



COSIA TAILINGS EPA

2018 Tailings Research Report

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Introduction

This report summarizes the recent progress for Canada's Oil Sands Innovation Alliance (COSIA) Tailings Environmental Priority Area (EPA) tailings research projects. Tailings are the sand, silt, clay, and water found naturally in oil sands that remain following the mining and bitumen extraction process. Member companies with the COSIA Tailings EPA are focused on improving the management of oil sands tailings throughout their production and treatment, storage, reclamation and closure phases.

Working with universities, government and research institutes, other companies and partners, the COSIA Tailings EPA is bringing together the shared experience, expertise and financial commitment of oil sands mining companies to find new technologies and solutions to tailings management.

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

- accumulation of fluid fine tailings (FFT) within tailings ponds through the development of new and improved tailings management technologies;
- treatment of process affected water, the water which remains once the FFT are removed; and
- acceleration of reclamation of the resulting tailings deposits so that they can be incorporated into the final reclaimed closure landscape.

The research projects summarized in this report are categorized into four principal research areas: tailings capping, tailings treatment technologies, froth treatment tailings, and consolidation modelling. Each research project seeks to advance the understanding of, and improve upon, the risks and uncertainties 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 shorten or lengthen the time for consolidation after the deposit is placed. For both tailings treatment processes and consolidation mechanisms, the industry is seeking a better understanding so that this 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.

This inaugural summary report from the COSIA Tailings EPA member companies highlights just some of the recent 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.



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://www.cosia.ca>).

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TAILINGS CAPPING

Suppression of Fines Re-suspension in Aqueous Deposition of Tailings

COSIA Project Number: TJ0088

Research Provider: Stantec Consulting Ltd., Barr Engineering and Environmental Science Canada Ltd., BGC Engineering Inc., and Deltares

Industry Champion: Teck Resources Limited

Industry Collaborators: Imperial

Status: Complete

PROJECT SUMMARY

The purpose of the project is to understand the ability of various types of materials that when placed on the tailings (i.e., to cap the tailings) prevent or limit fines re-suspension for different types of tailings. Fines are the mineral solids with particle size equal to or less than 44 microns (μm) and do not include bitumen. Capping materials being considered include organic material (grass, shrubs and aquatic plants), sand, coke (a by-product of the bitumen upgrading process), geofabrics, limestone, chemical amendments and polymers; while tailings material includes accelerated dewatering tailings (ADW), centrifuge fine tailings (CFT), thickened tailings (TT) with sand-to-fines ratio (SFR) greater than 1, and fluid tailings at $\sim 30\%$ solids (FT). The project will identify the body of knowledge on three mitigation approaches to reduce fines re-suspension. The approaches include:

- **Chemical treatment** to remove fines from the overlying water cap and/or to strengthen the fine tailings to reduce fines erosion;
- **Material capping** to isolate the tailings fines from the overlying water cap; and
- Establishment of **aquatic vegetation** to reduce fines erosion.

The objectives of the project are to:

1. Identify mitigation measures for the prevention of fine tailings re-suspension in an aquatic environment;
2. Capture the body of knowledge by performing a literature review of information available in the public domain. Appropriate databases and key words, conference proceedings, and documents available through COSIA will be reviewed. In addition, experience and expertise in the consulting community will be accessed; and
3. Summarize the results and identify the best options for the next phase of work to fill knowledge gaps; namely, to test the potential mitigation methods.

PROGRESS AND ACHIEVEMENTS

Key findings include:

Treatment of the water cap to increase settling velocity of suspended fines

Favourable results in lab beakers and columns with polymers and metallic salts were encountered but under very controlled and quiescent conditions. Some unfavourable results such as increased eco-toxicity and water quality degradation were found. The literature reviewed suggests chemical treatment will remain effective for five to 10 years or until covered by other sediments. Two relevant oil sands studies were reviewed, including a University of Alberta CO₂ lab study on oil sands process affected water. The clarity of the water did not improve despite a drop in pH from 8 to 6. Alum dosing for turbidity removal was also studied.

Increasing the erosion resistance of the tailings at the water cap-tailings interface

No *in situ* treatment studies were found for thin fine tailings (TFT) or fluid fine tailings (FFT). *In situ* treatment of contaminated sediments was performed at field pilot and full scale in rivers, lakes, and harbours, including:

- Biological/chemical: addition of microorganisms and/or chemicals to the sediments to initiate or enhance bioremediation; and
- Solidification/stabilization: addition of chemicals or cements to encapsulate the sediments.

In situ treatment is challenging from both an implementation and effectiveness standpoint. This is due to limited process control, typically unfavourable environmental conditions, lower efficiencies compared to *ex situ* treatments, and thick soft foundations that typically, will not support thick denser layers.

Create a cap-isolating layer with a water cap in place

Sand capping has worked with substrate strengths greater than 25 pascals (Pa) (for FFT this would be approximately 35% solids content (SC)), using very thin lifts. The literature reviewed suggests that oil sands fine tailings could support a sand cap in the 24 to 28% SC range, but that it would be unstable. Stability would increase with SC in excess of 30% and over time (deposit aging).

A sand raining field pilot demonstrated the ability to densify MFT and form a cap in a careful, low loading rate approach in a 4 metre (m) diameter casing filled with 3 m of FFT with a 2 m water cap. The study also demonstrated that the sand cap could fail – potentially due to mechanisms such as fingering and squeezing.

Development of aquatic vegetation to stabilize tailings/water interface

The study presents information using four tailings types grouped largely by geotechnical factors (i.e., strength/consistency) and by four water conditions. These four water conditions include: unsaturated/crusted conditions (dry surface), drained but saturated conditions, shallow water (0 to less than 2 m) and deep water (greater than 2 m). A set of plant communities was defined for use based on species tolerance for substrate and water conditions. The vegetation community types were assigned to the water conditions and tailings type categories based on the physical conditions of these individual categories. The physical conditions, soil structure, access (for planting), and issues that may be encountered during vegetation establishment, within each of the water conditions and tailings types, are also presented. Lists of candidate plant species (associated with the



community types) that may be used in testing during subsequent phases of the study are presented for each of four tailings types and expected water depths.

LESSONS LEARNED

1. There is a limited body of knowledge (directly relevant) on the three mitigation approaches to reduce fines re-suspension in an aquatic environment.
2. Older treated tailings (TT, ADW, CFT) and dried mature fine tailings (dMFT) are less likely to erode and become re-suspended than FFT or recently deposited treated tailings. Some mitigation may be needed in shallow, high-energy environments.
3. FFT and TFT layers are likely to become re-suspended and require mitigation.
4. Aquatic vegetation is most likely to succeed in shallower water cap deposits.

RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Carol Jones	Stantec	Soil Scientist, Principal		
Al Fandrey	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Senior Civil Engineer		
Todd Dejournet	Barr Engineering and Environmental Science Canada Ltd.	Senior Environmental Engineer		
Keith Pilgrim	Barr Engineering and Environmental Science Canada Ltd.	Senior Water Resources Scientist		
Arjan Wijdeveld	Barr Engineering and Environmental Science Canada Ltd./Deltares	Senior Consultant and Researcher		
Ben Sheets	Barr Engineering and Environmental Science Canada Ltd.	Senior Geologist		
Dirk Luger	Barr Engineering and Environmental Science Canada Ltd.	Senior Geotechnical Expert		

Surface Strengthening of a Soft Deposit

COSIA Project Number: TJ0090

Research Provider: BGC Engineering Inc., NAIT Boreal Institute of Technology

Industry Champion: Canadian Natural Resources Limited

Status: Year 3 of 5

PROJECT SUMMARY

Canadian Natural Resources Limited (Canadian Natural) is evaluating the potential to sand cap soft, deep, fine tailings deposits as a part of its mine closure efforts. As part of this evaluation process, Canadian Natural designed and constructed the 30 m wide by 60 m long Centrifuge Test Cell at Jackpine mine (JPM) in the fall of 2015 and filled it with 4.65 m of centrifuge fluid fine tailings (CFFT) in January 2016. The initial solids content of the CFFT after deposition was on average 47%.

Since then, a series of field investigations have been carried out and various tailings strength improvement technologies have been tested with the overall goal to place a cap on the deposit. Strength improvement and dewatering technologies implemented include: vertical wick drains, the seeding and planting of native slender wheatgrass seed and seedlings and sandbar willow seedlings and cuttings, and the pumping of ponded water from the deposit surface. Vegetation was installed both by hand and by custom-built amphibious rover. Wick drains were installed by custom-built Argo and by amphibious rover. Annually since 2016, the relative performance of strength-improving technologies has been compared with an un-amended “control” zone of the deposit.

The following activities have been conducted over the last three years at the Centrifuge Test Cell to evaluate the benefits of strength improvement technologies:

- Monitoring of instrumentation installed within the CFFT. The instrumentation includes: vibrating wire piezometers for pore water pressure; sonic ranger and settlement plates for deposit thickness; total pressure cells for vertical total stress; thermistors for temperature; time-domain reflectometry probes for volumetric water content; and suction sensors for matric soil suction.
- CFFT sampling and laboratory testing were carried out to measure profiles of the CFFT solids content and assess changes over time.
- *In situ* CFFT strength testing, including ball/cone penetration testing, electronic vane shear testing, and hand vane shear testing, were carried out to measure profiles of the undrained shear strength and assess changes with time.
- Modified plate bearing tests were conducted in 2016 and 2017 to determine the bearing capacity of the CFFT surface and evaluate the potential for sand capping.



This research project advances the understanding of the multi-year effects of strength and dewatering improvement technologies for CFFT at a field scale, using wick drains and vegetation, with the end goal of sand capping and terrestrial reclamation.

PROGRESS AND ACHIEVEMENTS

The following progress has been made since project inception to the end of 2017. Results from 2018 investigations have not yet been assessed.

- The deposit height has decreased by approximately 20% of its original deposition thickness.
- Solids contents at depth have increased by approximately 3%.
- The peak undrained shear strength of the CFFT at depth has increased minimally since deposition, from approximately 1.5 kPa in August 2016 to 2.5 kPa in September 2017.
- Pore pressure measurements indicate that little to no effective stress gain has occurred.
- A denser, stronger (approximately 5 kPa) crust, approximately 40 cm thick, has formed at the top of the CFFT, predominantly due to freeze-thaw consolidation, evaporation and periodic surface water removal.
- High, undrained shear strength values in the deposit crust are obtained when it is unsaturated, but these strength gains are quickly lost when rewetted.
- Six months after wick drain installation the benefits on deposit dewatering and strength gain are negligible. Compared to the un-amended control section, the CFFT surface is 5 cm lower, the CFFT strength is similar, and the solids content is 1% higher.
- Where the crust remained unsaturated on the side slopes of the deposit, the peak undrained shear strength in areas with high vegetation cover ranged from 20 to 80 kPa in the top 30 cm, versus values of 10 to 50 kPa in the un-amended control zone. However, due to cell configuration, vegetation survivorship was low in flooded areas leading to less strength gain in the central (thickest) portion of the deposit, highlighting the importance of surface water removal for upland plant species survivorship, strength gain and drying.

LESSONS LEARNED

The following emerging lessons are of significance to the oil sands industry, with the end goal of reclaiming soft tailings deposits:

- Wick drains can be efficiently installed from a custom-built Argo working in frozen conditions. Over a short six-month period, wick drains do not appear to appreciably enhance CFFT dewatering and strengthening.
- Native vegetation (sandbar willow and slender wheatgrass) can be successfully planted and grown within CFFT using a variety of methods such as seed, seedlings, and cuttings.
- Native vegetation can lead to an increase in CFFT strength in the top 30 cm over one growing season.
- Over a period of two years since deposition, strength amendment technologies have not significantly enhanced strength gain or dewatering. The deposit is not yet strong enough to support an operationally feasible sand capping trial.

- The deposit will continue to be monitored and investigated to assess the relative performance of the installed strength amendments (wick drains and vegetation) over an extended time period.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Nik, R. M., Freeman, G., McKenna, G. 2018. In Preparation. *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Sixth International Oil Sands Tailings Conference 2018, Edmonton, Alberta, December 9-12, 2018.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural Resources Limited

Principal Investigator: BGC Engineering Inc.

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Jack Seto	BGC Engineering Inc.	Principal Geotechnical Engineer		
Gord McKenna, PhD	McKenna Geotechnical Inc.	Geotechnical Engineer, Landform Designer		
Amanda Schoonmaker, PhD	NAIT Boreal Research Institute	NSERC Industrial Research Chair for Colleges in Boreal Reclamation and Reforestation		
Jason Song, PhD	O'Kane Consultants Inc.	Senior Geoscientist		

Literature Review for In-line/On-line Rheology Monitoring Technology

COSIA Project Number: TJ0092

Research Provider: Saskatchewan Research Council

Industry Champion: Teck Resources Limited

Status: Complete

PROJECT SUMMARY

Rheological properties (flow characteristics) are useful indicators of the degree of aggregation or dispersion of particles within slurries. Typical rheological parameters (such as viscosity and yield stress) represent different contributions toward overall slurry behaviour, and can be used to establish criteria for physical stability of the slurry and to control if the slurry property departs from the desired flow behaviour.

Despite the importance of rheological properties, yield stress and viscosity data are rarely leveraged to control and adjust mineral slurry processes. This is due to difficulties in measuring these parameters in real time. Currently, most rheology tests are conducted at-line or off-line, resulting in a time delay before data are available. It is difficult to use rheological data as control parameters when rheological results are obtained hours or days after a sample is taken.

In an effort to better understand the potential benefits of using rheological data as control parameters and the difficulties associated with this endeavour, Teck Resources Limited (Teck) contracted the Saskatchewan Research Council (SRC) to conduct a literature review to explore the current state of in-line/on-line rheology monitoring technology.

The review discusses the background and motivations for slurry rheology measurement along with the challenges facing rheology measurement for clay based slurries. Basic rheological concepts, models and pipe flow equations that could be used in the rheology measurement are presented along with general process measurement methods and essential features required for in-line/on-line measurement. The current developments and research on in-line/on-line rheology measurement technology and commercially available in-line/on-line viscometers identified from literature are summarized, followed by a summary of conclusions and comments relating to future development of rheology monitors.

LESSONS LEARNED

The following summarizes the author's observations from this study:

1. Rheological properties are useful indicators of the degree of aggregation and dispersion of particles within slurries. Rheological parameters (i.e., viscosity and yield stress) represent different contributions toward overall slurry behaviour, and can be used to establish criteria for physical stability of the slurry and

to control if the slurry property departs from the desired flow behaviour. Therefore, rheological values could be used as controlling parameters for feed forward or feedback control systems if in-line/on-line rheology monitoring systems were available;

2. For Newtonian and non-Newtonian homogeneous fluids (e.g., oil and flocculant solutions), rotational viscometry can be used as in-line/on-line and at-line/off-line rheology measurement devices; concentric cylinder rotational viscometry can also measure the rheology of homogeneous and non-settling slurries (e.g., well mixed fluid fine tailings (FFT) and mature fine tailings (MFT)) if solid particles in the slurry would not settle and jam the measuring components during measurement; a vertical, flow through design may prevent slurry settling in the measuring cup but have other complicating factors due to turbulent flow;
3. There are commercial in-line/on-line viscometers available which are capable of measuring the rheology for homogeneous fluids and non-settling slurries, and generating real-time viscosity and apparent yield stress data;
4. Pipe flow viscometry can be used to measure the rheology of homogeneous, heterogeneous and settling slurries, provided the solids particles would not settle during the measurement. A pipe flow viscometer is usually operated in at-line or off-line setup under controlled operation to avoid particle settling but could potentially be adapted for on-line measurement;
5. To measure the rheology of a non-Newtonian, heterogeneous and settling slurry (e.g., oil sand tailings with coarse particles) in an in-line or on-line basis, it must meet three criteria:
 - a) keep the slurry fully suspended during measurement;
 - b) operate continuously and generate data in real-time; and
 - c) generate a flow curve with multiple data points so rheology can be determined.

There are two commercially available on-line rheometers that have potential to meet all three criteria at the same time, if either of them can overcome the complications caused by settling slurries; and

6. Several in-line/on-line rheology measurement methods have been discussed in this review. Based on the process requirement of the application, some of the methods have potential to be developed as an in-line/on-line rheology measuring device.

LITERATURE CITED

This literature review gathered information from 77 publications.

RESEARCH TEAM AND COLLABORATORS

Institution: Saskatchewan Research Council

Principal Investigator: Ruijun Sun, M.Sc., MBA, P.Eng., Senior Research Engineer



TAILINGS TREATMENT TECHNOLOGIES

Fines Measurement Working Group

COSIA Project Number: TE0017 and TW0010

Research Provider: Fines Measurement Working Group

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Imperial, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Completed

PROJECT SUMMARY

The COSIA Tailings Environmental Priority Area (EPA) and its Fines Measurement Working Group (FMWG) was tasked with developing a standardized method for reporting per cent (%) fines at 44 micron for samples ranging from oil sands cores to fluid tailings, with incidental benefit to measuring the entire particle size distribution (PSD).

The COSIA Tailings EPA approved the project, “Fines Measurement Methodology for Directive 74” on April 3, 2013, with the following objective:

“The overarching objective is to develop a methodology which gives technically and statistically defendable, consistent measurement methodology for oil sands fines (<44 micron particle size) which is applicable across all areas of an oil sands processing facility. The measurement method must be consistent with the objective of producing a full fines balance across the facility and its operating processes. Therefore, the selected measurement protocol must be viable for measuring materials such as ore, slurry, rejects, beach fines capture and fluid fine tailings (FFT) in order to close a material balance.

This effort will result in the identification, development and industry-wide adoption of a standard measurement methodology for fines (<44 microns).”

The FMWG carried out a Design of Experiment (DOE) study primarily to understand the effect of sample preparation variables on the reported fines content. This led to the writing of a draft Unified Fines Methods. As a result of a pilot inter-laboratory study (ILS) and a formal study known as ILS 1, the FMWG revised the Unified Fines Method (Method) on several occasions. ILS 2 was intended to provide the repeatability and reproducibility statistics for the final Method. A decision about accepting this method for the purposes stated earlier was withheld with the rescinding of *Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes* (D074) (rescinded by *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects* in 2016 and updated in 2017).

As the work by the FMWG draws to a close the following recommendations are being made regarding communication of the final materials and findings by the FMWG.



Method for fines determination for less than 44 microns, FMWG

Given the results of the ILS, the FMWG acknowledged that the Method in its current form did not meet its original objective. With D074 rescinded and the perceived amount of work needed to meet the original objective, the FMWG has recommended to the Tailings EPA Steering Committee (SC) that no further updates be made to the Method of fines determination for less than 44 microns.

A commitment to share the ILS report with the labs participating in the ILS was made. Given the broad participation in the ILS by local labs supporting the industry, the release of the ILS report to these labs constitutes a form of limited public release. Both versions of the Method used during the ILS are attachments within the ILS Report, 2016, meaning that if the ILS Report is more fully released to the public domain via the COSIA website (as recommended below), the supporting documents would be available to readers of the report. Therefore, the FMWG has recommended to the SC that the fines measurement method as part of the ILS report supporting documentation be released through the COSIA website.

Method for Dean Stark

Although Dean Stark is a common practice across the industry, an actual formal method that is owned by an organization was discovered to be unavailable during the creation of the fines measurement method, as the previous owner, ACOSA, has disbanded. The Dean Stark method as described in the ILS report supporting documentation would also become available online, which would be an additional benefit of releasing the ILS report through the COSIA website.

PROGRESS AND ACHIEVEMENTS

Design of Experiment Report, 2015, by NARCOSS

In 2014 the Northern Alberta Institute of Technology (NAIT) Applied Research Centre for Oil Sands Sustainability (NARCOSS) produced a conference paper for the International Oil Sands Technology Conference (IOSTC) on the Design of Experiment (DOE) of a method for the measurement of <44 micron fines. At that time the report was not complete so a shorter summary was released through the conference proceedings.

Given the DOE is partially in the public domain already it is recommended by the FMWG that the completed DOE Report, 2015, be supported for release through the reports area of the COSIA website. The communications assessment process would be used to verify that release is in the interest of the COSIA member companies.

Inter-Laboratory Study (ILS) Report, 2016, by InnoTech Alberta

From 2014 through to 2016 InnoTech Alberta (InnoTech) facilitated the Inter-Laboratory Study following ASTM guidelines to produce a repeatability and reproducibility statement for the method designed by FMWG. The work is complete and has been endorsed by the FMWG.

FMWG recommends that the ILS report (including attached fines measurement and Dean Stark methods in the appendix) with accompanying memo about concerns be posted on the COSIA website.

The memo attached to the ILS report should make it clear that the method is not an industry standard.



Fines method variability paper(s), 2017

NARCOSS was retained again after the completion of the ILS Report to do further analysis of the effects of the procedures based on the data retained during the ILS. This further analysis was presented at the FMWG workshop in April of 2017. However, no further work has been pursued and no papers have been produced. Therefore, the FMWG has no recommendations related to this study at this time.

Next Steps

In the event that the Alberta Energy Regulator requests a method for the measurement of fines that are <44 micron the FMWG believes that further work would need to be completed to produce a universally satisfactory method.

LESSONS LEARNED

Although the FMWG did not agree upon a new method the DOE and ILS revealed and confirmed numerous findings about fines measurement. These findings will allow the operators to improve their own in-house methodologies.

PRESENTATIONS AND PUBLICATIONS

Canada's Oil Sands Innovation Alliance (COSIA) Fines Measurement Working Group (FMWG). 2016. Unified Fines Method for Minus 44 Micron Material and for Particle Size Distribution.
(<http://cosia.ca/uploads/documents/id18/COSIA%20FMWG%20Fines%20Method%20February%202016.pdf>).

Northern Alberta Institute of Technology (NAIT) Applied Research Centre for Oil Sands Sustainability (NARCOSS). 2014. COSIA Design of Experiment Study in Support of Development of a Standard for Fines Measurement in Oil Sands. <https://sites.google.com/a/ualberta.ca/iostc2014/>.

RESEARCH TEAM AND COLLABORATORS

Principal Investigator: COSIA Fines Measurement Working Group

Research Collaborators: Alberta Energy Regulator, Northern Alberta Institute of Technology Applied Research Centre for Oil Sands Sustainability, InnoTech Alberta

Long-term Dewatering of Amended Oil Sands Tailings

COSIA Project Number: TE0006 and TE0036

Research Provider: Carleton University

Industry Champion: Teck Resources Limited

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Syncrude Canada Ltd.

Status: Year 2 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 fine 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

We have found that structuration/aging is an important phenomenon in at least some kinds of polymer-amended 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 in 10 cm thick submerged samples of FFT mixed with standard anionic high molecular weight polymers, using mixing procedures designed to simulate short pipeline transport, such as the Atmospheric Fines Drying (AFD) technology. Structuration did not appear to progress beyond 100 days. We developed three



candidate methods to rapidly estimate the hydraulic conductivity-void ratio 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. 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 FFT, 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 preformed in industry using a large coquette 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.

Three creep models went into our UNSATCON model for simulating consolidation and desiccation of tailings deposits. We are implementing a structuration component to these models.

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. 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, we will work with COSIA member companies to examine their pilots and field trials to see 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.

The methods we proposed at our student-interaction day and in conference papers (Babaoglu et al. 2018 and Babaoglu and Simms 2018, 2017) 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. Specific lessons or findings determined from these tests include:

- using a single measured value of hydraulic conductivity at high void ratio substantially improves the accuracy of methods to estimate the complete hydraulic conductivity function that use Atterberg limits;
- the compressibility function itself can be used as a predictor for the hydraulic conductivity function; and
- the instantaneous profile method used in soil science to estimate hydraulic conductivity from *in situ* data can be adopted for slurries with high volume change such as FFT.



