaced with centrifuge cake of significantly lower sand content to promote LV survival. LV worm-based treatments are not expected to be successful in dewatering tailings with higher sand content.
2. LV worms overall are fragile and sensitive to the local environment. Earthworms are more robust and more likely to survive in tailings.
3. Both aquatic and terrestrial worms have increased likelihood of survival when paired with their preferred saturation conditions, and when provided straw as a food source.
4. Worm survival is difficult to assess at large scale, where individual counts are not feasible. Instead, success of worm-based tailings treatment may be gauged by shear strength gains in the deposit.
5. The *Carex aquatilis* and *Salix interior* plants studied in this project have been shown to thrive in oil sands tailings, especially in the larger barrels. This observation reinforces the hypothesis that plants are a environmentally friendly contributor to tailings remediation, and warrants further research at larger scale over longer growth cycles.

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PRESENTATIONS AND PUBLICATIONS

RESEARCH TEAM AND COLLABORATORS

Institution: Northern Alberta Institute of Technology (NAIT)

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

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Dr. Heather Kaminsky	NAIT	Research Chair, Principal Investigator		
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Simon Sun	NAIT	Research Associate		
Dr. Chibuike Chigbo	NAIT	Research Associate		
Dr. Victoria Collins	NAIT	Research Associate		
Kaela Walton-Sather	NAIT	Research Technician		
Dr. Miguel de Lucas Pardo	Deltas	Senior Researcher		
Floris van Rees	Deltas	Researcher		
Joel Tacas	NAIT	Chemical Engineering Technology Diploma	Sept 2018	April 2022
Ruth Delgado Garcia	NAIT	Chemical Technology Diploma	Sept 2018	April 2021
Katelyn Grado	NAIT	Biological Sciences Diploma	Sept 2018	April 2021
Emma Miller	NAIT	Forest Technology Diploma	Sept 2019	April 2021
Mallory Suvanto	NAIT	Forest Technology Diploma	Sept 2018	April 2020
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Research Collaborators: Deltas

Effect of Dispersants on Dispersion and Flocculation of Oil Sands Tailings

COSIA Project Number: TE0068 (IOSI19)

Research Provider: University of British Columbia

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Completed

PROJECT SUMMARY

This research investigates the behaviour and action of low molecular weight polymers in their novel application as dispersants of oil sands tailings. The purpose of the project is to investigate the addition of dispersants (various types of lignosulfonate, a by-product of the pulp and paper industry) to tailings to release bitumen from solids without affecting subsequent flocculation. The project objectives are to:

1. Determine the effect of dispersants on the degree of aggregation of oil sand tailings;
2. Assess the partition of dispersants between the solids from tailings and the water phase for water recycling purposes; and
3. Determine the effect of dispersants on the flocculation of fine solids into larger aggregates.

The main experimental work involved analysis of dispersant concentrations in solution after contact with the solids from oil sands tailings, determining the degree of dispersion of tailings suspensions, and evaluating the degree of flocculation as a function of dispersant dosage. A number of laser scanning methods were used to characterize the settled solids in relation to their water-release characteristics.

The results of this project will enhance our understanding of the fundamental problems with the disposal, handling, and dewatering of oil sands tailings, which is one of the most pressing challenges facing the oil sands industry. The results of this work are expected to guide development of more efficient tailings handling technologies, particularly for recovering bitumen from tailings and recycling of water trapped in oil sands tailings ponds.

For this research, three main types of lignosulfonate were selected for testing.

Table 1. Characteristics of Various Types of Lignosulfonate

Reagent	Ca [%]	Na [%]	Total Sulphur [%]	Sulfonate Sulphur [%]	Carboxylic Groups [%]	Molecular Weight [kDa]
D-619	0.0	9.0	7.0	6.0	3.2	25.0
D-648	0.1	15.9	11.1	8.1	7.4	5.0
D-750	0.0	8.0	3.2	2.7	7.4	6.0

The main difference in the reagents is the degree of anionicity and molecular weights. The results illustrate lignosulfonate capabilities as dispersants of oil sands tailings. Lignosulfonate is a by-product of the pulp and paper industry and is considered non-toxic ($LD_{50}=5\text{ g/kg}$). This reagent is a very strong dispersant and is typically used in oil well drilling muds as a mud thinner and as a water reducer for concrete.

PROGRESS AND ACHIEVEMENTS

Milestone	Activities	Methods	Status
1. Assessment of partition of dispersants between the solids and the solution phase. Determination of adsorption characteristics of dispersants on tailings.	<ul style="list-style-type: none">Characterization of tailings samples, mineralogy by X-RAY diffraction, particle size distribution, chemical assay including residual bitumen content.Adsorption experiments with the measurement of equilibrium dispersant concentration in the aqueous phase.Analysis of dispersant concentration in the aqueous phase using total organic carbon content.Determination of the adsorption density of the dispersants on the solids from tailings.	X-RAY Diffraction, X-RAY Fluorescence, Brunauer-Emmett-Teller (BET) analysis, Cations & Anions analysis, Dean Stark, Total Carbon,	100% Completed
2. Determination of the dispersing capabilities of the tested dispersants.	<ul style="list-style-type: none">Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage.Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions.Selection of dispersant dosages for flocculation studies.	Ultraviolet Visible (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	100% Completed
3. Determination of the dispersing capabilities of the tested dispersants.	<ul style="list-style-type: none">Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage.Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions.Selection of dispersant dosages for flocculation studies.	Ultraviolet (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	100% Completed

Milestone	Activities	Methods	Status
4.Determination of the dispersing capabilities of the tested dispersants.	<ul style="list-style-type: none"> Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage. Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions. Selection of dispersant dosages for flocculation studies. 	Ultraviolet (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	100% Completed
5.Effect of dispersants on flocculation of tailings suspensions.	<ul style="list-style-type: none"> Flocculation experiments to determine settling rates, sediment volumes, solids contents, and turbidity in the supernatant. 	Net water release	100% Completed

LESSONS LEARNED

Results of the experiments indicated settlement of fine particles, release of bitumen and release of water as a result of the addition of lignosulfonate to fluid tailings (FT) samples. In particular:

1. Addition of lignosulfonate to tailings released bitumen to the surface of the tailings samples.
2. Based on laser backscattering measurements, D-619 is the strongest dispersant and causes the most structural changes.
3. Based on partition analysis, most of the reagent gets adsorbed onto solid particles. UV-Vis spectrophotometry and total organic carbon (TOC) measurements gave very similar results and indicated that D-750 adsorbed more on the solid particles in comparison with D-619 and D-648. This is important for water recycling purposes, as less effort would be required for decontamination of the recycled water.
4. The magnitude of the average zeta potential of all tracked particles in tailings does not change significantly following the addition of the selected types of lignosulfonate. This is important for flocculation tests since the target is to enhance bitumen extraction while minimizing the impact on subsequent flocculation.
5. Amongst the selected types of lignosulfonates, adsorption of D-750 on particles was the most efficient and it attributed to a lower molecular weight and anionicity.
6. Addition of lignosulfonate to tailings does not adversely affect the flocculation process.
7. Pre- removal of bitumen from tailings improved water release during flocculation.



RESEARCH TEAM AND COLLABORATORS

Institution: University of British Columbia

Principal Investigator: Dr. Marek Pawlik

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Mechanics of Methane Bubbles In Tailings Ponds

COSIA Project Number: TE0069 (IOSI19)

Research Provider: University of British Columbia

Industry Champion: Suncor

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 1 of 4

PROJECT SUMMARY

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

The tailings consist of coarse sands, fine clays, silt, water, residual and unrecovered bitumen, naphtha, naphthenic acids, petroleum hydrocarbons and other extraction bi-products. These are deposited in the ponds as they are produced. Coarse sands form beaches upon discharge and some sediment to the pond bottom, then a gradient of mature fine tailings (MFT) to fluid tailings (FT), topped with a clear water zone. Tailings ponds are thus mostly stratified depth wise, with only slow lateral variations, and evolve over timescales of 1-10 years. The FT layer has been characterised rheologically as a thixotropic yield stress fluid (Derakhshandeh 2016). Thus, understanding how bubbles form, rise (or remain trapped), coalesce, interact etc. requires study of rheological and fluid dynamic questions, within a stratified media that varies from clear water through gelled layers to a porous media at the pond bottom.

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

Regarding risk, the main concerns here relate to the possibility of large-scale release of bubble clouds. The evidence suggests that a yield stress fluid such as FT may hold static a maximal volume fraction of gas, which will depend on the bubble size distribution, the yield stress, surface tension and on how the bubbles are spatially distributed. Ponds are subjected to annual/seasonal environmental changes in pressure and temperature (including freezing/thawing),



as well as local operational events (pond management, tailings deposition). These events could cause the trapped volume fraction to exceed the critical conditions, e.g. by expanding bubble volume with decreasing pressure, or simply by generation of motion locally. Similar risks underly limnic eruptions from deep lakes, except that here the depth is limited and gas is trapped rather than dissolved. The project aims to make a preliminary assessment of these risks via construction of large-scale mathematical models and their analysis. Questions include whether a cloud release can be stabilised once it starts, whether it may remain localised in one part of the pond or will it spread laterally to regions that were below criticality, etc.

For mitigation, the ideas are preliminary and depend largely on the first parts of the project and how our understanding improves. For example, should one try to “purge” parts of a pond to reduce risk (at an emissions cost)? Can one mechanically treat the FT/MFT layers to mitigate bubble coalescence and increase stability? Can one work directly with aspects of the bio-degradation, either chemically or addressing motility to limit bubble production.

PROGRESS AND ACHIEVEMENTS

To date, research has focused on understanding the fundamentals of bubble mechanics. Highlights are as follows.

- The theoretical conditions (the critical yield number) under which a single bubble remains static in a yield stress fluid have been derived, correcting some previous errors regarding the role of surface tension.
- Computational codes that are able to calculate the flow around single bubbles of specified shape, either axisymmetric or 2D, in the limits of low inertia have been developed and benchmarked. These codes include the yield stress effects exactly and use adaptive meshing, making them specifically suitable for calculating the critical yield number.
- The above codes have been used to calculate critical yield numbers for 2D bubbles of cylindrical, elliptical and other shapes, over wide ranges, and including surface tension effects. The latter dominate when the bubbles have high aspect ratio. We have also partly extended the theory of perfect plasticity to the 2D bubble shapes, exposing some limitations. Similar calculations have been performed for axisymmetric bubble shapes. A paper is in progress summarizing these results.
- The use of a multi-phase code (Basilisk) for studying transient flows has been developed. This open source code is specifically targeted at interfacial flows and contains state of the art methods for tracking the interfaces. The yield stress fluid implementation within the code is less exact than in our slow flow codes and this makes it less suitable for computing critical yield numbers. However, the code has been benchmarked for 2D bubbles and is promising as a tool for e.g. coalescence, study of bubbles crossing fluid interfaces (e.g. MFT/FT/water).
- A bubble column has been constructed within which single or multiple bubbles could be injected into laboratory fluids in a regulated way. The initial usage of this apparatus has been to study the effects of injection method on the bubble shape. In most yield stress fluid bubble propagation experiments to date, bubbles develop a pointed tail as they rise. An ongoing debate concerns whether this is an experimental artefact due to injection method or arises from the fluid rheology (specifically viscoelasticity). Evidently, in

tailings ponds the bubble formation is not mechanically driven so this is an important aspect of establishing our experimental protocols. Using a system of layered fluids we have shown that the injection method is not responsible for the later bubble shape (Pourzahedi *et al.* 2021). The above apparatus has been modified to incorporate a particle image velocimetry (PIV) setup, which will be used further in Summer 2021.

- A second interesting aspect of the reported experiments, as with other earlier observations (e.g. Dubash & Frigaard 2007, Lopez *et al.* 2018), is that after the first bubble enters the bubble column it appears to damage the structured fluid. Whether a viscoelastic or thixotropic mechanism is responsible is unknown. However, the effect is obvious in that subsequent bubbles typically follow the same pathway as the first. We have begun to study this phenomenon using the Basilisk code described above. The damaged channels are modelled as Newtonian fluid channels, constrained by yield stress fluid layers. Bubbles move towards the Newtonian channels, attracted even from many diameters distant, deform and move along the channels. Vertical and angled channels have been studied and we have also performed initial experiments in our bubble column, showing similar effects to our computations (Zare *et al.* 2021). Images collected from Base Mine Lake clearly show pockmarks on the interface of the water and FT layer, providing evidence for associated chimneys below (Zhao *et al.* 2020).
- A second apparatus has been built to address onset of bubble motion. This apparatus consists of a vacuum chamber in which a gelled fluid can be placed and visualised through the sides as the pressure is varied. We obtain a bulk measurement of the bubble volume from changes in the fluid height as the pressure is lowered. We observe gradual increase in both bubble size and overall volume. Each step decrease in pressure is followed by an apparently elastic relaxation response as the system attains its new equilibrium. Below a given critical pressure the bubble volume fraction (and bubble size) mobilise *en masse* and the fluid sample is degassed in an unstable way. This may mimic the field setting of pond instability, which may indeed be worse in that there can be a larger decrease in static pressure on the larger scale of the pond, rather than in our small apparatus. In Summer 2021 we will conduct systematic studies to map out critical conditions for our lab fluids and will also use some pond samples for the same purpose.
- Supplementing the above experimental study of bubble cloud stability, the slow flow codes have been used in order to explore critical yield number conditions for clouds of bubbles computationally. This is restricted to 2D flows due to computational resource limitations. The method is to populate a periodic 2D box with cylindrical bubbles randomly positioned. The flow is computed and the mean velocity of the liquid calculated. The yield stress is then increased and the calculation repeated. Eventually the liquid mean velocity decays to zero, giving a critical yield number. The procedure is repeated with a different bubble configuration, i.e. a Monte Carlo approach, and over many calculations we build up an estimation of the critical yield number and its sensitivity to bubble distribution. This work is ongoing.
- The vacuum chamber setup has also proven useful for studying the onset of single or pairs of bubbles. Here the fluid sample is initially degassed completely and the pressure released. A small bubble (or more) is then placed in the sample using a needle and we conduct an experiment in which the pressure is lowered and the bubble size increased until motion starts. Here we have also conducted preliminary experiments on coalescence. We intend to progress further on these, in combination with Basilisk computations, in year 2 of the project.

LESSONS LEARNED

To date, the group has been focused mainly on building up the fundamental knowledge, constructing experimental apparatus and developing protocols.

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Zare, M., Daneshi, M. and Frigaard, I.A. 2021. Effects of non-uniform rheology on the motion of bubbles in a yield stress fluid. Submitted to *J. Fluid Mech.*, under review.

PRESENTATIONS AND PUBLICATIONS

Pourzahedi, A., Zare, M. and Frigaard, I.A. 2021. Eliminating injection and memory effects in bubble rise experiments within yield stress fluids. Submitted to *J. non-Newtonian Fluid Mech.*, under review.

Zare, M., Daneshi, M. and Frigaard, I.A. 2021. Effects of non-uniform rheology on the motion of bubbles in a yield stress fluid. Submitted to *J. Fluid Mech.*, under review.

RESEARCH TEAM AND COLLABORATORS

Institution: University of British Columbia

Principal Investigator: Ian Frigaard

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Masoud Daneshi	UBC	Postdoc		
Emad Chaparian	UBC	Postdoc		
Tyler Dozzi	UBC	Summer intern	June 2020	August 2020
Miguel Eagleton	UBC	Intern	July 2020	April 2021
Babak Derakhshandeh	Suncor	COSIA Project Steward		

Research Collaborators:

Dr. Marjan Zare, UBC

Dr. Greg Lawrence, UBC

Dr. Ali Roustaei, University of Tehran

NAIT Chair in Applied Tailings Processes

COSIA Project Number: TE0075

Research Provider: NAIT – Heather Kaminsky

Industry Champion: Imperial

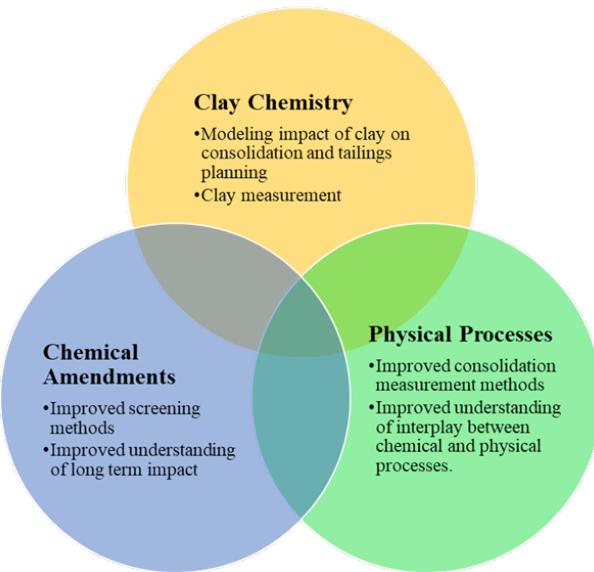
Industry Collaborators: Canadian Natural, Imperial, Suncor, Syncrude, Teck, Graymont Ltd., SNF, BASF, Thurber Engineering Ltd., Bureau Veritas, Enersoft Inc.

Status: Year 1.5 of 5

PROJECT SUMMARY

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

The theme of clay chemistry will focus on developing improved methods for measuring clays and methods for accounting for their influence in long range tailings planning models. The theme of chemical amendments will focus on developing improved screening methods to select appropriate chemical additives to reduce FT 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 FT. Finally, the last theme will target improving the understanding of the physical processes that are used to dewater tailings and the interplay between chemical and physical processes.



Specific innovation outputs to be targeted by the Chair include:

- Developing a laboratory gold standard of clay measurement to benchmark field instruments against.
- Validating at-line and online instruments that can measure the key properties of the clays for a given application (i.e., online and at-line methylene blue index (MBI))



- Developing screening methods that capture and measure the influence of clay chemistry on tailings treatment processes.
- Improving the understanding among chemical vendors and other innovators of what an ideal chemical treatment looks like for different applications, to inspire improved chemical treatments.
- Validating innovative means of treating clays – these may include mixing with sand or other waste materials to improve the ability to sustain plants or enhance the natural stability of the new mixtures.

PROGRESS AND ACHIEVEMENTS

Key progress on activities include:

- 1) Application Navigator workshop with 20 industry members representing partner chemical vendors, consultants and COSIA member companies. This workshop identified 25 unique process streams/areas for application of technology to improve tailings performance. Each process stream/area will have a different set of bench scale tests that are appropriate for proving technology performance. There are, however, tests that will apply to multiple applications. In addition, the workshop identified that proposed technologies that need to address technology gaps identified by COSIA member companies. A many-to-many relationship was identified between technology gaps and technology application. Key findings include:
 - a. For any technology targeting improvements to or replacement of existing tailings treatment technologies, it is critical that the new technology prove dewatering performance in short- and long-term equal to or exceeding the incumbent technology. It is also important that this performance be demonstrated on an appropriate range of feed materials and the relevant mixing conditions.
 - b. Proponents of technologies targeting in-situ improvements, such as capping technologies, must demonstrate safe site access and deployment.
 - c. Instrumentation or sensing technologies should consider fouling and wear in their design. In addition, these technologies should ensure the underlying mechanisms of measurement are clearly understood and the range of applicability noted. For instance, a technology that is very sensitive to a water signal used to detect non-water components should ensure calibration over a range of densities.
 - d. All technologies need to consider the range of temperatures on site (-50 to +30 ambient), the scale of operation and the safety of the components.
- 2) Tailings 101 course – Feedback from technology vendors, technology developers, and industry outsiders identified the specific need for training material to build their knowledge base in industry needs. In response to this, Dr. Kaminsky partnered with Mrs. Andrea Sedgwick (Ledcor Chair in Oil Sands Sustainability) to prepare and deliver a two day “Introduction to Oil Sands Tailings” short course. This course has now been offered twice and is planned to be offered in Q1 annually. Additional courses on specific aspects of tailings processes and measurements are in development.



- 3) Tailings Book Club – Dr. Kaminsky initiated a Tailings book club where key papers were reviewed and discussed. Offered on a regular basis, an objective of the book club is to generate networking opportunities for students and industry professionals, particularly during the COVID-19 pandemic. Papers discussed included:
 - State of Fluid Tailings Management for Mineable Oil Sands, 2018
 - Fine Fluid Tailings Management Methods – Recommended to help understand site specific constraints and cost in oil sands tailings management.
 - Variability in Oil Sands Tailings – Recommended to help understand variability in FT.
 - Royal Society of Canada Expert Panel Report - Environmental and Health Impact of Canada's Oil Sands Industry.
 - State of Fluid Tailings Management for Mineable Oil Sands, 2019 – recommended for key status updates on fluid tailings inventory.
- 4) Clay Minerals Society conference session on COSIA clay challenge – Dr. Kaminsky organized a session at the Clay Minerals Society conference (October 2020) targeted at sharing knowledge about the COSIA Clay Challenge.
- 5) Small study to evaluate the use of glass rods versus micropipette for methylene blue index (MBI) titration. Results found that 5mm glass rods provided statistically identical results in trained operators as using a 5-microliter micropipette. Spots from the micropipette were more uniform and consistent which makes it easier for less trained operators to recognize the halo. The glass rod is cheaper and easier to clean making it more suitable for experiments with many samples, but newer operators can have difficulty identifying the halo.
- 6) Characterization of tailings samples in support of students in the University of Alberta Industrial Research Chair program in Oil Sands Geotechnique (Dr. Ward Wilson). This partnership ensures that graduate students and researchers at the University of Alberta have properly characterized tailings samples upon which to base their research.
- 7) Evaluation of novel tailings technologies. Work is ongoing on evaluating a variety of novel tailings technologies for COSIA member companies and various chair member companies.

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RESEARCH TEAM AND COLLABORATORS

Institution: Northern Alberta Institute of Technology (NAIT)

Principal Investigator: Dr. Heather Kaminsky

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Yunhui Li	NAIT	Research Associate		
Yuki Gong	NAIT	Research Assistant		
Mohammed Ghuzi	NAIT	Research Assistant		
Patric McGlashan	NAIT	Student Research Assistant/Diploma in Chemical Technology Now a Research Assistant on another team.	September 2017	May 2020
Catalina Romero Calducho	NAIT	Student Research Assistant/Diploma in Chemical Technology → Now a Research Assistant	September 2018	May 2020
Joel Tacas	NAIT	Student Research Assistant/Diploma in Chemical Engineering Technology	September 2018	May 2022
Yousuf Iqbal	University of Alberta	Student Research Assistant/Mechanical Engineering, BSc	September 2015	April 2020
Ruth Delgado-Garcia	NAIT	Student Research Assistant/Diploma in Chemical Technology	September 2018	May 2021
Emily Devereux	NAIT	Student Research Assistant/Diploma in Chemical Technology	September 2019	May 2022
Jennifer Haverhals	Imperial	COSIA Project Steward		

Research Collaborators:

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

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

Tailings Fines Measurement Using a Wet Method by Laser Diffraction-Particle Size Distribution Analyzer

COSIA Project Number: TE0080

Research Provider: HexaChem Global Inc.

Industry Champion: Canadian Natural

Industry Collaborators: Imperial, Suncor, Syncrude, Teck

Status: Lab Scale Completed

PROJECT SUMMARY

Fines content plays an important role in defining the properties of tailings and oil sands (fines are mineral solid particles \leq 44 microns in size). The current method by Laser Diffraction Particle Size Distribution (LD-PSD) analyzer requires time-consuming and complex sample preparation. To address these concerns, HexaChem Global Inc. developed a simple and reliable method to measure the fines content of tailings composition within minutes, while the method¹ currently used in the oil sands industry requires several hours.

The current method of sample preparation to determine fines content includes:

- Utilizing the Dean-Stark method for testing mature fines tailings (MFT) samples can take up to 16 hours to remove the bitumen and water. The remaining solids undergo the following steps before introduction to the LD-PSD analyzer:
 - Drying to vaporize the residual solvent at 100 °C (usually overnight)
 - Disintegration by either mortar pestle or hammermill
 - Subsampling by static or rotary riffle
 - Dispersion of the sample (in dispersing reagent) overnight
 - Boiling, sonication, or the combination of both (20-30 minutes)

In this study, an alternative, simpler method to reduce complexity for field deployment was presented. The main idea was to introduce the tailings slurry directly into the LD-PSD analyzer without any sample preparation and treatment in advance. Certain considerations regarding the bitumen contaminants and amount of subsample were

¹ COSIA Fines Measurement Working Group. 2016. *Unified Fines Method for minus 44 micron material and for Particle Size Distribution*. Canada's Oil Sands Innovation Alliance, Calgary Alberta.

noted and evaluated. Finally, the results (fines content <44 microns) were compared with those of the standard industrial method (COSIA accepted method).

PROGRESS AND ACHIEVEMENTS

Ten independent MFT subsamples were received from COSIA member companies. Three subsamples from each vial were analyzed in triplicate using the LD-PSD analyzer 1 (Beckman Coulter LS 13 320, ULM size = 1000 mL) after sample preparation optimization. Sample MFT-165 had been studied in the two rounds of the previous InnoTech Alberta and oil sands industry interlaboratory study (ILS) conducted in 2015-2016. The MFT-165 fines content results were then used for the comparison.

Each sample was introduced to the analyzer in ten independent runs. Overall, 100 data sets were obtained providing a large set to evaluate the proposed method for repeatability, reproducibility, and accuracy.

Given the slurry nature of the sample, proper subsampling, especially for heterogeneous tailing specimens, is crucial. A gentle shaking and swirling for a few minutes ensured the homogeneity of the matrix and its suitability for subsampling. Subsampling using a disposable plastic pipette provided a sufficient representative sample for the analysis. However, for the heterogeneous samples where the particles are distributed widely and contain substantial sand and fines and/or where the samples contain high water content, segregation occurs quickly. Proper subsampling is an important factor in these circumstances.

Table 1 summarizes the cumulative volume percentage of particles less than different sizes for each analytical run (entries) obtained by the wet method. It was observed that the fluctuation of the measurement from sample to sample (N) and run to run (R) is significantly low. This study verified the acceptable range of repeatability throughout the particle size range.

Table 1. The average cumulative volume % (below) values using the wet PSD method on MFT-165

< Size (μm)	Average	\pm Standard Deviation (SD)	% Relative Standard Deviation (RSD)
5.5	59.3	1.3	2.3
11	79.1	1.6	2.1
22	92.5	1.3	1.4
44	99.1	0.8	0.8
88	100.0	0.1	0.1
125	100.0	0.0	0.0

To evaluate the reproducibility of the method, an alternative LD-PSD analyzer-(2) was used.

Analyses of two of the MFT-165 (N=2) vials were replicated (R=11). The similarity of the results suggests the high reproducibility of this method using different analyzers. Table 2 compares the relative percent difference (%RPD) between the mean values of the two methods at different volume sizes.

Table 2. The average cumulative values using the proposed method on the second LD-PSD analyzer

< Size (µm)	Average	±SD	% RSD
5.5	53.5	1.3	2.4
11	75.8	1.2	1.6
22	94.3	0.8	0.9
44	99.7	0.3	0.3

Finally, the fines content obtained here (99.1 ± 0.8) was compared with two series of standard industrial method results:

1. The results of the InnoTech Alberta-COSIA interlaboratory study in 2016 were obtained by the same LD-PSD analyzer (fines content: $96.3 \pm 2.3\%$). The overlap of 'Mean±SD' for two series represents the similarity in results.
2. The mean value of ALL participants of round 2 ILS. This provides a wide view of where this method stands amongst all the collected values. The number of recorded values for this method is 66 from four different paths (LD-PSD and sieve analysis) without any rejected value. The fines content from different labs was reported between 84.9-100% with a mean value of $97.36 \pm 3.19\%$. Once again, the overlap of the two mean values within the SD represents the similarity of these two datasets.

LESSONS LEARNED

The statistical results including repeatability, reproducibility, and accuracy suggest a reliable direct method for fines content measurement in tailings. The simplicity and high speed of analysis (from sample preparation to the analysis) result in cost reduction and fast data acquisition. Hence, the proposed method is suggested for further interlaboratory and laboratory practice for oil sand tailings.

RESEARCH TEAM AND COLLABORATORS

Institution: HexaChem Global Inc.

Principal Investigator: Dr. Zohrab Ahmadi

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Adnan Younis	HexaChem Global Inc.	Research Associate		
Tea Malkova	Canadian Natural	COSIA Project Steward		



Research Collaborators:

Argile Analytica

University of Calgary

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

COSIA Project Number: TE0083

Research Provider: Institute for Oil Sands Innovation (UAlberta)

Industry Champions: Syncrude and Suncor

Industry Collaborators: Canadian Natural, Imperial, Teck

Status: Year 1 of 1

PROJECT SUMMARY

End pit lakes represent a useful, cost-effective method for tailings disposal. These artificial lakes are created at the point of mine closure and consist, in most cases, of fluid tailings capped with fresh and/or process water. In incorporating end pit lakes into long-term closure plans, key attention must be paid to interventions that improve water quality, be these measured by aesthetic or laboratory means. To this end, water turbidity plays an important role in assessing end pit lake performance and in estimating the trajectory of an end pit lake as it evolves into a natural component of the local watershed.

A major factor that influences end pit lake turbidity is solids suspension due to bubble release (or ebullition) from the soft sediment along the lake bottom. Bubbles so generated cause mixing of the tailings and cap water leading to a destabilization of the mudline (Flynn et al., 2017). Also, rising bubbles may be responsible for a vertical transport of fine solids possibly across significant vertical heights (Srđić-Mitrović et al. 1999). Even when this is not the case, significant vertical transport may be realized when rising bubbles act in concert with other transport mechanisms e.g., lake turnover or wind forcing (Lawrence et al. 2016). As such, turbidity, and the manner that turbidity is influenced by ebullition, is of critical importance to reclamation efforts and the cost-motivated goal of bringing subaqueous tailings deposition to a level of technological maturity, regulatory approval and public acceptance.

Key uncertainties related to the above goal are twofold.

- (i) Is the supply of bubbles within the deposited tailings limited or large?
- (ii) Can chemical treatment of tailings in any event reduce the severity of solids suspension?

Whereas the former question may be related, in large part, to the degree of diluent present in the tailings at the point of deposition, the latter question is somewhat more generic and shall be the focus of the current study. To this end, it seems reasonable to suppose that the addition of a flocculant, say, will mitigate turbidity. However, the associated degree is presently unknown and depends, presumably, on the ability of treated tailings to better retain (small) bubbles and to develop interior channels that progressively “armour” over time.

The specific objective of our research is to perform a laboratory experimental investigation of the effect of bubble ebullition on the suspension and settling of fine tailings from end pit lake sediment. Guiding our work, the literature

contains examples of studies investigating the factors that affect ebullition rates (e.g., Martens and Berner 1974) and the relation between ebullition and solids resuspension. Most of the studies in question examined natural, rather than man-made, water bodies (e.g., Yuan et al., 2007). Therefore, it is uncertain if the findings are applicable to oil sands end pit lakes, particularly because the sediment associated with these end pit lakes can have visco-plastic properties that are atypical of natural muds (Flynn and Surma, 2015). The present study aims to fill this information gap by employing field materials in laboratory-based experiments where experiments are conducted using fluid tailings from an oil sands tailings facility.

Experiments are conducted in tall (approximately 2 m) clear acrylic columns. A metal foam is placed at the bottom of the column to distribute the incoming air and thereby facilitate bubbling. Tailings are poured on the metal foam; they are then capped with a deep layer of lake water. Bubbles are produced by supplying slightly compressed air to the column base through the metal foam. The effect of bubble ebullition is to be characterized by performing experiments with various sediment depths at various ebullition rates. The transport of suspended solids in the vertical (y) direction is to be examined as is the subsequent period of particle settling. In so doing, reference is made to the time rate of change of the cap water suspended solids concentration/turbidity. Water turbidity is measured using a turbidimeter and a non-intrusive optical system that estimates, pixel-by-pixel, suspended solids concentrations in digital images captured in the laboratory. For the latter technique, measurements are based on a series of calibration images that allow correlations to be derived between the pixel intensity and water turbidity. In turn, experimental images of the water column are taken at regular time intervals so that the temporal and spatial variation of turbidity may be recovered.

PROGRESS AND ACHIEVEMENTS

The study remains in progress with a (COVID-19 revised) end date of April 30, 2021. Preliminary experiments have been carried out using various ebullition rates, Q , i.e. $Q = 1, 3$ and $5 \text{ cm}^3/\text{minute}$ (CCM) where, in each case, the total mass of tailings material added to the column base was approximately 3 kg.

Representative experimental results are summarized in Figure 1, which shows the variation of water turbidity measured in Nephelometric Turbidity Units (NTU) as a function of time and vertical position. The left- and right-hand side panels respectively consider the two end-member air flow rates, i.e., $Q = 1$ and 5 CCM . In both cases, bubbling was applied until the upper portion of the column ($y/h \approx 1$) reached a turbidity of $\text{NTU}_0 = 700$, 700 NTU representing the maximum resolvable turbidity for the non-intrusive optical system described above. The vertical dashed lines (at $tQ/V = 0.027$) indicate the point in time where bubbling was stopped; to the right of these vertical dashed lines, particles settled to the base of the column without possibility of resuspension. Meanwhile the horizontal dashed lines (at $y/h = 0.09$) indicate the initial interface between the tailings and cap water prior to the start of either experiment.

During bubbling, water turbidity increased progressively from the mudline upwards. Non-dimensionalizing the data as in Figure 1, we found that the cap water just below the free surface attained a turbidity of 700 NTU at approximately $tQ/V = 0.027$ irrespective of the ebullition rate. (The value $tQ/V = 0.027$ corresponds to a dimensional time of about 460 min and 80 min for $Q = 1$ and 5 CCM , respectively; not surprisingly, the rate of solids suspension increases with Q -- Yuan et al., 2009). After bubbling, the suspended particles were allowed to settle for about $t_s = 900$ min in both cases. At the end of this settling period, we found that the solids volume was larger than what was measured initially. This effect can be quantified by defining a fluffing factor, f , as $f = h_f/h_i$, where h_i and h_f respectively

denote the initial and final mud heights, both measured with respect to the top of the metal foam. From Figure 1, we find that $f = 2.0$ and 1.4 when $Q = 1$ and 5 CCM, respectively. The fluffing factor decreases with Q because, at low air flow rates, bubbles likely appeared too intermittently to continuously suspend larger solid particles. Stated differently, with small Q vertical particle transport was more selective with comparatively finer particles held in continuous suspension. In turn, these finer particles settled more slowly and formed a less dense deposit in the long-time limit. By contrast, and for larger Q , vertical particle transport was more indiscriminate (and rapid). The mix of large and small particles that remained suspended during bubbling led, during the subsequent settling phase, to a more compact deposit.

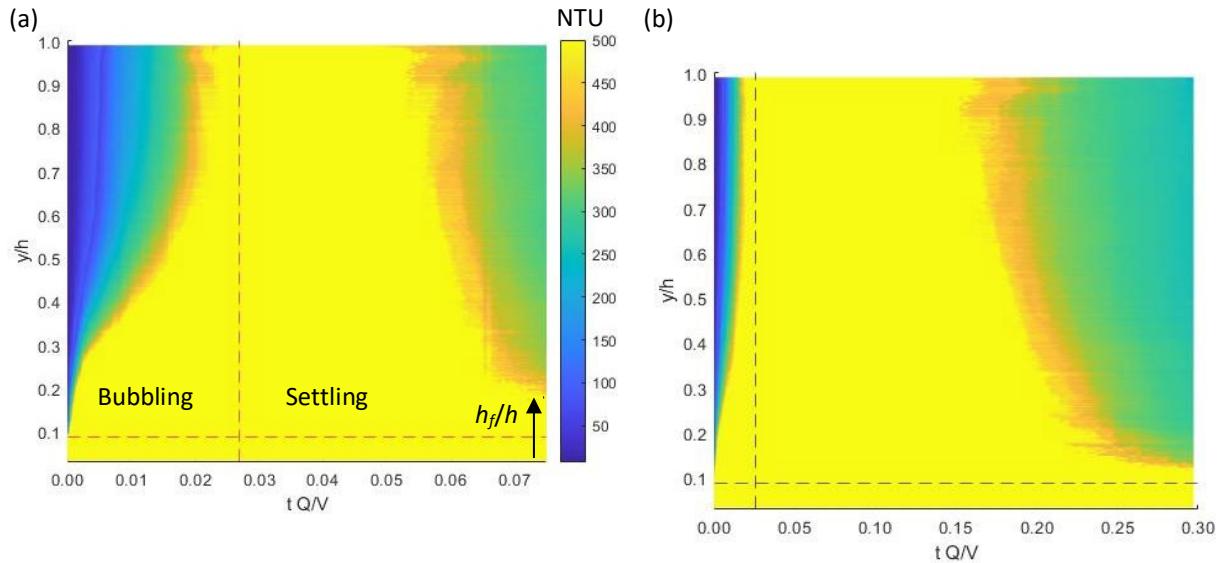


Figure 1. [Colour] Variation of turbidity vs. vertical position (non-dimensionalized with the column height as measured from the free surface to the top of the metal foam) and time (non-dimensionalized by V/Q where V represents the column volume as measured from the free surface to the top of the metal foam). Regions of the vertical time series shown in yellow indicate elevations/times where the turbidity is at or above 500 NTU, 500 NTU lying marginally below the maximum resolvable turbidity of 700 NTU. (a) $Q = 1$ CCM and (b) $Q = 5$ CCM.

In order to investigate the balance between solid suspension and settling more carefully, the time evolution of column turbidity is examined in Figure 2. More specifically, Figure 2 shows turbidity profiles for $Q = 1$ CCM at heights $y/h \approx 0.2, 0.5$ and 0.8 , corresponding, respectively, to the lower, middle and upper portions of the column. In Figure 2a, time is non-dimensionalized by the time scale t_m , which denotes the time when the turbidity reaches $NTU_0 = 700$ at the corresponding column height. Thus $t_m(y/h = 0.2) = 38$ min $< t_m(y/h = 0.5) = 307$ min $< t_m(y/h = 0.8) = 460$ min. The inset to Figure 2a shows the variation of t_m with y/h . Figure 2a shows a good collapse of the data, a feature also observed at the ebullition rates of 3 CCM and 5 CCM (not shown). The fact that the data are approximately linear suggests a near constant rate of solids loading into the water column: here, suspension by ebullition significantly outweighs particle settling, i.e., there is no evidence of channel “sidewall armouring,” which was noted in the experimental studies by Yuan and colleagues (Yuan et al. 2007 and Yuan et al. 2009).

After bubbling is arrested, there follows an extended period of particle settling. Settling is first evident for large y , i.e., water just below the free surface clarifies well before water lying closer to the mudline. We denote the time at which water at a particular elevation first experiences a reduction of turbidity as t_0 and note that $t_0(y/h = 0.8) = 320$

$\min < t_0(y/h = 0.5) = 380 \text{ min} < t_0(y/h = 0.2) = 580 \text{ min}$. The variation of t_0 with vertical position is examined in the inset of Figure 2b. Utilizing t_0 in Figure 2b proper, we note another good collapse of the experimental data over the three elevations $y/h \approx 0.2, 0.5$ and 0.8 . (A similar collapse is realized at the larger ebullition rates of 3 CCM and 5 CCM). The collapse of data in Figure 2b reveals two distinct settling regimes, one fast and the other slow. Correspondingly, we suppose that the particles suspended by the rising bubbles can be binned into one of two broad categories: large or small. Early on, settling is dominated by the large particles causing the turbidity to reduce comparatively quickly. Once large particles have settled out of the system, the settling of the remaining smaller particles takes place and here the rate of sedimentation is notably reduced.

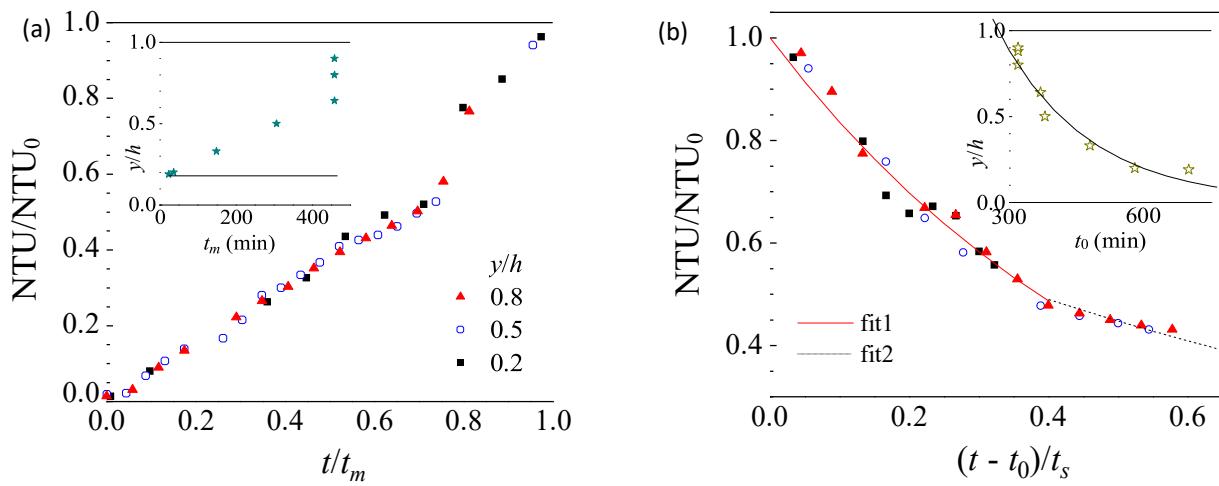


Figure 2. Turbidity evolution at three selected elevations for $Q = 1$ CCM during (a) bubbling, and, (b) settling. Here, t_m is the time when the turbidity first reaches the maximum value of $NTU_0 = 700$ for the elevation in question. Meanwhile, t_0 is the elevation-specific time, following bubbling, when the turbidity begins to decrease. The solid curve in the inset to panel (b) shows a curve of best fit whose equation reads $y/h = 0.8 \exp[-0.005 (t_0 - 320)]$ where t_0 is measured in minutes. The solid and dashed curves in panel (b) show curves of best fit whose equations read [fit1] $NTU/NTU_0 = \exp(-1.8 t^*)$ and [fit2] $NTU/NTU_0 = 0.49 \exp[-0.9(t^* - 0.4)]$. Here $t^* = (t - t_0)/t_s$.

The next phase of our work shall consist of repeating the above experiments but using field materials treated with a commercially-available flocculant. We thereby plan to compare the rate of solids suspension and also of particle settling to the control cases devoid of flocculant. This comparison will quantify the flocculant's role in mitigating cap water turbidity and will thereby provide important data that can be used to guide future discussions regarding end-pit lake interventions.

LESSONS LEARNED

In considering the application of our laboratory experiments to oil sands operations, the following conclusions apply:

1. Higher ebullition rates cause the water turbidity to increase quickly. On the other hand, lower ebullition rates may be associated with a larger fluffing factor, i.e., with a less consolidated layer of mud following bubbling and particle sedimentation. In turn, such a layer is expected to be easier to perturb and destabilize whether by ebullition or other means.
2. The use of scaling parameters such as NTU_0 , t_m , and t_0 allow us to collapse measured data collected at different elevations. As our experiments continue, these (and other) parameters will be used for the purposes of deriving correlations that can be extrapolated beyond the laboratory and to field-scale processes.

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RESEARCH TEAM AND COLLABORATORS

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Principal Investigator: Morris R. Flynn

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Mohammad Shajid Rahman	University of Alberta	Ph.D.		
Barry Bara	Syncrude	COSIA Project Steward		
Carla Wytrykush	Syncrude	COSIA Project Steward		
Babak Derakhshandeh	Suncor	COSIA Project Steward		

Clay Removal from Fluid Tailings

COSIA Project Number: TJ0031

Research Provider: Syncrude

Industry Champion: Syncrude

Industry Collaborators: Teck

Status: Year 6 of 7

PROJECT SUMMARY

Fluid tailings (FT) release water at an extremely slow rate due to its low hydraulic conductivity. It is known that the negatively charged clays in FT are the bad actors due to their high affinity for water (i.e., hydrophilic), small particle sizes and large specific surface areas. These properties lead to FT dewatering and consolidating at an extremely slow rate. To accelerate FT dewatering and the pace of reclamation, Syncrude R&D conceived the FT clay treatment project by targeting the bad actor clays in FT. The theory of this step-out technology is to use a polymeric flocculant to enlarge the effective size of clays and a collector to change the clay surfaces from hydrophilic to hydrophobic (to repel water). A flocculant-collector recipe was developed for FT clay treatment.

The process of FT clay treatment can take two paths. Process A, simply called clay flotation, removes clays from FT by flotation followed by natural desiccation of the clay froth. As the clay froth repels water (i.e., hydrophobic), the clay froth dewater and desiccates rapidly. Process B, simply called clay treatment, treats the entire FT stream first with a flocculant, and then with a collector. The treated FT is subjected to liquid-solids separation; e.g., centrifugation, filtration and/or sedimentation in a deposition cell. Syncrude has successfully conducted tests for laboratory proof-of-concept, small pilot for clay flotation, and field pilot for FT clay treatment. Both Processes A and B can be conducted in-situ or near a tailings pond.

The main objective of the project is to develop alternative technologies for deployment that would augment current commercial technologies such as composite tailings (CT), FT centrifugation and water capped FT.

In 2020, together with Teck as a joint industry project (JIP) partner, the activities of the project conducted were focused on: Inline FT clay frothing; large strain consolidometer (LSC) tests of FT samples treated with different chemicals; geotechnical beam centrifuge simulation tests of the same FT samples as the LSC tests; and clay flotation from the Aurora CT cyclone overflow and ML (Mildred Lake) Stream 73 (flotation tailings). In addition, evaluation of alternative chemicals for FT clay treatment-Phase 3 was completed.

PROGRESS AND ACHIEVEMENTS

The Syncrude EXP2000 pilot plant facilities were used for FT clay flotation tests conducted with mechanical flotation cells in 2016. The results showed about 90% solids recovery to the flotation froth. The hypothesis is that we may use an inline FT clay frothing system to turn all the hydrophobic FT solids into froth without using the mechanical

flotation cells. The idea was tested using a continuous inline clay frothing system configured with two types of air spargers. The diluted FT (15% solids content) and the flocculant solution were mixed with an inline dynamic mixer followed by injection and mixing of a collector in another inline dynamic mixer. The treated FT was then aerated in the pipeline with either a Cav-Tube or Slam-Jet air sparger. It was found that the feed flow rate and the ratio of air to feed flow are important variables. It was demonstrated that 67-80% froth recoveries were obtainable in a single pass, but the results were not repeatable due to the intermittent nature of the mixed flow regimes in the pipeline. The Cav-Tube air sparger worked better if the ratio of air to feed rate is less than 2, while the Slam-Jet air sparger worked better at a ratio of air to feed rate of greater than 2. The test results demonstrated that the inline FT clay frothing is challenging in a single pass without a better understanding of the frothing kinetics, flotation mechanisms and fluid dynamics in the pipeline.

Large strain consolidation (LSC) tests of four FT samples treated with new collectors were conducted. It was found that physical factors such as sand to fines ratio (SFR) play a much more important role than chemical factors in compressibility and hydraulic conductivity. For FT with SFR of 0~0.2, the use of chemicals (e.g., flocculants and/or collectors) can increase the initial dewatering rates at high void ratios. However, the chemical treatments did not show significant differences in consolidation of the FT deposits at low void ratios. Instead, the deposit with SFR of 2 obtained by co-processing the coarse tailings and FT with a flocculant demonstrated a significant increase in hydraulic conductivity compared with the flocculant-treated cohesive FT deposits.

Geotechnical beam centrifuge simulation tests of the same four FT samples were conducted. It was demonstrated that physical factors such as SFR play a much more important roles than chemical factors in beam centrifuge simulations of deposit consolidation. For cohesive FT deposits with SFR of 0~0.2, they all exhibited high potential settlements and low hydraulic conductivity regardless of the chemicals used in the FT treatments. Similar to the LSC tests, the co-processed deposit with SFR of 2 showed a significantly higher hydraulic conductivity at low void ratios.

The laboratory flotation tests demonstrated the possibility of selective clay flotation from the Aurora CT cyclone overflow and ML Stream 73 tailings. More work to refine the chemical recipes needs to be done.

The evaluation of alternative chemicals for clay treatment-Phase 3 was completed. It was found that using the combination of a nano-hybrid polymer with a new cost-effective non-toxic anionic collector, it is possible to selectively float clay from fresh tailings.

LESSONS LEARNED

The Syncrude EXP2000 pilot FT clay flotation tests conducted with mechanical flotation cells in 2016 showed about 90% solids recovery to the flotation froth. The hypothesis of using an inline FT clay frothing system to turn all the hydrophobic FT solids into froth without using the mechanical flotation cells was tested. The test results demonstrated that the inline FT clay frothing is challenging in a single pass without a better understanding of the frothing kinetics, flotation mechanisms and fluid dynamics in the pipeline. The intermittent nature of the mixed flow regimes and short residence time for air bubbles to collide and effectively attach to clay particles in a single pass in the pipeline could be one of the reasons leading to low and unstable clay froth recovery.