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RESEARCH TEAM AND COLLABORATORS

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Principal Investigator: Paul Simms

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Microbiological and Vegetation for Tailings Management (Bugs and Veggies)

COSIA Project Number: TE0039

Research Provider: Northern Alberta Institute of Technology

Industry Champion: Canadian Natural Resources Limited (Canadian Natural)

Industry Collaborators: Imperial, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Year 2 of 2

PROJECT SUMMARY

Early research by Silva (1999) examined plants as a dewatering technology for oil sands tailings wastes and found several species of grasses were successful in this application at small scale. However, oil sands tailings are deficient in soil nutrients required by plants to grow and would therefore require substantial quantities of fertilizer to be adopted as a dewatering technology at scale. It is well known that many plants depend on nitrogen fixing bacteria in their roots and soil to meet nutrient requirements; however, commercially available nitrogen fixing species are challenged by the high salinity, hydrocarbon content, and anoxic conditions that are characteristic of oil sands tailings. A study by Collins et al. (2016) found low numbers of nitrogen fixing bacteria were present in oil sands tailings and could be enriched to produce enough bioavailable nitrogen to support a community of organic acid degrading bacteria. By combining these two concepts at a larger scale using native boreal plant species in an outdoor environment, we sought to demonstrate the plausibility of plant-mediated tailings dewatering at scale.

The goal of this project is to demonstrate the integrated use of native boreal plant species and indigenous selected bacteria cultures capable of degrading residual hydrocarbons and organic acids, while fixing nitrogen in the soil as tools to further accelerate the transformation of mature fine tailings (MFT) into a reclaimed soil. These nitrogen-fixing bacteria have the potential to increase the plant-available nitrogen in tailings and accelerate the growth of native boreal plant species. These plants will in-turn dewater the tailings through evapotranspiration thereby increasing shear strength of the materials for deposition.

The current work is the first to attempt growing native boreal plant species supplemented with indigenous hydrocarbon degrading, nitrogen fixing bacteria on oil sands tailings. Previously published greenhouse studies did not contain bacterial inoculum or amendments, were small scale, and conducted indoors. Plant growth, nutrient requirements, and surface evaporation can all be affected by pot size and depth as well as environmental factors not replicable in a greenhouse. In addition to bacterial inoculum to meet nutrient requirements and amendments to promote bacterial growth, the “greenhouse” study was conducted in 7.8 litre (L), 1 m columns outdoors making this study more similar to field conditions than other studies. The data collected from this study will better inform our understanding of the synergistic benefits of using nitrogen fixing bacteria, amendments, and native boreal plant species to dewater tailings on a larger scale under environmental conditions. If one or more treatments are found to substantially increase the shear strength of tailings, this biotechnology can be scaled-up for field application at a pilot site.

PROGRESS AND ACHIEVEMENTS

Phase 1 work has been completed: During Phase 1, executed between September 2017 and February 2018, we evaluated several biocompatible solid particles as carriers for bacterial cultures isolated from well-characterized anoxic MFT and enriched to degrade specific organic compounds and fix N₂ to ammonium. We evaluated the following materials as substrates:

- engineered microporous silica material;
- activated carbon;
- diatomaceous earth (DE); and
- biomass-derived fly ash.

We investigated microorganisms enriched from the following tailings sources:

- Canadian Natural Muskeg River External Tailings Facility MFT;
- Syncrude Canada Ltd. Mildred Lake Settling Basin MFT; and
- two in-house enrichments using thickened tailings and tailings centrifuge cake provided by Imperial and Canadian Natural, respectively.

We evaluated substrate cultures by measuring methane production, hydrocarbon degradation, and acetylene reduction as an indicator of nitrogen-fixation. In these trials, cultures grown on DE produced the most methane with Syncrude Canada Ltd. and Canadian Natural's enrichments producing significantly more methane than tailings cake or thickened tailings cultures. Hydrocarbon degradation results are considered inconclusive due to changes in surface chemistry from microbial growth across different substrates. Canadian Natural Resources Limited cultures grown on DE were found to have the highest acetylene reducing activity, with no significant difference between other cultures. Based on methane and acetylene reduction results, Canadian Natural Resources Limited enrichment on DE had the highest metabolic and nitrogen fixing activity as compared to other culture-substrate combinations examined in this study. This culture and substrate combination was selected for scale up for Phase 2. Methane monitoring and hydrocarbon analyses in the scaled up cultures are currently underway with acetylene reduction assay in progress.

The most active culture with the highest level of microbial growth was scaled up during the period between March 2018 and May 2018. One conference proceeding focusing on Phase 1 was submitted and accepted for the International Oil Sands Conference (IOSTC) in December 2018.

Phase 2 work is nearing completion: During Phase 2, slender wheatgrass (*Elymus trachycaulus*) and sandbar willow (*Salix interior*) were grown on centrifuge cake and thickened tailings inoculated with the scaled up bacterial cultures as well as other organic amendments (hydrochar and peat) from the beginning of June 2018 and then destructively harvested in September 2018. Above and below ground biomass data, solids content, and tailings strength are under evaluation. Results are still being compiled; however, current data suggest significant differences in plant growth and tailings strength between treatments. A final report and manuscript detailing the findings will be prepared in March 2019.

LESSONS LEARNED

- Diatomaceous earth promotes the rapid development of oil sands microbial communities under nitrogen-limited conditions. Using methane production as a proxy, cultures grown on DE metabolized organic substrates 10 times faster than other substrates or nutrient media alone. Diatomaceous earth also prompted the highest rate of nitrogen fixation (as demonstrated using an acetylene reduction assay) out of the substrates examined.
- Canadian Natural and Syncrude Canada Ltd. enrichment cultures had significantly higher metabolism than other culture inoculum (235 μmol and 188 μmol methane (CH_4)), respectively as compared to $\sim 20 \mu\text{mol}$ CH_4 in thickened tailings and tailings cake tailings cultures). Canadian Natural cultures also had the highest mean average of nitrogen fixing activity at 12 μmol ethylene after 19 days incubation, while all other cultures produced less than 9 μmol ethylene (N_2 proxy). However the differences were not significant. One enrichment and one tailings culture, Canadian Natural and thickened tailings cultures, were selected for evaluation in the scale-up phase.
- During the scale-up phase, Canadian Natural cultures degraded toluene to methane significantly more effectively than thickened tailings and sterile cultures. By day 41, $\leq 2 \mu\text{mol}$ CH_4 were detected in thickened tailings and sterile control cultures whereas 123 μmol CH_4 was produced in Canadian Natural enrichment cultures. Canadian Natural cultures also degraded 7 mg toluene by day 42 as compared to 4 mg toluene in thickened tailings cultures. No significant decrease was observed in the sterile controls.
- Data are still being compiled from the outdoor growing trial phase; however, dewatering rates were roughly doubled in tailings columns with plants as compared to columns without plants.
- There is a direct correlation between plant growth and shear strength.
- Several amendments including bacteria + organic amendment (hydrochar) showed a significant increase in shear strength as compared to untreated plants on tailings.

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RESEARCH TEAM AND COLLABORATORS

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Principal Investigators: Dr. Paolo Musrone, Dr. Amanda Schoonmaker and Andrea Sedgwick

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Kaela Walton-Sather	Northern Alberta Institute of Technology	Student research assistant/Diploma in Biological Sciences Renewable resources	Sept 2016	June 2018
Carl Zhang	Northern Alberta Institute of Technology	Student research assistant/Diploma in Civil Engineering Technology	Sept 2017	June 2019
Taimur Qureshi	Northern Alberta Institute of Technology	Research Assistant		
Scott Laberge	Northern Alberta Institute of Technology/University of Alberta	Research Assistant		

Other financial supporters of this work: Natural Sciences and Engineering Research Council of Canada (NSERC) Applied Research and Development Grant and Alberta Innovates

Optimizing the Use of Tubifex to Enhance Densification and Strength of Oil Sands Tailings: Building on Recent Laboratory Test Success, Towards Pilot

COSIA Project Number: TE0040 (IOSI2016-08)

Research Provider: Deltares and University of Alberta

Industry Champion: Suncor Energy Inc.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Year 2 of 3

PROJECT SUMMARY

Tubifex is an anaerobic earthworm with the capability to live under various chemical, biological, and soil environments. When added to sediment, Tubifex “swims” and creates 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 Tubifex 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 the Tubifex on oil sands tailings, indicated that Tubifex could survive the tailings environment and that it was capable of 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 Tubifex survival and reproduction in tailings environment;
2. Quantify the ultimate solids content and shear strengths achieved by adding Tubifex to tailings; and
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 Tubifex.

Task 2 (Deltares): Perform a series of beaker tests with different biological parameters (i.e., nutrients and organic matter) for exploring optimization/survival of Tubifex 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 Tubifex and at optimized conditions established in Task 2.



Task 4 (University of Alberta): Perform large-scale column tests with optimal parameters from Tasks 1-3 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 Tubifex on dewatering and consolidation in fluid fine tailings and thickened tailings at 10 °C and 22 °C.

Task 2: Complete – A series of beaker tests were performed to study the effects of several “feeding strategies”, including low quality organic matter, high quality organic matter, inorganic nutrient (two concentrations), on reproduction of the Tubifex worms.

After completion of Task 2 in June 2018, the project team found studies indicating that Tubifex is a carrier of whirling disease and communicated this finding to the Institute for Oil Sands Innovation (IOSI) and COSIA. After discussions with IOSI/COSIA members, it was concluded that further research on using Tubifex to enhance consolidation of oil sands tailings should be discontinued. Instead, literature was reviewed to identify and select alternative “safe” species with similar characteristics to those of Tubifex. Based on the literature (see some selected references in the following sections) and after consultation with experts of the field, *Lumbriculus variegatus* (LV), also known as the blackworm, was selected as the alternative to Tubifex going forward in the project. LV, which is an aquatic species capable of surviving harsh environments, does not carry whirling disease according to the state of knowledge at the moment.

In order to accommodate the changes described above, the project team submitted a scope change document in July 2018 to pursue the rest of the program with LV. The change of scope was accepted by IOSI/COSIA on October 16, 2018. Project activities are planned to resume before the end of 2018.

Tasks 3 and 4: No activities have been performed given the findings and changes described above.

LESSONS LEARNED

The results of the project shows that Tubifex improves the dewatering properties of oil sands tailings in a laboratory environment and that Tubifex can live and reproduce in oil sands tailings. Since Tubifex is found to be a carrier of whirling disease, the effectiveness of LV on dewatering and consolidation of tailings should be tested as the next steps of the project. If testing of LV finds it effective, it will be used to study dewatering and consolidation of tailings in large columns at the University of Alberta (Task 4).

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RESEARCH TEAM AND COLLABORATORS

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Development of Rapid Screening Methods for Mature Fine Tailings

COSIA Project Number: TE0043 (IOSI 2016-12)

Research Provider: Purdue University

Industry Champion: Canadian Natural Resources Limited (Canadian Natural), Imperial

Industry Collaborators: Syncrude Canada Ltd., Suncor Energy Inc., Teck Resources Limited

Status: Year 1 of 1

PROJECT SUMMARY

The growing inventory of mature fine tailings (MFT) is the focus of large-scale efforts to reduce the volume through a range of treatment options. Analysis of MFT generally requires detailed and time-consuming laboratory analyses to obtain properties needed for effective tailings management. For this project, a set of spectroscopic- and thermal analysis-based rapid scanning methods were used in combination with chemometric modelling to rapidly predict key properties needed for effective tailings management. The proposed methods could be field deployed on site and some of the proposed methods could be potentially further developed as in-line sensors.

Effective stewardship of MFT is central to oil sands mining. The growing inventory of MFT ($\sim 109 \text{ m}^3$) is the focus of exploring a range of treatment options that include the addition of polymeric flocculants, coagulants (e.g., alum, gypsum), a combination of 'stacked technologies'—in a wide range of engineering solutions that include thin-lift drying, centrifugation, electrokinetic dewatering, and solid-liquid separation technologies—in order to achieve reclamation goals. Tailings management requires analysis of MFT that often include detailed and time-consuming laboratory analysis in order to obtain key tailings properties such as water chemistry, bitumen content, solids/clay/water contents, particle size, and clay mineralogy.

This project explored the application of a rapid screening method (RSM), attenuated total reflectance (ATR) FTIR (Fourier transform infrared), spectroscopy that has the potential to be field deployed on site. The project focused on collecting experimental data in the laboratory using spectroscopic- and thermal analysis-based methods in conjunction with available data sets. Chemometric models were built from the RSM data to predict tailings properties of interest. Some properties were strongly correlated with the RSM data; e.g., methylene blue index (MBI), but other properties (e.g., quantification of illite) were weakly correlated. The strength of these methods is that they provide multi-dimensional (clay type and amount, bitumen and water content) information from a single type of analysis.

FTIR methods have attracted significant interest in the past 10 years as a rapid, low-cost assessment tool in oil and gas applications (Breen et al. 2008; Herron et al. 2014). The strength of this method is in that all minerals have absorption bands in the mid-infrared (mid-IR) region and some of these spectral features are highly diagnostic (e.g., kaolinite, quartz). Moreover, water and bitumen both have characteristic absorption features in both the mid- and near-IR regions (Schoonheydt and Johnston, 2013; Nikakhtari et al. 2014; Osacky et al. 2013).

In a nutshell, the design and methodology for this research is to collect both spectroscopic and thermal analysis data (referred to as Rapid Screening Method or RSM data) of MFT with diverse bitumen/water/mineral contents and MBI values. For the mid-IR and near-IR measurements diffuse reflectance (DR-FTIR) method is used for dry powdered samples, and attenuated total reflection (ATR) method is used for both dry and MFT slurries. Thermal analysis is collected from these samples as solids and/or slurries. Then, chemometric modelling is used to rapidly predict key properties needed for effective tailings management. Potentially, the proposed methods could be field-deployed on site and some of them further developed as in-line sensors. The strength of the proposal is that multi-dimensional (clay type and amount, bitumen and water content) information is obtained from the same analysis.

Validation of the spectroscopic and thermal analysis methods will rely on statistical methods to derive predictive relationships from the measured data with operator- or Purdue-provided analytical data (e.g., quantitative powder X-ray diffraction, MBI, clay-to-water ratio, yield stress). Chemometric methods which will be used include, but are not limited to, partial least squares (PLS), simple Beer's law, classical least squares (CLS), stepwise multiple regression (SMLR), principle component regress (PCR) and principle component analysis (PCA) analyses. The 'whole spectrum' methods, like PLS and PCR, have been demonstrated to have improved predictive ability over analysis of discrete spectral bands and regions (simple Beer's law) (Igne et al. 2010; Vasques et al. 2008). Using a leave-one-out analysis, predictive relationships will be established for mineral constituents, water content, and bitumen content based on 'actual versus predicted' correlations. Further exploration of these methods to predict MBI, overall clay content, clay-to-water ratio, and particle size will be explored. Rapid prediction of key MFT parameters will be evaluated based on the precision, accuracy and reproducibility of derived parameters within the context of the sample preparation and presentation time.

OBJECTIVES

1. Source contrasting MFT.
2. Develop sampling protocols and collect statistically relevant RSM data from sourced MFT.
3. Develop and optimize predictive chemometric models based on collected MFT RSM data.
4. Validation of chemometric models. Working with operators, blind samples will be provided and targeted properties will be predicted based on the chemometric models developed under Objective 3.
5. Short-listing of RSM and chemometric models.

PROGRESS AND ACHIEVEMENTS

We obtained six tailings samples in 2018 in collaboration with Abu Junaid (Canadian Natural) along with some characterization data (see Table 1 below). In addition to the "new" MFT, five well-characterized MFT were also included. Mid-IR analysis was completed using DR-FTIR for powdered samples, single and multiple bounce ATR-FTIR spectra from solid and MFT suspensions and thermogravimetric analyzer (TGA) analysis was obtained in an inert (i.e., N₂) atmosphere.

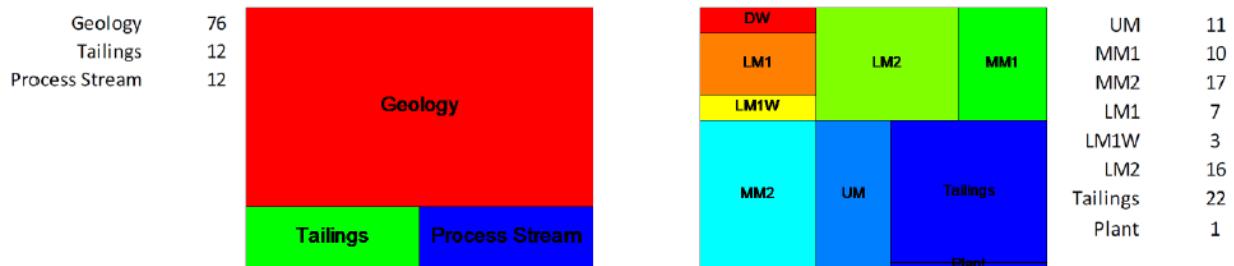
Prior to this project, Rob Mahood and Abu Junaid provided a set of 100 dry samples from the Albian Project that represented geology, tailings and process stream samples. In order to inform the spectroscopic and thermal analysis methods used in the current project, we revisited these samples because there was extensive

characterization work done on these samples, which is currently owned by Canadian Natural. The data included quantitative clay and bulk mineralogy, particle size and MBI testing.

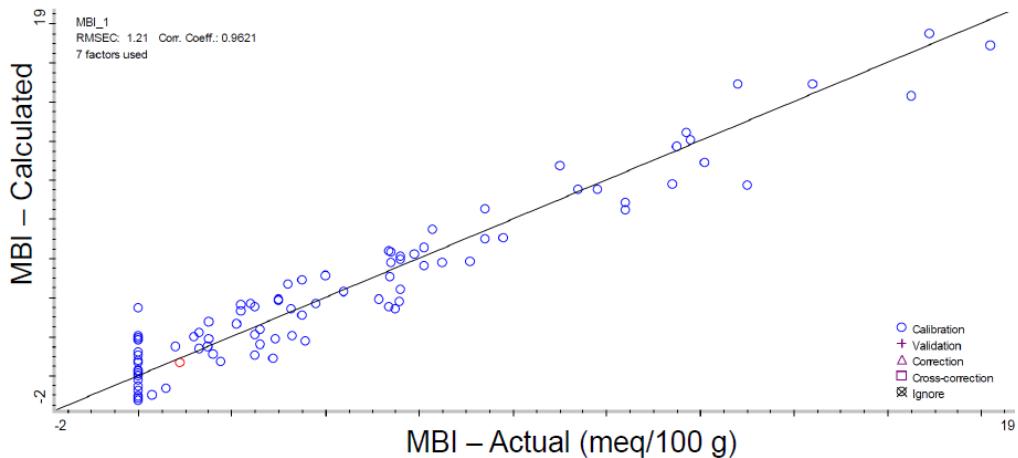
Table 1. Current and Legacy MFTs Used in This Project

Bucket Label	MBI meq/100 g	Bitumen (%)	Water (%)	Mineral (%)
CNU TSUP S1730 (ES-4081)	6.8	2.4	77.6	20.1
CNU TSUP S1727 (ES-4093)	6.9	2.4	71.8	26.0
CNU TSUP S1729 (ES-4091)	7.9	2.4	68.5	29.3
CNU TSUP S1734 (ES-4099)	8.1	2.0	72.1	26.0
CNU TSUP S1731 (ES-4100)	9.3	2.1	79.4	18.2
CNU TSUP S1725 (ES-2774)	11.5	1.6	67.0	31.5
8A	10.5	-	68	-
2/3	8.6	-	50.9	-
2/3 F	8.4	4.7	64.3	31
SHELL	11.0	1.5	65.1	33.4
STP	11.2	1.1	66.5	32.4

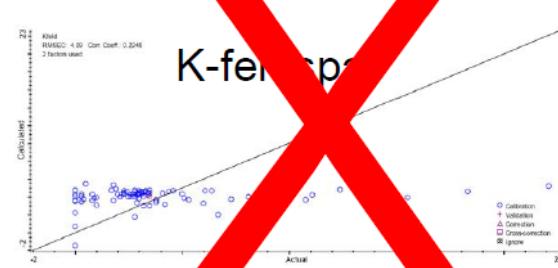
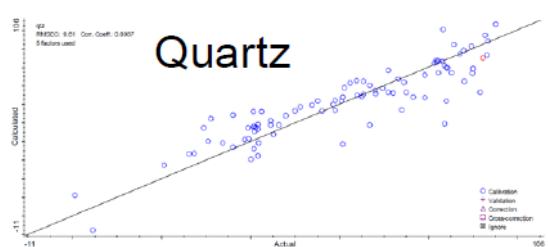
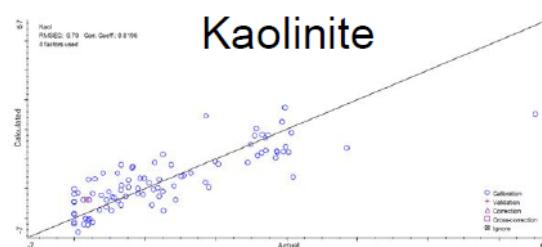
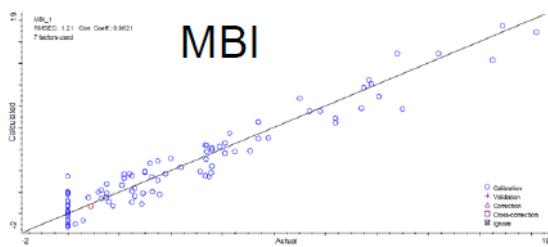
The data can be represented as:



One interesting result from this analysis is shown below where MBI values were predicted based upon diffuse reflectance (DR) FTIR spectroscopy.



The key results from this analysis are shown below:

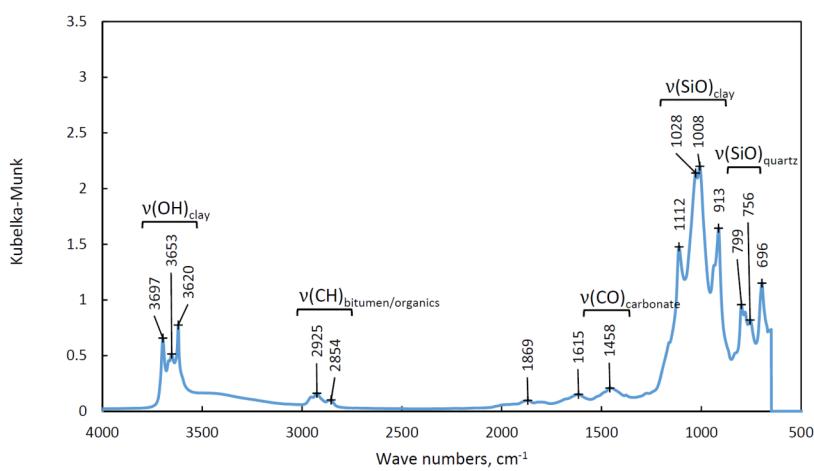


Good correlations were found for MBI, kaolinite and quartz. K-feldspar does not have unique spectral signature; as expected, the data were not correlated. Because these earlier samples were provided as dry powders and some of the samples had been subjected to Dean-Stark extraction, we were not able to predict water or bitumen content.