The LSC and geotechnical beam centrifuge tests of FT samples treated with different chemical recipes demonstrated that physical factors such as SFR play a much more important role than the chemical factors in compressibility,

hydraulic conductivity and deposit consolidation. While the chemical treatment of fine tailings enhances the initial dewatering rate, a proper SFR of the deposit may accelerate the long-term consolidation. Both the chemical and the physical factors in tailings treatment should be balanced to meet the mine closure and reclamation targets.

Selective clay flotation from oil sand tailings is technically feasible. The combination of a nano-hybrid polymer and a new cost-effective non-toxic anionic collector is a promising recipe. More work to refine the chemical recipes needs to be done.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigator: Simon Yuan

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Bradley Komishke	Teck	Tailings Advisor		
Mike Di Marco	Teck	Manager		
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Imran Shah	Coanda R&D Corporation	Engineer		
Amarebh Sorta	Coanda R&D Corporation	Geotechnical Engineer		
Gonzalo Zambrano	University of Alberta	Research Director		
Yazhao Wang	University of Alberta	Researcher		
Haihong Li	InnoTech Alberta	Researcher		
Randy Mikula	Kalium Research Inc.	Consultant		

Engineered Tailings Research

COSIA Project Number: TJ0033

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Year 6 of 8

PROJECT SUMMARY

Engineered Tailings Research is seeking new technology options for tailings treatment aimed at reducing capital and operating costs and speeding up deposit consolidation and reclamation. Beyond the existing tailings treatment technologies such as composite tailings (CT), paste and thickened tailings (P&TT), centrifugation of fluid tailings (FT), and water capping, etc., the scope of Engineered Tailings Research is to explore other new concepts and leading-edge technologies for tailings treatment. The scope of Engineered Tailings Research varies from year to year based on the priority of research activities. In 2020, the following two activities were the scope of Engineered Tailings Research:

- 1) LSC (large strain consolidometer) and geotechnical beam centrifuge simulation tests of the co-processed deposit with SFR (sand to fines ratio) of 2.
- 2) More fines capture from composite tailings (CT) cyclone overflow.

Following the successful lab and small pilot tests of co-processing of fresh tailings from bitumen extraction and legacy FT (as per D085²) using modern paste tailings technology, LSC and geotechnical beam centrifuge simulation tests of the co-processed deposit with SFR of 2 were conducted in conjunction with other cohesive FT deposit tests. The hypothesis of co-processing of fresh tailings and FT is that the dewatering rate could be accelerated with the increase in SFR in the polymer treated co-processed deposit. The objective of this activity is to further prove the hypothesis and provide the technical foundation to further develop the co-processing technology at a field scale, and eventually implement this technology at a commercial scale.

While the composite tailings (CT) process consumes FT dredged from the tailings ponds, the CT cyclone also generates fines in the cyclone overflow. Capturing more fines from the CT cyclone overflow is a business opportunity to enhance the total fines capture. Characterization and flocculation tests of the CT cyclone overflow were conducted to explore the feasibility in technology.

² Legacy tailings as defined in D085 (*Directive 085: Fluid Tailings Management for Oil Sands Mining Projects*. 2017. Alberta Energy Regulator), are fluid tailings in storage before January 1, 2015.

PROGRESS AND ACHIEVEMENTS

The geotechnical property measurements of the co-processed deposit with SFR of 2 demonstrated that the liquid limit and plasticity index decrease significantly compared with the cohesive deposits with SFR of 0~0.2, while the plastic limits were similar and irrelevant to SFR of the deposits. The LSC and beam centrifuge tests demonstrated that the hydraulic conductivities of the co-processed deposit with SFR of 2 increase significantly (i.e., >3 orders of magnitude) compared with the cohesive deposits at the same void ratio. The co-processed deposit is less compressible compared with the cohesive deposits under the same effective stress. The beam centrifuge simulations of consolidation of a 50-m deep deposit for 150 years showed that the co-processed deposit with SFR of 2 could complete the consolidation in about 3.5 years to reach to the solids content close to the plastic limit of the deposit. These results verified the hypothesis that the dewatering rate could be accelerated with the increase in SFR in the polymer treated co-processed deposit.

Characterization of the CT cyclone overflow showed that the Aurora CT cyclone overflow contains more than 90% less than 44 μm fines. The flocculation test results demonstrated that it is feasible to treat the CT cyclone overflow with the polymeric flocculant in the pipeline before it is discharged into the deposition cell.

LESSONS LEARNED

The geotechnical property measurements and beam centrifuge simulation of deposit consolidation showed that the hydraulic conductivities of the co-processed deposit with SFR of 2 increase significantly (i.e., >3 orders of magnitude) compared with the cohesive deposits at the same void ratio. These data proved the hypothesis and provided the technical foundation to further develop the co-processing technology at a field scale and implement this technology at a commercial scale. The potential benefit of co-processing fresh tailings and FT is that this technology not only treats the legacy FT but also captures the new fines from the fresh tailings generated from extraction. The rapid consolidation of the co-processed deposit at SFR of 2 will accelerate the pace of reclamation and create a terrestrial landform that meets closure plan objectives.

The flocculation test results demonstrated that it is feasible to treat the CT cyclone overflow with the polymeric flocculant in the pipeline before it is discharged into the deposition cell. This provides the technical basis for a business opportunity to capture more fines from the CT cyclone overflow.



RESEARCH TEAM AND COLLABORATORS

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Principal Investigator: Simon Yuan

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Gonzalo Zambrano Narvaez	University of Alberta	Director-Geotechnical		
Yazhao Wang	University of Alberta	Researcher-Geotechnical		
Amarebh Sorta	Coanda R&D Corporation	Researcher-Geotechnical		

Tailings Surveillance Technologies

COSIA Project Number: TJ0073

Research Provider: Imperial

Industry Champion: Imperial

Industry Collaborators: InnoTech Alberta

Status: Year 1 of 1

PROJECT SUMMARY

COSIA member companies are focused on improving the management of oil sands tailings throughout their production, treatment, storage, reclamation, and closure phases. One of the important areas for tailings research is instrumentation—online and at line—to improve process control operations in tailings treatment (Corriveau 2018).

Potassium-40 (^{40}K or K40), a naturally occurring radioactive isotope of potassium (K), is commonly found in clay minerals present in oil sands ore and tailings (Corriveau 2018). For this project, InnoTech Alberta's K40 Analyzer was evaluated as an online and real-time tool to quantify clay minerals in different tailings and process streams with the objective to improve process control operations. The InnoTech Alberta K40 Analyzer is a gamma radiation detection system optimized to detect the decay of the potassium-40 isotope (^{40}K). Previous improvements to the K40 Analyzer enable the detection of radiation emitting from two additional isotopes (thorium-232, ^{232}Th and uranium-238, ^{238}U), and the determination of total gamma counts.

The project also included development of a model using the InnoTech Alberta K40 analyzer for different slurries and tank geometries. Six different slurries were studied: fluid tailings (FT), thickened tailings (TT), solids from the tailings solvent recovery unit (TSRU), coarse sand tailings (CST), flotation Tailings (FLT), and hydrotransport (HT) slurry.

The project was expected to provide insight into the capability of the K40 Analyzer to obtain measurements for the different streams and compare them to the K40 predicted by the model. For this purpose, laboratory test results obtained for the flotation tailings from a previous study formed a baseline for the prediction of other process streams. The second aspect that was examined was to predict gamma signals for different tank dimensions and setups of the flow cell – K40 system.

For tailing slurries, the water portion can affect the K40 measurement due to variation in the K concentration; thus, change in the ^{40}K measurements may not be due to actual differences in the solid portion (i.e., the dilution/concentration of K in the slurry will give different ^{40}K readings for a consistent solid portion). Thus, for tailings there are two variables: 1) water portion (or solids portion) and 2) K fraction in the solids portion. As the K40 instrument measures the total sample, it would give an indication of the diluted K in the stream. This also shows that it is necessary for sample homogeneity to reduce the noise impact and improve measurement repeatability between samples. Again, it must be noted that the correlation between clay parameters and K concentration must be proved for tailings slurries.

The parameters that were considered in the K40 measurement study were:

- Different tank geometries and design (rectangular and cone bottom tank);
- Sample residence time; and
- Tank mixing consideration.

PROGRESS AND ACHIEVEMENTS

A model was developed to predict the K40 counts per second (CPS) output for various process fluids such as fluid tailings, thickened tailings, solids from the tailing solvent recovery unit, coarse sand tailings, flotation tailings, and hydro-transport slurry. The model was setup and calibrated against the results from a previous project at Imperial's Kearl oil sands mine. A rectangular tank was also studied to assess the impacts of alternate geometries.

Analytical results were also obtained to correlate real sample data in the model. The model was calibrated against the previous testing results and a strong, linear relationship was proven with an R^2 value of 0.9836.

Two extreme cases, high and low solids content of each stream, were picked for modelling the streams of interest in the cone bottom tank. Each stream has a unique slope, indicating the fluids corresponding K content in the solid portion (weight %), and a strong, linear relationship was observed, showing that the variation in the slope is due to the variation in K content measured in the solid portion of those samples.

Tank geometries and design (rectangular and cone bottom tank)

A rectangular tank was defined such that the width and length were equal to the diameter of the cone bottom tank as used in the previous testing. Also, the heights were made equal as well as the wall thicknesses. This was done so a direct comparison could be made between the cylindrical and rectangular designs to assess how the increase in slurry volume (due to a square shape over a circle) would change the K40 analyzer output.

It was observed that the model predicted a marginally larger output for each fluid for the rectangular design over the cone bottom tank, which was significantly smaller than the percentage increase in the observable slurry volume and top view surface area. This prediction is conservative, and it is expected the real increase would be larger as the model does not predict how signal from one grid impacts others.

It is expected that a rectangular/square tank will provide an increase in the CPS output of the K40 analyzer. However, this type of tank is more difficult to produce, and a sloped bottom is recommended to allow for adequate tank draining/discharge of sample.

Sample residence time

The longer and larger in diameter the pipe is, the longer the delay of the K40 measurement to process. Therefore, it is desirable to minimize both, without sacrificing operational success. Due to the high concentration of solids within some of the streams, a larger pipe is desirable to avoid plugging issues, so a balance between pipe diameter and length, fluid volumetric flowrate, and required residence time must be found on a sample per sample basis.

Tank mixing consideration

Inadequate sample mixing reduces the K40 CPS and increases the measurement noise. It is therefore necessary to have a mixing system in the tank that fully mixes the sample.

Note, these conclusions are based on a theoretical calculation and must be interpreted as such. For a more accurate and definitive conclusion, real testing of the representative slurry is recommended.

LESSONS LEARNED

The following conclusions can be made based on the modelling work and actual measurement of different tailings streams.

1. The calibrated model successfully trends with the previous study's results.
2. The model predicted that FT, TT, CST, and FLT materials could potentially be successfully measured based on the given solids concentration and K-fraction in the solids using a cylindrical, cone-bottom tank similar to the one used in the previous Imperial Kearn testing project.
3. The model predicted that measuring TSRU would not be successful, due to the low solids concentration and K-fraction in the solids material.
4. The model predicted that measuring hydrotransport slurry would be difficult due to the low variation in the K-fraction in the sample. The CPS range between the low and high cases is narrow for this material, which may potentially be hard to incorporate process control due to signal to noise limitations of the K40 instrument.
5. A rectangular tank provides an increase to both the expected K40 CPS but also the system complexity.

Based on the results, it was not recommended to pursue using a rectangular tank for the marginal ~1% improvement. It was also recommended to incorporate adequate mixing in the tank to avoid the expected signal loss. Lastly, it is anticipated that FT, TT, CST, and FLT could successfully be measured using a cylindrical, cone-bottom tank, similar to that used in the previous Imperial Kearn study. Measurement of HT may be difficult due to the narrow range of expected solids in the sample, even though the predicted K40 CPS are good. This is because the variation in signal may not be larger than the expected signal noise level.

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RESEARCH TEAM AND COLLABORATORS

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Alok Seth	ExxonMobil	Research Advisor		

Research Collaborators: InnoTech Alberta

Permanent Aquatic Storage Structure for Fluid Tailings

COSIA Project Number: TJ0082

Research Provider: Suncor, Coanda Research & Development Corporation, SRK Consulting (Canada) Inc., University of Saskatchewan

Industry Champion: Suncor

Industry Collaborators: Teck (prior to 2020)

Status: Year 5 of 5

PROJECT SUMMARY

The Permanent Aquatic Storage Structure (PASS) project is focused on the treatment of fluid tailings (FT) to create a substrate that could be reclaimed into a freshwater lake after the end of deposition in a mined-out pit. The PASS project is a multi-year, multi-stage project from concept development to concept validation at bench, pilot and field scales. The technology was deployed at Suncor in 2018 with treatment and deposition in the summer months.

The key research objectives of the PASS project include: identifying the materials of potential concern (principal parameters) that might impede the geochemical and geotechnical stability of a freshwater lake; and developing FT treatment solutions to bring the principal parameters to levels that meet federal and provincial guidelines for freshwater lakes after the end of deposition. The water expressed from the substrate during the deposition period must also meet the criteria for use in bitumen production, as the water is recycled to the bitumen extraction process water loop.

The FT treatment process has three main steps carried out over a six to eight km pipeline from the FT feed inlet to the treated FT discharge into the mined-out pit. The first step entails the addition of an acidic coagulant to immobilize the principal parameters of concern through precipitation and chemisorption reactions within the future lake sediment. This includes ultrafine clays, dissolved metals, organic acids and hydrocarbons that may be deleterious to a freshwater lake ecosystem. This is followed by the addition of a flocculant that aids rapid release of water from the treated FT for use in bitumen extraction. The treated FT is subsequently conditioned and conveyed over several kilometres of pipeline to a deposition area within a mined-out pit.

After the end of final deposition, the treated FT is analogous to lake sediment settling over a long period of time. As settlement of the treated FT occurs, clean pore water from the lake sediment (water surrounding the individual solid particles of the treated FT) is continuously expressed or released to the overlying lake water cap, which is connected to the surrounding watershed. The immobilization process ensures geochemical stability of the lake landform such that seepage through the pit walls or expressed water to the lake water cap meets federal and provincial guidelines for the protection of aquatic life.

The PASS FT treatment technology leveraged decades of research and development in oil sands and mineral mine fluid tailings, bitumen extraction processes and wastewater treatment to simultaneously create a geochemically and geotechnically stable aquatic reclamation substrate. And given the long deposition periods and variability of the FT feed, performance models were developed to predict the deposit geochemical and geotechnical trajectories. These



models are supported and validated by bench and pilot scale geocolumns that would be monitored over several years.

PROGRESS AND ACHIEVEMENTS

- Technology hypothesis: Long-term immobilization of material of potential concern (principal parameters) in a PASS deposit
 - Ongoing monitoring of the 5-m geocolumns simulating several treatment variables indicate that the principal parameters remain immobilized and in line with the design basis. The concentrations of the principal parameters in the expressed and pore water over the past two years of commercial operation are also tracking the 5 m geocolumns. The research also indicates that both aluminum and iron (III) based coagulants (beyond a threshold dosage) are effective at immobilizing the principal parameters in the short-term while minimizing the impact on rapid water release after flocculant addition.
 - Biogeochemical modelling of the principal parameters in the anoxic pore water and the transition to the oxic expressed water during settlement is ongoing to enable prediction of the principal parameters' trajectories in the long run.
- Technology hypothesis: Rapid dewatering of treated FT through flocculant addition
 - A few high molecular weight anionic polyacrylamides and one non-ionic, high molecular weight polyethylene oxide have validated to be compatible with the acidic coagulant without significant impact on the settlement and consolidation behaviour of the deposit.

LESSONS LEARNED

To date, the project has demonstrated that the FT treatment process can accelerate the reclamation timelines for aquatic landforms following in-pit deposition of FT.

PRESENTATIONS AND PUBLICATIONS

Omotoso, O. 2019. PASS: A new technology solution for tailings management. Presented at the CIM convention, Montreal. April 29, 2019.



RESEARCH TEAM AND COLLABORATORS

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Daryl Hockley	SRK Consulting (Canada) Inc.	Corporate Consultant		

Industry Collaborators: Teck - industry collaborator prior to 2020

Fluid Tailings In-line Flocculation and Co-deposition

COSIA Project Number: TJ0108

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 1 of 2

PROJECT SUMMARY

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

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

This pilot and the site investigation from the two deposits were completed in the fall of 2020. The analysis of the deposit is still in progress and therefore discussion on the data herein is limited and will evolve as more data become available and are evaluated.

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

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

This project fits within COSIA's innovation opportunity, "Optimize Flocculants/Coagulant Suite and Dosage to Improve De-watering" and "beach fines capture." The results will be analyzed and the final outcome will be communicated through COSIA's communications channels.

PROGRESS AND ACHIEVEMENTS

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

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

A geotechnical site investigation program was conducted at the eILF test cells about two weeks after the completion of the pour and was concluded in about 11 days. The objectives were to:

- Collect representative samples across the tailings deposits to characterize them for solids, water, and fines content.
- Run in-situ tests (Cone Penetration and Vane Shear) to assess the variations of strength across the deposit.

The following characterization tests were conducted on the samples:

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

LESSONS LEARNED

Results of the in-situ tests and samples are currently under review. The outcome of the pilot and lessons learned will be reported in 2021.



RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigator: Atoosa Zahabi

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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Accelerated Dewatering and Deposit Monitoring

COSIA Project Number: TJ0109

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Ongoing

PROJECT SUMMARY

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

The geotechnical performance of the latest ADW pilot deposits created in 2017 and 2018 at Syncrude are being monitored through in-situ monitoring, testing and sampling. The geotechnical properties and performance of the latest deposits were superior compared to the earlier (2009) ADW deposit. In addition, large-strain consolidation material properties determined for the latest ADW deposits showed superior mechanical and hydraulic properties compared to the 2009 ADW deposit. This observation confirms the preliminary findings previously reported (COSIA 2020) that the chemical amendment and mixing improvements implemented for the latest ADW deposits are effective in improving the geotechnical performance of the resulting deposits. All the pilot ADW deposits are continuously monitored in order to assess their long-term geotechnical performance.

PROGRESS AND ACHIEVEMENTS

The improvements in the geotechnical performance observed for the latest ADW deposits (2017 and 2018) over the 2009 ADW (as previously reported in COSIA 2020) continue. Two of the newer deposits (Cells 1 and 3) had a coagulant plus polymer as the chemical amendments. The coagulant for Cell 1 was gypsum, while that for Cell 3 is Syncrude's Flue Gas Desulphurization Solids (FGDS). The initial dewatering, settlement, profile solids content and fines-over-fines-plus-water (FOFW) for Cell 3 deposit was slightly higher compared to Cell 1. However, the initial profile undrained shear strength for both deposits are similar. The undrained shear strength profiles continued to increase year over year, for the entire depth of the deposits. Also, the density-shear strength relationship for both deposits is similar. In addition, the compressibility and hydraulic conductivity functions for Cells 1 and 3 are also similar, with both showing lower compressibilities and higher hydraulic conductivities compared to the 2009 ADW

deposit. These observations confirm that the improved ADW process was successful in creating tailings deposit with superior geotechnical properties and performance compared to the 2009 ADW deposit.

LESSONS LEARNED

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

LITERATURE CITED

[COSIA] Canada's Oil Sands Innovation Alliance. 2020. 2019 Tailings Research Report. Report available and downloadable at
https://cosia.ca/sites/default/files/attachments/2019%20Tailings%20Research%20Report_FINAL.pdf

RESEARCH TEAM AND COLLABORATORS

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In-line Flocculation of Fluid Tailings Field Pilot

COSIA Project Number: TJ0117

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 2 of 4

PROJECT SUMMARY

In-line flocculated fluid tailings (ILF FT) has been used successfully in the oil sands in combination with atmospheric drying and mechanical re-handling to produce ready-to-reclaim deposits. This project focuses on using ILF FT that is supplementary to thickening and co-deposited with high sands-to-fines ratio (SFR) materials (e.g., thickened tailings) to increase fines treatment volumes and enhance the consolidation of the ILF FT in a deep deposit. Figure 1 illustrates a FT line that can produce ILF FT when one or both thickeners are offline.

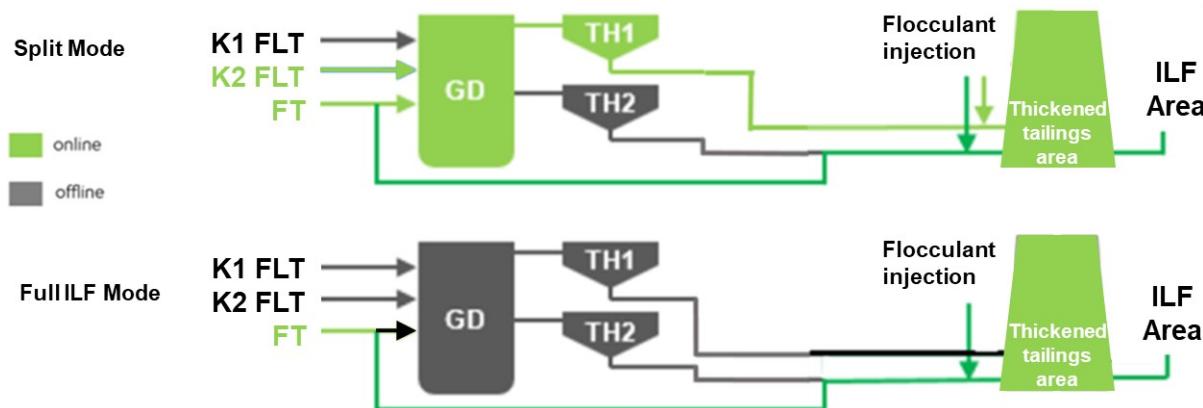


Figure1: Schematic diagram of In-line Flocculation Process

K1 Kefal Plant 1
TH1 Thickener 1

K2 Kefal Plant 2
TH2 Thickener 2

FLT flotation tailings
ILF In-line flocculation

FT fluid tailings

GD gravity distributor

The initial project phase was focused on evaluating optimal treatment conditions and material properties of ILF FT using laboratory testing and a field pilot. Phase two of the project comprises evaluation of ILF FT co-deposited with high SFR materials in the laboratory and in a field pilot.

PROGRESS AND ACHIEVEMENTS

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

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

The next phase of the project is to design an in-line flocculated FT co-deposit with high SFR TT or coarse sand tailings to create a product, which can achieve ready-to-reclaim criteria.

LESSONS LEARNED

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

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- [COSIA] Canada's Oil Sands Innovation Alliance. 2016. Unified fines method for minus 44 micron material and for particle size distribution. Compiled by COSIA fines measurement working group, February 2016.
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- [COSIA] Canada's Oil Sands Innovation Alliance 2012. Technical Guide for Fluid Fine Tailings Management. Compiled by Oil Sands Tailings Consortium Companies, August 2012.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigator: Sidantha Weerakone

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Atoosa Zahabi	Imperial	Tailings Technology Area Lead - Research		
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Enhanced In-line Flocculation of Fluid Tailings Field Pilot

COSIA Project Number: TJ0118

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 2 of 3

PROJECT SUMMARY

At Kearl, Imperial's oil sands mining operation, thickeners are used to remove water from the tailings prior to deposition in the tailings deposition area. In 2019, Imperial conducted an "Enhanced In-line Flocculation" (eILF) field pilot study at Kearl. This was a follow-up to the 2018 proof of concept laboratory study. The objective of the field-scale pilot was to assess the advantage of fluid tailings (FT) treatment using an enhanced chemistry (consisting of coagulant, colloidal silica, and flocculant) compared to a single flocculant or polymer.

The pilot study included two research areas or cells consisting of a single polymer and the enhanced chemistry. In addition to the polymer, the enhanced chemistry included a coagulant and colloidal silica. The source of the FT was from the Kearl thickened tailings (TT) deposition panels, located within the tailings deposit area. The sand-to-fines ratio (SFR) for the source material was in the range of 0.2-0.4 and solids content was in the range of 20 to 40 percent by weight (wt%). A pipeline was built to transfer the FT from the TT panels to the two research cells. Three chemical skids were used to inject the chemicals in-line, to ensure sufficient mixing energy for the chemicals and FT. The distance of the chemical injection locations from the end of the pipe was determined using computational fluid dynamics (CFD) modelling. The CFD modelling was informed by previous data as well as the design for the Kearl FT secondary treatment project. The objectives of the field pilot study were to:

- assess the feasibility of the enhanced chemistry regime (coagulant, colloidal silica, and flocculant) for treating FT;
- examine a wider operating window of eILF; and
- recommend eILF for commercial treatment of FT from the TT panels once the concept was proven.

Monitoring instrumentation was installed in the two cells to enable monitoring for up to one year. Monitoring parameters included pore pressure along the depth and length of the deposit, turbidity, change in solids and moisture content, and temperature. These parameters were the key performance indicators (KPIs) for the study.

A local lab was set-up at the study's location and samples were collected during the trial and tested in the local lab. The objective was to monitor the performance of the treated FT based on the KPIs and to apply any changes to the process and dosages, as required.

A commissioning cell was designed to direct the treated FT during optimization of the process and dosages before diverting the treated FT to the research cells. Treated FT could be diverted to the commissioning cell if major upset conditions were encountered during the study period.

This project fits within COSIA's innovation opportunity, "Optimize Flocculants/Coagulant Suite and Dosage to Improve De-watering." The results will be analyzed and the final outcome will be communicated via COISA's communications channels. The enhanced chemistry can substitute the current single polymer application for treating FT or mature fine tailings (MFT) with a wider operating window. Following this project, Imperial will evaluate various deposition scenarios—using the enhanced chemistry technology—to meet regulatory and closure criteria.

PROGRESS AND ACHIEVEMENTS

The lab scale study of the enhanced chemistry project showed improvement in the KPIs of treated FT when compared to the single polymer treated FT. Two field investigations were completed one year apart on both cells in 2019 and 2020. Data analysis of the results from the initial field investigation has been completed. The final site investigation will be evaluating the consolidation and strength gain after one freeze-thaw and evaporation cycle, also to confirm whether some fines have been captured in the underlying sand bed. These results will be shared in the subsequent COSIA tailings research reports.

In this report, the summary of the deposit analysis from the initial field investigation and the water chemistry modelling is shared.

Deposit analysis:

Surface cracking was observed on the enhanced treatment deposit a day after the pour. The initial cracking is potentially a result of the enhanced chemistry; however, it provides path for more dewatering from the deposit. Below are the outcomes of the data analysis from both cells.

- The enhanced treatment deposit formed a steeper slope (5.4%) close to the discharge point compared to the single polymer Cell (2.2%).
- Average solids content in the ILF phase 2 Cell was ~4% higher than the single polymer Cell, with maximum values at surface ~10% higher closer to the discharge point (61% at ILF phase 2 vs. 51% at single polymer Cell).
- Peak Shear Stress values from the Vane Tests were significantly higher in the ILF phase 2 Cell (~ 6kPa) compared to the single polymer Cell (1.5-2 kPa).
- Pore Pressure dissipation tests indicated a more porous deposit in the ILF phase 2 Cell (i.e. higher permeability resulting in higher dewatering rate).

Water Chemistry Modelling:

A water modelling study was completed to assess the effect of the enhanced treatment chemistry on the chemistry of the pond water. Water characterization was evaluated on samples of the release water collected during the pilot

for both cells. The results of the water chemistry analysis tests were utilized in water modelling software and mass balancing to assess the impact on pond water chemistry. The model showed the release water from the treated FT via the enhanced treatment chemistry does not change the pond water chemistry significantly. It was also shown that the treatment does not increase the ionic (monovalent and divalent) concentration to levels that negatively impacts the bitumen extraction process.

LESSONS LEARNED

The outcome of the study will be shared in 2021 after analysis of the second year of field investigation data.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigator: Atoosa Zahabi

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Physically Upgraded Trafficable Tailings Innovation (PUTTI)

COSIA Project Number: TJ0128

Research Provider: Imperial

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Teck

Status: Year 1 of 3

PROJECT SUMMARY

Filtration offers an opportunity to turn fluid tailings 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 and geotechnical and closure aspects) of Plate and Frame filtration of oil sands fluid tailings (FT). Prior to mechanical dewatering, the tailings were conditioned by a combination of a coagulant and a polymer. The plate and frame filtration process is 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 result showed filter cake of more than 60% solids were achievable with filtrate less than 1% solids. They 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 process 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 performance of alternative chemical treatment technologies including Imperial's Enhanced Chemical Treatment for mechanical dewatering (both batch and continuous filtration) and identify an efficient chemical treatment suitable for mechanical dewatering.

Phase 1

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



1. Benchmarking enhanced chemical treatment to flocculant coagulant treatments for application in mechanical dewatering (both batch and continuous).
2. Chemical treatment optimization including evaluation of alternative chemical treatments to mitigate filter cake plugging and cake discharge challenges
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 and testing
2. Deposit geotechnical and closure assessment

PROGRESS AND ACHIEVEMENTS

Laboratory mechanical dewatering testing to evaluate performance of pressure and vacuum filtration for enhanced inline flocculated fluid tailings and benchmarking with alternative treatment in progress.

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.

PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

Imperial Oil Resources Limited, Oil sand tailings treatment using flocculation and treatment with a coagulant and a silicate, CA3048297, Canadian Intellectual Property Office, 09 March 2021



RESEARCH TEAM AND COLLABORATORS

Institution: Imperial and Teck

Principal Investigator: Givemore Sakuhuni

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John Clark	Teck	Acting Manager		

Enhanced Fines Beach Capture Using Carbon Dioxide in Coarse Sand Tailings

COSIA Project Number: TJ0129

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 3 of 4

PROJECT SUMMARY

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

In 2018, Imperial's tailings research team conducted a laboratory program to evaluate the increase in fines capture by CO₂ injection, determine the dosage requirements and the effects on pH and rheology, and water release. Results of the lab program indicated a significant increase in fines capture after CO₂ injection, a reduction in pH which recovered with time, no significant impact on rheology, and an increased rate of water release. The CO₂ dosage was also determined for commercial scale trial.

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

- evaluate the changes in fines content and fines capture of the beaches formed as a result of CO₂ treatment; and
- understand the potential impact on geotechnical characteristics and behaviour of the deposit.

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

- be within one of the existing internal dykes at the Kearl External Tailings Facility;
- accommodate typical hydraulic upstream construction technique and equipment (i.e., dozers) to build two cells and beaches for pouring untreated CST and CO₂-treated CST streams. Dozers construct and compact the cells but beaches are not track packed.

A site investigation program was conducted in December 2020 to carry out in-situ tests and to collect samples for further laboratory analysis.

PROGRESS AND ACHIEVEMENTS

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

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

LESSONS LEARNED

The laboratory testing and data analysis are in progress. Lessons learned specific to the results will be provided in subsequent reporting.

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

REFERENCES

[COSIA] Canada's Oil Sands Innovation Alliance Carbon Dioxide Amended Tailings, online publication by COSIA:
<https://cosia.ca/initiatives/tailings/projects/carbon-dioxide-amended-tailings> accessed on Feb. 24, 2021.

RESEARCH TEAM AND COLLABORATORS

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NSERC-Syncrude Industrial Research Chair in Mine Closure Geochemistry (Term 2)

COSIA Project Number: TJ0130

Research Provider: University of Saskatchewan

Industry Champion: Syncrude

Status: Year 1 of 5 (Term 2 of IRC)

PROJECT SUMMARY

The second five-year term of the NSERC-Syncrude Industrial Research Chair (IRC) in Mine Closure Geochemistry started on April 1, 2019 with support from NSERC, Syncrude, and the University of Saskatchewan (USask). Led by Dr. Matthew Lindsay in the Department of Geological Sciences at USask, the overall IRC goal is to generate scientific knowledge and tools to mitigate geochemical risks to mine closure.

Mine closure research has traditionally focused on improving our understanding of the chemical, biological and physical aspects of individual mine waste deposits, and the past decade has seen an expansion of research into strategies for managing or reclaiming these deposits. Although deposit-focused research is appropriate for many mining operations, 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 studied 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 renewal term is to improve estimates of contaminant source terms for reactive mine wastes, and to develop strategies for decreasing chemical mass loading from the closure landscape to the receiving environment. These strategies have the potential to improve environmental outcomes and to minimize costs for mine closures for industry. This research focuses on the geochemistry of reactive wastes, such as froth treatment tailings (FTT), and how they interact with other materials in closure landscapes. Specific research activities fall under four interrelated themes:

Theme 1: Mineralogy and geochemistry of solid waste 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 geochemical and mineralogical characterization



of solid waste materials is focused both on end-of-pipe mine wastes and solid waste materials generated at various steps during processing. Field sampling, field and laboratory experiments, and numerical modelling examine the geochemical evolution of FTT deposits, and evaluate potential geochemical stabilization methods. Finally, laboratory experiments evaluate passive water treatment strategies that could be integrated into the mine closure landscape.

Ultimately, this research explores strategies to mitigate negative impacts on water quality. Overall, the research findings will provide critical new information for long-range mine closure planning including improved contaminant source term estimates for reactive mine wastes, positive and negative implications of mine reclamation strategies, and new opportunities for integrated mine waste management and reclamation. Consequently, information generated through this IRC program will offer new strategies to decrease environmental impacts and financial liability of oil sands mining operations.

PROGRESS AND ACHIEVEMENTS

Progress had been made on many proposed research activities despite unforeseen challenges related to student recruitment, drilling activities, and the COVID-19 pandemic. Revisions to the original activity schedule have been made to accommodate these challenges without compromising research goals and objectives. The most substantial delays are related to drilling activities and the COVID-19 pandemic. The drilling program was initially delayed due to equipment and crew availability, and later due to extreme cold and subsequent crew availability. Additionally, the onset of the COVID-19 pandemic in Canada led USask to mandate a shutdown of all research activities on March 16, 2020, and postponement of all field-based research activities by Syncrude. USask initiated staged laboratory reopening in July 2020, but all field-based research activities were deferred to 2021 due to travel restrictions and health concerns.

The drilling program, which focused on the commercial-scale Plant 6 FTT deposit in the Mildred Lake Settling Basin, was initiated in November 2019 and nearing completion when on-site activities were halted in January 2020. After careful consideration, we determined that research objectives dependent upon this drilling program could be met with existing samples. Several IRC trainees were permitted to resume laboratory activities between July and December 2020. These trainees have focused their laboratory activities processing and analyzing samples from the completed drilling program. This research included pore-water extraction and analysis, along with geochemical and mineralogical analysis of associated solids.

Data generated from the drilling program have directly informed other research activities and, in retrospect, delays in other research projects due to the COVID-19 pandemic have provided opportunities to refine subsequent research objectives and activities. Although activity schedules have been revised to minimize delays, the IRC program will likely require an extension beyond the original five-year timeline. Nevertheless, student recruiting, research planning, laboratory activities, and field work will continue ramp up as pandemic restrictions are eased.

The following summarizes progress by theme and activity since April 1, 2019:

Theme 1: Mineralogy and Geochemistry of Solid Waste Materials

Following meetings between Lindsay and Syncrude Mine Closure Research (MCR) team, Activities 1.1 and 1.2 were refocused on the commercial-scale FTT deposit. There were three reasons for this decision: (i) an improved



understanding of mineralogical separation during the extraction and froth treatment process; (ii) initial results from the drilling program indicate greater sample heterogeneity than originally thought; and (iii) this information will support ongoing research efforts and mine closure planning.

Activity 1.1: Characterize process mineralogy and geochemistry

Drake Meili (MSc) initiated this research in September 2019 focussing on core samples ($n > 150$) obtained from the Plant 6 FTT beach drilling program (see Activity 2.1) below. Progress during 2020 was limited by COVID-19 restrictions, but sample processing and analysis is now underway. Bulk geochemical and mineralogical analyses will be completed by August 2021. Electron microscopy and electron microprobe analysis will be completed by December 2021.

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

Student (MSc) recruiting was paused in winter 2020 due to unforeseen drilling and COVID-19 delays. A prospective student has been identified and research will now be initiated in September 2021. This research will explore various methods commonly used to assess potential for acid generation and metal leaching from mining wastes and other materials. Longer term experiments may be initiated in May 2021 to prevent additional delays.

Theme 2: Geochemical Evolution of Closure Landforms

This research theme is directly dependent upon results of the 2019/2020 drilling program. As previously mentioned, this drilling program experienced delays due to equipment availability, crew availability, and extreme cold. The majority of the original drilling program scope was completed before the COVID-19 pandemic. In total, continuous sonic cores were collected at eight locations along a ~1.6 km transect of the Plant 6 FTT deposit. This drilling program produced ~175 samples that (i) directly support research Activities 1.1, 1.2, and 2.1, and (ii) support research planning for Activities 2.2, 3.1, 3.2, 4.1 and 4.2.

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

Josh Paulsen (MSc) initiated this research in September 2019 with support from Dr. Valerie Schoepfer (PDF). This research is focused on core samples obtained at high spatial resolution (i.e., 0.10 to 0.25 m intervals) within the upper 5 to 10 m of the Plant 6 FTT deposit, where evidence of sulfide-mineral oxidation was previously noted. Pore water has been extracted from samples at 6 locations and associated solids were retained for geochemical, mineralogical and microbial analysis. Geochemical and mineralogical analysis is underway, and microbial analysis will be initiated in fall 2021. Reactive transport modelling will be initiated in 2023 once sufficient data are available to support model parameterization. Trainees will be recruited to support the microbial and modelling studies when appropriate.

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

This activity has also been delayed due to COVID-19 restrictions. However, construction and instrumentation of field experimental systems will be completed during summer 2021 in conjunction with those described under Activity 3.1. Recruiting is underway for an MSc student to assume responsibility for this research project starting in May 2022. To limit travel and site access, initial monitoring will be supported by other members of the IRC Team.



Theme 3: Geochemical Stabilization of Reactive Wastes

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

Eduardo Marquez (PhD student) initiated this research remotely on May 1, 2020. Construction and instrumentation of field experiments was postponed until summer 2021 due to travel and site access restrictions. Progress to date has included initial hydrogeological modelling to support experimental design. Field, laboratory, and modelling related to this activity will ramp up dramatically during 2021.

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

This project has been delayed due to COVID-19 restrictions. Research plans will be discussed and timelines will be revised during upcoming meetings between Lindsay and the Syncrude MCR team.

Theme 4: Passive Water Treatment in Closure Landscapes

Activity 4.1: Examine potential for water treatment by end pit lakes

The scope of this activity has been revised following discussions between the USask IRC and Syncrude MCR teams. Rather than focussing solely on end pit lakes, this activity will more broadly consider opportunities for passive in-situ treatment of FTT drainage. Specifically, this activity will now focus on selective placement of various mine materials (e.g., overburden, extraction wastes, upgrading byproducts) to limit contaminant transport and discharge. Sanaz Hasani (PhD student) was recruited to initiate this research in May 2020, but her start date was pushed back to September 2020 due to previously discussed delays and restrictions. Laboratory research activities will be initiated in May 2021 once Sanaz, an international student, is able to travel to Canada.

Activity 4.2: Evaluate passive treatment options for FTT drainage

Jake Marchi (MSc Student) started his degree program remotely in September 2020 and will initiate field and laboratory activities during summer 2021. Initial experiments will examine the role of sulfate reduction within FTT deposits in passive water treatment.

LESSONS LEARNED

This report describes progress made during Year 1 of a five-year research program. Due to delays described above, we cannot yet provide any information on lessons learned.

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., In Review. 2020. Metal leaching from oil sands fluid petroleum coke under different geochemical conditions. MSc Thesis, University of Saskatchewan, Saskatoon, Canada.

Journal Publications

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 Space Chem.* 4(7), 1114-1126. DOI: 10.1021/acsearthspacechem.0c00099

Vessey, C.J., Schmidt, M.P., Abdolahnezhad, M., Peak, D., Lindsay, M.B.J. 2020. Adsorption of (poly)vanadate onto ferrihydrite and hematite: An in situ ATR-FTIR study. *ACS Earth and Space Chemistry*, 4: 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 and Technology*, 54: 4007–4015. DOI:10.1021/acs.est.9b06250

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

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

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

Conference Presentations/Posters

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

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

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

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

Lindsay, M. 2019. Geochemical considerations for improved management of sulfide mine tailings. Society for Geology Applied to Mineral Deposits (SGA) 2019, August 27 – 30, Glasgow, United Kingdom.

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

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

Reports & Other Publications

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

RESEARCH TEAM AND COLLABORATORS

Institution: University of Saskatchewan (USask)

Principal Investigator: Dr. Matthew Lindsay

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Matthew Lindsay	USask	Principal Investigator		
Emily Champion	USask	BSc – Summer Student	2019	2019
Drake Meili	USask	BSc – Summer Student	2019	2019
Josh Paulsen	USask	BSc – Summer Student	2019	2019
Matthew Fellwock	USask	BSc – Research Student	2020	2021
Mojtaba Abdolahnezhad	USask	MSc	2016*	2020
Mattea Cowell	USask	MSc	2016*	2021
Drake Meili	USask	MSc	2019	2022
Josh Paulsen	USask	MSc	2019	2022
James Schulte	USask	MSc	2018	2021
Jake Marchi	USask	MSc	2020	2023
Eduardo Marquez	USask	PhD	2020	2024
Sanaz Hasani	USask	PhD	2020	2024
Valerie Schoepfer	USask	PDF	2019	2022
Mohamed Edahbi	USask	PDF	2019	2020
Noel Galuschik	USask	Research Assistant		
Brenda Bews	USask	Research Engineer		
Dr. Lee Barbour	USask	Professor Emeritus		
Dr. Lesley Warren	University of Toronto	Professor		
Dr. Rich Amos	Carleton University	Associate Professor		
Dr. Michael Wieser	University of Calgary	Professor		
Hamilton Jordan	Syncrude	Project Steward		



*Research projects initiated during IRC Term 1.

Optimized Seasonal Mature Fine Tailings Dewatering

COSIA Project Number: TJ0131

Research Providers: Suncor, Coanda Research & Development Corporation, NAIT, SRK Consulting (Canada) Inc., Thurber Engineering Ltd.

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

The optimized seasonal mature fine tailings (MFT) dewatering project was set up to identify an optimal approach for MFT storage and treatment to achieve a terrestrial closure landscape. The dewatering mechanisms examined for the project included: flocculation assisted dewatering; atmospheric drying; freeze-thaw action; and long-term consolidation to maximize production intensity, cubic metre of fluid tailings (FT) per square metre of surface area. The dewatering potential for each mechanism, including process dewatering, atmospheric drying, climatic effects, and impact of freezing on compressibility and hydraulic conductivity, was also examined. The applicability of the optimized seasonal approach to froth treatment tailings (FTT) Affected fluid tailings was studied. FTT-affected FT is a potential source of acid rock drainage (ARD) within the deposit.

PROGRESS AND ACHIEVEMENTS

The following studies were completed during the project:

1. FTT Affected FT Slurry to Soil Testing: Determination of the strength parameters as relate to reduction in moisture content for FTT affected FT
2. Freeze-thaw Study: Investigation of the climatic performance of Northern Alberta and stochastic modelling of expected freezing depths
3. Treated FT Conveyance Testing: evaluation of the low pipeline shear transportation of treated FT, and its impact on flocculant assisted process dewatering
4. Qualitative treated FT Freeze-thaw Testing: investigation of the effect of different treatments and process conditions on freeze-thaw dewatering
5. Freeze-thaw Consolidation Study: determination of the change in consolidation properties associated with FT undergoing a freeze-thaw cycle
6. FTT Affected FT Geochemical Study: Desktop study into the potential of atmospherically dried FTT affected FT to develop acid rock drainage



7. Statistical analysis of process performance: stochastic investigation into expected flocculant assisted process dewatering rates based on previous MFT Drying Performance
8. In-line flocculation of FTT Affected FT: confirmation of process dewatering and low shear conveyed dewatering performance.

LESSONS LEARNED

Operational guidance for the treatment of FTT Affected FT deposit includes:

- Achieve a 2 kPa residual vane shear strength for each lift of dried FTT Affected MFT;
- Maintain a CWR of less than 3×10^{-9} ;
- Maintain drying times of less than 1 month and neutral conditions within deposit;
- Utilize freeze thaw on deposit by maintaining rate of rise of 1 m to assist long term consolidation and increase robustness of flocculation and drying operations; and
- Freeze-thaw will destroy flocculated MFT structure and effectively make a different soil. These properties of strength and permeability are still compatible with operational deposit objectives

The long-term deposit objectives during closure are:

- Maintain saturation of > 85% within the deposit and minimize oxygen diffusion into deposit with suitable cap
- Avoid lateral groundwater flow in aquifers at the deposit interfaces with water flow and deposit should remain below potential long-term erosion surface

The gaps that remain prior to applying the project results to a full FTT Affected MFT include:

- Determine diluent mass balance on flocculated, atmospherically dried MFT
- Validate deposition and cell utilization of treated FTT Affected MFT across long shallow cells for selected treatment process
- Determine what the likely geochemical impacts of exposing this material as part of long-term closure for site specific conditions
- Quantify Naturally Occurring Radioactive Materials (NORM) risk at CWR <1 drying states
- Conduct laboratory validation on ARD predictions as per the vendor's recommendations
- Conduct sensitivity of the process between process dewatering, drying, freeze thaw and long-term consolidation to determine production rates and optimized operating strategy

- Odour of FTT Affected MFT during drying

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor and numerous internal and external professionals

Principal Investigator: Fergus Murphy

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Fergus Murphy	Suncor	Principal Investigator Sr. Engineer – Tailings Technology Development		
Ardalan Sadighian	Suncor	Ph.D Tailings Researcher		
Sean Wells	Suncor	Tailings STEN Lead		

Research Collaborators: Researchers from the following institutions included:

1. SRK: Daryl Hockley, Macoura Kone, Peter Luedke
2. Coanda: Benny Moijs, Amarebh Sorta, Nick Byford, Neville Dubash, Mirko Moeller
3. NAIT: Heather Kaminsky, Simon Sun, Yunhui Li
4. Thurber: Sam Proskin, Randal Osicki, Silawat Jeeravipoolvarn, Nick Beier (UofA)



FROTH TREATMENT TAILINGS

Laboratory Investigation of Transport, Segregation and Deposition of Tailings Solvent Recovery Unit Tailings

COSIA Project Number: TE0035 RWG (IOSI)

Research Provider: University of Minnesota

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 3 of 3 – Project Complete

PROJECT SUMMARY

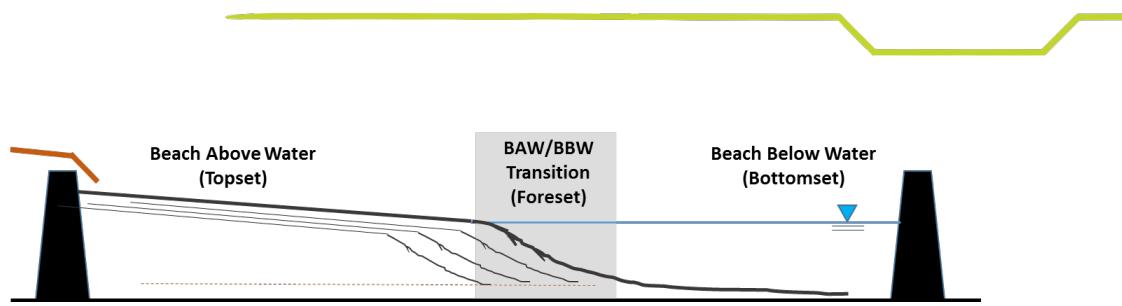
Tailings solvent recovery unit (TSRU) tailings are generated during the froth treatment process of the oil sands bitumen extraction process. Light hydrocarbons are used as the solvent/diluent in froth treatment. The solvent/diluent is recovered in the TSRU and recycled back into the bitumen extraction process. The residual water, solids (including asphaltene aggregates), and trace amounts of solvent from the TSRU—collectively the TSRU tailings—are deposited in tailings facilities. TSRU tailings represent a small fraction of the overall tailings volumes produced but have unique characteristics, which affect their behaviour in the tailings facilities.

The motivation of the project was to develop insights into the unique processes that are associated with TSRU tailings and determine if there are opportunities to improve processes and outcomes of tailings storage in tailings facilities. Here we report on a series of laboratory experiments investigating the **transport, segregation, and deposition** of TSRU tailings in external tailings facilities (ETFs). Sometimes TSRU tailings are treated with a flocculant prior to deposition, however in this project a flocculant was not used.

The experiments used field and operational data to design a specialized facility and hydraulic conditions that replicated full-scale hydraulic conditions. The unit discharges (discharge per unit width) were estimated for the field and modelled in the lab. The 0.1 m wide by 10 m long flume represented the dynamics existing within a quasi-2D “slice” (or cross-section) of a fully 3D beach deposit. The experiment effectively simulated an active channel flowing over the beach and entering the pond environment. The clear walls of the flume provided opportunity to study the physics of transport, segregation, and deposition associated with TSRU tailings disposal.