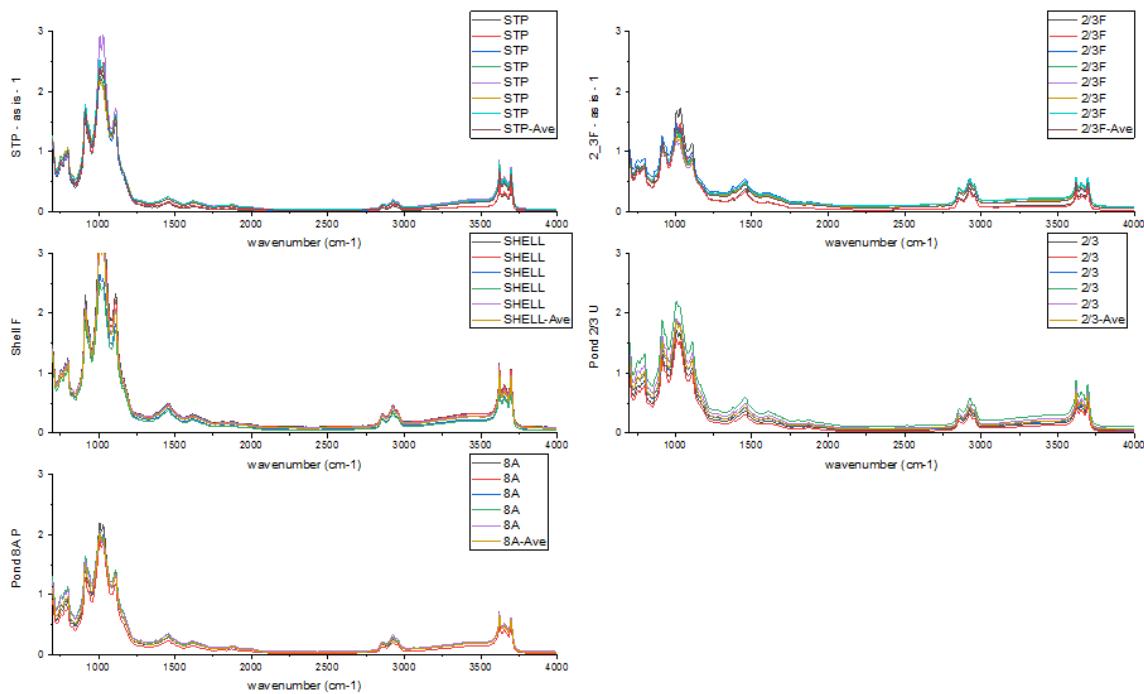
In the current project, the MFT samples were sampled after sufficient mixing. The attenuated total reflectance FTIR method does not require any sample preparation. Samples could be analyzed as-received slurries, or as dried deposits, using a Pike "Gladiator" single-bounce, diamond ATR crystal. For analysis using DR-FTIR and thermogravimetric analysis, samples were allowed to air dry.

A representative FTIR spectrum of a dry MFT samples is show below. Starting on the left side of the figure, the sharp $\nu(\text{OH})$ bands between 3700-3600 cm^{-1} correspond to the stretching bands of hydroxyl groups in kaolinite and illite. The bands between 3050 and 2800 are the $\nu(\text{C-H})$ bands from bitumen. Water bands appear between 3400-3100 cm^{-1} and around 1630 cm^{-1} . Carbonate bands are found between 1500-1400 cm^{-1} . Strong structural $\nu(\text{SiO})$ bands of clay minerals are found between 1200-1000 cm^{-1} , and the characteristic “quartz doublet” bands occur at 800 and 780 cm^{-1} . This illustrates that FTIR spectra can be used to identify clay, bitumen and water in MFT.

Using these methods, we characterized the MFT shown above in Table 1.



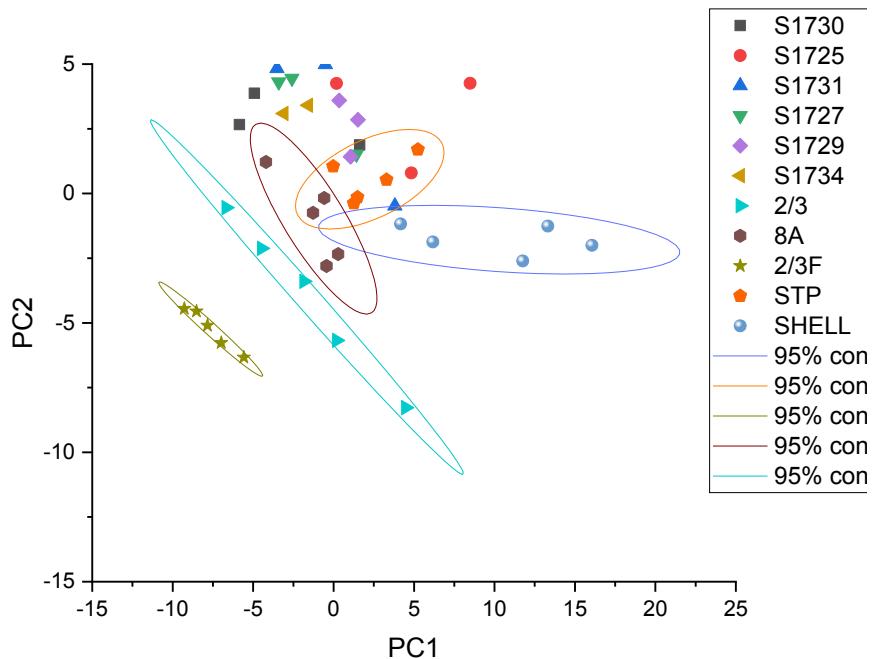
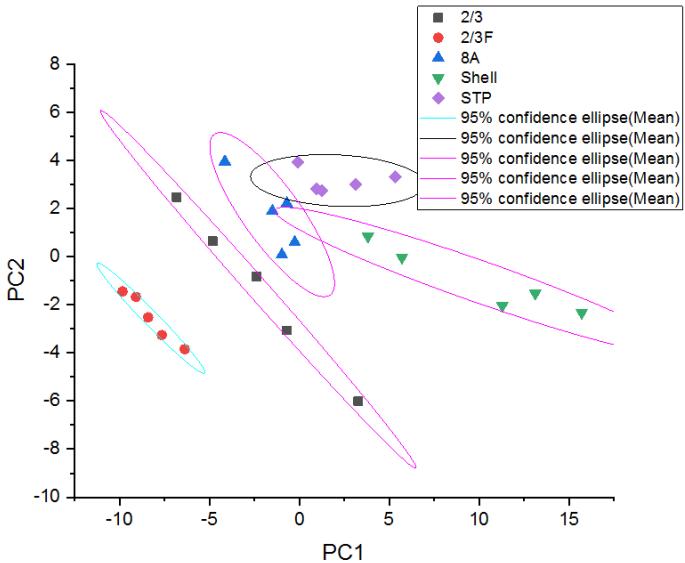
Our first objective was to obtain consistent samples. Data are shown below for DR-FTIR spectra of five replicates of the MFT shown in Table 1. We selected these MFT because we had more extensive characterization data than for the CNU-TSUP samples.



We followed a similar approach using TGA and ATR-FTIR.

We then applied discriminant analysis (principal component analysis [PCA]) methods. Results are shown on the right. As the plot indicates, the MFT show distinct groupings, meaning that they are statistically resolved. The 95% confidence ellipses are also shown. Thus, with no "user intervention" these data inform us that spectral characteristics of the MFT are statistically different.

The project supplied MFT were somewhat uniform in nature. MBI values ranged 6.8 to 11.5% and bitumen contents ranged from 1.6 to 2.4%. The results including the "project supplied" MFT listed in Table 1, the MFT showed no clearly resolved spectra distinctions.



CONCLUSIONS

- Replicated spectroscopic and thermal analysis data were collected from 11 MFT (considerably more data have been collected because we have also used these methods to look at polymer-treated MFT).
- These methods provide some mechanistic insight about MFT composition.
- Partial least squares methods were successfully applied to predict key properties of ~ 90 Albian Project samples (run as dry powders). The model was able to 'predict' MBI, kaolinite, quartz and clay – but not other constituents (e.g., illite).
- Discriminant analysis of spectroscopic and thermal data was able to distinguish five contrasting MFT (but not for six similar MFT).
- Data have been collected on slurries "as is".

IMPLICATIONS

Because FTIR spectra can be obtained rapidly, with suitable calibration and chemometric modelling from robust data sets (e.g., quantitative XRD, particle size analysis, MBI), the proposed methods can potentially provide a rapid and reliable screening tool to monitor key MFT properties of interest.

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RESEARCH TEAM AND COLLABORATORS

Institution: Purdue University

Principal Investigator: Prof. Cliff T. Johnston, Earth, Atmospheric and Planetary Sciences

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Mohammadhasan Sasar	Purdue University	PhD Candidate	2014	2019

Potential Application of Volute Screw Press Filter to Treat Oil Sands Fluid Fine Tailings – Phase 2

COSIA Project Number: TE0044

Research Provider: University of Alberta

Industry Champion: Syncrude Canada Ltd.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Teck Resources Limited

Status: Year 1 of 1

PROJECT SUMMARY

In the Phase 1 work performed with the new Volute Screw Press (VSP) filter, the capability of continuously producing a filter cake of more than 60 weight per cent (wt%) solids and a filtrate of less than 1 wt% solids from fluid fine tailings (FFT) was demonstrated. It was found that the pre-treatment of FFT with chemical schemes was the key factor to determining the filtration results with the VSP. Also, a new controlled vertical strain test (CVST) device was developed to provide good correlation with the solids content of VSP filter cake. The CVST values could potentially be used to identify promising chemical schemes ahead of the VSP tests.

In Phase 2, the main objective is to investigate different chemical schemes that could result in a VSP filter cake of more than 65 wt% solids as well as a filtrate of less than 1 wt% solids. Chemical screening tests and controlled vertical strain tests (CVST) were performed to identify the optimal dosages and combinations of chemical schemes. The CVST data were compared against the cake solids contents from the subsequent VSP tests. In Phase 2, the following chemical schemes with a primary polyacrylamide (PAM) flocculant and a secondary chemical were tested:

- A. PAM Flocculants + Coagulants;
- B. PAM Flocculants + Collectors; and
- C. PAM Flocculant + Coagulant tested in Phase 1 as control for Phase 2.

In addition to the PAM flocculant and coagulant tested in Phase 1, more PAM flocculants and coagulants from different polymer vendors and collectors were evaluated using the VSP filter in Phase 2. One of the advantages of the Volute Screw Press is that it runs continuously as opposed to intermittent/batch operation as in a conventional filter press.

PROGRESS AND ACHIEVEMENTS

In the first four months of the project (January to April 2018), bench-scale settling tests and CVST were performed with chemical recipes from chemical schemes A, B and C at various dosages and combinations. Optimal chemical

dosage ranges and CVST performance indicators were collected and promising recipes were identified and prioritized.

Site planning, procurement, equipment installing and commissioning, as well as logistics took place throughout May and June 2018 after the test site access agreement was signed. At the end of June 2018 it was possible to run a number of trial VSP tests to further optimize the process and finalize the standard operating procedures. Several important hardware adjustments were made and a number of equipment assessment tests were carried out. After optimizing the process and set points, the formal VSP tests were performed with the chemical schemes A, B and C throughout July to October 2018. Data analysis and report preparation are in progress.

From the VSP tests, operating with chemical scheme C successfully resulted in greater than 65 wt% solids cake, as well as a clear filtrate with less than 1 wt% solids. Some combinations from chemical scheme A yielded 64-65 wt% solids cake and a clear filtrate of less than 1 wt% solids. On the other hand, all combinations from chemical scheme B could not produce > 65 wt% solids cake, with filtrate solids ranging from 0.5 – 1.5 wt%. The reason is unknown. However, the much smaller molecular weights of the collectors compared with the larger polymeric coagulants could be one of the causes. It seems that the Volute Screw Press filter would require strong pre-treated FFT flocs.

The compression data from the CVST matched the results from the VSP tests. Chemical scheme C was found to have the largest compression value that is closely followed by recipes from chemical scheme A. In contrast, the CVST values from chemical scheme B were four to five times smaller than those from schemes A and C. It was determined the CVST data can be used to distinguish between chemical schemes specifically used for the Volute Screw Press. To clearly differentiate between recipes within a given chemical scheme, further improvements in CVST measurement precision are recommended.

LESSONS LEARNED

Although it is too early for final conclusions, the following are the preliminary lessons learned from this project:

- the Volute Screw Press (VSP) filter is capable of continuously producing $\geq 65\%$ cake and < 1% solids filtrate from FFT. Pre-treatment of FFT with chemical schemes and optimally configured operation parameters are mandatory to achieve these production targets; and
- the current VSP equipment has a limited dry solids throughput, which is good for proof-of-concept tests. It is advised to utilize a larger VSP to investigate the dry solids throughputs.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Zhenghe Xu

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Zhenghe Xu	University of Alberta	Professor, PI		
Chen Wang	University of Alberta	Postdoctoral Fellow / Project Manager		
Jason Ng	University of Alberta	Research Assistant		
Wenfei Zhang	University of Alberta	Research Assistant		
Dan Zhang	University of Alberta	Research Assistant		

Mature Fine Tailings Spiking of Horizon Thickeners

COSIA Project Number: TJ0011

Research Provider: Canadian Natural Resources Limited (Canadian Natural), Paterson & Cooke Canada Inc.

Industry Champion: Canadian Natural

Status: Completed in 2015

PROJECT SUMMARY

Background

In 2014, Canadian Natural submitted a Tailings Management Plan (TMP) application to the Alberta Energy Regulator (AER) for the Horizon mine, noting that 200 million tonnes (t) of dry fines (i.e., particles less than 44 microns in diameter) would be captured by adding or “spiking” mature fine tailings (MFT) into the Non-segregating Tailings (NST) matrix over the life of the mine. Non-segregating tailings are produced by a treatment process that includes cyclones to separate coarse sand from the fines tailings streams, and thickeners, to capture and remove warm water from the fines in the flotation tailings streams. The warm water that is removed is then reused in the bitumen recovery process. The coarse sand and thickener underflow are then mixed and combined with carbon dioxide (CO₂) to produce NST. The MFT would be harvested from the tailings ponds.

The NST spiking design from the 2014 TMP was based on adding MFT to NST in the NST pump box. However, an earlier pilot study on the impact of adding MFT to NST indicated the potential for increasing segregation of the NST if MFT was added to NST in the NST pump box. It was later postulated that treating MFT in combination with flotation tailings (FLT) in the thickener prior to mixing with the coarse fraction in the NST pump box could mitigate NST segregation.

A 2014 laboratory study by FLSmidth & Co. (FLSmidth) demonstrated that the addition of MFT to the thickeners was feasible. However, uncertainties regarding the accuracy of some of the input data such as the sand-to-fines ratio (SFR) of the thickener feed, which had been altered by the addition of sand and flow rate, and undertaking the thickening tests in batch mode rather than using a continuous system, raised concerns about the applicability of the project findings. With these uncertainties considered, FLSmidth concluded that MFT could be added to the thickeners up to a minimum feed SFR of 0.8, while still maintaining good overflow clarity (<0.5 wt% solids) and high (>50 wt% solids) underflow solids concentration.

Between 2010 and 2015 the mean SFR for Horizon’s flotation tailings was 1.1, which supported the concept of dewatering MFT in the thickener feed, thereby improving the overall site-wide fines capture.

Test Purpose and Hypothesis

The objective of this project was to determine thickener performance when MFT spiking occurred in the thickener feed rather than in the NST pump box. The project hypothesis was that a thickener feed with SFR > 0.8 can be spiked with MFT to produce NST with SFR as low as 0.8, which can be processed in the thickeners (with an available unit area of 0.07 m²/tonne/day).

The evaluation criteria to be tested were:

- Underflow with a solids content of ≥ 55 wt%
- Overflow of ≤ 0.5 wt%.

Testing Strategy

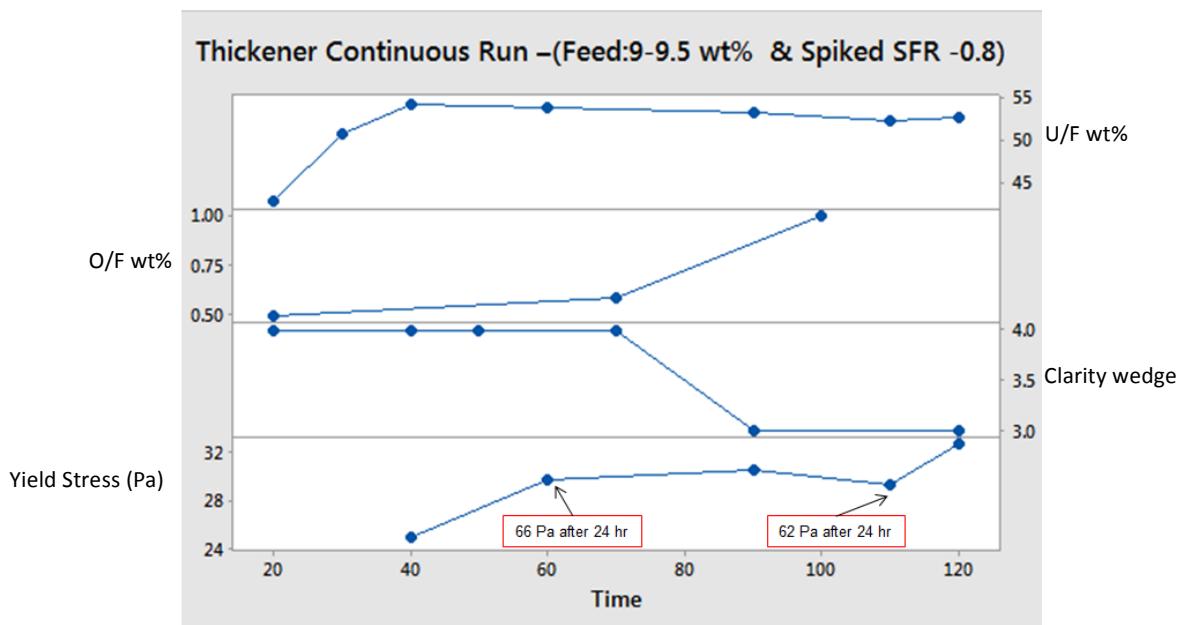
The tests were done in two phases: jar tests followed by pilot thickener tests. A series of jar tests were conducted to evaluate flocculation performance of two industrially available flocculants. Pilot thickener tests followed using a 3 m high by 0.5 m wide pilot thickener and the flocculant selected from the jar tests.

PROGRESS AND ACHIEVEMENTS

A flocculant was selected during jar test analysis based on initial settling test and overflow clarity.

Three tests were conducted to evaluate the performance of the pilot thickener before and after spiking:

- Case 1: Base case semi-continuous – feed at SFR 1 without MFT
- Case 2: MFT spiked case semi-continuous – SFR from 1 to 0.8
- Case 3: MFT spiked case continuous – SFR from 1 to 0.8



Because Case 3 is continuous and provided the best results, only this case was considered for further evaluation. The results (thickener feed with SFR of 1 spiked with MFT to SFR 0.8) summarized in the figure shows that underflow reached a steady state flow with an acceptable solids content of 55 wt% after 40 minutes. The target values for solids content and clarity were difficult to meet at the start of the test and declined over time (75 minutes). This was likely a result of particle size distribution shifting to more fine solids. The problem with overflow clarity of spiked thickener feed was further evaluated in a different study which showed that using a different flocculant would improve the overflow clarity resulting in meeting the target value.

To mitigate potential pumping issues, a shear loop with a flow rate of 45 L/min was implemented. This lowered the yield stress to an acceptable value of about 30 Pa. The measured yield stress of the collected underflow samples after 24 hours was approximately 60 Pa.

LESSONS LEARNED

These results support the hypothesis that spiking the thickener feed with MFT, while maintaining the required overflow and underflow solids contents, is feasible; specifically at an operational envelope of SFR 0.8 to 1.2 and at higher flocculant dosages than the current practice (1.5 times higher dosage).

Introducing clays to the thickener feed might also change the characteristics of the thickener underflow, resulting in different geotechnical characteristics such as hydraulic conductivity, dewatering and consolidation of the produced NST. Geotechnical analysis and the simulation of consolidation behaviour of spiked NST is the subject of the study, Spiked NST Deposition Monitoring (COSIA Project Number TJ0099).

RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Reza Salehi	Canadian Natural Resources Limited	Process Engineer - Project Lead		
John Clark	Paterson & Cooke Canada Inc.	Process Engineer		
Ferdinand Widjojo	Canadian Natural Resources Limited	Process Engineering Student		

Thickened Tailings Re-flocculation and Mixing Tests

COSIA Project Number: TJ0013 and TJ0075

Research Provider: Coanda Research & Development Corporation

Industry Champion: Imperial

Industry Collaborators: Canadian Natural Resources Limited (Canadian Natural)

Status: Complete

PROJECT SUMMARY

Imperial's Kearl Fine Tailings Treatment (KFTT) current tailings management strategy involves secondary chemical treatment of thickened tailings (TT) from the thickener underflow. Thickened tailings (TT) from two thickeners are transported to the deposition area via a pipeline approximately 6 km in length. The TT must be re-flocculated to build floc structure after pipeline and pump shear. Secondary mixer and polymer injection takes place 1.5 km from the deposition area. The mixer, located downstream of the last pump, should provide turbulent flow in the mixer throat whilst minimizing pipeline shear post flocculation. Previous studies by COSIA only evaluated in-line mixing of fluid fine tailings (FFT). The current study focused on in-line flocculation of TT. The objectives of the study included:

- evaluating inline mixing of polymer for TT, floc breakage due to shear prior to deposition; and
- determining required mixing energies for different TT compositions with the overall goal of validating the adequacy of the inline mixing rig.

The study was divided into two phases:

Phase I: Batch mixing study

Phase I consisted of a series of batch flocculation tests in a 315 mm mixing tank using TT material with varying properties. The results of the batch tests provided an understanding of the effect of feed variability (i.e., slurry density, clay content, and rheology) of the initial TT on the mixing parameters that define successful TT re-flocculation performance. The results were used to define the operation window for TT inline flocculation.

Phase II: In-line mixing study

The focus for Phase II was a series of selected in-line TT flocculation tests to validate the performance of the Kearl injector design for TT re-flocculation at a reduced scale (1/10th of field), and for a selected range of relevant TT material properties, based on the results from Phase I. The in-line rig was well instrumented to allow measurement of velocity and floc structure. These laboratory scale in-line flocculation tests were expected to provide a link between the TT re-flocculation process and the MFT flocculation process, for which extensive in-line injector laboratory and field scale data and performance correlations exist. This would enable building linkages



between laboratory tank mixing and inline mixing. To assess the effect of pipeline shear on floc breakage, samples were collected at the end of pipe and were exerted to additional shear in a Couette cell. Results led to better understand the potential impact of pipeline length post flocculation.

PROGRESS AND ACHIEVEMENTS

The project was completed in 2016 and results were instrumental in designing an integrated tailings pilot study conducted at Canadian Natural's Applied Process Innovation Centre (APIC) research facility. Lessons derived from both study phases were integrated to inform commissioning of the integrated KFTT system.

No showstoppers were identified for flocculating TT inline. The study showed length to diameter ratio (L/D) in the injector throat is important for ensuring sufficient polymer mixing for good flocculation performance. However, if the flow is turbulent post injector, the effective length is extended. The Couette results highlighted that shear can potentially inhibit initial dewatering. Moving the injection location closer to the tailings disposal area could reduce the impact of pipeline shear but needs to be confirmed after KFTT start up.

LESSONS LEARNED

The study showed the importance of maintaining adequate throat L/D for the injector to ensure optimum flocculation. For injector design, longer injector throat and increasing the injection ports from three to four yielded better flocculation. Optimizing shear is critical both during and post flocculation to ensure good dewatering. It was also observed that floc breakage under shear was dependent on the quality of the flocs and the focused beam reflectance measurement (FBRM) was a useful tool for monitoring flocculation performance by enabling generation of the relationship between shear rate and floc size.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Sakuhuni G, Ren W, Mattson K, Gallow, K, Hickman S, Rennard, D. 2016. Secondary Chemical Injector design and mixing studies. Tailings Environmental Priority Area (TEPA).