The research involved two phases of study covering a range of different particle size distributions and included surrogate tailings materials (Surrogate Mixtures A and B) (Phase 1) and real TSRU tailings (Phase 2). We also investigated effects of changing influent discharge and solids concentrations. The results between the TSRU tailings and surrogate tailings were qualitatively similar. With these similarities and the quantitative differences, the project reveals insight into parameters that influence effectiveness of particle capture on the beach of a tailings pond.

The experiments identified three regions or zones within the simulated ETF with distinct transport, segregation and deposition processes. The figure below defines these three regions and below we summarize the salient transport, segregation, and deposition processes in each region.



PROGRESS AND ACHIEVEMENTS

I. Transport

At a typical time in the beach build-out process, tailings are carried along with the fluid via several different processes, depending on their relative weight and sizes and the local slope. The typical transport modes are described below:

1. The smallest and least dense particles move as a suspension in the fluid; that is, they move almost entirely like they are an integral part of the fluid. In other words, the smaller lighter particles move locally essentially as a single phase with the fluid.
2. The larger and denser particles sink to the bottom of the flow and often have interactions with other particles and the bed. They are transported from this lower point in a way that depends on flow dynamics and local slope. Four possible processes (categories) are described below:
 - (a) For conditions of vigorous flow and lower slopes, particles are transported downstream along the bottom boundary of the flow by the fluid in a moderately dense sheared layer. This is often defined in the geology literature as “vigorous bedload conditions” or “bed sheet flows.”
 - (b) For conditions of gentle flow along low slopes, particles are transported downstream by the fluid under bedload and suspended load transport conditions.
 - (c) For conditions of less vigorous flow and higher slopes, particles are carried primarily by their own weight in a high density layer that cascades or slides down the slope.
 - (d) For conditions of vigorous flow and higher slopes, the particles are transported by a combination of gravity down the slope such as described above in (c) but may also be influenced by the flow field resulting in measurable downstream transport of coarse material.

At any instant in time, most or all of these phases exist concurrently at different parts of the flume. For this summary, it is most useful to envision this in the context of steady state, after an initial deposit is built up.

Transport in the Beach Above Water (BAW)

After the particle-fluid flow (discharge) exited the pipe and passed through the plunge pool, it entered the BAW, characterized by a relatively low self-formed slope. The transport in this region was that of category (a) above. The



smallest particles were contained in a narrow high-speed turbulent flow and the medium and larger particles moved along the bed in a multi-particle thick sheared flow.

Transport in the BAW/BBW Transition

At the downstream extent of the BAW, the slope of the deposit abruptly steepened into what is defined as the foreset or the BAW/BBW Transition. As the flow entered the pond, it slowed relatively quickly, leading to a transition from category (a) to (d) to (c) as described above. The finest particles stayed in suspension, while medium and larger particles were increasingly carried down the slope by their own weight or, as will be discussed below, through particle avalanching and kinetic sieving processes.

Transport in the Beach Below Water (BBW)

The third and final stage of the transport consisted of a much gentler and slower average local velocity and low slope; transport of category (b) above. Once the flow reached the bottom or toe of the foreset, the slope became much lower. We observed two primary transport processes in this region. For experiments with significant fine or medium sized solids, such as Surrogate Mixture B and TSRU tailings, a sediment laden, sustained turbidity current formed and moved particles into the BBW region. At distances far from the foreset, the flow became nearly stationary. This region is the analog of the tailing ponds far from the BAW.

II. Segregation

In this section we describe the active *segregation dynamics*. That is, we summarize the observed physics of the segregation processes that dominated while the particles were flowing.

Segregation in the BAW

As the particle-fluid flow (influent) entered the BAW at the inlet there was a near-instantaneous segregation of the smaller less dense particles from the rest of the particles. The vigorous flow over the relatively low slope transported a range of the lighter particles in suspension. Only the heavier (larger and/or denser particles) fell to the bottom boundary and were transported as a sheared layer. In this sheared layer another segregation mechanism was evident, known as dynamic sieving. Specifically, the smaller particles in the sheared layer find openings to drop toward the bottom of the layer, forcing the larger particles upward to the top of the sheared particle layer. The segregation dynamics observed in the BAW include:

- The top of the flow flowed at maximum velocity and carried lighter particles along with the flow and at a relatively low concentration.
- The bottom of the flow was sheared much more slowly and consisted of a relatively high concentration of larger particles. What is often called “kinematic” or “dynamic” sieving (in the granular physics literature) led to the largest of the coarse particles rising to the top of this shear layer and the smallest of the coarse particles sheared slower at the bottom.

Segregation in the BAW/BBW Transition

At the upstream extent of the foreset or transition region, the slope abruptly steepened and local flow depth increased resulting in a dramatic decrease in flow velocity. The segregation processes that dominated in this region were controlled by this transition from fast to slow velocity and also the concentrated near-bed shear flow that



occurs in a gravity-driven dense particle flow. Specifically, as the local fluid velocity slowed, the intermediate sized particles rapidly fell out of suspension and drop into the shearing gravity-driven flow on the bed. This gravity-driven flow was dominated by “kinetic sieving,” where the largest particles move toward the surface of the sheared gravity-driven particle layer, and the smaller large particles move away from this interface toward the deposit.

- The finest particles remained in suspension, though the average size in this suspension was finer than the BAW because of the slower velocities and thus lower “suspension dynamics.” This material passed to the BBW.
- The shear region adjacent to the bed, somewhat thicker than the shear region on the BAW, had a wider range of particle sizes from the (smaller) particles that dropped out of the flow during kinetic sieving to the largest particles segregating at the top of foreset.
- The gravity-driven particle flow often (depending on the mixture and flow conditions) appeared to be episodic with failures occurring every 5-15 seconds.

Segregation in the BBW

Segregation within the BBW was primarily based on two transport processes. The first was the segregation associated with gravity current dynamics. Within the TSRU tailings experiments in particular, and to some extent Surrogate Mixture B, a persistent gravity current or turbidity current formed along the bottom of the pond. The density contrast of this current and the surrounding pond water drove the flow down the foreset and onto the BBW deposit transporting solids to the end of the research flume. Solids settled out of this current resulting in a downstream fining. The second process was associated with particle settling out of nearly stationary flow occurring well away from beach or after the experiment was complete.

III. Deposition

In this section, we relate the effects of the transport dynamics and active segregation dynamics on preferential deposition of specific particle sizes in the different regions of the deposit. It is important to state here that, while the transport and segregation discussion above consider the instantaneous process at work, the final deposit is an assemblage of many processes. The foreset and beach are continually prograding into the pond and as they do they build on top of BBW deposits. The full thickness of the BAW deposit includes BBW deposit, BAW/BBW Transition processes and BAW processes.

Deposition in the BAW

In the BAW, the particle and fluid supply were held constant during an experiment. The bedload transport dynamics under these conditions forced the bed slope to adjust toward an equilibrium transport condition that was independent of influent flow rate. Once formed the BAW slope remained relatively throughout the experiment. Data from both surrogate and TSRU tailings experiments showed an inverse relationship between BAW slope and discharge. Average flow depth increased with influent discharge. The data suggest the BAW depth and slope self-adjusted to equilibrium bed shear stress that was unique to the specific tailings mixture being studied and inlet flow conditions.

In general, the deposition of material on the BAW topset was a small percentage of the total beach volume and this is attributed to the shallow slope of the beach. Furthermore, the particles added to the deposit in this region were limited to the particles at or near the bottom of the “bed sheet layer.” The smallest of the larger particles were in suspension during the transport conditions, and the largest were moving at the top of the shear layer in this region. Thus, the particles that were deposited in this region (near the top of the deposit) represent the middle of the grain size distribution.

Deposition in the BAW/BBW Transition

At the foreset, particles dropped out of transport at a dramatic rate. For the surrogate tests, this region was responsible for the majority of the beach growth. It was also a major component of the TSRU tailings beach; however, TSRU tailings also had a substantial BBW deposit. In terms of grain size, intermediate to smaller sized particles dropped out of suspension and then, through kinetic sieving, were quickly transported away from the surface of the gravity-driven shear layer. Thus, somewhat counter-intuitively, they deposit in the top and middle of this slope. The larger particles continue to the bottom and comprised most of the bottom of this layer.

Deposition in the BBW

The transport and segregation processes observed with the BBW included those associated with sustained turbidity currents and particle settling. The turbidity currents had the effect of distributing coarser solids farther into the BBW. Surrogate Mix B (Tests 5 and 6) had a visible turbidity current and the BBW deposits were thicker than Surrogate Mixture A that had a very weak turbidity current. The TRSU tailings experiments formed strong turbidity currents and developed thick BBW deposits downstream of the foreset. Grain size analysis from these deposits showed the sand content within the BBW increased in concentration and distance into the pond with increasing discharge. Data also indicate high discharges yielded lower concentrations of fines in the deposit suggesting the fines were washed out of the flume during the experiments.

In experiments without a strong turbidity current or after the experiments were complete, deposits were formed primarily of the last solids to drop out of suspension, the finest particles. In reality, these also were transported farther and farther into the pond and in some cases out of the flume.

LESSONS LEARNED

Summary of findings specific to TSRU tailings

TSRU tailings undergo segregation during deposition and appear to be influenced by parameters that presumably can be controlled by plant operation.

1. Influent flow rate and composition of solids (grain size and particles density) appear to influence the resulting BAW slope. For a given mixture, increases in flow rate result in a decrease in BAW slope.
2. The percentage of influent solids that contributes to the beach deposit decreased with increasing discharge and range from 83% at the lowest discharge to 65% at the highest.
3. Froth formation at the inlet, resulting from air entrainment at the plunge-pool/scour hole, appears to promote the segregation of bitumen and fines and the amount of fines segregation increased with



discharge. The experimental data suggest that at higher discharge, more fines are removed as froth resulting in a lower concentration of solids (fines and sand) leaving flowing off the beach.

4. Froth islands formed over the channel and resulting in pressurized flow, scouring nearly complete bypass of solids to downstream of the froth.

Distinct transport, segregation and deposition processes were observed in this study. Understanding the mechanism(s) involved in transport and deposition provides greater ability to optimize deposit characteristics and effectively operate ETF facilities.

1. The grainsize distribution of tailings solids influences processes in BAW and BBW such as slopes, foreset height, thickness of BBW deposit, and formation of sustained turbidity currents offshore of the BAW.
2. BAW/BBW transition is a region of active deposition in a pond as is the BBW. Deposition on the topset of the BAW region was minor, comparatively.

The project highlights the usefulness of controlled laboratory experiments to study field-scale process that are otherwise impossible to visualize and where tailings materials are challenging to work with.

This project was funded by a grant from the Institute for Oil Sand Research (IOSI Grant 2016_01) and the Canada's Oil Sands Innovation Alliance (COSIA). In-kind resources were provided by the University of Minnesota.

This project is complete and the final report has been submitted to COSIA member companies.

LITERATURE CITED

Beier, N., Wilson, W., Dunmola, A., & Sego, D. (2013). Impact of flocculation-based dewatering on the shear strength of oil sands fine tailings. *Canadian Geotechnical Journal*, 50(9), 1001-1007.

Xu, Y., Dabros, T., & Kan, J. (2013). Investigation on alternative disposal methods for froth treatment tailings—part 1, disposal without asphaltene recovery. *The Canadian Journal of Chemical Engineering*, 91(8), 1349-1357

PRESENTATIONS AND PUBLICATIONS

Published Theses

Widmer, Rochelle, Laboratory Studies of Segregation in Prograding Deltas of TSRU Tailings, MS thesis, University of Minnesota, December, 2020.

Unpublished Reports & Other Publications

Marr, JD; Hill, K., and Widmer, R., 2019, Laboratory investigation of transport, segregation and deposition of TSRU tailings in subaerial beach environments. Final report, IOSI COSIA (internal/ongoing work not published)

RESEARCH TEAM AND COLLABORATORS

Institution: University of Minnesota

Principal Investigator: Jeffrey 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	Principal Investigator Assoc. Director		
Kimberly Hill	University of Minnesota	Associate Professor		
Rochelle Widmer	University of Minnesota	Graduate Student	MS	2019
Atoosa Zahabi	Imperial	COSIA Project Steward		
Karsten Rudolf	Canadian Natural	COSIA Project Steward		

Froth Treatment Tailings Evaluation

COSIA Project Number: TE0050 and TJ0110

Research Providers: Golder Associates Ltd., InnoTech Alberta, SRK Consulting (Canada) Inc.

Industry Champions: Imperial, Suncor

Industry Collaborators: Canadian Natural, Syncrude, Teck

Status: Year 4 of 4

PROJECT SUMMARY

Over the past years, Froth Treatment Tailings (FTT) have received increased attention with respect to assessment of their long-term biogeochemical behaviour in the tailings and closure landscape. The FTT stream is generated during contact of the primary bitumen extraction froth with a light hydrocarbon (either a linear alkane or a naphtha cut, depending on the operator) in the secondary extraction circuit. The stream generally shows elevated levels of oleophilic minerals like pyrite and mineral phases containing rare earth elements compared to other tailings streams such as coarse sand tailings or fluid tailings. Some of the minerals are known to show acid rock drainage (ARD) potential, while others are classified as naturally occurring radioactive materials (NORM) due to their potential for uranium and thorium inclusions. The FTT stream further contains trace levels of unrecovered light hydrocarbon as a result of thermodynamic limits on light hydrocarbon recovery in the secondary extraction circuit. This light hydrocarbon is bioavailable and will serve as a carbon source to the naturally-present microbiome in the tailings deposits. The COSIA Tailings Environmental Priority Area (EPA) conducted a four-year research program dedicated to gaining insight into FTT characteristics and their effects within tailings deposits to inform operations, reclamation, and closure activities.

Between 2017 and 2019, the oil sands operators conducted three FTT sampling campaigns. Tailings ponds of various deposit ages, tailings placement histories, and tailings characteristics were sampled to identify and close knowledge gaps around the behaviour of the sediment layer after placement. By analyzing the composition of the gas, aqueous, organic and solids phase, as well as the microbiology, a complete picture could be established of the main geochemical and biological processes that are occurring. This has led to the development of site-specific (and sometimes tailings pond specific) conceptual models that are now available to inform long-term tailings management strategies.

PROGRESS AND ACHIEVEMENTS

As with most research activities, this program was impacted in 2020 by COVID-19. The primary impact was an increased turnaround time for laboratory analyses. This delayed refinement of the conceptual models for the sites. With the bulk of the analyses available now, the focus has been on interpreting the data set to yield a consistent description of the bio-geochemical processes. These results build on findings previously reported at the 2018 and 2019 Oil Sands Innovation Summits (OSIS):



- Detailed analysis of the free gas phase in the FTT-affected mature fine tailings (MFT) deposits have helped shed light on the distribution and composition of reduced sulfur compounds. A key finding was that components are generally *not* normally distributed, but show outlier concentrations in a limited number of samples. Further, carbonyl sulfide (COS) was the most commonly detected reduced sulfur compound, followed by hydrogen sulfide and thiosulfates. The origin of COS is unknown at present and will be subject to further study.
- In addition, in-situ CH₄:CO₂ ratios are found to be consistent with methanogenic degradation of diluent. The ratio is found to be higher than the surface emission ratio, suggesting that other processes like e.g., methane oxidation in the upper part of the tailings and water column may be significant. This finding may be subject to further study; e.g., through isotope analysis of the gas phase compounds.
- Detailed inspection of the RNA information has shown that microbial populations do appear to cluster by tailings pond. To capture the details of the biogeochemical behaviour, it may be necessary to develop conceptual models for individual ponds. This suggests that generic models may be inadequate and likely do not sufficiently capture operational history of the tailings facilities.

While analysis is ongoing, the key findings of the program are already being used to inform closure design and mitigation strategies where appropriate.

LESSONS LEARNED

COSIA continues to engage with the “Fort McKay Air Quality and Odour Recommendations Program” (FMAQO – recommendation 9³⁴) e.g. through sharing of the reduced sulfur compound data described earlier.

PRESENTATIONS AND PUBLICATIONS

The COSIA Tailings EPA is currently in the process of determining how findings from this program can be published in peer-reviewed journals.

³ Recommendation 9: Assess fixed- and fugitive-emission sources, focusing on the parameters in the air quality focal parameter list (section 6.6.4 of the report) and on polycyclic aromatic hydrocarbons in order to develop a roadmap for a systematic process for examining the dominant emission sources of the parameters in the focal parameter list.

⁴ The report is *Recurrent Human Health Complaints Technical Information Synthesis Fort McKay Area*, September 2016. Prepared by the Alberta Energy Regulator and Alberta Health. (https://static.aer.ca/prd/documents/reports/FortMcKay_FINAL.pdf, accessed 2021-03-15)



RESEARCH TEAM AND COLLABORATORS

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

COSIA Project Number: TE0055 RWG (IOSI18)

Research Provider: Queen's University

Industry Champion: Suncor

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 3 of 3

PROJECT SUMMARY

The main sources of carbon dioxide (CO₂) and methane (CH₄) emissions in tailings ponds are from the biodegradation of diluent (naphthenic or paraffinic solvents) used in froth treatment, and to a lesser extent, from residual bitumen. However, different types of tailings can be mixed in the same tailings pond and can influence the composition of the microbial community involved in degradation. Differences in diluent composition and deposition practices make it difficult to extrapolate the relationship between microbial activity and CO₂ and CH₄ emissions from one tailings pond to another. CH₄ has a global warming potential (GWP) of 28-36 times that of CO₂, therefore reducing or eliminating CH₄ emissions can be of significant environmental and economic benefit under Alberta's Technology Innovation and Emissions Reduction (TIER) Regulation and must be addressed. In the tailings ponds, CH₄ production is due to the bio-oxidation of hydrocarbons coupled to the reduction of terminal electron acceptors (TEAs) such as acetic acid or CO₂ at low redox conditions (~ -250 mV) when other TEAs are absent. When other TEAs are present, the redox potential increases and methanogenesis is inhibited.

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

1. Evaluate the impact of the concentration of different TEA (such as sulphate and nitrate), of diluent (e.g., naphtha), and of nutrients such as phosphate (PO₄³⁻) and ammonium (NH⁺) on biogenic gas production from tailings obtained from different types of tailing ponds (impacted by froth treatment tailings [FTT]) at different depths and lateral locations on the rates of biogenic gas production, consumption of TEA, and hydrocarbon degradation in laboratory microcosm studies.
2. Evaluate the effect of bitumen aggregates on biodegradation rates in static microcosm studies and whether residual solvent trapped inside bitumen aggregates offer a mass transfer resistance that may limit biodegradation rates.
3. Develop a first-generation model coupling mass transfer and reaction rates to provide basic information on CO₂ and CH₄ emissions based on pond chemistry, and to use the model to potentially identify dominant mechanisms which may aid in developing strategies for minimizing CH₄ emissions in-situ or for manipulating the biodegradation rate of the diluent (naphtha).

PROGRESS AND ACHIEVEMENTS

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

At the start of the project, three mature fine tailings (MFT) samples from different ponds were collected. For one of the MFT samples, phosphate (PO_4^{3-}) may have been a key nutrient limiting degradation rate since it was found to be below detectable levels in pore water ($\text{PO}_4^{3-} < 1.0 \text{ mg/L}$) and addition of NH_4^+ and/or PO_4^{3-} appeared to enhance biological activity in initial experiments. However, careful re-examination of earlier and more recent data shows that although there was some enhancement, there was no direct correlation of biological activity with increasing addition of NH_4^+ and/or PO_4^{3-} . While the reason for this is not totally clear, a partial understanding of what might be occurring exists. With increasing concentrations of PO_4^{3-} up to 1400 mg/L and NH_4^+ up to 1000 mg/L, there was a rapid abiotic loss of about 75% and 40% of these ions respectively within the first day.

X-Ray diffraction (XRD) of dried MFT solids did not detect any precipitates such as struvite ($(\text{NH}_4\text{MgPO}_4 \cdot 6\text{H}_2\text{O})$), and PHREEQC (Ilnl database) (U.S. Geological Survey) modelling using the MFT pore-water chemistry did not predict precipitation of these species at the concentrations tested. Few publications have reported on the adsorption of cations and/or anions onto the MFT matrix while there are numerous studies in the literature showing that PO_4^{3-} , SO_4^{2-} , NO_3^- , NH_4^+ , Na^+ etc. are capable of sorbing to many of the components of MFT such as kaolinite (~30%), muscovite (~20%), quartz (~30%) and calcite (~1%). Among these, kaolinite is the most frequently studied. For example, kaolinite has a higher cationic than anionic exchange capacity and can sorb both cations and anions.

Cations like NH_4^+ can sorb via two mechanisms. One mechanism occurs via the permanent negative charge on the basal planes of the clay surface whereby the cations (e.g., Al^{3+} or Si^{4+}) can be displaced by a species with a lower charge; e.g., NH_4^+ , and hence, does not depend on pH or ionic strength. However, the other mechanism depends on pH and ionic strength as the cations are sorbed to the surface by electrostatic interaction with OH^- groups arising from the deprotonation of the aluminol and silanol groups of the variable charged edges (Lazaratou et al. 2020). Although the cation exchange capacity of silicate clays is higher than their anion exchange capacity, the disappearance of less NH_4^+ compared to PO_4^{3-} may be due to high concentrations of competing cations (e.g., Na^+ , K^+ and Ca_2^+) in MFT. These cations have been shown to decrease sorption of NH_4^+ onto montmorillonite (Mazloomi and Jalali 2017). Adsorption of anions occurs by the latter mechanism, and hence, depends strongly on pH. However, adsorption of PO_4^{3-} is thought to be more complex, is linked to Al sites and may also involve multilayer adsorption, penetration into the inter-lamellar spaces and surface precipitation (which is very slow) (Gerard 2016). We believe that a significant amount of NH_4^+ and PO_4^{3-} nutrients (especially PO_4^{3-}) that we added to enhance microbial activity, sorbed to the MFT matrix and that bioavailability of these nutrients was potentially limited by its adsorption/desorption equilibrium. It is likely that this is one of the mechanisms which influences/limits the degradation rates in the tailing ponds. We are attempting to incorporate this aspect into our modelling.

To date, experiments with alternate terminal electron acceptors (i.e., NO_3^- or SO_4^{2-}) using one of the MFT samples have been completed. Experiments with other MFT samples collected from other ponds at 5 and 15 m have been set up but are not yet completed. So far, results with increasing NO_3^- and SO_4^{2-} concentrations with addition of PO_4^{3-} nutrient did not result in abiotic loss of NO_3^- or SO_4^{2-} . This might be because PO_4^{3-} preferentially occupies binding sites on the MFT matrix and blocks adsorption of NO_3^- or SO_4^{2-} (Violante and Pigna 2002). For the MFT samples collected at 5 m depth, H_2S was generated from sulphate reduction and was consumed in the microcosms of samples collected from one pond but not for the other pond. When nitrate is used as a terminal electron acceptor, it can be reduced through a series of intermediates (nitrate $\text{NO}_3^- \rightarrow$ nitrogen dioxide $\text{NO}_2^- \rightarrow$ nitric oxide $\text{NO} \rightarrow$ nitrous oxide

$\text{N}_2\text{O} \rightarrow$ nitrogen gas N_2) to nitrogen gas. N_2O is undesirable because it has a global warming potential 265 to 298 times that of CO_2 over 100 years. Under nitrate-reducing conditions, N_2O was produced in MFT samples and was consumed to non-detectable levels with time. Its transient accumulation increased with the increasing amounts of nitrate added.

Another mechanism that may be limiting the biodegradation of naphtha is its bioavailability when solubilized in bitumen. Experiments with increasing naphtha concentrations do not show a consistent trend in terms of a dependence on naphtha concentration. This phenomenon is the focus of Objective 2.

Objective 2 – Effect of bitumen on naphtha biodegradation:

In developing an initial protocol to meet this objective, sacrificial experiments in triplicate were performed under abiotic conditions in which a known amount of bitumen containing a known amount of naphtha was added to a series of vials containing simulated pore water. Over time, vials were sacrificed to measure naphtha components in the aqueous phase. Initially, the diffusion of the naphtha surrogates out of a bitumen “droplet” was measured by gas chromatography with flame ionization detection (GC/FID) and the reproducibility of the results was not satisfactory. We have now performed studies with a refined protocol and measured naphtha surrogates by fluorescence using a very sensitive PTI QuantaMaster™ 1. These recent results are more reproducible and sensitive than what was obtained by GC/FID and are being evaluated in Objective 3. We did the original experiments with simulated pore water but found in many instances that the bitumen separated into a dense non-aqueous phase liquid (DNAPL) and a light non-aqueous phase liquid (LNAPL). Several modifications had to be made – one of which was to use water instead of simulated pore water and to improve the clean up of the bitumen to minimize the LNAPL fraction. Future experiments will replace water with simulated pore water and we will also evaluate biodegradation in a model system with and without a diffusion component. We have been developing enrichment cultures from MFT for this purpose.

Objective 3 – First generation model:

Development has begun on a numerical model to address Objective 3. An existing model that accounts for diffusion within an oil mixture and mass transfer at the oil-water interface has been modified to include degradation in the water phase. Preliminary simulations have been conducted to investigate the sensitivity of light hydrocarbon release from a mixed oil drop to drop size, oil mixture viscosity, and degradation rate in the water phase. At present, we are focusing on xylene and methylnaphthalene because of analytical limitations. The model simulates the experiments described in Objective 2 to determine mass transfer parameters and assess the potential for mass transfer limitations on either side of the bitumen-water interface. Additional simulations will be conducted for a variety of conditions, including bitumen viscosity and composition, in both one-dimensional and three-dimensional domains for a range of droplet sizes. The biodegradation of soluble naphtha components will also be incorporated, using results from Objectives 1 and 2.

LESSONS LEARNED

1. Microbial activity may be limited by phosphate (and ammonium) adsorption onto the MFT matrix.
2. Fluorescence spectroscopy using the PTI QuantaMaster™ 1 to analyze individual naphtha surrogates was more reproducible and sensitive than GC/FID in objective 2.



3. Addition of terminal electron acceptors; e.g., NO_3^- and SO_4^{2-} , effectively suppressed CH_4 production.
4. Yields of how much electron acceptor is required for a given amount of naphtha degradation and the yield of methane from naphtha can be evaluated.

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Violante A, Pigna M. 2002. Competitive Sorption of Arsenate and Phosphate on Different Clay Minerals and Soils. *Soil Science Society of America Journal*. 66:1788-1796.

RESEARCH TEAM AND COLLABORATORS

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Investigations into the Biogenic Methane Potential of Diluent Containing Tailings: In-depth Microbiological and Chemical Analysis of Microcosms

COSIA Project Number: TJ0134

Research Provider: InnoTech Alberta

Industry Champion: Canadian Natural

Status: Complete

PROJECT SUMMARY

Despite decades of research into the microbiology of oil sands tailings ponds (Foght et al., 2017), numerous gaps in the understanding of the factors controlling anaerobic microbial degradation of residual diluent in froth treatment tailings (FTT) into methane still exist. Some of these gaps include the impact of diluent concentrations and composition on degradation rates and which microbes are key in diluent degradation (An et al., 2013, Wilson et al., 2016). Limiting factors such as nutrients and bacterial competition affecting microbial activities are also poorly understood.

Microcosm culturing is a technique used to investigate microbial growth and activity on compounds of interest. It allows the investigation of numerous variables and factors affecting microbial degradation of compounds under a variety of reducing conditions (Coelho et al., 2013). The advantages of using microcosms are the ease of replication and being able to tightly control treatments and investigation of effects of environmental parameters (Coelho et al., 2013). The main disadvantage of microcosms is that they may not adequately represent the ecosystem under study on a spatial and temporal scale. Multitrophic interactions, such as sulfate reducers and methanogens that are likely occurring in the tailings ponds, may not be replicable in microcosms.

During the 2017 COSIA Froth Treatment Tailings Evaluation Project (COSIA project number TE0050), a series of microcosms (in triplicate) consisting of parallel active and sterilized controls were prepared under methanogenic conditions from selected tailings material from four sites within Canadian Natural deposits, representing both naphtha and paraffinic diluent-affected tailings material. The objectives of the microcosm study were:

- To determine methane production potential and obtain initial yields and rates from the degradation of different concentrations of residual diluent in tailings deposits.
- To determine changes in tailings microbial community composition upon incubation in the microcosms and determine key species involved in diluent degradation.
- To identify which hydrocarbon components of the diluent are degraded and which ones are recalcitrant.

Information derived from the microcosm study can be used towards developing strategies in managing methane production from ponds.

PROGRESS AND ACHIEVEMENTS

A series of microcosms were prepared from sampling campaigns conducted in 2017 and 2018. The 2017 microcosms have been sacrificed and analyzed for a number of parameters including microbial taxonomy, residual hydrocarbon composition and pore-water chemistry. Key findings from these end-point analyses include:

- Differences in methane production rates were observed between naphtha and paraffinic tailings, the highest methane production rates occurred with the paraffinic tailings.
- Methane yields in most of the microcosms appear to correlate with the F1⁵ concentration and thus presumably residual diluent.
- C5 and C6 alkanes, similar to the expected composition of the paraffinic solvent were the primary hydrocarbons consumed in the microcosms containing paraffinic tailings. Differences between the hydrocarbon compounds present in the test and killed control microcosms (abiotic) showed a shift from consumption of C6 paraffinic hydrocarbons to consumption of C5 paraffinic hydrocarbons as the incubation period progressed. This suggests that a similar selectivity may occur in paraffinic tailings, with utilization of C6 paraffinic hydrocarbons occurring before C5 paraffinic hydrocarbons.
- The organics data from the naphtha tailings microcosms showed a wide range of hydrocarbons were consumed, though the most active microcosm showed a preference for the degradation of C10 alkenes and alkynes.
- The microbial communities that developed in the microcosms were different from the ones in the tailings samples and tended towards typical methanogenic community assemblage consisting of a dominant primary degrader, syntrophic bacteria and methanogens.

LESSONS LEARNED

- The methanogenic microcosms prepared from FTT samples provided insights into factors contributing towards methane production from residual hydrocarbons and may be useful for pond management strategies.
- The microcosm methane generation data suggest there is a threshold concentration of diluent that triggers enhanced methane generation. Further testing is required to verify this finding.
- Factors such as the water solubility of the hydrocarbons and the partitioning of the diluent in residual bitumen may impact the bioavailability of the hydrocarbons for microbial biodegradation. The long lag times observed in some microcosms before methane production occurred may be explained by differences in the bioavailability of the hydrocarbons.

⁵ F1 is a laboratory hydrocarbon measurement

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RESEARCH TEAM AND COLLABORATORS

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Naphtha Recovery Unit Tailings – Preliminary Biogeochemical Conceptual Model

COSIA Project Number: TJ0136

Research Provider: Golder Associates Ltd., InnoTech Alberta

Industry Champion: Canadian Natural

Status: Year 1 of 1

PROJECT SUMMARY

During the froth treatment process, naphtha (a diluent) is added to assist in separating the extracted bitumen from the solids and liquids phases. Most of the naphtha is recovered in the Naphtha Recovery Unit (NRU), although the tailings from this process contain some residual naphtha. To better understand the complex biogeochemical processes that may be occurring within the NRU tailings deposit, and to predict potential risks, development of a conceptual model was initiated. New analytical data collected in 2020 were combined with the available geochemical datasets from the NRU deposit to investigate and understand the biogeochemical processes that may be occurring within the deposit. The overall goal was to provide Canadian Natural a conceptual understanding of biogeochemical processes and risks that may be present or develop within the deposit and may need to be considered for tailings management planning and/or mitigated under closure design.

The conceptual model was developed from the analysis of tailings solids, tailings porewater, process water (i.e., pond surface water), diluent, tailings gas, and microbiology from pond and/or beach locations within the NRU deposit. These media were analyzed using one or more of the following techniques: X-ray diffraction; inorganic and organic chemistry; acid-base-accounting; humidity cell testing (HCT); gamma spectroscopy; gas compositional analysis; and microbial identification and microcosm testing.

PROGRESS AND ACHIEVEMENTS

Insights from the NRU Preliminary Biogeochemical Conceptual Model include:

- Inorganic Parameter Dissolution/Transport: The co-deposition of process water within NRU tailings pore space provides a source of total dissolved solids (TDS) and chloride within the porewater. These parameters may increase with time due to water recycling and as mineral-water interactions continue in the depositional environment. Elevated total metal concentrations in the porewater suggests that colloidal (i.e., not dissolved) transport is likely an important transport mechanism for metals.
- Sulphide Oxidation: Pyrite (FeS_2) content is higher in beach environments compared to pond environments, and the neutralizing potential of NRU tailings is limited. Acid Rock Drainage (ARD) classification suggested that NRU tailings might be classified as potentially acid generating (PAG) or as having an uncertain acid generation potential. Kinetic tests are ongoing and will provide more information on the rates of sulphide

oxidation and dissolution of neutralizing minerals, the likelihood and timing of ARD onset, and the timing to sulphide depletion.

- Radioactivity: The source of naturally occurring radioactive materials (NORM) is believed to be the presence of uranium and thorium-bearing minerals in NRU tailings. Heavy minerals, those that are likely associated with uranium and thorium, appear to concentrate in the beach depositional environment. Gamma spectroscopy measurements from the pond NRU tailings are lower than Health Canada NORM guidelines. Analysis is ongoing to assess the NORM potential of the NRU beach.
- Organics/Gases/Microbes: The sources of organics and gases in the NRU tailings are bitumen, residual diluent, microbial generation of gas, and gases entrained in the tailings during deposition. The current understanding is that the deposit is a mixture of microenvironments with anaerobic and aerobic processes occurring throughout the deposit. Potential risks include: 1) bitumen may be buoyant and susceptible to degradation; 2) light hydrocarbons, primarily from diluent in tailings, can degrade readily by microorganisms to produce gas; and 3) gases such as methane (CH_4) and carbon dioxide (CO_2) released from the surface of the NRU tailings facility.

LESSONS LEARNED

The depositional environment of the NRU tailings (i.e., sub-aerial beach versus pond) plays a key role in the presence or absence of the risks highlighted above. Further work is required to reduce uncertainty in the risks associated with the NRU deposit.

RESEARCH TEAM AND COLLABORATORS

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TAILINGS CAPPING

Planning and Design of Deep Cohesive Tailings Deposit Guide

COSIA Project Number: TE0046

Research Provider: McKenna Geotechnical Inc.

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 3 of 3

PROJECT SUMMARY

The mandate of COSIA's Deep Deposit and Soft Deposit Capping Working Group (DDWG) is to identify and develop approaches and technologies for designing and implementing deep fines-dominated tailings deposits in the oil sands and explore different types of capping strategies to support a terrestrial landform (with wetlands) in a timely manner. Deep fines-dominated deposits are cohesive materials with associated depositional and consolidation behaviour that are considered an appropriate tailings management approach for mines where disposal areas and storage volumes are available (typically in-pit). A deposit is formed by continuous discharge of treated/reprocessed fluid tailings with a sand-to-fines ratio (SFR) <1.

The guide, which is under development as part of the DDWG mandate, describes the technical requirements, activities and process flows needed to develop and execute a deep deposit from design through to capping, consistent with the requirements of the desired closure landforms. The guide uses existing data, experience and knowledge to describe the current state of practice for the design and implementation of deep cohesive tailings deposits in the oil sands and their expected performance during reclamation and closure. The guide is a technical manual and reference document for mine and tailings planners, geotechnical engineers, technical specialists and closure landform design teams.

PROGRESS AND ACHIEVEMENTS

Work on the project commenced in 2018 with preparing a work plan, assembling relevant technical and process inputs, and beginning the task of drafting the guide. Work was about 95% complete at the end of 2020 with completion targeted for early 2021.

The guide is a compendium of deep deposit planning, design, placement, management, and reclamation knowledge and experience accumulated over several decades by the oil sands industry. Three COSIA workshops in particular: the 2017 Deep Deposit Capping Workshop; and the 2015 and 2018 Deep Deposit Consolidation Workshops provided valuable case histories, research data, and design information that form the basis of the guide. Other oil sands and international literature cited in the guide augments information from the workshops.

LESSONS LEARNED

Guidance on the application and use of deep cohesive deposits in mining and tailings planning schemes is included. The accumulated knowledge from industry experience and observations obtained during development of the guide has resulted in the advancement of DDWG research and investigation initiatives, which include:

- Methods of consolidation enhancement and limitation of long-term settlement, and
- Characterization of treated fines and the conditions that might lead to static liquefaction.

LITERATURE CITED

There will be several hundred references cited in the completed guide including previously unpublished research data and information, and case history documents.

RESEARCH TEAM AND COLLABORATORS

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Derrill Shuttleworth	Independent Consultant	Illustrator		
Paul Cavanagh	Imperial	COSIA Project Steward		

Modelling the Cap Placement with Tailings Deformation and Consolidation

COSIA Project Number: TE0073 (IOSI19)

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 2 of 2

PROJECT SUMMARY

Hydraulically placed sand caps are potentially cost-effective and practical for use in the oil sands. The 2018-2019 project, “Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings,” (COSIA project number TE0059; Solseng, 2019) demonstrated that hydraulic sand capping held promise, justifying further examination. While that project used fixed dimensions for the caps, this project introduces certain elements of more realistic cap and tailings behaviours to test for potential fatal flaws in the deltaic capping concept. The current research uses a deformation-based geotechnical model and focuses on subaerial hydraulic capping (sometimes called beaching or deltaic capping) of treated soft, fines-dominated tailings.

DESIGN AND METHODOLOGY

The modelling considered tailings of 1 to 5 kPa undrained shear strength, weaker than those that could normally be capped using mechanical methods. The project systematically examined four factors to assess their influence:

1. the settlement and deformation of the tailings in response to the loading from the cap;
2. infilling of the resulting depression by fresh cap material;
3. advance of the cap with time; and
4. strain softening⁶ of the tailings as they deform.

The research used the advanced geomechanics program FLAC® (Fast Lagrangian Analysis of Continua) for numerical simulation of the behaviour of the tailings and the interaction between tailings and cap. The modelling was carried out using FLAC 2D in large strain mode. The tailings properties were held constant with depth to focus on the role of tailings shear strain in potential cap failure. A wedge-shaped cap consisting of sand was modelled as a surcharge

⁶ strain softening is a geotechnical engineering term referring to a shear-strain response in which an increase in the soil's strain or deformation causes its yield stress to decrease; i.e., the increased strain causes the soil grains to dilate leading to a decrease in its yield stress



load, with no water cover over the tailings. The cap was considered successful if it advanced 300 m over a 400 m deposit.

A matrix of tailings strengths (1 to 5 kPa) and cap top slopes (0.1% to 0.5%) were modelled to see how each of the four factors would influence cap success and failure. Modelled cases were a stationary cap where the resulting settlement was not infilled with additional cap material, a stationary cap with infilling, and an advancing cap with infilling. These three cases were modelled with and without strain softening.

PROGRESS AND ACHIEVEMENTS

The FLAC 2D model was successfully applied to show the influence of the four factors on the predicted success of deltaic capping on soft tailings. Some of the important conclusions from the modelling research include:

- Including tailings deformation and settlement in response to capping and the natural infill of cap material in a hydraulically-placed cap had a dramatic effect on predicted failure, and consequently is an essential element in analysis of failure potential.
- Cap advance had an influence on failure prediction, so that modelling a stationary cap, even with infill, is not an adequate surrogate for predicting failure for deltaic capping – the model should include cap advance as well as infill.
- Strain softening behaviour increases the failure potential and can be decisive in characterizing the potential for success or failure of a cap, so should be included in modelling.
- For the 300-m cap modelled, the results suggest that for successful deltaic capping at a cap slope of 0.5%, a tailings strength of 5 kPa is required, while for a cap slope of 0.1% a tailings strength of 2 kPa is required (note that this is based on constant tailings strength with depth, which fails much more readily than a profile of increasing strength with depth).

The model was also applied to stronger tailings, 25 kPa, and a cap slope of 3% was successful (3.5% slope failed). The practical significance of this result is that deltaic capping could be a viable alternative to mechanical placement for caps on deposits strong enough to support low-ground-pressure bulldozers. The efficiency of hydraulic transport could make deltaic capping a cost-effective alternative.

LESSONS LEARNED

To reasonably represent the tailings and cap behaviour, it is essential that the model account for large-strain deformation of the tailings and associated infill of the cap in response.

Modelling of deltaic capping should represent the dimensions of the tailings basin in question. The current work has used a 300-m-long cap on a 400-m-long tailings deposit, which allowed failures to manifest that were not evident in work using smaller dimensions.

LITERATURE CITED

Solseng, Philip, 2019. "Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings," IOSI Project 2017-11, final report published July 4, 2019.

RESEARCH TEAM AND COLLABORATORS

Institution: Barr Engineering and Environmental Science Canada Ltd. (Barr)

Principal Investigator: Jim Langseth

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Jim Langseth	Barr Engineering and Environmental Science Canada Ltd.	Principal Investigator Vice President		
Jed Greenwood	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Sr. Geotechnical Engineer		
Farzaan Abbasy	Barr Engineering and Environmental Science Canada Ltd.	Geotechnical Engineer		
Philip Solseng	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Sr. Geotechnical Engineer		
Nav Dhadli	Barr Engineering and Environmental Science Canada Ltd.	Project Manager		
Luca Sittoni	Deltaires	Project Manager		
Ebi Meshkati	Deltaires	Geotechnical Engineer		
Dirk Luger	Deltaires	Sr. Geotechnical Engineer		
Nan Wang	Syncrude	COSIA Project Steward		

Research Collaborators: Deltaires



CONSOLIDATION MODELLING

NSERC-COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique

COSIA Project Number: TE0010

Research Provider: University of Alberta (UAlberta)

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 1 of 5

PROJECT SUMMARY

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

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

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

Theme 3: Capping Soft Tailings Deposits

These complementary themes will look to the future of tailings deposits as well as immediate/interim challenges. It is anticipated that 15 highly qualified personnel will be trained in state-of-the-art reclamation techniques through the research program. Further, the collaboration will enable fundamental discoveries for the behaviour and management of fluid tailings, benefitting the engineering discipline, and bolster UAlberta, COSIA, and Canada's position as international leaders in mining reclamation and oil sands tailings geotechnique.

PROGRESS AND ACHIEVEMENTS

The NSERC/COSIA Industrial Research Chair (IRC) in Oil Sands Tailings Geotechnique was started September 1, 2019, and a Workshop and Laboratory Tour was held with industry supporters in December 2019. Graduate students on the research team were primarily recruited to conduct the research as part of their graduate programs, which include full-time graduate coursework. In 2020, for this project, as well as other oil sands research initiatives, the COVID-19 pandemic presented challenges that affected progress on laboratory and fieldwork. To overcome these schedule and access challenges, alternative ways of engaging in research activities such as holding a two-day Virtual Knowledge Sharing Workshop between UAlberta, NAIT and Carleton University were pursued. Limited laboratory work resumed in 2020 as public health measures were partially lifted for a brief period of time.



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

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

Objective: Understand the influence of high plastic versus low and no clay content on the blending of various treated and untreated mature fine tailings (MFT) with Clearwater shale.

Recruitment is ongoing for a suitable graduate student to undertake this research.

Project 1-2: Developing appropriate mixtures of FT with alternative solids for dry stacking

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

A comprehensive literature survey of different disposal techniques focused on the advantages of co-disposal to achieve a ready-to-reclaim deposit and the design of a co-disposal mixture of overburden and tailings based on particle packing theory are underway. Different methodologies that leverage co-disposal and dry stacking technology to alleviate mine closure issues and facilitate land reclamation are being assessed. Advanced experimental testing (slurry consolidometer, centrifuge testing and computerized axial tomography (CAT) scanning) to study the effect of design variables on geotechnical behaviour and to compare the results with numerical modelling techniques (FLAC3D) using simulated geotechnical properties of the co-mix material is planned.

Project 1-3: Progressive deposition of co-mixtures on deep deposits

Objective: Investigate the impact of progressively adding solids to various mixtures of FT and other solids to form a “Thick Cap” on soft deep deposits.

An extensive literature review and design of a laboratory testing program to examine the rheological properties and the tailings strength for various mixtures of MFT / FT and Clearwater shale when pumped and co-disposed are underway. Solids will be progressively added to various types of FT, such as MFT or thickened tailings, while the depth of the soft deposit is increased to form a “thick transition surface” to support subsequent placement of a sand cap and future reclamation materials. Computational simulations to assess beach deposition, strength, deformation, and stability analysis will also be undertaken.

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

Objective: Investigate the properties of the fines fraction that influences the behaviour of tailings mixtures in the transition zone of the tailings classification chart.

A literature review that focuses on the prediction of Transition Zone (ternary diagram) material properties and the design of a laboratory testing program to investigate baseline characterization of Transition Zone materials index and engineering properties (hydraulic conductivity, shear strength and liquefaction potential) is underway. This is expected to lead to developing equations governing performance prediction for transition zone materials that integrate cohesive and non-cohesive aspects of soil behaviour.



Theme 2: Influence of Bio-geochemical Interactions on the Behaviour of Soft Tailings

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

Objective: To develop design criteria that will optimize the geotechnical properties (coupled with biogeochemical properties) of an engineered deep deposit to accelerate the transition of the deposit to a natural ecosystem that sequesters the constituents of potential concern.

This research will aid in developing design criteria to optimize the geotechnical and biochemical properties of an engineered deep deposit (end pit lake) to accelerate the transition of the deposit to a natural ecosystem. Preliminary bench-scale experiments were started at the end of 2019 and are ongoing.

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

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

This project is in its early stages and evaluates the long-term biogeochemical and geotechnical behaviour of end pit lakes. As such, this research will address some of the knowledge gaps that exist surrounding the use of end pit lakes for tailings reclamation, such as water cap quality. Further, this work will reveal differences in the behaviour of untreated versus polymer-treated tailings deposited in end pit lakes. Sixty-four aging columns have been constructed for experiments on the long-term behaviour of water capped tailings.

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

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

A PhD Student has been recruited to conduct this research and will begin January 2021.

Theme 3: Capping Soft Tailings Deposits

Project 3-1: Optimization of capping soft tailings deposits

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

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

Project 3-2: Deformation behaviour of crusted tailings

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

A PhD candidate was working on the project objectives prior to September 1, 2019, and made considerable progress on the project execution in 2020. Currently, comparisons between the laboratory test results with available field data are underway to gain insight into dewatering mechanisms from seasonal weathering. Numerical models will be used to predict the treated tailings field behaviour for future planning purposes.

LESSONS LEARNED

2020 was the first year of a five-year program. Notwithstanding the schedule and productivity being materially disrupted by COVID-19 impacts, important lessons were realized:

Project 1-3

- The advantages of co-disposal include relatively easy reclamation due to stable and trafficable beaches; reduced total volumes due to combined coarse and fine fractions, and increased return water. (Williams et al., 1995).
- Co-mixture deposition creates the possibility of an immediately trafficable deposit (Williams and Kuganathan, 1992) and advance the time to being ready-to-reclaim.

Project 1-4

- The research is expected to provide industry with a mature understanding of dewatering characteristics and greater understanding of the rates and magnitudes of self-weight consolidation in transition zone materials. Findings from this research will also support the design of mixtures of FT and overburden.

Project 2-1

- The experimentally measured properties (pH, EC, turbidity) plateaued at 4-6 months;
- Larger scale volumes and experimental vessels are needed for wider analytical approaches;
- Proposed treatments (permeable reactive barrier + sand layer) worked at the beginning (control vs capped MFT), but in 6 months the measured parameters became identical. Therefore, other capping layers or/and bigger thickness need to be explored.

Project 3-1

- Preliminary numerical models indicated a 30% increase in safety factors and bearing capacities in thin-lift fines-dominated tailings deposits capped by coarse tailings sand.
- As the upper region of the deposit becomes progressively stronger, the dominant failure mechanism changes from rotational to primarily punch-through, which is potentially a less catastrophic.
- Crumb test results (ASTM D6572-20) and vane shear tests on rewetted tailings indicated potential dispersive behaviour and strength loss even at gravimetric water content below its shrinkage limit.
- Strength loss at water contents above the plastic limit is similar to typical values expected in kaolinite clay from literature.

Project 3-2

- Differing dewatering behaviour and strength characteristics between centrifuge cake samples were predominantly attributed to the variations in temperature gradient. The laboratory results can be

expected to predict the field response if the temperature gradients are in the same range and the depth of snow covers are minimal. Lower temperature gradient samples overall contribute to higher dewatering and subsequent strength gain.