Hickman, S, Sakuhuni G, Rennard, D, Gallow, K. 2017. Small scale experiments to determine performance of flocculation in Kearn Fine Tailings Treatment secondary mixers and pipelines. Process Development and scale up enterprises symposium, The Woodlands, TX.

Rennard et al. 2016. Thickening and Re-flocculation pilot plant. Proceedings of the Fifth International Oil Sands Tailings Conference, pp. 270 -279.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigators: 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)
Clara Gomez	Coanda Research & Development Corporation	Principal Investigator		
Neville Dubash	Coanda Research & Development Corporation	Researcher		
Konstantin Pougatch	Coanda Research & Development Corporation	Researcher		
Givemore Sakuhuni	Imperial	Researcher		
Wei Ren	Imperial	Researcher		
David Rennard	Imperial	Researcher		
Gavin Freeman	Canadian Natural Resources Limited	Researcher		

Accelerated Fluid Fine Tailings Consolidation with Electrokinetics

COSIA Project Number: TJ0016

Research Provider: ElectroKinetic Solutions Inc. (EKS)

Industry Collaborators: Alberta Innovates, Sustainable Development Technology Canada, Canadian Natural Resources Limited (Canadian Natural), Suncor Energy Inc.

Status: Lab-scale Pilot - Complete, Field Demonstration - Ongoing

PROJECT SUMMARY

ElectroKinetic Solutions, Inc. (EKS) (<http://electrokineticsolutions.com/>) has developed a technology for *in situ* dewatering of oil sands fluid fine tailings (FFT) using electrokinetics (i.e., the ElectroKinetic Solutions – Dewatering Technology (EKS-DT) process). Starting in 2011, bench scale tests confirmed the potential for electrokinetics to dewater oil sands tailings. In 2015, EKS conducted two larger-scale tests (i.e., 130 m³ and 25 m³) at the C-FER Technologies facility in Edmonton. Canadian Natural (previously Shell Canada) and Suncor Energy Inc. provided financial support for these lab-scale pilot tests.

The C-FER tests assessed the scalability of the technology and produced significant results in the ongoing development of this technology. The results demonstrated that EKS-DT can be scaled up and that process efficiencies can result from scaling up. Subsequently, EKS improved the design of the technology and conducted further research programs to optimize the design and operation of the technology. This research resulted in innovations that improved dewatering performance and the maximum achievable final solids content.

Building on the development to-date planning for a field demonstration starting in the spring or early summer of 2019 is currently underway. A built-for-purpose test cell will be constructed in early spring 2019 at the InnoTech Alberta Vegreville research facility (Figure 1.). The test cell will be a 20 m x 25 m and 6 m deep and filled with a 4.5 m layer of FFT, which will be overlain by a 1.5 m water cap.

This field test will demonstrate the capability of the technology to operate year-round and to achieve a stable geotechnical state suitable for final reclamation. The field test is expected to run for 18 months. Following the dewatering process, comprehensive geotechnical and chemical sampling will be undertaken.

The field tests results will be used to answer the following issues that are critical for commercialization of the technology.

1. The capital costs of the installation (e.g., electrode arrays, power supply system, control system, instrumentation);
2. The efficiency, time and costs associated with the deployment of the electrodes arrays;
3. The maximum power requirements over the course of the dewatering process;

4. The energy costs associated with different stages of the dewatering process;
5. The dewatering rate for each stage of the dewatering process;
6. The vertical movement of the electrodes during the dewatering process;
7. The vertical and horizontal density gradients within the dewatered FFT;
8. The formation of cracks during the dewatering process; and
9. The amount and pattern of anode corrosion at the end of the dewatering process.

Canadian Natural is providing the FFT for the field test from the Jackpine mine. The initial solids content will be approximately 30% by weight and the sand-to-fines ratio (SFR) will be less than 0.2.

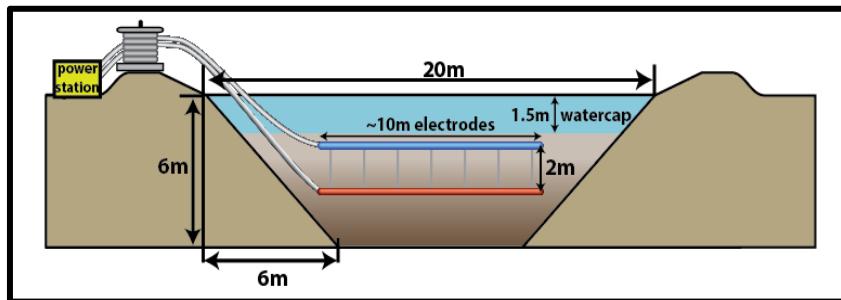


Figure 1: Schematic of the EKS-DT Field Test

PROGRESS AND ACHIEVEMENTS

The detailed engineering for the power supply system, the electrode arrays and the control system is underway. The engineering design is undergoing external expert review. Procurement of the installation components will begin in February 2019. Delivery of the components to the test cell site is scheduled for early May 2019.

To support this field test, the design for an instrumentation system has been prepared. The data from this network of instruments will be fed back to the control system to guide the operation of the installation and to provide a comprehensive research database for developing the technology further. The field test will also provide a basis to assess the functionality of these instruments for commercial-scale systems.

Concurrently, a comprehensive research program comprising small-scale and larger-scale lab experiments is underway in collaboration with the Universities of Alberta and Guelph.

LESSONS LEARNED

A major challenge with the technology has been forecasting how the technology will scale up. EKS has developed a detailed forecasting system for scaling up the technology. This analytical system allows the following design parameters to be forecast at different scales:

- power requirements;
- energy consumption;
- capital costs;

- dewatering time;
- final solids content (i.e. geotechnical strength); and
- anode corrosion.

This forecasting system is supported by empirical results from the supporting research programs and the extensive literature available on electrokinetics. The results of the field test will provide the data required to confirm the calibration of the forecasting system for the design and operation of the commercial-scale applications of the technology.

PRESENTATIONS AND PUBLICATIONS

A series of Microsoft PowerPoint presentations, research reports and question and answer documents have been prepared. As well, a comparative life cycle analysis has been prepared that analyses the economic, environmental and social responsibility dimensions of the EKS-DT process relative to current tailings management practices. These documents are available from EKS on request.

RESEARCH TEAM AND COLLABORATORS

Researcher: ElectroKinetic Solutions Inc.

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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Edward Hanna	EKS	Researcher		
Doug Kimzey	EKS	Researcher		
Steve Spencer	EKS	Researcher		
John Vandersleen	EKS	Researcher		
Prof. Bassim Abassi	University of Guelph	Expert Advisor		
Prof. Ted Roberts	University of Calgary	Expert Advisor		
Prof. Julie Shang	The University of Western Ontario	Expert Advisor		
Prof. Thomas Thundat	University of Alberta	Expert Advisor		
Prof. Japan Trivedi	University of Alberta	Expert Advisor		

Research Collaborators (2011 – present): Alberta Innovates; Shell Canada (up until June 2017); Canadian Natural; InnoTech Alberta; Suncor Energy Inc.; Sustainable Development Technology Canada

Clay Removal from Fluid Fine Tailings

COSIA Project Number: TJ0031

Research Provider: Syncrude Canada Ltd.

Industry Champion: Syncrude Canada Ltd.

Status: Year 4 of 6

PROJECT SUMMARY

Fluid fine tailings (FFT) release water at an extremely slow rate due to its low hydraulic conductivity. It is known that the negatively-charged clays in FFT 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 FFT dewatering and consolidating at an extremely slow rate. To accelerate FFT dewatering and the pace of reclamation, Syncrude R&D conceived the FFT clay treatment project by targeting the bad actor clays in FFT. 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 FFT clay treatment.

The process of FFT clay treatment can take two paths. Process A, simply called clay flotation, removes clays from FFT 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 FFT stream first with a flocculant and then with a collector. The treated FFT is subjected to liquid-solids separation, e.g., centrifugation, filtration and/or sedimentation in a deposition cell. Syncrude Canada Ltd. has successfully conducted lab proof-of-concept tests, small pilot tests for clay flotation, and field pilot test for FFT clay treatment.

The main objective of the project is to develop alternative technologies for deployment that would augment commercial technologies in the current suite of tailings treatment activities such as composite tailings, FFT centrifugation and water capped FFT.

PROGRESS AND ACHIEVEMENTS

In the laboratory proof-of-concept tests of Process A, FFT was diluted and conditioned with a flocculant first and then with a collector. When the treated FFT was aerated the clay froth was generated from the flotation cell. The hydrophobic clay froth dewatered and desiccated rapidly, resulting in >95% solids in three days in the lab.

The pilot clay flotation tests were conducted in a continuous mode using the same chemical recipe as that in the lab clay flotation. A large flume measuring 7.32 m long x 0.61 m high x 0.30 m wide was filled with a thickness of 0.61 m clay froth generated and pumped from the froth launder of the flotation machines. The clay froth segregated after 5 hours, with the hydrophobic froth on top and the clear release water at the bottom of the flume. After decanting the clear water from the flume over the following three days, the froth was left in the flume for monitoring the natural desiccation. The entire clay froth deposit in the flume desiccated to 95-98% solids in three months at the room temperature of 21°C.

For Process B; i.e., clay treatment for the entire FFT stream followed by physical separation (e.g., filtration, centrifugation and/or sedimentation in a deposition cell, etc.), the lab filtration test showed that even under a very low pressure of 138 kPa (20 psi), the flocculant-collector recipe resulted in significantly faster filtration rate than the flocculant alone. Building on this idea, a field test cell of 100 m x 100 m x 10 m deep (with a 0.5 m layer of sand filter under-drain system) was designed and constructed for the 2017 field tests. The feed FFT was slightly diluted to about 28% solids and mixed with a flocculant in an inline dynamic mixer and then mixed with a collector in another inline dynamic mixer in sequence. The treated FFT stream was pipelined to fill the 100 m x 100 m x 10 m deposition cell. The clear water was released and simultaneously pumped out of the deposition cell. Consolidation of the deposit in the test cell will be monitored for several years. The initial deposit sampling data showed that the treated FFT with the flocculant-collector recipe had dewatered from the initial 28% solids content to ~50% solids content just one month after the field pilot test was completed.

LESSONS LEARNED

The lab proof-of-concept tests demonstrated that the initial dewatering rate of FFT was accelerated after being treated with the flocculant-collector recipe, which rendered the FFT clays hydrophobic. This was indicated by the significant increase in clay froth desiccation rate and filtration rate of the treated FFT.

Long-term consolidation of FFT treated with the flocculant-collector recipe in the field test deposit will be monitored over many years; preliminary results are, however, promising as noted above.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude Canada Ltd.

Principal Investigator: Simon Yuan

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Simon Yuan	Syncrude Canada Ltd.	Senior Associate – Chemical		
Jim Lorentz	Syncrude Canada Ltd.	Team Leader		
Barry Bara	Syncrude Canada Ltd.	Senior Associate – Mechanical		
Ron Siman	Syncrude Canada Ltd.	Senior Technologist		
Allan Christianson	Syncrude Canada Ltd.	Senior Technologist		

Engineered Tailings Research

COSIA Project Number: TJ0033

Research Provider: Syncrude Canada Ltd.

Industry Champion: Syncrude Canada Ltd.

Status: Year 4 of 7

PROJECT SUMMARY

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

- 1) Geotechnical property measurements of the low sand-to-fines ratio (SFR) products resulting from co-disposal of tailings directly from the extraction process and FFT using modern paste and thickened tailings technology.
- 2) Evaluation of new polymers and chemicals for engineered tailings that provide the state-of-art polymeric flocculant information for fine tailings treatment.

Following the successful lab and small pilot tests of co-disposal of fresh tailings from bitumen extraction and legacy FFT (as per D085) using modern paste and thickened tailings technology, the geotechnical properties of the low SFR co-disposal products were measured to evaluate the Atterberg limits (liquid and plastic limits), compressibility and hydraulic conductivity of the polymer-treated samples with SFR varying from 0 to 3. Large-strain consolidation testing of the samples was completed for this purpose. The hypothesis of co-disposal of fresh tailings and FFT is that the dewatering rate could be accelerated with the increase in SFR in the polymer treated co-disposal deposit. The objective of this activity is to prove the hypothesis and provide the technical foundation to further develop the co-disposal technology in a field scale and eventually implement this technology at a commercial scale.

For the polymer evaluation, lab FFT flocculation tests were performed for 21 polymers supplied by different polymer vendors. The flocculant performances were evaluated according to the four established success criteria of CST (capillary suction time), yield stress, centrifuge index, and visual observation of the floc structures. The objective of this activity is to seek more effective and lower cost alternative polymers for fine tailings treatment.

PROGRESS AND ACHIEVEMENTS

The geotechnical property measurements of the low SFR co-disposal products demonstrated that the Atterberg limits; i.e., liquid limit, plastic limit and plasticity index, decrease with the increase in SFR in the co-disposal products. The hydraulic conductivities increase significantly with the increase in SFR in the co-disposal products at the same void ratio. The compressibility of the co-disposal products under the same effective stress is also enhanced when the SFR in the co-disposal products is increased. These results verified the hypothesis that the dewatering rate could be accelerated with the increase in SFR in the polymer treated co-disposal deposit.

The polymer evaluation tests demonstrated that three of the 21 polymers tested gave the best flocculation performance, which was equivalent to the flocculation performance of the polymer currently used in commercial fine tailings treatment. This increases the flexibility and options available for chemical treatment of FFT to produce deposits that can be progressively reclaimed.

LESSONS LEARNED

The geotechnical property measurements showed that the hydraulic conductivities significantly increased with the increase in SFR in the co-disposal products at the same void ratio. These data proved the hypothesis and provided the technical foundation to further develop the co-disposal technology in a field scale and implement this technology at a commercial scale. The potential benefit of co-disposal of fresh tailings and FFT is that this technology not only treats the legacy FFT but also captures the new fines from the fresh tailings generated from extraction.

The polymer evaluation results provide the polymer end users with the diversity of polymer supplies and potentially the flexibility of FFT treatment operations. It should be recognized that the assessments of polymers were for initial dewatering only. Further consolidation and hydraulic analysis may be required to gain the insight required for long-term dewatering rates before considering these other polymers for commercial operations.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude Canada Ltd.

Principal Investigator: Simon Yuan

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Simon Yuan	Syncrude Canada Ltd.	Senior Associate – Chemical		
Ron Siman	Syncrude Canada Ltd.	Senior Technologist		
Xinghua Mo	InnoTech Alberta	Researcher		
Haihong Li	InnoTech Alberta	Researcher		
Joe Zhou	InnoTech Alberta	Researcher		

Alternative Polymers for Mature Fine Tailings (MFT) Drying

COSIA Project Number: TJ0056

Research Provider: Coanda Research and Development Corporation

Industry Champion: Suncor Energy Inc.

Status: Ongoing

PROJECT SUMMARY

The purpose of this project is to screen chemicals (polymers) for suitability in Suncor Energy Inc.'s (Suncor) current Tailings Reduction Operation (TRO™) mature fine tailings (MFT) drying systems, with a focus on cost reduction and/or improved system performance as measured by increased MFT dewatering rates and amounts in the field. A field trial was conducted in 2016 at the TRO™ process to assess two different polymers, "Polymer A" and "Polymer B", in comparison with the incumbent chemicals, "Polymer C" and "Polymer D", respectively. The evaluation involved bench scale comparison of the polymer chemistries in addition to a field trial. The results of both the bench testing and field trial were compared against the modified Polymer Testing Protocol and Success Criteria (Table 1). Overall success of the trial has been defined as superior technical performance of the polymer at an advantageous cost profile in comparison with the incumbent polymer chemistries. In 2017 "Polymer E" was tested against "Polymer B" but was unable to match or better its dewatering capability at a similar or lower dose. Testing of "Polymer E" was discontinued prior to a field trial.

PROGRESS AND ACHIEVEMENTS

Comparative testing of Polymer A and Polymer B with the incumbent polymers, Polymer D and Polymer C, between an initial clay-to-water ratio (CWR) range of 0.25 to 0.35 are shown in Table 1.

**Table 1: Polymer Testing Protocol and Success Criteria
(Comparative Evaluation of Results for an Initial CWR Range of 0.25 to 0.35)**

	Polymer Dose (% Reduction)	24 Hour CWR (% Increase)
Polymer B: Polymer A	18	24
Polymer B: Polymer C	22	21
Polymer B: Polymer D	21	25
Polymer A: Polymer C	5	6
Polymer A: Polymer D	4	10

Two options were considered following the comparative evaluation: use a combination of Polymer A and Polymer B (Option 1); or use Polymer B in all plants (Option 2).

Option 1: Use a combination of Polymer A and Polymer B – This option is not the technical optimum solution for Suncor; however, it has commercial benefits as it encourages competitive pricing between polymer vendors. Additionally, this option captures business benefit as it is bridges Suncor's Operations/Technical with other tailings research initiatives such as Accelerated Dewatering (ADW) and Permanent Aquatic Storage Structure (PASS).

Option 2: Use Polymer B in all of Suncor's plants – This option is the most technologically advantageous for Suncor; however, vendor pricing and manufacturing capability for Polymer B has yet to be confirmed.

This project supports Suncor patent CA 2820324 "Enhanced Techniques for Dewatering Thick Fine Tailings."

LESSONS LEARNED

Lessons learned from the field and bench scale trials include:

- Polymer A and Polymer B outperformed the incumbent polymers in terms of polymer dosage (less polymer was required) and the 24-hour CWR;
- The performance for each polymer was identical at different scales tested but the larger scale demonstrated a 30% increase in the CWR;
- Changing mixing parameters results in a unique response from each polymer;
- No significant deviations were observed in laboratory drying performance or strength gain for Polymer B; and
- Polymer A exhibited a higher final strength at a CWR = 1 than its reference Polymer D during a bench scale comparison.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor Energy Inc.

Principal Investigator: Adrian Revington

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Adrian Revington	Suncor Energy Inc.	Team Lead		
Benny Moyls	Coanda Research and Development Corporation	Process Engineer		

Thickener Operation Optimization

COSIA Project Number: TJ0071

Research Provider: Coanda Research & Development Corporation, Pocock Industrial

Industry Champion: Imperial

Status: Year 5 of 5

PROJECT SUMMARY

The focus of COSIA's Tailings Environmental Priority Area (EPA) is improving the management of oil sands tailings. Improved management includes a wide range of activities, including overcoming operational challenges during the tailings treatment process. Operational challenges for oil sands tailings treatment include clay and bitumen content as well as feed variability. At the Kearl Oil Sands mine (Kearl), Imperial selected thickeners and flocculation as the principal treatment technologies for its fluid fine tailings (FFT). To assist with the Kearl fines tailings treatment (KFTT) process, Imperial's technical team performed a series of laboratory studies and processing trials, including:

- thickener feed variability testing and thickener tests with a wide range of sand-to-fines ratio (SFR) to extend the operating envelope of the thickener from 0.5-1.2 to 0.5 -3 SFR;
- thickening and flocculation performance with high bitumen fluid tailings feed;
- high fines ore and tailings fines distribution study;
- semi-continuous operating strategy development and implementation; and
- developing an operating strategy with varying oil sands ore feed.

The purpose of a thickener is to recover water and produce concentrated slurry. Thus, the overflow water clarity and underflow density and solids content are key process indicators of success for the fluid tailings thickening process. Other process variables monitored include:

- thickener feed composition – including volumetric flow, solids rate, particle size distribution, clay content, and bitumen content;
- underflow composition – including volumetric flow, solids rate, particle size distribution, clay content, bitumen content and yield stress, as required;
- bed level, pressure and density gradient;
- rake torque reading; and
- flocculant dosage and concentration.

During the KFTT process, flocculant is injected into the tailings stream upstream and downstream of the thickeners. The benefits of the second flocculant injection are to:

- rebuild the floc structure and enhance the thickened tailings permeability;
- reduce the footprint and volume for thickened tailings storage through accelerated dewatering; and

- increase the yield stress slowly at discharge and allow the thickened tailings to flow in the deposit area and gain strength after further dewatering.

Optimal flocculant dosage and mixing energy is needed for both the initial flocculation and re-flocculation. The optimal flocculant dosage is determined by the thickened tailings composition (i.e., fines or clay content) and water chemistry. The mixing energy required depends on solids rate, thickened tailings volumetric flow and density, pipeline shear and injector design. With a given flocculant injector, the mixing energy required is influenced more by the thickened tailings density than the volumetric flow. This means that the density should be controlled within a desired range to minimize the impacts of mixing.

PROGRESS AND ACHIEVEMENTS

Following the laboratory and processing trials, Imperial's KFTT started-up successfully and the technology was proven at a commercial scale. During normal operations, to avoid the production of off-spec thickened tailings when the solids loading rate is consistently low, a semi-continuous operating mode was developed and implemented. During the optimization of the thickener operation critical factors were identified that impact thickener performance, including:

- stable feed and feed variability management;
- reliable and operable facilities;
- instrumentation and control systems.

As the floc size and structure are critical for re-flocculation performance, capillary suction time (CST) provides a good measurement of dewatering for flocculated material. The key process indicators are:

- capillary suction time (CST);
- initial yield stress and yield stress gain after 24 hours and 7 days deposition; and
- solids content gain in 24 hours and 7 days following deposition.

Additionally, the thickened tailings density, flow and flocculant dosage should be monitored to ensure the generated tailings are within specifications.

LESSONS LEARNED

Oil sands tailings treatment has engineering challenges. Selected tailings treatment technologies should be able to treat fines tailings at an acceptable rate while maintaining short term and long term dewatering capabilities. Reduction of clay or FFT/MFT in treated tailings deposits can improve short and long term dewatering capability. FFT/MFT ratio reduction in tailings feed, however, will also reduce fines treatment efficiency. Optimal mixes of fresh tailings and FFT/MFT can enhance dewatering while maintaining efficient fines storage volume.

In general, tailings mixtures of medium SFR (preferred~1), with approximately 30-40% MFT was identified as the optimum composition for short-term dewatering and long-term consolidation. Identification of the correct recipe should consider both efficient fines treatment and creating reclaimable deposit in a relatively short time. An application of selected treatment envelope, with thickening and re-flocculation process, can produce favourable



deposit properties for timely reclamation and was discussed in detail with key process performance indicators and successful commercial scale deposit performance. Most importantly, re-flocculated thickened tailings illustrated that the treated tailings deposit can be successful in both short- and long-term time periods with a variable feed range.

LITERATURE CITED

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Ren, W. 2018. *Expanded Operational Envelope of Thickening and Reflocculation Through Semi-continuous Operation*. Presented at 2018 Oil Sands Innovation Summit, Calgary, Alberta, Canada, June 7-8, 2018.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Ren, W. 2018. *Expanded Operational Envelope of Thickening and Reflocculation Through Semi-continuous Operation*. Presented at the 2018 Oil Sands Innovation Summit, Calgary, Alberta, Canada, June 7-8, 2018.

Ren, W., Sury, K. and Clingman, S. 2014. *Enhanced thickened tailings performance via additional chemical treatments*. Paste 2014, Proceedings of the 17th International Seminar on Paste and Thickened Tailings, Page 245 – 255.

Ren, W. and Weerakone, S. 2018. *Accelerated Oil Sands Tailings Dewatering with Thickening and Reflocculation*. Presented at IOSTC 2018. International Oil Sands Tailings Conference 2018, Edmonton, Canada, December 9-12, 2018.



RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Sidantha Weerakone	Imperial	Geotechnical Engineer		
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Clara Gomez	Coanda Research & Development Corporation	Principal Investigator		
Konstantin Pougatch	Coanda Research & Development Corporation	Researcher		

Permanent Aquatic Storage Structure for Fluid Fine Tailings

COSIA Project Number: TJ0082

Research Provider: Suncor Energy Inc., Coanda Research and Development Corporation, SRK Consulting (Canada) Inc., University of Alberta, University of Saskatchewan, University of Waterloo

Industry Champion: Suncor Energy Inc.

Industry Collaborators: Teck Resources Limited

Status: Year 3 of 5

PROJECT SUMMARY

The Permanent Aquatic Storage Structure (PASS) project is focused on the treatment of fluid fine tailings (FFT) to create a substrate that could be reclaimed into a freshwater lake shortly 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 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 FFT treatment solutions to bring the parameters to levels that meet federal and provincial guidelines for freshwater lakes.

The FFT treatment process is a two-step process. The first treatment is with an acidic coagulant to immobilize certain parameters, which might be of concern in a freshwater lake, such as some metals, organic acids and hydrocarbons. This is followed by the addition of a flocculant that aids rapid release of water from the treated FFT. The treated FFT is subsequently conditioned and conveyed over several kilometres of pipeline to a deposition area that acts as a settling basin.

After the end of deposition, the treated FFT is analogous to lake sediment settling over long periods of time. As settlement of the treated FFT occurs, pore water (water surrounding the individual solid particles of the treated FFT) is continuously expressed or released from the treated FFT to the overlying 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 meet federal and provincial guidelines for the protection of aquatic life.



PROGRESS AND ACHIEVEMENTS

A treatment process for FFT that minimizes the mobility of the key parameters of concern in the environment was developed. The treatment process has been validated at bench, pilot and commercial scales. Several 5 m geocolumns are being monitored over a five-year period to develop predictive models of the geochemical and settlement trajectories of the lake landform.

The treatment process uses an acidic coagulant to chemically immobilize, through precipitation or chemisorption, dissolved parameters of concern such as organic acids and some metals, as well as to coagulate bitumen and ultra fines. This ensures that the parameters of concern are permanently sequestered within the mineral matrix of the FFT. This is followed by flocculant addition to rapidly dewater FFT to enable water recycling to the extraction plants during mining operations.

A bench scale geotechnical centrifuge for simulation of treated-FFT settlement in a deep deposit was also developed.

LESSONS LEARNED

To-date the project has demonstrated that the FFT treatment process is capable of accelerating the reclamation timelines for aquatic landforms following in-pit deposition of FFT.

The bench top centrifuge developed as part of the PASS project could be used as a process monitoring tool during deposition to ensure that settlement targets are achieved for the majority of treated FFT placed in-pit.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Omotoso, O. 2018. PASS: A technology solution for tailings management. Presented at the 2018 Oil Sands Innovation Summit, Calgary, Alberta, Canada, June 7-8, 2018 (submitted to COSIA).



RESEARCH TEAM AND COLLABORATORS

Institution: Multiple institutions

Principal Investigator: Multiple researchers

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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Jon Martin	University of Alberta			
Gonzalo Zambrano	University of Alberta			
Matt Lindsay	University of Saskatchewan			
Andrea Farwell	University of Waterloo			

Mature Fine Tailings Polymer Injector Redesign

COSIA Project Number: TJ0084

Research Provider: Coanda Research & Development Corporation

Industry Champion: Suncor Energy Inc.

Status: Ongoing

PROJECT SUMMARY

The success of both the Tailings Reduction Operations (TRO™) and Permanent Aquatic Storage Structure (PASS) technologies partly relies on successful flocculation of the tailings material to facilitate its dewatering. The flocculation is achieved by the addition of polymer to mature fine tailings (MFT) flow in the in-line injector. Therefore, the effectiveness of the polymer injector (AR5) plays an important role in the process. Existing laboratory and field data for TRO™ suggest that dewatering and polymer dosage requirements are influenced by the mixing/dispersion of polymer into MFT and the turbulence generated at the injector; where both can result in changes to the micro and meso mixing conditions at the injector. This observed influence creates an opportunity to improve mixing and turbulence generation through injector design modifications to reduce polymer dosage and/or improve dewatering performance at a given dose. The reduced polymer demand will not only result in significant cost savings but also in increased MFT processing capabilities.

PROGRESS AND ACHIEVEMENTS

Suncor Energy Inc. (Suncor) carried out two field testing campaigns to investigate the effect of micro and meso mixing scales on MFT flocculation and dewatering in the 2015 and 2016 seasons, respectively. Based on the findings of the field tests, a comprehensive research program that comprised both laboratory-based experimental and computational modelling components aimed at developing an improved injector design for MFT flocculation was initiated in 2017. The experimental part focussed on the utilization of the available flocculation facilities at the Coanda Research & Development Corporation (Coanda) Edmonton location to carry out flocculation experiments for a variety of injector modifications for scaled-down versions. The modelling part included application of the tools already developed such as single-phase turbulent flow simulations, and development of the sophisticated multi-phase population balance model (PBM) that would incorporate floc formation and breakage mechanisms, flow regime transition, fractal growth of flocs and other important phenomena. The objective of the flocculation modelling was to gain insights about the process and provide a bridge between laboratory and field operating conditions.

The key achievements of the injector redesign program are:

- Design and examination of multiple injector designs
- Identification of superior injector design which can generate higher quality flocs at a lower polymer dosage



- The new injector design also has a wider range of operation compared to the incumbent (Suncor original AR5)

LESSONS LEARNED

Lessons learned include:

- Flocculation performance is a strong function of injector design.
- Optimization of injector design can result in lower chemical dosage and improvement in process key performance indicators such as floc size.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor Energy Inc.

Principal Investigator: Ardalan Sadighian

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Benny Moyls	Coanda Research & Development Corporation			
Konstantin Pougatch	Coanda Research & Development Corporation			

Outotec PSI500i[®] Instrument Field Test

COSIA Project Number: TJ0094 and TJ0115

Research Provider: Teck Resources Limited CESL test facility/ Teck Resources Limited (TJ0094) and ExxonMobil Research / Imperial (TJ0094)

Industry Champion: Teck Resources Limited (TJ0094), Canadian Natural Resources Limited (TJ0115)

Industry Collaborators: Imperial, Suncor Energy Inc., Outotec Oyj

Status: Year 3 of 4

PROJECT SUMMARY

The oil sands tailings process generates tailings slurry that must be settled for final deposition. The tailings contain fine material with poor water release characteristics that makes water recovery challenging. Polymer flocculants are added to assist in settling and dewatering the fine tailings. The amount of polymer addition is dependent on the fine fraction of the tailings. If the particle size distribution (PSD) of the tailings is unknown, an excess amount of polymer needs to be added in the dewatering stage to flocculate the fines. Over flocculation also has a detrimental effect on the water release characteristics. Measuring the particle size distribution using an on-line analyzer could have major benefits over common laboratory methods as it provides on-line and fast insight into the process. This enables the operators to implement required changes to minimize the reagent consumption, while achieving optimal flocculation. The Outotec PSI500i[®] has been successfully used in other mining industries to provide real-time particle size distribution of slurries by laser diffraction.

COSIA Project TJ0094 – A series of tests using Outotec PSI500[®] particle size analyzer on oil sands tailings samples from different operations were conducted. Tests were performed by recirculating the slurry in a closed circuit to simulate real plant conditions. Two of these analyzers have been installed at oil sands sites but have never been used commercially. Three phases of work were proposed for this scope of work.

Phase 1: The existing Outotec PSI500[®] oil sands units were removed from site and transported to the Teck Resources Limited (Teck) CESL test facility in Richmond, BC. One of the units was commissioned and run through a series of tests to assess the robustness, accuracy and operating range of the unit.

Phase 2: Fouling Management Lab Program – Based on the outcomes of the first phase of lab testing at CESL, additional testing was performed at the ExxonMobil Research lab to test various surfactants/solvents ability to clean fouled bitumen windows, determine ability of surfactants to prevent fouling and effective dosage range. Sapphire windows were submersed in relatively dilute slurry pails with high bitumen content (either from mature fine tailings (MFT) or raw oil sands ore) along with different surfactants and solvents (sodium dodecyl sulphate (SDS), polyethylene glycol octylphenyl ether and a degreaser containing amorphous silica in water) to see if they would reduce fouling. Pails were lightly stirred for a set period of time and then the windows were qualitatively assessed for cleanliness.

Phase 3: Based on the outcomes of the Phase 2 testing, improvements/modifications were made to the Outotec Probe at CESL to minimize bitumen fouling of the window. The coated window testing was done in the instrument's dilution tank.

COSIA Project TJ0115 – With the promising results from the previous Joint Industry Project (JIP), a longer term testing in the field is needed to further validate whether the Outotec instrument can be useful for oil sand tailings treatment operations. The objective of the current JIP is to test the Outotec PSI 500i® on-line particle size analyzer in the field with a few improvements and determine if this instrument is fit for the in-line tailings treatment process control. This work will include assessing PSD measurement performance, fouling mitigation solutions, and the frequency and scope of operator intervention required to maintain operability. The hypothesis is that the instrument can give accurate PSD analysis without any manual cleaning within a week.

This scope of work is to install the Outotec PSI 500i® on the flotation tailings line and continuously test for at least 30 days.

The instrument key performance will be evaluated on-line through:

- Accuracy – the accuracy will be monitored by comparing the laser diffraction signal to samples taken and analyzed by conventional Laser Diffraction methods
- Operating range – how does the instrument perform with various SFR and solids content range of flotation tailings
- Maintenance requirement (with/without automatic wiper) – how often the instrument maintenance and manual cleaning is needed to obtain useful PSD signal, and what steps, time requirements and other challenges and opportunities are associated with these maintenance activities

The information generated from this work will be used for the instrument commercial design.

PROGRESS AND ACHIEVEMENTS

COSIA Project TJ0094

A series of test work using Outotec PSI500® particle size analyzer on oil sands samples from different operations have been conducted. Tests were performed by recirculating the slurry in closed circuit to simulate real plant conditions. This JIP, led by Teck Resources Limited, found that the Outotec PSI 500i® can be designed to perform useful on-line tailings particle size characterization. Fouling was the major challenge, and the method for mitigating bitumen fouling was investigated. It was found that with cold dilution water, the analyzer ran for 42 h without manual cleaning.

COSIA Project TJ0115

For the 2018 program, the instrument was upgraded with fouling mitigation options (window wipers and chemical wash). The software was upgraded to enable setting of wiper and chemical wash sequence and duration. A new 200 mm laser head was leased and installed. The upgraded system was installed.

It was found that the 200 mm laser head performs better than the 300 mm version, which was used in **COSIA Project TJ0094**. The laser head alignment is stable and there is no disabling of detectors required which gives wide

measurement range up to 1200 μm . Chemical wash and wiper system works well but the parameters need to be further optimized.

The instrument requires slurry feed rate of 50-100 L/minute. It is challenging to control the feed flow rate because any throttling causes plugging due to the existence of the petrified wood in the analyzer feed.

LESSONS LEARNED

COSIA Project TJ0094 – The lessons learned from the initial lab and pilot testing included:

On-stream analyzer performed well at detecting different size fractions accurately. Good agreement between lab and analyzer for fine fractions $<44 \mu\text{m}$, and clay $<10 \mu\text{m}$ and $<2 \mu\text{m}$. More focus needs to be put on distinguishing coarse particles from air bubbles to ensure the readings are correct and correlate well to lab data.

The instrument had issues with high bitumen content samples. Optics fouling strategies (chemical and mechanical cleaning) will continue to be investigated but the best strategy so far is to keep the temperature of the dilution water below 20 °C.

COSIA Project TJ0115 – The lessons learned from the preliminary field test are outlined below:

The instrument installation and configuration must be adapted for the location and application. This instrument is very promising so far and it should eventually be incorporated in oil sands tailings treatment control systems with the proper configurations and fouling mitigation strategies. Although the analyzer itself shows promise, continuous testing has been hampered by upstream sample line plugging. In this field trial, the feed to the analyzer is simply tapped off the mainline through a small diameter valve and pipe. The plugging issue that occurred in the current field trial configuration may be able to be solved by a proper commercial solution that would involve a purpose-designed mainline sample splitter that would reject tramp material.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Komishke, B. 2018. Advances in On-line PSD Measurement for Tailings. COSIA 2018 Innovation Summit, June 7-8, 2018. Calgary, Alberta.

Schwartz, D., Komishke, B., Heffel, R., Koresaar, L., Sharifi, E. 2018. Evaluation of On-line Particle Size Distribution Measurement for Oil Sands Tailings Treatment. 50th Annual Canadian Mineral Processors Conference, Ottawa, ON, January 24, 2018.



RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Darren Schwartz	Teck Resources Limited			
Bradley Komishke	Teck Resources Limited			
Rory Heffel	Teck Resources Limited			
Jiangying Wu	Canadian Natural Resources Limited			
Ashar Mirza	Canadian Natural Resources Limited			
Michael Marr	Imperial/Suncor Energy Inc.			
Brent Moisan	Suncor Energy Inc.			
David Rennard	ExxonMobil			
Yijun Liu	ExxonMobil			
Lauri Koresaar	Outotec (Finland) OY			
Erfan Sharifi	Outotec (Canada) Ltd.			

Pilot Scale Test Program of Non-Segregating Tailings Enhancement

COSIA Project Number: TJ0097

Research Provider: Canadian Natural Resources Limited (Canadian Natural), Thurber Engineering Ltd.

Industry Champion: Canadian Natural

Status: Complete

PROJECT SUMMARY

Canadian Natural's Horizon mine produces Non-Segregating Tailings (NST) as part of its tailings management plan. NST technology is the main tailings treatment method adopted by Canadian Natural at Horizon. NST are tailings that have been treated (dewatered) to form a homogeneous, semi-cohesive mass when deposited. The NST process creates a pumpable mixture of coarse sand and fines that settles rapidly, densifies, and becomes trafficable upon consolidation. The current method for producing base case NST is to use thickener underflow combined with a sand stream from a cyclone underflow, which is then treated with carbon dioxide.

To improve the consolidation performance and reliability of the NST process and to increase fines capture in the tailings deposit, Canadian Natural has evaluated various technology options that can be deployed in the event of process upsets and off-spec NST production. Improving fines capture along with accelerating deposit dewatering will result in less mature fines tailings (MFT) being generated, improve reclamation timelines—all of which translate to significant cost savings over the life of the mine.

Promising chemical treatment options have been tested on the off-spec NST mixture. The selected chemical treatment process is known as enhanced NST. The enhanced NST (eNST) treatment process is an in-line injection of a selected chemical to NST upstream of the point of discharge into the deposit. Subsequent to the eNST treatment process, and to improve the fines capture capacity, Canadian Natural tested injecting MFT into the NST stream to produce a lower sand-to-fines ratio (SFR44) NST. This additional treatment is known as enhanced spiked NST (esNST).

The intent of the field pilot scale test program was to compare the geotechnical performance of NST with different NST enhancement methods. Lessons learned from the program can be implemented at the Horizon and Albian operations, as well as other current or future oil sands operations interested in active tailings streams management.

Key Performance Measures and Criteria

The program objectives were to compare the performance of NST (as the control sample), off-spec NST, eNST, and esNST materials in a pilot scale test by monitoring or measuring the following key performance measures.

1. The segregation and fines capture performance (solids content (SC) and fines content (FC44)).
2. The consolidation (settlement and excess pore pressure dissipation) performance.
3. The strength (vane strength and cone penetration (CPT)) over the length and depth of the deposit.
4. The qualitative performance during deposition through visual observations and time-lapse images.

Design and Methodology of the Research

The NST pilot scale test program consisted of separate cells for the above noted material types. Each cell was monitored for deposition performance, geotechnical performance (settlement, consolidation and strength) and fines capture evaluation of NST, eNST, off-spec NST, and esNST. NST subsamples were taken from the extraction plant feed source (i.e., NST Lines) which was then transported via cement trucks to keep the material mixed and then off loaded into a pumper truck which then pumped NST to the test cells. To ensure all inputs were close to operational conditions, plant process water was trucked and stored in a tank at the pilot program site for dilution and to make up the polymer solution. Water and polymer solution were injected upstream of the discharge point at various rates and dosages in order to reach the target recipe for each cell.

PROGRESS AND ACHIEVEMENTS

Four test cells were filled with different NST treatments. Post-deposition geotechnical performance measurements of the NST treatments included monitoring pore pressure dissipation, *in situ* strength measurements and laboratory measurements from deposit samples. The piezometer data provided information on the state of consolidation of the deposits through dissipation of excess pore pressures. The *in situ* strength measurements by field vane and cone penetrometer provided strength profiles at four locations in each cell. Post-deposition sampling provided specimens to determine SC and FC44 and evaluate segregation index. Results included:

- Deposit Slope: Cell #1 (esNST) and Cell #2 (eNST) formed a sloped deposit surface, which was thicker at the discharge point and thinner at the toe of the deposit. Cell #4 (NST) deposit had a fairly uniform thickness.
- Solids Content (SC): Cell #1 (esNST) exhibited a fairly uniform SC over the length and depth compared to the other cells.
- FC44: Cell #2 (eNST) had the overall highest fines capture, although FC44 was not uniform over the length of the deposit.
- FC44: Cell #1 (esNST) exhibited a fairly uniform FC44 over the length and depth of the cell. Fines content values were close in value to the feed fines content.
- FC44: Cell #3 (off-spec NST) field values were all below the field value implying that fines were lost from the cell.
- FC44: Cell #4 (NST) field values averaged around the feed, FC44 is fairly uniform across the length and depth of the deposit.



Following the completion of the pilot scale test program in 2016 a one dimensional consolidation simulation was conducted using available self-weight consolidation geocolumns, and large strain consolidation cells (LSC) data from previous studies to better understand and predict the long-term behaviour of the deposit for each treatment.

Results from the consolidation simulation can be summarized as:

- The least post-deposition settlement was for eNST.
- The highest pore pressure dissipation rate was for eNST (it essentially completes dissipation during filling) although with slightly lower final solids content due to lower compressibility (higher void ratio at high stress ranges compared to NST and enhanced spiked NST).
- Overall, the best performance results were from the eNST simulation.

LESSONS LEARNED

Based on these findings, the eNST commercial demonstration program was run from June 27 to September 7, 2017 at the Horizon site. A total of 5.5 Mt of solids was deposited from which 3.5 Mt was treated by in-line injection. Subsequent analyses of the annual tailings pond survey results suggest potential improvement in consolidation and overall fines capture at the Horizon site.

The eNST technology will be commercially deployed at the Horizon site beginning in March 2019. Enhanced spiked NST will be commercially piloted from June to October 2019.

RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Reza Salehi	Canadian Natural Resources Limited			

Fluid Fine Tailings In-line Flocculation and Co-deposition

COSIA Project Number: TJ0108

Research Provider: Imperial, Paterson & Cooke Canada Inc., Thurber Engineering Ltd., Barr Engineering & Environmental Science Canada Ltd., Deltares

Industry Champion: Imperial

Status: Year 2 of 4

PROJECT SUMMARY

Imperial's research team studied the feasibility of co-depositing flocculated fluid fine tailings (FFT) into the currently operational thickened tailings (TT) panels (deposit areas) at Kearl, Imperial's oil sands mining operation. Currently, Imperial's tailings treatment plan at Kearl consists of thickening fluid fine tailings (FFT) and flotation tailings (FLT) with the addition of a flocculant as the tailings enters the thickeners, followed by secondary chemical (flocculant) treatment downstream of the thickeners and finally, deposition of the thickened (re-flocculated) tailings in a multi-layer, deep deposit. Dewatering of the tailings occurs during the thickening process and in the TT deposit area. As the TT settles in the deposit area, water is released during deposition and sedimentation and is reused in the bitumen extraction process. The current plan includes a flocculant, thickeners, and a second flocculant (chemical).

Co-deposition is a concept whereby FFT is flocculated in-line and then deposited in the TT deposit area. Co-deposition provides the opportunity to decouple FFT treatment from the thickener operation, and to take advantage of thickener downtime to treat more FFT, as co-deposition is not a continuous process. The focus of the FFT in-line flocculation and co-deposition research study is to understand and determine the limits of co-deposition without compromising; for example, by running off or displacing, any of the deposited TT or FFT-flocculated layers. To test the concept, and prior to undertaking any lab work, modelling with computational fluid dynamics (CFD), moving boundary model (MMB) and Delft3D was done.

The key research objectives of the program were to:

- understand the success rate of co-deposition by computer modelling;
- model the consolidation performance of the TT deposit with interlayered flocculated FFT;
- conduct a laboratory study to determine the efficacy of the single flocculant treatment of the FFT stream using the second flocculant (chemical) injection point (downstream of the thickeners); and
- test the settling and consolidation rate of the TT deposit with the co-deposited (interlayered) flocculated FFT.

The future plan for this project is to run a staged pilot in 2019/2020. For the first stage, the Alberta Energy Regulator (AER) has approved placing flocculated FFT east of current TT deposit area to monitor its performance.

The key performance indicators for the flocculated FFT are an increase in solids content, consolidation behaviour, and water chemistry of the released water.

For the modelling work, Imperial contracted Paterson & Cooke Canada Inc., Thurber Engineering Ltd. and Barr Engineering and Environmental Science Canada Ltd., and Deltares to run the models. The results of the modelling showed that there are few scenarios that depositing flocculated FFT on TT or vice versa will run-off the existing layer or will be displaced by the subsequent layer. The stability of the system depends on the rheology and dewatering properties of each layer. The consolidation behaviour of the interlayered deposit was then modelled using SOILVISION and FSConsol software. The consolidation model showed that there is no significant difference between the mixed TT-flocculated FFT and the interlayered TT-flocculated FFT.

After obtaining the modelling results, the experimental work was designed. The first round of laboratory tests was designed to understand the flocculation performance of FFT using a single stage flocculation (at the second chemical injection at point). FFT with a range of solids content from the fluid tailings deposit area, the west external tailings area (WETA), was tested and the mixing and flocculant dosage was optimized.

After this stage, the laboratory co-deposition test matrix was designed. The main scenarios tested were:

- depositing on-spec and off-spec flocculated FFT onto TT to understand the run-off behaviour; and
- depositing TT onto flocculated FFT to understand the displacement of FFT by TT over time (between 30 minutes to 24 hours) and varying solids content and yield stress.

All the tests were conducted in flumes of the same size (20 m by 100 m).

After the laboratory testing, interlayered TT samples with flocculated FFT and mixed TT-flocculated FFT were prepared for consolidation behaviour tests using the beam centrifuge at the University of Alberta (U of A) to confirm the consolidation modelling results with actual tailings samples.

The importance of this project for Kearl is to treat FFT even when the thickener is not running and decouple the second flocculant (chemical) injection point from upstream operation. Based on the consolidation modelling, and some limited lab studies using beam centrifuges, the performance of the TT material with interlayered flocculated FFT compare to TT deposit was not significantly different. With the field trial, there would be better understanding of the behaviour of TT with interlayer flocculated FFT performance to evaluate the reclamation activities.

The plan for the field trial includes:

- Phase 1 – deposition of flocculated FFT to the east of the TT panels in the current TT deposit area; and
- Phase 2 – deposition of flocculated FFT within the TT panels.

The current regulatory pilot authorization is for the deposition of a limited volume of flocculated FFT to the east of TT panels until the end of 2019. Future phases are being planned and will be subject to additional pilot authorizations for these phases from the AER.

In designing this project, previous work at other oil sands facilities using in-line flocculation of mature fine tailings (MFT), as well as optimizing the mixing and dosage of the polymer with the MFT, was examined. The upcoming field trial will contribute to the growing body of knowledge for improving oil sands tailings management.