- Both of the investigated tailings required approximately five seasonal cycles to meet a threshold strength (>80 kPa) when moisture content approached the plastic limit. These threshold values were confirmed through the wetting behaviour when strength reduction due to moisture infiltration became insignificant. At higher solids content and very low moisture content, the suction (not measured) becomes high so that the suction loss due to hysteretic soil-water retention behaviour induced by alternate drying-wetting cycle results in an insignificant impact on shear strength.
- A decrease in temperature gradient along with an increase in the freeze-thaw cycles results in cessation of moisture infiltration effects on strength.
- The volume changes due to freeze-thaw is largest in the first cycle and progressively decreases with subsequent cycles due to progressively reduced freeze-thaw dewatering but not on evaporation/drying.
- Upward salt migration mechanism during freeze-thaw is one contributing factor for increased ion concentration at the surface. Salt/ion migration additionally facilitates the osmotic suction component that, overall, increases the total suction. Increasing suction during freezing is responsible for attracting unfrozen water towards the freezing zone and overall dewatering.
- The formation of a surface crust does not ensure a trafficable surface if the depth of the crust is limited. The crust can be formed when it is unsaturated but strength loss can occur upon rewetting. Control of surface water is needed to realize full potential of seasonal weathering.

LITERATURE CITED

Williams, D.J., Gowan, M. and Keefer, P. 1995. Practical co-disposal deposition. Proceedings of the 7th Australian Coal Preparation Conference, September 9-15. Mudgee, New South Wales. Sydney: Australian Coal Preparation Society. pp. 371-383.

Williams, D.J. and Kuganathan, V. 1992. Co-disposal of fine- and coarse-grained coal mine washery wastes by combined pumping. International Journal of Environmental Issues in Minerals and Energy Industry, pp. 53-58

PRESENTATIONS AND PUBLICATIONS

2020 was the first year of a five-year program. Notwithstanding the schedule and productivity being materially disrupted by COVID-19 impacts some publications related to this research were issued.

Journal Publications

Zheng, T. Beier, N. 2021. Simulation of water storage in a reclamation cover incorporating tailings consolidation. Environmental Geotechnics. <https://doi.org/10.1680/jenge.20.00143>

Beier, N. Zheng, X.T., Sego, D. 2020. Development of an oil sands tailings simulation model. Environmental Geotechnics. <https://doi.org/10.1680/jenge.18.00168>

Media Interviews

“Up and coming researcher wins Vanier award” Canada’s Oil Sands Innovation Alliance (COSIA) website <https://www.cosia.ca/blog/and-coming-researcher-wins-vanier-award> (July 1, 2020)

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Dr. G. Ward Wilson

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. G. Ward Wilson	University of Alberta	Principal Investigator Professor		
Dr. Nicholas Beier	University of Alberta	Assistant Professor		
Dr. Ania Ulrich	University of Alberta	Professor		
Dr. Ahlam Abdulnabi	University of Alberta	Research Associate		
Dr. Louis Kabwe	University of Alberta	Research Associate		
Dr. Petr Kuznetsov	University of Alberta	Research Associate		
Heidi Cossey	University of Alberta	PhD student	2019	2023
Aniseh Dadashi	University of Alberta	PhD student	2017	2022
Peter Kaheshi	University of Alberta	PhD student	2019	2023
Umme Rima	University of Alberta	PhD Candidate	2016	2021
Tony Zheng	University of Alberta	PhD student	2019	2023
Paul Cavanagh	Imperial	COSIA Project Steward		

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

Long-term Dewatering of Amended Oil Sands Tailings: Co-funded by COSIA and NSERC (an NSERC Collaborative Research and Development Grant)

COSIA Project Number: TE0036

Research Provider: Carleton University

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 4 of 4

PROJECT SUMMARY

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

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

The specific objectives and deliverables to achieve these goals include:

- a) Improving methods and experimental techniques to rapidly estimate consolidation properties, namely the compressibility and hydraulic conductivity functions;
- b) Investigating time-dependent behaviours in polymer-amended fluid tailings (fFT) (creep and thixotropy/structuration) that potentially influence long-term consolidation predictions;
- c) Incorporating such behaviours into our research group's consolidation-desiccation model UNSATCON;
- d) Extending UNSATCON from a one dimensional (1D) to two dimensional (2D) model;
- e) Evaluating long-term dewatering potential for a range of polymer types, and providing feedback to polymer developers on how to optimize polymers for long-term tailings dewatering; and
- f) Studying changes in pipeline rheology and linking to post-pipe dewatering behaviour to optimize polymer dosage and to assisting operators develop improved technologies for on-spec and off-spec detection.

PROGRESS AND ACHIEVEMENTS

Progress up to 2020

We have found that structuration/ageing is an important phenomenon in at least some kinds of polymer-amended FT (fFT). Structuration means the compressibility of the material decreases (the material stiffness increases) over

time, independent of density. The consequence is that current predictions of long-term dewatering in deep deposits of tailings may over-predict long-term dewatering if compressibility measured over a short duration is used in the predictions – which it usually is. Specifically, structuration generated pre-consolidation pressures over 50 kPa over a period of 100 days. The samples of fluid tailings (FT) were 10 cm thick, submerged and mixed with standard anionic high molecular weight polymers. The mixing procedures were designed to simulate short pipeline transport such as the Atmospheric Fines Drying (AFD) technology. Structuration did not appear to progress beyond 100 days.

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

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

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

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

For the work linking pipeline transport to dewatering we replicated earlier work performed in industry using a large couette rheometer to simulate pipeline transport. We are now progressing to understand how material changes and recovers after shearing during pipeline transport, using optical microscopy and advanced rheometry. We plan to generate tailings exposed to different flow regimes and test them in our specialized column experiment to measure consolidation properties.

We have advanced in our use of the torque rheometer to optimize mixing and to simulate pipeline shear, to the point where we can optimize short-term dewatering based on the torque measurements during mixing, for different polymers, different fluid tailings (FT), at different solids contents. We also know how the rate of polymer injection affects optimization. We are working on correlating polymer mixing and pipeline transport to long-term dewatering. The tests conducted to date show that in the majority of cases, while short-term dewatering may be reduced due to pipeline transport, long-term dewatering is similar or slightly enhanced compared to the non-sheared samples.

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

Progress in 2020

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

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

A large consolidation test (a 0.3 m by 0.3 m by 0.7 m tall steel box) was completed on centrifuge cake tailings. This last test was performed to examine consolidation at a large enough scale, such that the test cell could be instrumented with multiple pore-water pressure sensors and water content sensors. The test showed quite clearly how creep and ageing affect the consolidation process of centrifuge cake tailings. It showed that a pre-consolidation pressure could develop in a more realistic physical simulation than a simple oedometer test. It showed how creep suppresses pore-water pressure dissipation after the pre-consolidation pressure is exceeded. An example result is shown in Figure 1 below, where the settlement predicted from a large strain consolidation model is compared with the measured settlement. The effect of the pre-consolidation pressure, developed sometime before the end of the initial self-consolidation phase, is clearly evident. More details are in Igbinodion (2020).

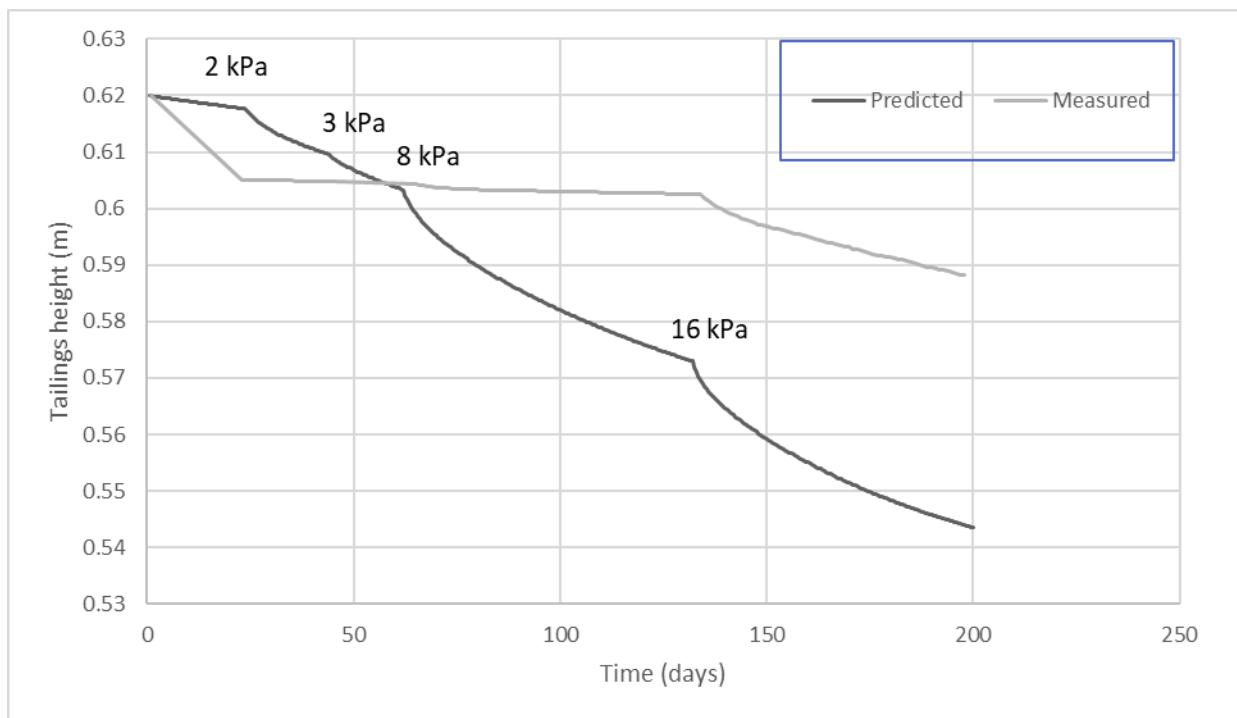


Figure 1: Measured settlement and settlements predicted by a large strain consolidation model in a large consolidation test on centrifuge cake tailings (Igbinedion 2020)

On the modelling side, PhD student Gheisari has developed a large stain consolidation model that incorporates creep and structuration. This model seems to work well, but unlike the previously-developed creep-consolidation models, it has several novel elements, that we are endeavouring to test rigorously. We are not only using experimental and pilot data from tailings, but also using the much large dataset from soft soils to validate and develop her model. Part of the data set to be used for model validation is the large consolidation test discussed above.

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

The analyses were also included in Gheisari's model with ageing, which was presented at the industry student-interaction day event in December 2020. The ageing model presents less settlement, higher void ratios (lower density), but also higher effective stress than the other models. As stated above, because of several novel additions to this model, we are still not certain that the ageing model is the best we can do, and we continue to test the model against other tailings data and soft soil data from around the world.



Our plans to scale up findings from our torque monitoring studies during flocculation and simulated pipeline shear were delayed, and we are planning for implementation in the summer of 2021. This includes monitoring flocculation by torque feedback with mechanical stirrers placed in a 4 m long pipe at Carleton University, and in University of Alberta's flow loop.

LESSONS LEARNED

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

The methods we proposed at our student-interaction day and in conference papers (Babaoglu et al. 2018 and Babaoglu and Simms 2020, 2018, 2017), in journal papers (Babaoglu and Simms 2020, Qi and Simms 2019, Qi et al. 2020) to rapidly estimate the consolidation properties are sufficiently accurate to be used at least as screening tools. Industry can adopt these methods as tests for key performance indicators, if convenient. We are increasingly confident now that these methods can be used by industry to rapidly estimate $k-e$, removing either slow or expensive consolidation testing as a barrier to innovation.

Feedback from mechanical devices interacting with the tailings seems to be an excellent means to optimize flocculation, and to monitor tailings during pipeline transport. Our own group is moving towards testing an application in a small pipeline, where a series of mixers, with torque measurements and feedback control, will be used to control and optimize polymer mixing in real time. We intend to conduct experiments where the properties of the feed are varied with time to challenge the optimization system.

Following research from a previous grant from COSIA, we are pleased we are now able to simulate channel formation during tailings deposition in computational fluid dynamics (CFD) simulations of non-Newtonian flow.



PRESENTATIONS AND PUBLICATIONS

Theses

Igbinedion, D. 2020. Aging and Large-Scale Consolidation in Centrifuge Cake Oil Sands Tailings. M.A.Sc. thesis, December 2020.

Salam, Muhammad. 2020. Effects of polymers on short- and long-term dewatering of oil sands tailings, Ph.D. thesis, January 2020.

Parent, Etienne. 2019. Field Scale Flow Modeling Of Thixotropic Mine Tailings Using The Material Point Method. M.A.Sc. thesis, January 2019.

Khattack, Muhammad Hissan. 2018. Microstructural Quantitative Analysis of Polymer Amended Fluid Fine Tailings Using Digital Image Processing Techniques. M.A.Sc. Thesis.

Qi, S. 2017. Numerical Investigation for Slope Stability of Expansive Soils and Large Strain Consolidation of Soft Soils. Ph.D. thesis

Journal Publications

Abdulnabi, A., Amoako, K., Moran, D. Vanadara, K., Abdulrahman, A.A., Esmaelizadeh, A., Beier, N., Soares, J., Simms, P. 2021. Evaluation of candidate polymers to maximize the geotechnical performance of oil sands tailings. Submitted to Canadian Geotechnical Journal, December 2020.

Abdulghader, A., Simms, P., Soares, J. 2020. Torque-based Evaluation of Mixing Optimization and Shear Sensitivity During Transport for Flocculated Tailings. Submitted to Minerals Engineering, Dec 2020.

Salam, M., Simms, P., Ormeci, B. 2020. Ageing in natural clays and in polymer amended clayey tailings. Submitted to Soils and Foundations, Dec. 2020

Sanchez-Sardon, M., Simms, P., Rayhani, M, Beier, N. 2021. Void ratio dependency of the SWFC in a clayey tailings. Submitted to Canadian Geotechnical Journal.

Babaoglu, Y. Simms, P. 2020. Improving consolidation parameter estimation for soft clayey soils and sediments using predictors at high void ratio. ASCE Journal of Geotech. And Geoenv. Engineering, [https://doi.org/10.1061/\(ASCE\)GT.1943-5606.0002344](https://doi.org/10.1061/(ASCE)GT.1943-5606.0002344)

Qi, S.,Chen, X., Simms, P.,Zhou, J.: Yang, X. 2020. Method for determining the permeability function of soft soils considering simultaneous sedimentation and consolidation.Computers&Geotechnics, [10.1016/j.compgeo.2020.103781](https://doi.org/10.1016/j.compgeo.2020.103781), 127, 103781

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Qi S., Simms, P. 2019. Robust methods to estimate large strain consolidation parameters from column tests. Canadian Geotechnical Journal, published ahead of print, <https://www.nrcresearchpress.com/doi/10.1139/cgj-2018-0870#Xm-7jS0ZMyk>

Qi, S., Simms, P., Daliri, F., Vanapalli, S. 2019. Coupling elasto-plastic behaviour of unsaturated soils to large strain consolidation. Geotechnique, Published online ahead of print, <https://doi.org/10.1680/jgeot.18.P.261>

Qi, S., Simms, P., Vanapalli, S. 2018. Discussion of “From saturated to unsaturated conditions and vice versa”, Acta Geotechnica, 13: 489 (<https://doi.org/10.1007/s11440-017-0577-6>)

Babaoglu, Y. Simms, P. 2017. Deposition Modelling of High Density Tailings using Smoothed Particle Hydrodynamics. Korean-Australian Journal of Rheology, DOI: 10.1007/s13367-017-0024-0

Mizani, S., Simms, P. & Wilson, W. 2017. Rheology for deposition control of polymer-amended oil sands tailings. Rheologica Acta, DOI: 10.1007/s00397-017-1015-2

Simms, P., Soleimani, S., Mizani, S., Daliri, F., Dunmola, A., Rozina, E. and Innocent-Bernard, T. 2017. Cracking, salinity, and evaporation in mesoscale drying experiments on three types of tailings. Env. Geotechnics, DOI: 10.1680/jenge.16.00026

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Conference Presentations/Posters

Baboaglu, Y. Simms, P. 2020. A rapid measurement method to determine hydraulic conductivity of tailings under self-weight consolidation. Tailings and Mine Waste 2020, Electronic proceedings.

Igbinedion, D. Simms, P. 2020. Ageing and large scale consolidation of centrifuge cake oil sands tailings. GeoVirtual /GeoCalgary 2020, Electronic proceedings.

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Esmaeilizadeh, A., Simms, P. 2020. 2D and axisymmetric large strain consolidation modelling for tailings applications. GeoVirtual /GeoCalgary 2020, Electronic proceedings.

Gheisari, N., Simms, P. 2020. Consolidation-creep modeling of pilot data on deposition of flocculated fluid fine tailings. GeoVirtual /GeoCalgary 2020, Electronic proceedings.

Abdulrahman, A.A., Simms, P. 2020. Flocculation optimization of clayey tailings using Torque Rheology. GeoVirtual /GeoCalgary 2020, Electronic proceedings.



Peruga, H., Cascante, G., Simms, P. 2020. Evaluation of oil sands tailings using ultrasonic waves. GeoVirtual /GeoCalgary 2020, Electronic proceedings.

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Qi, S., Esmaelizadeh, A., Simms, P. 2019. The UNSATCON model for tailings deposition. Proceedings of Tailings and Mine Waste '19, Vancouver, B.C, Nov. 17-20, 2019.

Gheisari, N., Salam, M., Qi, S., Simms, P. 2019. Structuration in natural clays, dredged sediments, and oil sands tailings. Proceedings of GeoSaintJohn's 2019. September 27-30, 2019, Saint John's, NL.

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Hurtado, O., Simms, P. 2017. Desiccation in mesoscale deposition experiments on centrifuge cake tailings. In Proceedings of GeoOttawa 2017, Canadian Geotechnical Conference, October 2-4, 2017, Ottawa, Ontario. Electronic proceedings.

Kazemi, K., Simms, P. 2017. Post-failure runout analysis from tailings dams using viscosity bifurcation rheology. Proceedings of Tailings and Mine Waste 2017, November 5-8, 2017, Banff, Alberta.

Khattak, M.H., Simms, P. 2018. Image Processing For Quantitative Analysis Of Fluid Fine Tailings, Dosed With Anionic Polyamide Based Flocculant. GeoEdmonton, 71st Canadian Geotechnical Conference, September 23-26, 2018, Edmonton, Alberta.

Qi, S., Thomas, W., Simms, P., and Hmidi, N. 2017. Hydro-geotechnical analysis of a thickened tailings deposit in Northern Canada. Proceedings of Tailings and Mine Waste 2017, November 5-8, 2017. Banff, Alberta.

Qi, S., Simms, P. 2018. Analysis of dewatering and desaturation of generic field deposition scenarios for thickened tailings. Accepted to Paste 2018, International Seminar on Paste and Thickened Tailings, Perth, Australia, April 10-12 2018.

Qi, S. Simms, P. 2018. Hydro-mechanical coupling in dewatering simulations for mine tailings management. UNSAT2018, International Conference on Unsaturated Soils, Hong Kong, August 4-8, 2018.

Qi, S., Salam, M, Simms, P. 2018. Creep and Structuration in Tailings and in Natural Clays. Proceedings of IOSTC 2018.

Qi, S., Salam, M. Simms, P. 2017. Modelling thixotropy in polymer amended oil sands tailings. In Proceedings of GeoOttawa 2017, Canadian Geotechnical Conference, Oct 2-4, 2017, Ottawa, Canada. Electronic proceedings.

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RESEARCH TEAM AND COLLABORATORS

Institution: Carleton University / University of Alberta

Principal Investigator: Paul Simms, P.Eng.

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

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Arazooben Patel	Carleton University	PhD Candidate	2019	2023
Oswaldo Hurtado	Carleton University	MSc Candidate	2016	2018 (complete)
David Ignaeblion	Carleton University	MSc Candidate	2018	2020 (complete)
Hissan Khattack	Carleton University	MSc Candidate	2017	2018 (complete)
Hirlatu Peruga	Carleton University	MSc Candidate	2018	2021
Nadine Salam	Carleton University	MSc Candidate	2019	2021
Linda Botha	University of Alberta	Postdoctoral Fellow	2017	2017 (complete)
Sarang Gumfekar	University of Alberta	PhD Candidate	2018	2021
Vahid Vajinejad	University of Alberta	Postdoctoral Fellow	2017	2019 (complete)
Yunhai Zhang	University of Alberta	PhD Candidate	2019	2023
Kwaku Amoako	University of Alberta	M.A.Sc. Candidate	2018	2020 (complete)
Adedeji Dunmola	Syncrude	COSIA Project Steward		

In-situ Real Time Measurements of Solids Content in Settling Tailings

COSIA Project Number: TE0041 RWG (IOSI)

Research Provider: University of Alberta, Northern Alberta Institute of Technology

Industry Champion: Canadian Natural

Industry Collaborators: Syncrude, Suncor, Imperial, Teck

Status: Year 3 of 3.75 (project extended 8 months because of slow down due to COVID-19 restrictions)

PROJECT SUMMARY

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

Milestones include:

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



8. Demonstration of calibration of optical scattering detectors with low-level X-ray detectors in test columns.
9. Development of a modelling code for light scattering from kaolinite and FT.
10. Development of a modelling code for X-ray transmission through kaolinite and FT.

PROGRESS AND ACHIEVEMENTS

This is the third year of reporting on the project. The results to date include:

2018

1. Lab bench measurements of the scattering of laser light at various angles and at various wavelengths were completed.
2. A test column and detector mounting tube was developed.
3. Scattering measurements of the settling of tailings in a test column began over periods of up to one month.
4. Fouling tests were carried out on various plastic and glass windows.
5. The ability to measure inorganic solids content in test samples of kaolinite and FT was demonstrated using a low level X-ray source.
6. The development of a first principles modelling code began using 3D Finite Difference Time Domain (FDTD) Electromagnetic Scattering calculations to model the scattered light from one to a few irregular shaped particles.
7. A first principle modelling code based on GEANT4 (GEometry ANd Tracking) was developed for the low level X-ray scattering measurements and compared to the measurements obtained in kaolinite and FT.

2019

Building on the 2018 activities:

1. Lab bench measurements of the scattering of laser light at various angles and at various wavelengths were completed and an optimum wavelength for measuring solids content was determined.
2. Fouling tests were completed on various plastic and glass windows and the best “anti-fouling” optical material was determined.
3. The ability to measure inorganic solids content at few percent accuracy in test samples of kaolinite and FT was demonstrated using two low-level X-ray sources.



4. A specially designed compact, portable, and economical gamma ray detector was fabricated. The custom-made gamma ray detector can be fabricated at a significantly lower cost than a typical commercial gamma ray detector.
5. A first principle modelling code based on GEANT4 was developed for the low-level X-ray scattering measurements and compared to the measurements obtained in kaolinite and FT for different setups. The calculations accurately model the X-ray source and measurement system giving good agreement with the experimental results to within a few percent.
6. Scattering and low-level X-ray measurements were used to track the temporal change of solids content in a settling column filled with a kaolin and water mixture and showed consistent results.

2020

Building on the previous years' activities:

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

LESSONS LEARNED

The lessons learned from the 2020 activities are:

1. Long wavelength near infrared (NIR) laser sources are advantageous for solids content detection.
2. Accurate absolute measurement of solids content can be made with low-level X-ray transmission diagnostics.
3. Compact, portable and high accuracy custom-designed gamma ray detectors can be fabricated economically.



4. Accurate modelling of X-ray diagnostic response requires incorporation of both absorption and scattering in the X-ray model.
5. Solids settling in a test column can be monitored by measuring backscattered light with a multiple detector array and low-level X-ray transmission diagnostics.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Priyesh Dhandharia, Wei Wang, Yu Wan, Bo Yu, Andrea Sedgwick, Abu Junaid, R. Fedosejevs, Manisha Gupta, and Ying Y. Tsui. 2018. "Optical Scattering Technique to Monitor Solids Content in Fluid Fine Tailings (FFT)", presented at the 6th International Oil Sands Tailings Conference (IOSTC), December 9-12, 2018, Edmonton, Alberta. (Presentation and Written Conference Proceedings Report)

Bo Yu, Wei Wang, Felipe Goncalves, Priyesh Dhandharia, Andrea Sedgwick, Abu Junaid, Manisha Gupta, R. Fedosejevs and Y.Y. Tsui. 2018. "Measuring Solids Content in Fluid Fine Tailings (FFT) Using a Low-Level X-ray Radiation Source", presented at the 6th International Oil Sands Tailings Conference (IOSTC), December 9-12, 2018, Edmonton, Alberta. (Presentation and Written Conference Proceedings Report)

Reports & Other Publications

Fedosejevs, R; Tsui, Y.Y.; Gupta, M. and Sedgwick, A. 2018. "Technology for In-situ Real Time Measurements of Solids Content in Settling Tailings ", Presented at the COSIA Tailings Project Dissemination Review, November 15, 2018, Calgary, Alberta.

Gupta, M.; Fedosejevs, R.; Sedgwick, A. and Tsui, Y.Y. 2019. "Technology for In-situ Real Time Measurements of Solids Content in Settling Tailings ", Presented at the COSIA Tailings Project Dissemination Review, November 21, 2019, Calgary, Alberta.