PROGRESS AND ACHIEVEMENTS

Results from the co-deposition and consolidation modelling study were promising—supporting the feasibility of co-depositing flocculated FFT and thickened tailings. Modelling showed that flocculation of FFT using a single flocculant was successful at a higher flocculant dosage. Modelling also indicated that a solids content of 20% (wt) (i.e., different than the initial solids content of the FFT) resulted in improved dewatering and consolidation.

The beam centrifuge results demonstrated that interlayering flocculated FFT and TT does not change the performance of the TT consolidation in a one-dimensional (1D) cell, confirming the modelling results from SOILVISION and FSconsol.

Co-deposition of flocculated FFT and thickened tailings in the laboratory scale flume showed that for on-spec flocculated FFT, the material will stay in place and will not run on top of the deposited TT. The laboratory test also demonstrated the success of depositing TT on flocculated FFT. For example, the FFT layer was not displaced after a certain length of time following deposition, indicating that the FFT had gained enough strength and reached a certain solids content.

The efforts to date support the concept that co-deposition of TT and flocculated FFT is feasible under certain operational and deposit conditions. The next step will test the concept at a commercial field scale.

LESSONS LEARNED

The study proved the feasibility of additional FFT treatment using in-line flocculation and co-deposition under certain conditions with TT without impacting the long-term performance of TT. The concept will be studied at a larger scale during the trial at Kearl.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Zambrano, G., Wang, Y., Chalaturnyk, R., Zahabi, A., Rennard, D. 2018. *Assessment of Self-weight Consolidation of Co-deposition Deposits in the Geotechnical Beam Centrifuge*. Presented at IOSTC 2018. Sixth International Oil Sands Tailings Conference 2018. Edmonton, Alberta. December 9-12, 2018.



RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Atoosa Zahabi	Imperial	Research Scientist		
Yijun Liu	Imperial	Research Scientist		
Givemore Sakuhuni	ExxonMobil	Research Scientist		
Dave Rennard	ExxonMobil	Research Scientist		
Paul Cavanagh	Imperial	Senior Technical Advisor		

Research Collaborators: Geotechnical Centrifuge Experimental Research Facility (GeoCERF), University of Alberta

Accelerated Dewatering / Rim Ditching

COSIA Project Number: TJ0109

Research Provider: Syncrude Canada Ltd.

Industry Champion: Syncrude Canada Ltd.

Status: Ongoing

PROJECT SUMMARY

Accelerated dewatering (ADW) or rim ditching is a tailings treatment process that involves the mixing of a chemical amendment with fluid fine tailings (FFT) followed by careful control of the deposit surface water. The surface water is controlled by creating perimeter and lateral ditches around the edges and on the surface of the deposit, respectively. The lateral ditches direct surface water towards a decant structure from where the water is removed. To date, three sets of pilot deposits have been created, each using different chemical amendments. The first was a polymer treatment only. It was deposited in 2009 and has been monitored since. Mixing was not optimized for this first pilot deposit and it is estimated that only about 80% of the deposit was ideally mixed. A second pilot deposit in 2017 employed state of the art mixing technology as well as a gypsum pre-treatment of the FFT prior to polymer addition. Monitoring of the flocculated FFT during the cell fill suggested that 100% of this deposit was ideally mixed. A third pilot deposit was filled with ideally mixed and hydrophobic flocculated FFT. This third deposit was created from a process that produces the ideally-flocculated FFT, and then treats the resulting flocs to make them hydrophobic. This hydrophobic flocculated FFT could potentially have an improved dewatering rate because of the greater hydraulic conductivity. Each of these pilot deposits was approximately 10 m deep with a volume of 60,000-70,000 m³. Long-term dewatering and consolidation trajectories for the pilot deposits are tracked through in situ monitoring, testing and sampling.

PROGRESS AND ACHIEVEMENTS

Several years of monitoring data are available for the initial ADW deposit created in 2009, and the monitoring program has only just begun for the more recent 2017 deposits. For the 2017 pilot deposits, the cell floor was sloped and the decant structure was placed at the lowest elevation in order to make rim ditching and control of surface water more efficient compared to the 2009 pilot deposit. Experience was gained in understanding the mixing operating window as feed FFT fines content changed during the deposition, as well as the relationship between mixing efficiency and solids content. Density control was used during the fill, so the only mixing variable was the fines content in the FFT. At approximately 30% FFT feed solids, the operation required minimal monitoring to ensure consistently “ideal” mixing. Control of the deposit release water was easier than in the 2009 test program because the ideal mixing in 2017 created a more significant deposit slope resulting in a deeper and easier to pump water cap at the far end of the deposit. Monitoring and rim ditching to minimize and eliminate surface water will continue and comparison to the 2009 deposit performance will continue for several years.

LESSONS LEARNED

The dynamic in-line mixers used in the 2017 pilot program were reliable, with little operating downtime. This obviated the need for extraordinary process monitoring and control. The flocculated FFT maintained its dewatering potential over significant pipelining distances from the mixing point (in excess of 700 m), supporting previous work that suggested floc integrity could be maintained under laminar flow conditions. The physical configuration of the field pilot did not allow for testing pipeline distances where floc degradation might occur. The dynamic in-line mixers designed by Syncrude Canada Ltd. were effective at flow rates in excess of 600 m³/h, but hydraulic limitations prevented confirmation of higher rates. It is notable that 600 m³/h only required 50 to 60% of the maximum mixer speed; indicating significantly higher throughputs should be possible. Controlling the chemicals and mixing regimes to allow for hydrophobic treatment of the flocculated FFT was challenging due to the multiple components and elevated temperatures required for the treatment reagents. Protocols and effective process control strategies were developed to achieve flocculation and hydrophobic treatment on a continuous basis. The expertise is now available at Syncrude Canada Ltd. to create these large deposits, on a routine basis, if required.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude Canada Ltd.

Principal Investigator: Barry Bara

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 Lorentz	Syncrude Canada Ltd.	Team Leader		
Eric Leneve	Syncrude Canada Ltd.	Senior Associate		
Barry Bara	Syncrude Canada Ltd.	Senior Associate - Mechanical		
Simon Yuan	Syncrude Canada Ltd.	Senior Associate - Chemical		
Ron Siman	Syncrude Canada Ltd.	Senior Technologist		
Chris Schroeter	Syncrude Canada Ltd.	Senior Technologist		
Randy Mikula	Kalium Research	Consultant		

Mixing Coarse Tailings into *In situ* Fine Tailings: *Literature and Operational Case Study Review*

COSIA Project Number: TJ0111

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Imperial

Industry Collaborators: Teck Resources Limited

Status: Completed

PROJECT SUMMARY

Mixing one type of tailings such as fine tailings with a different type such as coarser sand tailings might improve the strength and consolidation rate within the tailings deposit. The mechanisms or physical processes by which fine tailings are captured or admixed with *in situ* tailings previously deposited in the tailings basin are, however, not well understood.

The overarching purpose of the study was to assess whether fines (fine tailings) capture might be the result of subaqueous (below the water surface) gravity flows of tailings—turbidity currents, debris flows, or grain flows—transporting sand fines to the deeper sections of basins and generating admixtures of sand and fines.

The study reviewed literature from natural systems (erosion of sediments into marine environments and rivers), reservoirs created from damming rivers, and mine tailings basins, including oil sands mines.

A path forward and recommended technology development steps are outlined in the study.

PROGRESS AND ACHIEVEMENTS

Progress and achievements are highlighted in the section, Lessons Learned.

LESSONS LEARNED

All of the case studies reviewed indicate that mixing sand into pre-existing fine tailings to improve the deposit's reclamation characteristics is possible. Questions remain, however, about the viability of sand mixing at an operational-scale at oil sands operations. Several of the non-oil sands mine examples show how operators manipulate tailings stream characteristics to optimize turbidity current behaviour. Similar approaches could be used in oil sands operations to promote turbidity current formation, and delivery of sand from the beach to deeper portions of the basins. However, enough insight from the oil sands studies did not determine whether turbidity current sand mixing could lead to reclamation-ready deposits.

To minimize the risk associated with future field or commercial studies, the viability of the sand mixing must be determined. Recommended technology development steps; i.e., additional studies are recommended for:

1. the development of sand mixing theory and numerical modelling;
2. re-analysis of existing and ongoing oil sands laboratory and field data sets; and
3. laboratory-scale experiments to validate theories developed while conducting studies for items 1 and 2.

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)
Atoosa Zahabi	Imperial			
Ben Sheets	Barr Engineering and Environmental Science Canada Ltd.			

Geobags Pilot Study

COSIA Project Number: TJ0112

Research Provider: Canadian Natural Resources Limited

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Teck Resources Limited

Status: Completed in 2018

PROJECT SUMMARY

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

The goal of the pilot was to collect all of the necessary information to create a commercial design for evaluation and comparison against other technologies. FFT was drawn from an existing transfer line from the Muskeg River mine (MRM) external tailings facility (ETF) and stored in a holding pond with 10,000 m³ of storage. The FFT was pumped from the pond through a system where it was amended with chemical amendments and exposed to a variety of shear regimes prior to flowing into the bags. Four different chemical amendments were tested. A site was prepared that enabled drainage while maximizing the use of the bag volume. Bags of different sizes were used to test the effects of scaling. Bags were stacked one on top of the other. Run-off water from the bags was collected for analysis. Much attention was paid to operational issues as well. Safety and efficiency were principal operational considerations for the pilot study. Lessons learned from the pilot study will be valuable for future commercial evaluation of the technology.

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

PROGRESS AND ACHIEVEMENTS

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

- 11 geobags were filled. Four were “recipe” geobags testing different chemical amendments; four were “stacking” geobags, one on top of the other; three were “scaling” geobags. The three scaling geobags were of varying size, ranging from one full scale commercial geobag (100 m length by 40 m



- circumference), one medium scale geobag (30 m length by 27 m circumference), and one small scale geobag (30 m length by 18 m circumference);
- recipes tested included commercially available polymers (flocculants) and alum. The polymers included Dow XUR, SNF 3338, and BASF 1047. The recipes included Dow XUR, SNF 3338 polymer and alum (three dosages were tested), and BASF 1047 and alum. Mixing/shear was varied as well; and
- operational lessons learned will inform the design for a viable commercial operation.

The bags will continue to dewater over time. The impact of freeze-thaw will be of particular interest. Solids content and strength will be monitored through until the summer of 2019. Final conclusions on the performance of the pilot study will be summarized in a final report.

It is anticipated that extrapolation of the pilot study's results will enable prediction of solids content and strength for a commercial operation. It is also expected that the number of bags required for a given amount of FFT and the ultimate height to which the bags may be stacked can be determined. Further optimization of the chemical amendment at an operating scale may be possible. From there, a plan to incorporate geobags into a final landform can be formulated.

LESSONS LEARNED

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

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural, Chevron

Principal Investigator: Jason Hill

Research Collaborators: Teck Resources Limited

Pressure Filtration for Fluid Fine Tailings Treatment

COSIA Project Number: TJ0113

Research Provider: Canadian Natural Resources Limited

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Teck Resources Limited

Status: Lab scale pilot complete; commercial pilot ongoing

PROJECT SUMMARY

The filter press is a well-known technology that improves water recovery by mechanically pressing water out of fine clay materials to form a dense clay-like cake suitable for transport to a reclamation area. Eventual clogging of filter materials by fines (solid particles less than 44 microns) and residual bitumen has, however, prevented adoption of the technology for treating fluid fine tailings (FFT). The added step of chemically treating the FFT before mechanical filtration resulted in promising results at a laboratory scale. This project is a commercial scale demonstration study that builds on the success of the previous laboratory scale results. The goal is to deliver in excess of 70% solids by weight in the pressed product (cake). The purpose of the current project is to deliver all of the information required to design a commercial plant and to evaluate the technology with alternative treatment technologies.

Laboratory scale presses and a pilot scale press operated by Ledcor Nalco were used during the first phase of testing to identify important parameters such as operating pressure and which chemical amendments are more effective. The commercial scale demonstration plant will be deployed in the field, with live feed coming from a FFT harvesting operation. This demonstration plant will consist of a feed conditioning system and two filter presses of different design. Engineering for the commercial scale demonstration plant was completed in 2018. Construction commenced in 2018 and will continue through the spring of 2019. The demonstration plant will operate through the summer of 2019 with results available late in 2019.

It is expected that the commercial scale demonstration plant will deliver the following information for a future commercial operations design:

- required operating pressure;
- cycle time;
- need for bladder squeeze;
- need for low shear pumps;
- requirement for decanters on the feed;
- economical chemical amendment strategy; and
- filter press product and discharge management system.

PROGRESS AND ACHIEVEMENTS

The laboratory scale programs, including the Ledcor Nalco pilot, have provided results that inform the following decisions on design parameters for the commercial demonstration to be taken:

- operating pressure range, 700 kPa to 2 100 kPa;
- incorporation of both a basic press and one with an additional bladder squeeze option;
- two stage amendment treatment, coagulant and flocculant;
- different feed pump options with different shear profiles (shearing of the treated FFT was identified as a key operating parameter).

Based on the results achieved during the laboratory-scale study, filter presses appear to be a competitive technology for producing a sufficiently dense product from FFT that is suitable for rapid terrestrial reclamation (and creating a dry landform).

LESSONS LEARNED

Solids content of more than 70% by weight was achieved at reasonable cycle times during the laboratory scale pilot study. If similar results are achieved with the commercial scale demonstration and plant reliability is good, the chemical treatments of FFT followed by mechanical filtration provides another competitive tool in the suite of FFT treatment technologies.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural Resources Limited

Principal Investigators: Gavin Freeman, Cynthia Cote

Research Collaborators: Teck Resources Limited, Ledcor Nalco Services (laboratory scale pilot)

Managing Tailings from the Creating Value from Waste Process

COSIA Project Number: TJ0114

Research Provider: Canadian Natural Resources Limited (Canadian Natural)

Industry Champion: Canadian Natural

Industry Collaborators: Titanium Corporation Inc., Thurber Engineering Ltd., SNF Mining

Status: Year 1 of 2

PROJECT SUMMARY

Titanium Corporation Inc. has developed a process called Creating Value from Waste (CVWTM) that recovers hydrocarbons and valuable minerals from froth treatment tailings and is being considered for implementation at Canadian Natural's Horizon site. The process creates a tailings stream with characteristics different from traditional froth treatment tailings, opening opportunities as to how to manage these tailings once the bulk of the hydrocarbon is removed. For example, they are easier to densify and the methanogenesis (the formation of methane by microbes under anaerobic conditions) potential is greatly reduced.

The CVWTM tailings stream has not been handled previously on a commercial scale. The focus of this project is to collect the engineering data required to optimize the processing and deposition of this new tailings stream.

Model tailings streams were created that spanned the range from current naphtha recovery unit (NRU) tailings to clean (all hydrocarbons removed) tailings. The tailings were thickened in a laboratory scale dynamic thickener and the necessary data collected to size and design a commercial scale thickener, associated pumps, and pipelines. Samples of the tailings are currently undergoing testing in large strain consolidation (LSC) cells. These tests will provide the information required to develop a deposition and reclamation strategy.

Assuming a positive result from this work and an engineering study on the CVWTM process, this work will be incorporated into future tailings management plans.

PROGRESS AND ACHIEVEMENTS

Three types of model tailings were prepared, spanning the range that could potentially be seen from the CVWTM process. Thickening tests were completed in 2018. The results from the testing were used to size and design a high rate thickener and establish flocculant type and dosage required to achieve proper thickening. It was found that the material could be thickened up to > 55 % solids by weight. Rheology tests were also completed on the thickened tailings. These tests revealed that the shear stress increases dramatically beyond ~50 % solids by weight, making such a dense stream impractical to pump with a centrifugal pump.



The above information was sufficient for sizing a thickener and pumping system, as part of the larger engineering study of the CVW™ process.

A total of five LSC tests, including sedimentation and index testing, were initiated in 2018. The LSC test results will be available in 2019 and will be incorporated into the tailings management plan for CVW™ tailings.

LESSONS LEARNED

Once the program is complete, enough data will have been collected to design a system for handling CVW™ tailings. The outcomes will also help inform the deposition strategy for this stream. The economics of the management strategy for this specific tailings stream are site specific and must be considered within the overall context of the operator's tailings management plan.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural Resources Limited

Principal Investigator: Danuta Sztukowski

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Danuta Sztukowski	Canadian Natural Resources Limited	Process Engineer, Process Innovation		
Peter Stapleton	Canadian Natural Resources Limited	Lead Engineer, Process Innovation		
Kevin Moran	Titanium Corporation Inc.	Vice President, Technology		
Niel Erasmus	Titanium Corporation Inc.	Vice President, Mineral Sands		
Saidul Alam	Thurber Engineering Ltd.	Tailings Engineer		
Silawat Jeeravipoolvam	Thurber Engineering Ltd.	Geotechnical Engineer		
Mark Niederhauser	SNF Mining	Director, Mining Applications		



FROTH TREATMENT TAILINGS

Froth Treatment Tailings Evaluation

COSIA Project Number: TE0050 and TJ0110

Research Provider: Golder Associates Ltd., Innotech Alberta

Industry Champion: Imperial, Suncor Energy Inc.

Industry Collaborators: Canadian Natural Resources Limited, Syncrude Canada Ltd., Teck Resources Limited

Status: Year 2 of 4

PROJECT SUMMARY

Froth Treatment Tailings (FTT) is the smaller of two tailings streams that form during bitumen extraction from mineable oil sands. In the froth treatment process step, bitumen froth from the primary extraction process is contacted with a light hydrocarbon mixture (naphthenic or paraffinic in nature, depending on the oil sands operation) to facilitate separation of solids and water from the bitumen phase. The water and solids, combined with some unrecovered bitumen and trace light hydrocarbon report to tailings containment areas for storage and water recovery.

The FTT composition is unique due to its elevated concentrations in oleophilic (oil-loving) minerals that preferentially associate with the bitumen froth in primary extraction. Some of these minerals are known acid rock drainage (ARD) precursors (e.g., pyrite), and can contain naturally occurring radioactive minerals (NORM). Further, the trace light hydrocarbons from the froth treatment circuit are known to support microbial activity in the tailings containment areas. In order to manage short-term operational requirements as well as long-term closure needs, a more detailed understanding of the bio-geochemical behaviour of this stream was desired.

The Froth Treatment Tailings Evaluation project was initiated in 2017 to close knowledge gaps around the long-term environmental behaviour of FTT deposits. The project kicked off with an industry-wide sampling campaign in 2017. The program was aimed at comparing and contrasting the deposit composition of materials of different age, deposition environment and light hydrocarbon type. Specifically, gas, aqueous, hydrocarbon and solids chemistry were analysed, and the microbiology present in the deposits was characterized. The initial intent was to determine *in situ* bio-degradation rates of residual light hydrocarbons. The program has since expanded to help assess ARD/NORM related effects as well. Deeper fundamental insight of the deposit behaviour can inform closure plans for the individual operators in future, and serve as a starting point for dedicated mitigation options if required. A follow-up campaign was executed in 2018 for several operators in an attempt to determine *in situ* kinetic information. Analysis of the generated data sets is currently underway.

PROGRESS AND ACHIEVEMENTS

Results from the first sampling campaign have revealed a number of new insights in the dynamics of FTT deposits, initial results of which were presented at the 2018 Oil Sands Innovation Summit (OSIS). Highlights included:



- Evidence of entrapped gas in some deposits. This suggests that bio-gas *generation* rates are not necessarily equal to bio-gas *release* rates.
- Higher than expected variability within the deposits (both laterally and vertically), as well as between operations. This emphasizes that FTT management will likely have a site-specific component, and operational history of the deposits may play a significant role in the observed behaviour of the deposits.
- Significantly enhanced insights in diversity and abundance of microbial activity within the various deposits. A core micro-biome is present within all tailings facilities, capable of light hydrocarbon degradation amongst other functions.

Work is ongoing to further interpret the data. The focus is currently on extracting *in situ* kinetic relations from the information, to enable predictions of long-term deposit behaviour. In addition, attempts are made to identify rate-limiting (micro-)nutrients in the deposits. This could provide a means to steer microbial activity towards desired end states.

LESSONS LEARNED

This program is in its early stages therefore results are too preliminary to be presented as lessons learned.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Innovation Summit 2018, June 7-8, 2018, Hyatt Regency, Calgary, Alberta:

- S. Fawcett, "Region-Wide Froth Treatment Tailings Deposit Sampling"
- K. Budwill and J. Birks, "Regional Assessment of Diluent Degradation in Tailings: Preliminary Insights from Microbiology and Hydrocarbon Analyses"
- S. Fawcett "Development of an Analytical Program and Data Interpretation Approach for Assessing Acid Rock Drainage Risks in Oil Sands Tailings"
- S. Fawcett "First Look at *In situ* Gas Concentrations Measured in Froth Treatment Tailings Ponds"



RESEARCH TEAM AND COLLABORATORS

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Skya Fawcett	Golder Associates Ltd	Associate, Senior Geochemist		
Jean Birks	InnoTech Alberta	Principal Researcher, Water Research		
Karen Budwill	InnoTech Alberta	Senior Researcher, Processing Technologies		

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 Energy Inc.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Syncrude Canada Ltd., Teck Resources Limited

Status: Year 1 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 tailing ponds 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 Climate Change Strategy and must be addressed. In the ponds, CH₄ production is due to the bio-oxidation of hydrocarbons coupled to the reduction of terminal electron acceptors (TEA) such as acetic acid or CO₂ at low redox conditions (~ -250 mV) when other TEA are absent. When other TEA 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 and ammonium on biogenic gas production from tailings obtained from different types of tailing ponds (impacted by froth treatment tailings) 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:

Since the start of the project, we have put many protocols in place for our experimental setup and for the analytical techniques to monitor greenhouse gas (GHG) production and naphtha degradation. In June, we reviewed with Suncor Energy Inc. (Suncor) the water chemistry of relevant tailing ponds and, based on these data, it was decided that mature fine tailings (MFT) samples should be taken from two separate Suncor tailings ponds. These samples arrived at our lab in August 2018 and we have begun setting up static microcosm experiments to address Objective 1. For each TEA, an initial series of factorial design experiments based on three factors (the TEA, naphtha and the N:P [ammonium phosphate] ratio) at two or three concentrations of each of the three factors were setup to help identify the most important factors affecting GHG production and naphtha degradation rates. These results will also be useful in refining the concentration ranges that should be studied.

Results from preliminary experiments, with a MFT sample provided by Suncor suggest that phosphate (PO₄³⁻) was one of the key nutrients limiting degradation rates. This is consistent with high performance liquid chromatography HPLC/ Ion chromatography analysis of the pore water of the two tailings ponds, both of which were below detectable levels (PO₄³⁻ < 1.0 mg/L).

Objective 2 – Effect of bitumen on naphtha biodegradation:

In developing an appropriate protocol to meet this objective, initial sacrificial experiments in triplicate are currently being set up under abiotic conditions in which a known amount of bitumen containing a known amount of naphtha is added to a series of vials containing simulated pore water. Over time, vials will be sacrificed to measure naphtha components in the aqueous and bitumen phase. Once this methodology is established, similar biotic experiments will be performed in which a naphtha-degrading culture enriched from MFT will be added.

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 (benzene, xylene, ethylbenzene) release from a mixed oil drop to drop size, oil mixture viscosity, and degradation rate in the water phase.

LESSONS LEARNED

This program is in its early stages therefore results are too preliminary to be presented as lessons learned.



RESEARCH TEAM AND COLLABORATORS

Institution: Queen's University

Principal Investigator: Juliana Ramsay

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Kevin Mumford	Queen's University	Co-Principal Investigator		
Bruce Ramsay	Queen's University	Co-Principal Investigator		
Debajyoti Ghosal	Queen's University	Postdoctoral Fellow		
Saeid Shafieiyoun	Queen's University	Postdoctoral Fellow (part-time)		
Sreemoyee Ghosh Ray	Queen's University	Postdoctoral Fellow (part-time)		
Mickel Tawadrous	Queen's University	MSc Candidate	September 2017	August 2019
Avery Ling	Queen's University	BSc student		
Alison Holman	Queen's University	BSc student		



CONSOLIDATION MODELLING

NSERC/COSIA Industrial Chair in Oil Sands Tailings Geotechnique

COSIA Project Number: TE0010

Research Provider: University of Alberta

Industry Champion: Syncrude Canada Ltd.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Teck Resources Limited

Status: Year 4 of 5

PROJECT SUMMARY

In 2013, the COSIA Tailings Environmental Priority Area (EPA) and the University of Alberta joined forces to establish the NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique (IRC) to address the challenges of managing oil sands tailings and remediating tailings pond sites. Upon consultation with industry, four major areas of innovative research were determined for the IRC program as follows:

- 1) investigating the unsaturated soil mechanical properties of oil sands tailings;
- 2) investigating consolidation processes for various forms of fluid fine tailings (FFT), mature fine tailings (MFT) and amended MFT;
- 3) assessing and improving tailings deposition; and
- 4) understanding the long-term geotechnical behaviour of fine tailings through laboratory testing and simulations.

Through the IRC program, 18 highly qualified personnel (HQP) have been trained to conduct research under these four IRC themes with individual project objectives primarily aimed at assisting the industry to achieve the mandate of Alberta Energy Regulator (AER) Directive 074¹. While the industry made progress under Directive 074, experience demonstrated that further advances were needed. A new Directive issued by the AER in 2016 and updated in 2017, Directive 085, specifies that new FFT deposits must be ready to reclaim ten years after the end of mine life, and that all legacy² tailings must be ready to reclaim by the end of mine life. Thus, adjustments to individual projects within the four IRC themes were made to accommodate the shift in research priorities.

The collaborative research is resulting in the development of new field investigation techniques, tailings simulation models and unsaturated soil mechanical models, which have been transferred to Canada's oil sands tailings industry. Several of the field investigations are being carried out in collaboration with the industry sponsors. Thus, the results are directly being developed with and transferred directly to the sector users. Also, the HQP have

¹ Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes was rescinded in 2016 and replaced by Directive 085: Fluid Tailings Management for Oil Sands Mining Projects

² legacy tailings are defined in Directive 085 as fluid tailings in storage before January 1, 2015.



presented their findings at conferences, such as the International Oil Sands Tailings Conference or COSIA Innovation Summit, disseminating their work to the wider oil sands community. Additionally, in-person meetings with the Industrial Research Chair Research Advisory Committee provide industry with opportunities to learn about the IRC research progress, to provide feedback to the research team to ensure the industrial relevancy of the work and to engage in further discussions between their organizations and the HQP to advance the research projects. The collaboration between the COSIA Tailings EPA and the University of Alberta enables fundamental discoveries for the behaviour and improved management of fluid fine tailings, benefitting the engineering discipline, mining reclamation and oil sands tailings geotechnique.

PROGRESS AND ACHIEVEMENTS

The current IRC program is providing COSIA members with novel technologies to measure the effectiveness of current tailings remediation efforts, new and innovative processes for reducing the amount of post-production tailings, understanding the long-term geotechnical behaviour of fluid fine tailings, as well as tailings simulation models to assist industry with tailings planning and management. These novel approaches to the industrial research challenges have increased the research capacities of both the University of Alberta and industry partners.

For example, water separation and removal from saturated tailings (e.g., mature fine tailings) is the first step in densifying and consolidating tailings. One of the completed projects from the IRC developed empirical correlations between total suction and hyperspectral imagery for thin section drying tests for a range of fluid fine tailings. The PhD student (who graduated in 2016 and is currently working in industry to operationalize the technology developed during his PhD program for tailings characterization) investigated the remote estimation of moisture content, evaporation rate and total suction to help oil sands operators assess the drying process, determine when the deposit has stopped drying and decide when the next lift should be deposited. Our work provided low-risk, cost-effective quick surveys to the tailings operators to manage their large volume of tailings, and thus, facilitated the acceleration of the conversion process of tailings to reclaimable landscapes.

In another example, a postdoctoral fellow worked on coupling freeze-thaw and desiccation dewatering codes into one common modelling platform using MATLAB . This project is complete and developed a computer program to simulate the dewatering of thickened tailings using natural processes, including freeze-thaw, consolidation and desiccation, which are relevant to the oil sands industry in the Fort McMurray region. The code developed by the postdoctoral fellow under the IRC program, Freeze-Thaw-Consolidation-Desiccation (FTCD), is currently being trialed in industry. In 2014, the postdoctoral fellow was hired by industry as a result of this numerical modelling work in the IRC program.

The blending and mixing of FFT with the overburden Clearwater Shale to form ready-to-reclaim deposits is considered a highly significant contribution of the current IRC to the industrial partner. One of COSIA's member companies has taken this new technology through pilot scale testing and on to commercial scale implementation with great success. Further research is proposed for the IRC renewal program that will extend the technology to other COSIA member companies for use with a wider range of tailings and overburden material properties, and for the construction of dry stack tailings deposits that do not need containment.

Finally, the current IRC program proposed using unmanned systems to reduce the risk and cost of deploying standard geotechnical tools in challenging terrains (i.e., oil sands tailings deposits). Oil sands tailings deposits are



generally soft and not readily accessible to humans and manned vehicles. Robots with low ground pressure requirements can conduct surveys using automated geotechnical tools and deploy other payloads. During the current IRC, our robots have collected samples from oil sands tailings deposits and deployed terramechanics instruments for estimating soil properties in tailings deposits with no bearing capacity. This novel approach aims to automate the standard geotechnical tools that have been traditionally used to measure the shear strength of the deposits and track changes over time to estimate the time it will take to reach terrestrial reclamation. Additionally, we have proposed new tools to estimate soil parameters from robot-terrain interactions to calculate the shear strength of the terrain. Strength properties can be used to calculate load-bearing limits of the terrain that are necessary to track the consolidation performance of the deposit and plan for reclamation of the area.

The IRC program has conducted high-impact research and has extended multidisciplinary collaborations between the Faculty of Engineering and Faculty of Science by engaging world-class researchers in the Departments of Civil & Environmental Engineering, Mechanical Engineering and Earth & Atmospheric Sciences. For example, one project has focused on the novel design of high-resolution field-deployable vane shear test tools to assess the consolidation and shear strength properties of saturated/unsaturated oil sands tailings, combining the efforts of a Geotechnical Engineering PhD student and a Mechanical PhD student. Earth & Atmospheric Science and Geotechnical Engineering HQP have collaborated to obtain field measurements to predict the dewatering performance of current tailings ponds. These are exceptional opportunities for HQP and their supervisors to understand the industrial challenges of Alberta's oil sands from multiple viewpoints and to enrich the training experience of the HQP.

The IRC program has trained and mentored seven PhD, eight MSc students and three postdoctoral fellows, who have demonstrated their potential for tremendous impact through their current IRC research. Four of our HQP won awards from local and national professional engineering societies based on their IRC research papers and presentations; nine HQP held 24 institutional or national (i.e., NSERC) scholarships. Another HQP has had media coverage of her IRC research by CBC, among other media outlets, and has been invited by industry to present her IRC research seven times. Of particular significance, the Canadian Dam Association (CDA) has recognized our IRC HQPs' significant contributions to engineering practice and potential for research impact through the award of the National CDA Gary Salmon Memorial Scholarship three years in a row (2016, 2017 and 2018), which is unprecedented in the history of the Association.

LESSONS LEARNED

Theme 1: Unsaturated Soil Mechanics for Oil Sands Tailings Deposition

1.1 Methods to Measure and Predict Dewatering Performance of Fluid Fine Tailings Deposits

- i. *Develop empirical correlation between total suction and Hyperspectral imagery for thin section drying tests for a range of FFT*

Atmospheric fines drying with thin lift deposition is used to de-water FFT. Hyperspectral imagery has been employed to quantify total suction at the surface of the FFT, which in turn controls evaporation and dewatering rates for the development of shear strength. In addition, flocculation of the tailings can dramatically influence field performance. This project focused on investigating the potential of hyperspectral imagery to monitor the flocculation performance of tailings.

In this study, the flocculation performance of tailings was examined through spectral measurements and ensuing image analysis for flocculated tailings samples generated in the laboratory. The results showed that a ratio of bands at 1678 and 1930 nm is an effective spectral metric to assess the texture of the flocculated samples and reveal differences amongst samples. The variation in the surface micro-topography of the samples appeared to be the main factor deriving the variation in the texture captured by the 1678 and 1930 nm band ratio. More texture was observed when larger flocs were formed as a result of a better flocculation process. This study has shown that although it is feasible to detect under-dosed and/or over-sheared samples using hyperspectral imagery, further flocculation tests are required to calibrate the method, validate the results, and ultimately develop online instrumentation for real-time assessment of flocculation performance.

Benefits to Canada: Water removal from saturated tailings is the first step in densifying and consolidating tailings. The separation of water from mature fine tailings (MFT) is thus an operational and environmental challenge of tailings management. Remote estimation of moisture content, evaporation rate, and total suction would help operators to assess the drying process, determine when the deposit has stopped drying, and decide when the next lift should be deposited. Therefore, our work provides low-risk, cost-effective quick surveys to the tailings operators to manage their large volume of tailings and thus accelerates the process of converting tailings to reclaimable landscapes.

ii. Using ECV to Measure and Predict Dewatering Performance

In this project, actual evaporation rates were measured using a micrometeorological technique known as eddy covariance (ECV). The ECV was installed on a scaffolding system that accessed the center of the pond. Actual evaporation rates were found to be low, which suggested that current drying models might overestimate how much dewatering occurs due to evaporation. To calculate latent heat flux, required for determining evaporation rates, dry air molar volume and the water mixing ratio had to be measured. The core variables measured directly by the ECV system are ambient temperature, ambient air pressure, mixing ratios of gases, wind speed, and wind direction. The ECV system takes measurements at a frequency of 10 Hz, and then the measurements are compiled into 30-minute intervals and means and standard deviations are calculated. The data were analyzed in EddyPro, and in order to calculate water flux, the dry air molar volume had to be determined.

Benefits to Canada: By having accurate and actual evaporation rates, oil sands operators would know when the tailings surface has reached its driest state and new tailings can be placed on the surface. As different tailings volumes (lift thicknesses) dry at different rates, the optimum point where the most tailings is placed to dry for the least amount of time could be determined. This would ensure that the tailings pond is consolidated to its maximum potential, which would aid in the reclamation of these tailings ponds.

iii. Tailings Characterization Using an Unmanned Ground Robot

In this project, novel technologies for characterizing soft ground terrains, such as tailings deposits, were developed, including automated vane shear tools that are typically used for laboratory and field campaigns to estimate the deposit's peak, residual, and remolded shear strength. Additionally, we developed new tools to estimate soil parameters from robot-terrain interactions to calculate the shear strength of the tailings. Strength properties can be used to calculate load-bearing limits of the tailings, which are necessary to track the consolidation performance of the deposit and plan for reclamation of the area. Finally, we developed novel tools for unmanned robotic systems to reduce the risk and cost of deploying payloads and tools in challenging soft

tailings. Robots have been used to collect samples from previously inaccessible materials and to deploy terramechanics instruments for estimating soil properties in tailings deposits with no bearing capacity.

Benefits to Canada: The development of autonomous systems for environmental studies is generally applicable to tailings operators and will support the efforts for reclamation of tailings impoundments. These systems can be used to obtain in situ tailings properties from treated fluid fine tailings deposits that are not trafficable. The new technologies will enable characterization of deposits that are not available using conventional geotechnical tooling. This new information will aid in the understanding of how tailings change over time, which is very important to the oil sands operators as well as the decision-making on process control and post-deposition work; and are of direct economic benefit to the oil sands industry and Canada's economy.

1.2 Determination of Saturated/Unsaturated Properties for High Volume Change Materials

This project focused on the development and verification of a revised methodology to estimate the coefficient of permeability function and the water storage function for high volume change materials. Both degree of saturation and void ratio were taken into account when developing the revised technique for the estimation of the coefficient of permeability for soils that undergo volume change as soil suction is increased (e.g., Regina clay and oil sands tailings). The scope of this program was limited to a theoretical study and a research program investigating several soils that change volume as soil suction is increased for the verification of the proposed theory.

Benefits to Canada: The coefficient of permeability function and the water storage function are two important hydraulic properties required in the numerical modeling of geotechnical problems such as transient seepage or contaminant transport that occurs during mine waste or tailings disposal. The inaccurate estimation of the hydraulic properties will cause erroneous numerical modeling results, which will then cause engineers to make inappropriate decisions concerning a project. Existing estimation techniques, such as the van Genuchten-Burdine (1980) equation, the van Genuchten-Mualem (1980) equation and the Fredlund, Xing and Huang (1994) permeability function, produce reasonable results when estimating the coefficient of permeability function and the water storage function for unsaturated soils with low compressibility such as sands or silts, but the analysis protocols require changes when predicting the coefficient of permeability and the water storage for materials that undergo volume change as soil suction changes (e.g. oil sands tailings slurry). The revised theory could be applied in numerical modelling to facilitate an improved design of tailings disposal, reducing potential engineering costs that could have been caused by decisions based on misinformation.

1.3 Assessment of Shear Strength of Saturated/Unsaturated Oil Sands Tailings

This project investigated whether fluid fine tailings (FFT), when subjected to a number of technologies to facilitate the dewatering of FFT deposits, adhere to the principles of soil mechanics and generate stress-strain curves, as well as other engineering properties such as compressibility curves and conductivity curves. Numerous tests were conducted to characterize the consolidation behaviours of oil sand tailings. Large strain consolidation tests were utilized to produce properties, which were used to compute the consolidation behaviour of deposits. These properties were employed in versatile numerical models that can analyze and predict the saturated and unsaturated properties of FFT deposits. The laboratory tests conducted under this program provide a basis to establish constitutive relations of deposited FFT in relation to the stress-strain state using independent variables.

Benefits to Canada: The research focused on investigating fundamental soil mechanics principles such as stress-strain relationships and the engineering properties of FFT under saturated/unsaturated conditions. These

fundamental principles will be used to predict the behaviours of FFT as accurately as possible by incorporating them into available numerical modeling software. Subsequently, the software will be used as a tool for analysis during engineering designing at various stages such as bearing capacity earth fill structures that will be used as containment. The research program will provide a laboratory data set and analysis that leads towards narrowing the existing knowledge gap and contributes towards resolving challenges facing mine operators.

1.4 Modelling of Pore Fluid in the Computation of Actual Evaporation

The objective of this research is to evaluate the effects of cyclic freeze-thaw on the suction behaviour of centrifuged tailings through a laboratory experimental study. The research seeks to establish the relationship between the multiple cycle freeze-thaw processes, the soil suction and the electrical conductivity. Whether this cyclic phenomenon is effective in forming a surface crust to increase osmotic suction will also be investigated.

Testing to obtain geotechnical index properties, solids mineralogy and pore water chemistry was completed. Currently, an experimental set up for repeated freeze-thaw cycles is underway. A laboratory filter paper test will be conducted to determine the total and matric suctions. The osmotic suction will then be obtained by subtracting the matric suctions from the total suction. Five consecutive freeze thaw cycles will be performed at two different temperatures.

Benefits to Canada: The findings of this research work are expected to establish and enhance understanding of the influence of the effects of freeze-thaw cycles on the suction behaviour of centrifuged tailings. Knowledge of the development of osmotic suction and electrical conductivity through freeze-thaw cycles is required to evaluate potential capping and reclamation schemes in the design and construction of cover systems on centrifuged tailings.

Theme 2: Consolidation Processes for Mature Fine Tailings

2.1 Observations and Analysis for a 30-Year Large-Scale Consolidation Experiment and Oil Sands Mature Fine Tailings / 2.2 Theory and Computer Modelling of Sedimentation, Consolidation and Creep of MFT

These research projects focused on sedimentation and consolidation processes governing the transition of mature fine tailings to a soil state, as well as fundamental processes for consolidation and creep in MFT. The goal was to understand and describe, both qualitatively and quantitatively, the processes at work in MFT consolidation for the advancement of our understanding of soft soil behaviour. The data collected during the experiment clearly demonstrated that the majority of volumetric deformation observed in the tailings is associated with creep rather than with consolidation. A modern theory of creep deformation by Vermeer et al. (2014) appears to provide an adequate fit for the data, with an important implication being that creep is a major deformation mechanism in under-consolidated soils such as the high void ratio oil sands tailings. The review concluded that a compressibility function is required to perform modelling using the creep theory by Vermeer et al. Ideally, an odometer test should be conducted, but this test is not suitable for high void ratio soft soils such as MFT. Therefore, alternative tests must be considered. The chief objective of any consolidation test would be to minimize the amount of creep that occurs over the duration of a step loading. The review also concluded that a hydraulic conductivity function is required for successfully modelling the settlement column behaviour using the creep theory by Vermeer et al. This function is necessary to account for the consolidation processes occurring in parallel with creep deformation.

2.3 Modelling MFT Consolidation with a Geotechnical Centrifuge

The objective of this research project is to modify the current geotechnical centrifuge testing procedure of oil sands tailings samples to better represent the field conditions of oil sands tailings ponds. Current testing procedures do not allow for the continuous addition of tailings material during the centrifuge testing. This is equivalent to the instantaneous filling of a tailings pond in the field; therefore, centrifuge test results using this current method may provide erroneous results. By modifying the centrifuge test to accept continuous addition of tailings material during testing and comparing these results to those obtained by the original testing procedure, we can better represent the field conditions of an actual oil sands tailings pond.

The experimental procedure for this research project was to modify the current testing procedure in the geotechnical centrifuge to accommodate the layered addition of test material during the centrifuge cycle. Laboratory characterization of the chosen test materials and two rounds of centrifuge tests have been completed. Results from the different test procedures included settlement curves, void ratio profiles, compressibility parameters and segregation (for oil sands tailings test materials).

Benefits to Canada: This research provides the opportunity to improve understanding of the consolidation behaviour of oil sands tailings through testing in a geotechnical centrifuge. Results obtained from this research project will also guide future experimental design for the testing of oil sands tailings using the geotechnical centrifuge. Understanding the consolidation behaviour and correct interpretation of test results is crucial to the prediction and modelling of the long-term behaviour of the tailings deposits as required for reclamation and closure activities.

Theme 3: Assessing and Improving Deposition of Tailings

3.1 Deep Fines-Dominated (Cohesive) Deposits

This research evaluates the effect of natural conditions (repeated freeze-thaw cycles, summer drying and precipitation) on the strength of existing treated centrifuged tailings deposits prior to reclamation. This research aims to see whether the multiple cyclic freeze and thaw process is effective in forming a surface crust capable of gaining sufficient strength. The research has two components: a comprehensive laboratory testing and numerical simulation. In the first phase, cyclic freeze thaw tests were followed by atmospheric drying and re-wetting tests to depict summer drying and rainfall events, respectively. Conversely, the second phase depicted the combined effect of drying-wetting between each freeze thaw cycle that represents seasonal weathering. Finally, the results of the lab tests are being implemented in numerical modelling to develop the thermal properties of tailings. The numerical simulation will predict how deep a certain deposit will freeze and thaw and develop shear strength in a particular season. Based on the numerical analysis, the time required for developing a crust can be estimated and thus, an approximate time of exposing the tailings pond to the atmosphere prior capping can be predicted that can save a significant reclamation cost.

The HQP is completing lab work and numerical modelling that can illustrate how deep a certain deposit will freeze and thaw in a particular season. Field deposit data has been provided by two mine operators and will be compared with the findings of the lab and numerical modeling results. Cyclic freeze-thaw tests showed that the undrained shear strength can be increased just by exposing the tailings to the atmosphere. Further separation of water from thickened tailings is a challenging task of tailings management. Therefore, the correct interpretation of the effect of seasonal weathering can potentially help the operators to decide when the next lift should be deposited or when reclamation cover systems can be placed.

Benefits to Canada: The research is expected to establish an enhanced understanding of the volume change and engineering behaviour of deep tailings deposits exposed to surficial seasonal weathering. Understanding the development of a surficial crust is required to evaluate potential capping and reclamation scenarios and ultimately guide the design and construction of reclamation cover systems on deep tailings deposits. This work will provide design criteria and data that will aid in the design of closure landforms for tailings deposits.

3.2 Co-deposition and Blending of Fluid Fine Tailings with Overburden

This project is focused on applying the “co-deposition” technique to oil sands mining; mixing fluid tailings with Clearwater shale overburden. A series of consolidation tests were completed at University of Queensland in 2017, in collaboration with Dr. David Williams. A specialised slurry consolidometer cell was used to simulate the rapid placement of co-disposal stacks and then used to measure the generation and dissipation of excess pore pressure. Tests were carried out on a range of shale lithologies, mix ratios and initial sample heights. The results show the potential for large generation of pore pressures exists; however, it is dependent upon the mix ratio. Dissipation of excess pore pressure is governed by both consolidation and transfer of moisture from the MFT into the shale lumps. The moisture transfer process occurs quickly and allows for rapid construction of stable stacks, such as those that have already been demonstrated in the field trials. Consolidation alone would take many years.

Following the success of the initial computed tomography (CT) scanning trial at Alberta Innovates, a second, more comprehensive test was run. CT scanners measure x-ray attenuation; this can be calibrated to density (or moisture content). Laboratory testing was carried out to determine the in-situ density of the shale lumps. Based on this a sample was prepared such that the volumetric mix ratio at initial conditions was precisely known, enabling the x-ray attenuation thresholds for shale lumps and tailings to be determined. This enabled calibration of the scanner.

Analysis of the testing is still underway. Possible next steps include comparing the measured results to a theoretical model based upon unsaturated soil mechanics principles, and running further tests at different mix ratios. Field trials consisting of test piles of blended Kc and tailings materials at a range of solids contents are currently in progress at an oil sands operator’s mine site. Core samples have been obtained for testing. This together with cone penetration testing data from the mine site will be very useful for verifying and calibrating models that are based upon laboratory data.

Benefits to Canada: Dewatering of MFT remains a significant, largely unresolved challenge, and complicates reclamation and closure. Whilst most approaches currently in use or development aim to increase the solids content of the FFT by removing water, the current project aims at increasing the solids content by adding solids. This has great potential because of the high water absorption capacity of the overburden material. The Clearwater formation often has natural water contents below the plastic limit. Upon mixing, water is rapidly transferred from the MFT to the shale. Early indications have shown that this can create a stable material with shear strengths in excess of 5 kPa, eliminating the need for containment and having the potential to create post-closure terrestrial landscapes.

Theme 4: Tailings Simulation Modelling and Long-term Behaviour of Fine Tailings

4.1 Assessment and Simulation of Tailings Dewatering Methods

i. *Coupling Freeze-thaw and Desiccation Dewatering Codes into One Common Modelling Platform Using MATLAB*



This project aimed to develop a computer program to simulate the dewatering of thickened tailings using natural processes, including freeze-thaw, consolidation and desiccation, which are relevant to the oil sands industry in the Fort McMurray region. The code developed under this program, FTCD (Freeze-Thaw-Consolidation-Desiccation), is currently being trialed in industry.

ii. Validating the Freeze-thaw and Desiccation Dewatering Models with Laboratory and Field Data for Flocculated Fluid Fine Tailings. Using TMSim and FTCD, Investigate Operating Strategies and Design Alternatives to Improve Thin Lift Dewatering Processes

Tailings planning is an iterative and complex process that involves a multitude of physical and chemical processes over time with both deterministic and stochastic components. The numerical model in this project adopts a System Dynamics approach that is frequently used in business, ecology and public health, but rarely in tailings management. The System Dynamics (SD) technique is well suited for high-level modelling of inter-related systems across disciplinary boundaries. In a SD-based model, both quantitative and qualitative or even tentative knowledge are incorporated. The ease with which causal loop diagramming (CLD) method can be taught allows for participatory modelling from non-technical stakeholders. The quantitative processes use GoldSim as the main simulation engine with spreadsheet as user input support.