Tsui, Y.Y.; Gupta, M.; Fedosejevs, R. and Sedgwick, A. 2020. "Technology for In-situ Real Time Measurements of Solids Content in Settling Tailings", Presented at the IOSI-COSIA Tailings Project Dissemination Workshop, November 23, 2020, online.



RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Ying Tsui

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Ying Tsui	University of Alberta	Professor Principal Investigator		
Robert Fedosejevs	University of Alberta	Professor		
Manisha Gupta	University of Alberta	Assistant Professor		
Andrea Sedgwick	Northern Alberta Institute of Technology	Applied Research Chair		
Nathaniel Zirk	University of Alberta	Technician (2017-8)		
Felipe Goncalves	University of Alberta	BSc Co-op student	2015	2020
HaMy Dong	University of Alberta	BSc Co-op student	2015	2020
Wendy Wan	University of Alberta	MSc student	2016	2018
Priyesh Dhandharia	University of Alberta	Postdoctoral Fellow (2018)		
Bo Yu	University of Alberta	MSc student	2017	2020
Wei Wang	University of Alberta	MSc student	2017	2021
Tulika Srivastava	University of Alberta	Postdoctoral Fellow		
Talwinder Kaur Sraw	University of Alberta	Postdoctoral Fellow		
Channprit Kaur	University of Alberta	Postdoctoral Fellow		
Jiangwen Zhang	University of Alberta	MSc student	2019	2021
Allen Feng	University of Alberta	BSc Co-op student	2016	2021
Bo Yu	University of Alberta	Research Assistant		
Xiaoxuan Liu	University of Alberta	PhD student	2020	2023
Abu Junaid	Canadian Natural	COSIA Project Steward		

Research Collaborators: NSERC

Assessment of Liquefaction Potential of Unsaturated Tailings Subjected to Future Saturation

COSIA Project Number: TE0071 (IOSI19)

Research Provider: Thurber Engineering Ltd. and the University of Western Ontario

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 1 of 2

PROJECT SUMMARY

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

The laboratory program comprises tri-axial, ring shear, shear velocity (V_s), and soil-water characteristic curve (SWCC) tests on loose to medium dense tailings sand samples over a range of fines contents (7 to 25%), confining stresses (100 to 800 kPa) and saturation levels (85 to 100%). The research aims to develop new insight into liquefaction mechanisms, reduce design uncertainties and minimize the likelihood of catastrophic flow failure of tailings dams.

PROGRESS AND ACHIEVEMENTS

The project was initiated in the summer of 2020 with delivery of oil sands tailings samples to University of Western Ontario (UWO) and development of a testing matrix comprising approximately 50 individual tests to be completed over a period of 1.2 to 1.5 years. Following finalization of the test matrix and proposed schedule, the preparation of the individual test samples was commenced and the test program is currently underway. Index tests, including particle size distribution (PSD), minimum and maximum void ratio assessment and scanning electron microscope (SEM) imaging is largely complete. Overall the test program was about 30% complete at the end of 2020.

Extended laboratory closures and the pandemic related restrictions have caused a significant delay in meeting the project milestones and objectives. We're now slowly and solidly moving towards the planning research objectives. We have completed the triaxial tests on the saturated samples, and currently working on setting up a specialized triaxial cell for measuring matric suction and shear/compression wave velocities for unsaturated testing of the oil sand tailings samples.

LESSONS LEARNED

- Preliminary results on unsaturated samples indicate that static liquefaction could be circumvented even by a slight reduction (5 – 10%) in saturation ratio.
- The sand tailings indicate a semi-logarithmic critical state line.

LITERATURE CITED

Atigh, E., and Byrne, P.M. 2004. Liquefaction flow of submarine slopes under partially undrained conditions: an effective stress approach. Canadian Geotechnical Journal, **41**(1): 154-165. doi:Doi 10.1139/T03-079.

He, J., Chu, J., and Liu, H. 2014. Undrained shear strength of desaturated loose sand under monotonic shearing. Soils and Foundations, **54**(4): 910 - 916.

Hossain, M.A., and Yin, J.-H. 2010. Behavior of a compacted completely decomposed granite soil from suction controlled direct shear tests. Journal of Geotechnical and Geoenvironmental Engineering, ASCE, **136**(1): 189 - 198.

Lu, X., Huang, M., and Andrade, J.E. 2018. Modeling the static liquefaction of unsaturated sand containing gas bubbles. Soils and Foundations, **58**: 122 - 133.

PRESENTATIONS AND PUBLICATIONS

There have not been any publications or presentations yet. Once there are sufficient results, closer to project completion time, the results of the work will be published.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Western Ontario (UWO)

Principal Investigator: Abouzar Sadrekarimi

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Abouzar Sadrekarimi	UWO	Principal Investigator PhD, Student Supervisor		
Farshad Zehforoosh	UWO	MSc, Student Candidate	2019	2022
Paul Cavanagh	Imperial	COSIA Project Steward		

Research Collaborators: Thurber Engineering Ltd. (TEL)

Principal Collaborator: Iain Gidley

Name	Institution or Company	Degree and Job Title
Iain Gidley	TEL	MSc, Project Manager
Silawat Jeeravipoolvarn	TEL	PhD, Project Engineer
Sam Proskin	TEL	PhD, Project Reviewer

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

COSIA Project Number: TE0072 (IOSI19)

Research Provider: Thurber Engineering Ltd.

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 1 of 2

PROJECT SUMMARY

The centrifuge consolidation test technique places a tailings specimen at the end of a rotating centrifuge arm that subjects the specimen to inertial radial acceleration, simulating an increased acceleration gravity many times that of the earth's gravity. The increased level of acceleration improves the rate of hindered sedimentation and consolidation, allowing the processes to be completed within a shorter time frame.

Currently, the conventional large strain consolidation test method for oil sands tailings takes months or up to a year to complete on fine-grained tailings. This test time could be reduced to days using the centrifuge consolidation technique. A much shorter turnaround time would benefit the oil sands industry in several ways, including accelerated analysis and planning, more testing and in-depth assessment of options, additional tailings quality assurance and control, and a probabilistic tailing planning approach.

This research investigated the use of a benchtop centrifuge to rapidly obtain tailings consolidation parameters for oil sands tailings materials. These parameters were assessed by comparing them with those from geotechnical beam centrifuge and conventional large strain consolidation testing.

To achieve the above objectives, the following research activities were conducted:

- Literature review
- Laboratory test program
 - o Index testing
 - o Rapid centrifuge consolidation (RCC) test
 - o Large strain consolidation (LSC) test
 - o Geotechnical beam centrifuge (GBC) test

- Validation standpipe (VS) test
- Comparative data analysis

Three tailings samples used for this study included raw fluid tailings (FT), polymer treated FT and thickened tailings (TT). The RCC, LSC and VS were executed at the Thurber Calgary tailings laboratory using Thurber's existing test methodologies and FSCA software (FSCA is finite strain consolidation analysis software for determining rate and settlement of tailings) for data analysis. The GBC tests and additional LSC tests were performed by two independent research units at the University of Alberta.

PROGRESS AND ACHIEVEMENTS

The literature review and laboratory test program have been completed. Comparative data analysis is nearly completed.

LESSONS LEARNED

Preliminary findings indicated that the RCC test method reduces the total test time and provides compressibility and hydraulic conductivity data similar to the conventional LSC test method for fine-grained oil sands tailings.

Additional observations and findings will be disclosed following the completion of the ongoing comparative data analysis.

RESEARCH TEAM AND COLLABORATORS

Institution: Thurber Engineering Ltd.

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

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Silawat Jeeravipoolvarn	Thurber Engineering Ltd.	Principal Investigator Ph.D., P.Eng., Geotechnical Engineer		
Samuel Proskin	Thurber Engineering Ltd.	Ph.D., P.Eng., Senior Geotechnical Engineer		
Trempeess Moore	Thurber Engineering Ltd.	M.Eng., P.Eng, Principal		
Reza Moussavi Nik	Imperial	COSIA Project Steward		

Research 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)
Rick Chalaturnyk	University of Alberta	Ph.D., P.Eng., Professor		
Gonzalo Zambrano	University of Alberta	Ph.D., P.Eng., Research Director		
Nicholas Beier	University of Alberta	Ph.D., P.Eng., Assistant Professor		
Ahlam Abdulnabi	University of Alberta	Ph.D., EIT., Research Associate		

Geotechnical Modelling of Surface Strengthening for Soft Tailings Capping

COSIA Project Number: TE0074 (IOSI19)

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 1 of 1

PROJECT SUMMARY

Hydraulically placed sand caps are potentially cost-effective and practical for use in the oil sands for the reclamation of tailings ponds. This research explores the potential benefits of a strengthened surface for capping success on soft, fines-dominated treated tailings. Deltaic capping (sometimes called beaching) is sub-aerial placement (i.e., placement above water with exposure to the atmosphere) of a cap using hydraulic transport and deposition of a sand (or other granular) slurry, applying the processes that nature uses to build river deltas. The 2019-2020 project “Modelling the Cap Placement with Tailings Deformation and Consolidation” (COSIA project number TE0073 (IOSI19); Greenwood, 2020) demonstrated that deltaic capping was very promising, but was unlikely to be successful on tailings of less than 5 kPa strength unless the cap slopes were very flat – less than 0.5%. The current research looked at whether a strengthened surface could allow capping of weaker tailings without very flat cap slopes.

Design and Methodology

The research used the advanced geomechanics program FLAC[®] (Fast Lagrangian Analysis of Continua) for numerical simulation of the behaviour of the tailings and the interaction between tailings and cap. The modelling was carried out using the model developed for the TE0073 (IOSI19) project to keep comparability of results between the projects. Modelling used FLAC 2D in large strain mode, representing an advancing cap that included infilling in response to tailings settlement and strain softening of tailings. A wedge-shaped cap consisting of sand was modelled as a surcharge load, with no water cover over the tailings. The cap was considered successful if it advanced 300 m over a 400-m-long and 50-m-deep deposit.

The modelling considered caps with surface slopes of 0.25%, 0.5%, and 1% advancing across tailings exhibiting undrained shear strength of 2, 3, and 4 kPa. The strengthened surface was a 2-m-thick zone with strengths of 6, 50, and 150 kPa to represent various treatments – from vegetation to cement-treated tailings. Two tensile strengths, 15 and 150 kPa, were modelled to represent vegetation roots and geotextile. Finally, a tailings profile of increasing undrained shear strength with depth was modelled; the strength profile increased linearly from 2 kPa immediately below the strengthened surface to 10 kPa at 50 m, which was the bottom of the model.

PROGRESS AND ACHIEVEMENTS

The FLAC 2D model was successfully applied to show the influence of surface strengthening on the predicted success of deltaic capping. Some of the important conclusions from the modelling research include:

- For constant undrained shear strength profiles with depth (e.g., 3 kPa tailings down to 50 m), the failure surfaces went very deep, to the bottom of the deposit. The 2-m-thick strengthened surface zone was only 4% of the deposit depth (representing even less of the overall failure surface length) and generally had little effect on the potential for failure.
 - Surface strengthening provided only a minimal benefit for these deposits. Poor performing cases were not made successful with the modelled surface strengthening.
 - Combining tensile strength with surface strengthening provided only a small added benefit for these deposits.
- A profile of increasing undrained shear strength with depth had a dramatic favourable impact on the benefit obtained from surface strengthening treatments.

LESSONS LEARNED

Assuming the tailings have a uniform strength profile for a 50-m depth, although useful for making comparisons between different scenarios, results in misleading outcomes for assessing the potential benefits of surface strengthening. Tailings deposits often have increasing undrained shear strengths with depth, which, when combined with even modest surface strengthening, substantially improves the predicted success of deltaic capping.

Additional work is needed to explore the sensitivity of profiles of increasing undrained shear strength with depth. For these profiles, tensile strength combined with surface strengthening should be examined. Tensile strengths representative of fibre addition or vegetation that dewateres and adds root strength are recommended.

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Greenwood, J., 2020. "Modelling the Cap Placement with Tailings Deformation and Consolidation," IOSI 2018-06, final report April 21, 2020. This work is internal/ongoing and not published.

RESEARCH TEAM AND COLLABORATORS

Institution: Barr Engineering and Environmental Science Canada Ltd.

Principal Investigator: Jed Greenwood

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Philip Solseng	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Sr. Geotechnical Engineer		
Nav Dhadli	Barr Engineering and Environmental Science Canada Ltd.	Project Manager		
Dirk Luger	Deltares	Sr. Geotechnical Engineer		
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Research Collaborators: Deltares

Deep Cohesive Deposit Modelling

COSIA Project Number: TJ0045

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Ongoing

PROJECT SUMMARY

Deep cohesive deposits (DCDs) of oil sands tailings are an important tailings management option that offers reduced footprint requirements and eliminates the multiple re-handling of fluid tailings associated with thin-lift dewatering operations. By nature, though these deep deposits have various dewatering mechanisms that can be relevant for long-term dewatering, self-weight consolidation is by far the dominant mechanism driving their long-term geotechnical trajectories. The ability to predict the long-term performance of these deposits is critical to their planning, design, deposition, operation, stabilization, capping and closure. Numerical and physical modelling are two techniques for predicting the long-term trajectories of DCDs. The triangulation of numerical and physical modelling techniques in predicting the long-term geotechnical trajectories of these DCDs, along with calibration using pilot field deposits data, increases the certainty of managing and eventually incorporating these deposits into the final closure landscape. This project aimed at developing fit-for-purpose numerical and physical predictive tools that are calibrated to suitable pilot field DCDs. The ultimate goal is to use these predictive tools in making decisions related to the reclamation and closure of these important elements of the final closure landscape. The validity of physical modelling of DCDs using the geotechnical beam centrifuge was established, with general agreement between physical model predictions and field deposit performance data. Also, predictions from numerical analysis of a DCD were found to agree well with physical modelling results from an equivalent prototype deposit simulated using the beam centrifuge.

PROGRESS AND ACHIEVEMENTS

A large-strain consolidation (LSC) numerical model has been developed and calibrated for application to DCDs, as previously reported (COSIA 2019). Numerical predictions of a DCD using the LSC model was found to agree well with beam centrifuge test that modelled an equivalent prototype of the DCD. Also, the beam centrifuge data from a prototype testing of 10 m deep DCD was found to be in general agreement with field data from the prototype. Ongoing calibration of the LSC model with data from various field DCDs is planned for the future.

LESSONS LEARNED

The triangulation of numerical and physical modelling techniques with field pilot data achieved under this project is significant for the reliable prediction of the long-term geotechnical performance of DCDs. This, in turn, increases the certainty in the ability to plan, design, operate, stabilize, cap and close these DCDs as important components of the

closure landscape. It also affords the ability to promptly identify any discrepancy between long-term closure goals and short- to medium-term tailings management plans, and inform decisions to implement appropriate adaptive management measures to ensure successful closure outcomes.

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COSIA. 2019. 2018 Tailings Research Report. Report available and downloadable at https://www.cosia.ca/sites/default/files/attachments/2018%20Tailings%20Research%20Report_FINAL%2003Jun2019.pdf

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigator: Adedeji Dunmola

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Deep Deposit Filling, Monitoring and Modelling

COSIA Project Number: TJ0072

Research Provider: Golder Associates Ltd.

Industry Champion: Imperial

Status: Year 6 of 8

PROJECT SUMMARY

The objective of this project is to develop a database of parameters for modelling consolidation behaviour of new and existing commercial scale, deep thickened tailings (TT) deposits. This project aims to develop a set of consolidation modelling input parameters with samples and data periodically collected from a commercial scale deep TT deposit currently under construction.

The TT in the deposit is produced by combining fresh flotation tailings (FLT) with aged fluid tailings (FT) from an existing tailings pond. The hydraulically transported thickener underflow can shear the TT flocs prior to deposition so re-flocculation of the material near the discharge point is used to enhance dewatering and accelerate water release. Fine Fluid Tailings (FFT) collection regularly includes peat (and other debris) that could affect the deposit behaviour.

Zones of dissimilar composition (clay/fines content, void ratio, etc.) and consolidation characteristics develop within the TT deposit due to thickener feed and flow variability, and material segregation during deposition, which necessitates the application of zone-specific consolidation parameters to model the overall deposit behaviour. The work may result in changes to current operational and construction practices to achieve closure objectives.

PROGRESS AND ACHIEVEMENTS

In Phase one of the project, laboratory scale testing was carried out on samples with different compositions of FLT and FT. Large strain consolidation (LSC) cells (or oedometer cells) were used to measure compressibility and hydraulic conductivity of the tailings mixtures.

In Phase two of the study, in-situ samples were collected and tested to determine the deposit properties and to model consolidation behaviour. The consolidation parameters obtained from in-situ samples augmented the previously determined parameter database from laboratory constituted samples.

The deposit was then divided into three distinct zones based on solids content, sand-to-fines ratio (SFR) and clay content. Consolidation parameters were applied to each zone of the deposit using one-dimensional (1-D) consolidation models at ultimate deposit height based on in-situ deposit characteristics and distribution of properties, and double drainage boundary conditions due to sandy foundation conditions.

The modelling results indicated that:

- the 60 m thick deposit could take up to 250 years for complete settlement;
- most of the surface can be capped before the end of mine life; and
- most of the deposit will undergo between 15 and 30 m of settlement by completion.

Capping volumes will be based on residual settlements of up to 45 m in some parts of the deposit. The results also indicated that the current deposition strategy may need to change and mitigations may need to be applied to achieve final reclamation objectives and outcomes.

The initial laboratory test program was expanded to evaluate impact of peat in polymer treated fines deposits. Polymer treated samples with known amount of peat (by weight) were tested in large strain consolidation cells to measure compressibility and hydraulic conductivity at various mixtures and compared with a baseline sample without peat. The results indicated that up to 25% (by weight) of peat in treated FT has negligible impact for long-term consolidation of the treated tailings deposit.

LESSONS LEARNED

It was recognized that variability in laboratory and field-derived parameters is unavoidable and that a range of consolidation properties need to be evaluated and considered to understand the sensitivity of the results to the inputs, and to develop appropriate closure schemes. The laboratory results also indicated that peat inclusion in the deposits do not significantly impact long-term consolidation of treated tailings deposit.

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[COSIA] Canada's Oil Sands Innovation Alliance. 2016. Unified fines method for minus 44 micron material and for particle size distribution. Compiled by COSIA fines measurement working group, February 2016.

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PRESENTATIONS AND PUBLICATIONS

Weerakone, W. M.S.B., Ren, W. 2018. *Accelerated oil sand tailings dewatering with thickening and re-flocculation*, Presented at IOSTC 2018. International Oil sand Tailings Conference, Edmonton, Canada, December 2018.



RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigator: Sidantha Weerakone

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Paul Cavanagh	Imperial	Senior Technical Advisor		
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Seepage Induced Consolidation Testing for Permanent Aquatic Storage Structure

COSIA Project Number: TJ0132

Research Provider: University of Colorado

Industry Champion: Suncor

Status: Year 3 of 3

PROJECT SUMMARY

The Permanent Aquatic Storage Structure (PASS) Seepage Induced Consolidation Testing (SICT) Project was initiated to support technology development of PASS and to assist with the predictive capability of long-term consolidation of the PASS deposit. The PASS technology is one of Suncor's primary tailings treatment technologies that use a coagulant, followed by a flocculant to treat mature fine tailings (MFT). The SICT technology was selected as the best available assessment method based on positive experience of consolidation prediction with treated and untreated MFT. Thus, it was felt that the SICT could be suitable for the new PASS treated material, but that this should be investigated, and a methodology and procedure documented for future use.

PROGRESS AND ACHIEVEMENTS

During the first year of PASS support, the SICT procedure as initially defined was found to be inadequate for predicting dewatering of the PASS treated material. It was theorized that a dewatering mechanism outside of the large strain consolidation theory is the cause of this. As a result of this initial failing, the second year of the program focused on evaluating the short-comings of the procedure and apparatus, and a potential mechanism of geotechnical "creep" was identified and investigated in dewatering of the PASS treated MFT. It was subsequently found that there were time-dependent void ratio changes that could not be explained by large strain consolidation theory. These changes were quantified, and implemented numerically using the newly developed CONCREEP software, which showed that the SICT could be used to predict the dewatering of PASS treated MFT with a modified testing procedure.

LESSONS LEARNED

The following were the main lessons learned from the program:

- The dewatering behaviour of the coagulated and flocculated fluid tailings (FT) was not effectively captured in the initial SICT tests, nor in the wider large strain consolidation theory
- Creep behaviour was measured in the dewatering PASS treated tailings, which was primarily present in the lower effective stress ranges, tapering off to no-creep in the high effective stresses



- The SICT procedure was modified to capture this creep behaviour and determine creep parameters for use in simulations
- A numerical model was developed based on the CONDES software to incorporate creep parameter and determine its role in dewatering rate and magnitude. This new software is call CONCREEP

LITERATURE CITED

The foundation for the work Dobroslav Znidarcic's considerable experience with large strain consolidation theory developed by Gibson et al. in 1967. The creep component is a rational mathematic expression of creep behaviour, which was incorporated into Gibson's large strain consolidation theory but is empirical in nature.

RESEARCH TEAM AND COLLABORATORS

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Principal Investigator: Dr. Dobroslav Znidarcic, Professor Emeritus University of Colorado, Boulder

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Dobroslav Znidarcic		Principal Investigator Professor Emeritus		
Gordan Gjerapic	University of Colorado, Boulder	Researcher		
Fergus Murphy	Suncor	Project Steward		

Research Collaborators:

Coanda Research & Development were tasked with completing some testing under this scope. Amarebh Sorta of Coanda was the principal researcher at Coanda who assisted with the project from 2017 – 2020.

Acronyms and Glossary

ADW	accelerated dewatering
AER	Alberta Energy Regulator
AFD	atmospheric fines drying
behaviour of fluid tailings	measured response of the fluid tailings in a tailings deposit over time
BAW	beach above water
BBW	beach below water
centrifuge cake	clay material produced following centrifuging (spinning) polymer-treated fluid fine tailings
CFT	centrifuge fine tailings
coagulation	The agglomeration of fine particles in a tailings slurry, usually by the addition of a chemical agent that alters the electrical charge on those particles, thereby reducing inter-particle repulsive forces
COSIA	Canada's Oil Sands Innovation Alliance
CST	capillary suction time
Directive 085	<i>Directive 085: Fluid Tailings Management for Oil Sands Mining Projects</i>
EPA	Environmental Priority Area
FFT	fluid fine tailings – a liquid suspension of oil sands fine tailings or fines-dominated tailings in water, with a solids content greater than 2% but less than the solids content corresponding to the Liquid Limit.
FT	fluid tailings – as defined in <i>Directive 085</i> – any fluid discard from bitumen extraction facilities containing more than 5 mass per cent suspended solids and having less than an undrained shear strength of 5 kilopascals
fines	mineral solids with particle size equal to or less than 44 µm (does not include bitumen)
flocculation	The “clustering” of fine particles in a tailings slurry into groups or “flocs,” usually by the addition of a chemical agent that binds to those particles, thereby tying them together
FLT	flotation tailings
geotechnical fines content	mass of fines divided by mass of solids x 100%
geotechnical water content	mass of water divided by mass of solids x 100%
LAI	leaf area index is the leaf area per unit of ground area
Liquid Limit	The geotechnical water content defining the boundary between a liquid and a solid in soil mechanics. This state is defined by a standard laboratory test modified for use in oil sands tailings containing bitumen. It can also be described in terms of an equivalent FOFW (fines over fines + water ratio) or solids content. This test results in an equivalent remoulded shear strength of 1 to 2 kPa.
MFT	mature fine tailings – fluid fine tailings with a low sand-to-fines ratio (<0.3) and a solids content greater than 30% (nominal)

PSD	particle size distribution
SC	solids content – mass of solids divided by mass of (solids + bitumen + water) x 100%
SFR	sand-to-fines ratio – the mass ratio of sand-to-fines; i.e., the mass of mineral solids with particle size >44 μm divided by the mass of mineral solids with particles $\leq 44 \mu\text{m}$
solids	sand, clay and other solid particles contained in oil sands tailings (does not include bitumen)
TEA	terminal electron acceptors
TFT	thin fine tailings – a subset of fluid fine tailings with a sand-to-fines ratio of less than 1 and a solids content less than 30% (nominal)
TMF	<i>Lower Athabasca Region: Tailings Management Framework for the Mineable Athabasca Oil Sands</i>
TRO TM	Tailings Reduction Operation
TT	thickened tailings
void ratio	volume of voids divided by volume of solids
water content	mass of water divided by mass of (solids + bitumen + water) x 100%
μm	microns or micrometres (one millionth of 1 m)