Several modifications and extensions to the Tailings Management Simulation (TMSim) modelling software have been made, including construction of concept maps using System Dynamics and Causal Loop diagramming methods and the stochastic simulation of tailings consolidation process using nested Monte Carlo techniques. Currently, the student researcher is creating an integrated model linking tailings consolidation with cap or cover performance, calibrating and validating the integrated model, and evaluating the impact of initial tailings properties on the capping performance during closure.

Benefits to Canada: The integrated model provides a quick method to test hypotheses and gain insights into the interaction between capping material and tailings substrate over the long term. It can be used by regulators and producers as a high-level analytical tool for due diligence and regulatory audits; builds a common qualitative language for interdisciplinary collaboration; and fosters the culture of participatory modelling across disciplinary boundaries and among non-technical stakeholders. This model also brings transparency and flexibility to the modelling process (as opposed to the black-box commercial models).

4.2 Influence of Chemical Amendments and Dewatering Processes on the Geotechnical Behaviour of Oil Sands Tailings Fines

i. Short-term Effects on Geotechnical Behaviour

Large volumes of fluid fine tailings (FFT) from oil sands mining operations pose difficult engineering challenges because they do not readily dewater and, due to their fluid state, require containment. A common approach to reduce FFT volume by water removal is to treat the clay suspension with a coagulant and flocculant to form highly porous aggregates called flocs. This work investigated the effect of increased floc size on geotechnical properties of FFT. A method utilizing a flocculation system and images of flocs was developed to determine floc size distribution of a treated FFT sample. Floc size was measured with image analysis software using images obtained directly after flocculation. Treatment recipes, combining an optimal dose of coagulant and polymer, were designed to give clear release water and highly visible flocs suitable for measurement. Floc size distributions were then determined for each of the optimal treatments. Two of these treatments were further analyzed to assess

compressibility, hydraulic conductivity, and vane shear strength. Both compressibility and vane shear strength were found to be sensitive to changes in floc size distribution while hydraulic conductivity did not appear to be largely impacted by floc size.

Benefits to Canada: This research builds toward technologies and processes that remove water from saturated tailings to assist in densifying and consolidating the tailings. The ultimate goal is for oil sands operators to manage the dewatering of tailings prior to deposition in tailings dams, which require more intensive reclamation technologies. This research contributes to industry's goals of accelerating the process of converting tailings to reclaimable landscapes.

ii. Long-term Effects on Geotechnical Behaviour

The objective of this research is to determine the influence of chemical amendment degradation on the long-term geotechnical behaviour of oil sands tailings. The impact of aging on the shear strength of polymer amended FFT is being investigated currently. In 2017, a unique opportunity existed to deconstruct and characterize an old flume test containing flocculated/dewatered tailings. This will help assess whether the aging of the tailings (>3 years) has an impact on the geotechnical parameters. In the laboratory testing program, samples were cured to degrade the flocculant to provide a conservative representation of tailings that have undergone some level of degradation of the flocculants. The tailings samples were fully characterized before and after the curing process to assess any changes in the geotechnical behaviour. The microstructure of the tailings before and after curing treatment was also assessed. Geotechnical index properties were also investigated to determine the geotechnical behaviour of as-received tailings. Tailings with void ratios ranging from 2 to 1 will be used to simulate the additional impact of consolidation on the shear strength of polymer amended tailings.

Benefits to Canada: This research provides the opportunity to further understand the long-term strength behaviour of amended tailings deposits. Currently available correlations of strength to material characteristics such as clay to water ratio or void ratio may not account for changes in strength with time (thixotropy) or sensitivity. A good understanding of the transient nature of the strength of tailings deposits is required for the design of the capping and reclamation. This information will ultimately guide the design and construction of a cover system on flocculated/dewatered tailings deposits in the oil sands.

4.3 Freezing Characteristics of Fluid Fine Tailings and their Relation to Unsaturated Soil Properties

The objective of this research is to assess the validity of using a soil freezing characteristic curves (SFCC) to estimate the soil water characteristic curve (SWCC) for fine grained tailings like oil sands FFT. A laboratory testing program was developed to determine the SFCC. To determine the validity of the SFCC to estimate the SWCC, conventional SWCC measurements were conducted on samples of different types of tailings. SFCC and SWCC testing was completed on Devon silt, gold tailings, copper tailings, and an oil sands centrifuge cake. These materials were selected for testing to assess the validity of using SFCCs to estimate the SWCC for fine grained tailings such as oil sands FFT and then defining the range of slurry tailings for which this method may be applicable.

The measured SFCCs were used to estimate the SWCC. The estimated SWCCs were compared to SWCCs measured using traditional methods. Based on the results of the testing, a number of key conclusions can be made. First, the method appears to be applicable to metal tailings that have large quantities of sand sized particles with some degree of fines. Second, this estimation technique requires that the soil be classified as colloidal or non-colloidal for selection of a soil dependent constant. However, it can be difficult to classify certain soils as purely colloidal or

non-colloidal, as with the copper tailings in this research. This limits the applicability of this method. Regardless, this method is useful as a screening tool as it can be used to rapidly test a large number of tailings to decide which materials should have detailed traditional SWCCs conducted. Third, it does not appear that this method can be used to estimate the SWCC from the SFCC for oil sands tailings. This is attributed to the high clay content (and associated adsorbed water) and water content of the tailings. Based on the results of the testing, it does not appear that the salinity of the centrifuge cake is responsible for the mismatch between the SWCC estimated from the SFCC and the SWCC measured using traditional methods. Finally, estimating the SWCC from the SFCC for metal tailings is much more accurate than estimating it from the grain size distribution. The SFCC is performed directly on the soil. This is a significant advantage over estimating the SWCC from the grain size distribution, especially since this method generally is not recommended for man-made materials.

Benefits to Canada: As discussed, the SWCC is time-consuming and challenging to determine. A single test can take anywhere from weeks to months to complete. The SFCC test takes approximately two days to perform. This is a great advantage over the SWCC. Ultimately, this method would provide an alternative to a time-consuming test which is advantageous, as the SWCC is needed to predict the rate of dewatering and magnitude of strength gain during desiccation dewatering. Overall, the experimental method produced repeatable and reliable results. The results showed that the SWCC could be estimated from the SFCC for tailings from metal mines (gold tailings and copper tailings) with a high portion of sand and a small amount of clay. The SFCC was not able to estimate the SWCC for oil sands tailings. Regardless, this method is highly promising as a screening tool to rapidly test a wide variety of tailings to determine which should have additional traditional SWCC testing.

4.4 Landscape Architecture and Engineering Design for Mined Earth Structures and Reclamation

There are over 20 above-ground tailings dams currently built or proposed in northern Alberta, which will eventually need to be decommissioned (“closed”) and re-integrated into the post-mining landscape. While designing for stability and optimal functionality throughout the operational life is imperative, a shift in the relative importance of forces acting and corresponding failure mechanisms occurs post-closure. For example, pore water pressure rise due to pond filling may be a risk during operation; this is no longer a failure mechanism once filling ceases. Forces that rouse little concern through the active dam stage eventually dictate the stability and functionality of these structures once they transition from a dam into a landform. These dominant post-closure forces are acting on the landforms/dams in perpetuity as opposed to a set time period, making them equally as important as those acting throughout operation; as such, they too require consideration when these dams are being initially designed.

As global best practices in tailings dam design for closure move towards a design-life in excess of 1000-years, geomorphic changes need to be considered as they may threaten stability and fines containment over this time frame. This research proposes a secondary stage in dam design, following traditional assessment methods, that uses landscape evolution models to identify erosion prone areas, excessive flow velocities, high deposition zones, etc. such that the dam design can be modified for optimal closure performance over long time frames.

The immediate benefit of Landscape Evolution Modelling with regard to ring dykes is that an entire landform can be modelled as it is exposed to precipitation over long time frames (10 - 1000 years). Areas of concern can be highlighted early and dam designs altered such that post-closure work, maintenance, and downstream environmental degradation are reduced. This research is anticipated to assist in determining whether dam designs are likely to meet closure criteria (withstand Probable Maximum Precipitation-PMP events, flow velocity



thresholds, sediment loads, etc.), in turn providing less liability and more stable structures moving forward. Progress has continued on the landform evolution modelling component of this research, and a quantitative inventory and classification of erosional features on an oil sands tailings facility was completed. Climate change will be integrated into the 100-year model to learn how recent climate scenarios are likely to alter landform performance. Additionally, erosion mitigation techniques will be modelled in order to evaluate relative effectiveness.

Benefits to Canada: Erosion of oil sand tailings dams has been a known concern since the 1970s, but has not been studied in detail or evaluated to determine cause, characteristics, or quantity such that the risk is fully understood. This erosion quantification work provides evidence of the geomorphic processes actively taking place on above ground tailings dams in the oil sands such that industry may be better prepared to reclaim and identify problems post-closure. Given the size of the oil sands mining region, post-closure monitoring is expected to be a grandiose undertaking in terms of effort and cost. The remote methods tested in this project provide a cost-effective tool to aid regulators and oil sand companies in evaluating landscape performance during active and passive reclamation stages.

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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. Nicholas Beier	University of Alberta	Assistant Professor		
Christine Hereygers	University of Alberta	Research Technician		
Dr. Louis Kabwe	University of Alberta	Research Associate		
Dr. Michael Lipsett	University of Alberta	Professor		
Dr. Benoit Rivard	University of Alberta	Professor		
Ralph Burden	University of Alberta	PhD Student	2014	2019
Kelsey Cunningham	University of Alberta	MSc Student	2016	2019
Jordan Elias	University of Alberta	MSc Student	2013	2018
Iman Entezari	University of Alberta	PhD Student	2013	2016
Iman Entezari	University of Alberta	Postdoctoral Fellow	2016	2017
Bereket Fisseha	University of Alberta	PhD Student	2013	2019
Taylor Hall	University of Alberta	MSc Student	2016	2019
Janeen Ogoza	University of Alberta	MSc Student	2013	2017
Nicolas Olmedo	University of Alberta	PhD Student	2013	2019
Prempeh Owusu	University of Alberta	MSc Student	2016	2019
Nam Pham	University of Alberta	Postdoctoral Fellow	2013	2015
Umme Rima	University of Alberta	PhD Student	2016	2020
Haley Schafer	University of Alberta	MSc Student	2015	2018
Neeltje Slingerland	University of Alberta	PhD Student	2014	2018
Elena Zabolotnii	University of Alberta	MEng Student	2013	2016
Feixia Zhang	University of Alberta	PhD Student	2013	2016
Feixia Zhang	University of Alberta	Postdoctoral Fellow	2017	2019
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Research Collaborators:

Name	Institution or Company	Degree or Job Title
Dr. David Carrier III	Argila Enterprises Inc.	CEO
Dr. Rick Chalaturnyk	University of Alberta	Professor
Dr. Delwyn Fredlund	University of Saskatchewan	Professor Emeritus
Dr. Murray Fredlund	SoilVision Ltd.	CEO
Dr. Derek Martin	University of Alberta	Professor
Dr. Norbert R. Morgenstern	University of Alberta	Distinguished University Professor Emeritus
Richard Nelson	Alberta Innovates	Program Director, Oil Sands Tailings
Dr. Leonidas Perez-Estrada	University of Alberta	Assistant Professor
Dr. Arturo Sanchez-Azofeifa	University of Alberta	Professor
Dr. J. Don Scott	University of Alberta	Professor Emeritus
Dr. Dave Sego	University of Alberta	Professor Emeritus
Dr. Paul Simms	Carleton University	Professor
Dr. David Williams	University of Queensland	Professor

Impact of Bitumen on Tailings Consolidation

COSIA Project Number: TE0027

Research Provider: Syncrude Canada Ltd, University of Alberta

Industry Champion: Syncrude Canada Ltd.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Teck Resources Limited

Status: Ongoing

PROJECT SUMMARY

The impact of residual bitumen on the long-term consolidation behaviour of fluid fine tailings (FFT) is unknown. This understanding is critical for the development of new FFT treatment technologies, as well as optimization of current technologies. Also, this understanding is important for making the right decisions with respect to the need for any FFT pre-treatment prior to treatment and deposition in order to accelerate the pace of reclamation. In addition, for water-capped FFT, this understanding is important for predicting the long-term settlement trajectory of the underlying FFT and associated impact on water chemistry evolution. This project aimed at developing an acceptable methodology for modifying the bitumen contents of a parent FFT and characterizing the modified FFT samples in terms of long-term consolidation performance. Past efforts aimed at modifying the bitumen contents of a parent FFT prior to consolidation testing by using a solvent-wash procedure have been criticized due to uncertainties related to the likely impacts on surface/pore chemistry and clay mineralogy of the FFT. This project avoided the use of chemical amendments by developing a procedure for creating FFT samples with varying bitumen contents (1.69%, 3.53% and 5.71%) from the same parent FFT. The FFT samples were self-weight consolidated using the geotechnical beam centrifuge at the University of Alberta for an approximate prototype time of 35 years. The bitumen modification procedure was effective in creating FFT samples with variable bitumen contents with the same key index properties (per cent solids, particle size distribution, etc.) from a parent FFT. The FFT samples exhibited similar consolidation performance despite the range of bitumen contents. This implies that for the range of bitumen contents and the prototype times examined, residual bitumen content did not affect the settlement behaviour of FFT. Subsequent tests to further investigate if this trend holds for higher bitumen content, variable FFT mineralogy and longer consolidation timeframes, is planned for the future.

PROGRESS AND ACHIEVEMENTS

A procedure for modifying the bitumen contents of the same parent FFT, without the use of chemical amendments or solvent was successfully developed. The procedure involved adding variable amounts of a bitumen froth and process water to the parent FFT in order to create samples having similar composition (physical, chemical and rheological), with bitumen content being the only variable. Characterizing the FFT pre- and post-bitumen addition confirmed that all key index properties of the parent FFT remained the same after the bitumen

content modification procedure. The long-term (35 years) consolidation performance of all three FFT samples showed no difference in terms of settlement and pore pressure evolution.

LESSONS LEARNED

Modifying the bitumen content of a parent FFT by using a methodology that does not introduce uncertainty regarding the chemistry or mineralogy of the modified FFT is important in characterizing the long-term consolidation behaviour of FFT. This was successfully accomplished in this study. There were no differences in the consolidation trajectories of the modified FFT samples over the 35 years simulated in the current study. If this observation holds true for other types of FFT and for longer consolidation time horizons (beyond 35 years), then a bitumen removal pre-treatment step for FFT prior to commercial treatment may not be necessary. It is noted that bitumen contents higher than 5.7% were not tested in the current study, and the conclusions from this study may or may not be extrapolated to FFT with higher bitumen content. Future studies assessing the findings in this study on FFT samples with different mineralogical compositions will be conducted.

RESEARCH TEAM AND COLLABORATORS

Institution/Company: Syncrude Canada Ltd.

Principal Investigator: Adedeji Dunmola

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 Lorentz	Syncrude Canada Ltd.	Team Leader		
Adedeji Dunmola	Syncrude Canada Ltd.	Geotechnical Associate		
Randy Mikula	Kalium Research	Consultant		
Gonzalo Zambrano	University of Alberta	Research Associate		
Ron Siman	Syncrude Canada Ltd.	Senior Technologist		
Mohamed Ali	Syncrude Canada Ltd.	Technologist		
Rick Chalaturnyk	University of Alberta	Professor		

A Research Trajectory Towards Improving Fines Capture Prediction – Verification, Application and Improvement of Delft3D

COSIA Project Number: TE0028

Research Provider: Deltares

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Imperial, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Complete

PROJECT SUMMARY

Oil sands tailings are a diluted mixture of sand, fines (solid particles with a diameter of less than 44 microns), residual bitumen (from the bitumen extraction process), and process water. Depending on the tailings treatment process, tailings are transported to storage locations such as external (external to the mine pit) tailings containment areas, deep deposits, in-pit (once the oil sands ore has been mined) tailings areas, etc. These tailings containment areas or deposits, once reclaimed, will be part of the closure landscape after mining operations cease. As such, the ability to improve the prediction capabilities of the distribution of sand and fines in a tailings deposit—as a function of tailings densities, sand-to-fines ratio (SFR), discharge rate, location and time—offers a cost effective opportunity to optimize current tailings management operations and plan for the closure landscape.

This project is the first phase of a multi-phase, multi-year research project that seeks to improve the understanding of tailings and slurries depositional flow behaviour through modelling to:

- optimize deposition operations;
- minimize segregation and production of fluid fine tailings (FFT) (i.e., maximize fines capture); and
- support the design of closure landscape or land reclamation projects (total settlement and settlement rates, bearing capacity).

Phase 1 of the project includes:

- a review of COSIA oil sands tailings fine capture data;
- a review, modification and embedding of rheological and sand settling analytical models that describe depositional flow and sand settling behaviour of tailings and soft sediments into a new Delft3D-Slurry (D3Ds) module of Delft3D. Delft3D is an open source numerical model developed and maintained by Deltares. Delft3D is used in hydrodynamic, sediment transport and water quality studies worldwide; and



- the application (testing) of the new module to predict oil sands tailings flow behaviour and sand segregation for various rheological properties and sand-to-fines ratios along a typical tailings beach cross section in a two-dimensional (2DV) configuration.

To minimize the production of fluid fine tailings (FFT), decrease water volumes, and accelerate tailings consolidation times, the oil sands industry is treating FFT to produce tailings with thick non-Newtonian behaviour (i.e., flow behaviour changes as force is applied). Delft3D models alluvial delta and beaches in Newtonian flow, hence the desire to upgrade Delft3D to simulate specific oil sands tailings characteristics.

PROGRESS AND ACHIEVEMENTS

Phase 1 activities were completed as planned. The main activities and findings from this phase of the project (to upgrade Delft3D to D3Ds) included:

- analysis of data from COSIA;
- collection and modification of rheological and sand settling models;
- implementation and verification of the model in 1DV (one-dimensional) and 2DV (two-dimensional);
- comparison of the 2DV model results with oil sands data; and
- application of the 2DV model to a specific oil sands tailings.

This phase of the project delivered a D#Ds version that can model tailings depositional flow and sand settling in 2DV mode, in accordance with theoretical expectations and laboratory observations. At this stage of the model, it can be used for a general assessment of depositional behaviour of oil sands tailings. Additional model verification and development is necessary, however, to bring D3Ds to a quantitative engineering predictive level.

Phase 1 produced two MSc. theses (Hanssen, 2016 and Van Es, 2017), three conference publications and a D3Ds workshop in Calgary for COSIA members and researchers.

LESSONS LEARNED

Preliminary results from the project confirm the applicability of the new D3Ds module to oil sands tailings. The first phase highlighted the need for further investigation to address the following:

- the model is sensitive to the rheology (flow characteristics) of the tailings materials (sand, fines concentrations and SFR);
- erosion or pick-up of the aged or underlying tailings layer by fresh incoming flow;
- mixing mechanisms between the layers and the resulting rheological properties if the two layers are of different initial rheology; and
- the role of density stratification versus yield stress when determining mixing or displacement of existing tailings.

PRESENTATIONS AND PUBLICATIONS

Published Theses

Hanssen, J.L.J. 2016. Towards improving predictions of non-Newtonian settling slurries with Delft3D: theoretical development and validation in 1DV. Master's thesis, Delft University of Technology.

Van Es, H.E. 2017. Development of a numerical model for dynamic deposition of non-Newtonian slurries. Master's thesis, Delft University of Technology.

Conference Presentations/Posters

Talmon, A., Van Rhee, C., Winterwerp, H., Hanssen, J., Sittoni, L. 2016. *Implementation of Tailings Rheology and Tailings Segregation in a Predictive Open-Channel Beaching Model*. Paste2016. 19th International Seminar on Paste and Thickened Tailings. Santiago, Chile. July 5-8, 2016.

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Ansah-Sam, M., Sheets, B., Langseth, J., Sittoni, L., Hanssen, J. 2017. *Delft3D Modelling of Sand Placement on an Oil Sands Treated Tailings Deposit*. Presented at Tailings and Mine Waste '17. Banff, Canada. November 5-8, 2017.

RESEARCH TEAM AND COLLABORATORS

Institution: Deltires, Delft University of Technology

Principal Investigator: Dr. Arno Talmon

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Luca Sittoni	Deltires	Project Manager		
Dr. Arno Talmon	Deltires	Principal Technical Investigator		
Jill Hanssen	Delft University of Technology		MSc.	2016
Hugo van Es	Delft University of Technology		MSc.	2017
Dr. Cees van Rhee	Delft University of Technology	Professor		
Dr. Han Winterwerp	Delft University of Technology	Professor		

Limitations to the Geotechnical Properties of Polymer-Treated Fluid Fine Tailings

COSIA Project Number: TE0030

Research Provider: SRK Consulting (Canada) Inc.

Industry Champion: Syncrude Canada Ltd.

Industry Collaborators: Canadian Natural Resources Limited, Imperial, Suncor Energy Inc., Teck Resources Limited

Status: Completed

PROJECT SUMMARY

The broad objectives of this project were to contribute to the understanding of what can ultimately be expected of treated fluid fine tailings (FFT) in reclaimed mine landscapes and to provide insights leading to modified FFT management methods that will result in geotechnically-viable material. Oil sands operators currently treat FFT with polymer flocculants, followed by initial dewatering, thickening, centrifugation or air-drying. These processes can result in significant increases in solids content. However, the further development of polymer-treated FFT into geotechnically-viable material remains a challenge.

The project tested the following hypotheses: (1) there are fundamental limitations to the ability of polymer-treated FFT to consolidate, to drain or transmit water, and to gain strength; (2) these limitations are due to colloidal and surface chemistry effects associated with FFT; (3) the addition of polymer as is currently practised does not address surface chemistry effects and may even exacerbate the associated limitations; and (4) the addition of both coagulant and polymer to FFT can produce materials with better geotechnical properties. The first and fourth hypotheses were confirmed. The second and third hypotheses were found to be probable but were not confirmed.

Four FFT samples from two oil sands operators were tested. The initial samples were characterized for both physical properties and water chemistry. Subsamples were amended by addition of various amounts of inorganic coagulant ($MgSO_4$) and then flocculated with a polymer. The coagulant was selected to change the cation composition of the FFT water and clay surfaces while having a minimal effect on pH, alkalinity or other minerals. The polymer was a high molecular weight polyacrylamide in common use for FFT treatment.

The treated and control samples were then subjected to range of settling, surface potential and geotechnical tests. Specifically, the relationships between coagulant dosage, solids content, and undrained shear strength were characterized by fall cone testing of all treated and control samples. Selected samples were also subjected to seepage induced consolidation tests. The test results were then used as inputs to a series of consolidation models to examine effects of the coagulant on rates of dewatering and strength gain.



Treatment of FFT with a combination of coagulant and polymer is expected to increase porosity, compressibility and hydraulic conductivity, all of which should lead to more rapid consolidation and strength gain. The findings of this study were not conclusive about these effects, largely because of the limitations of the consolidation testing. However, assessment of the remaining uncertainties showed they are all either neutral or positive with respect to consolidation and strength gain for treated FFT.

PROGRESS AND ACHIEVEMENTS

Findings show that FFT treated with both coagulant and polymer start to gain strength at a lower solids content compared to polymer-treated FFT, and continues to display higher strength as the solids content further increases. In very practical terms, improving FFT strength by treatment with both coagulant and polymer means that FFT can be ready for reclamation in times that are 10% to 30% less than those needed for FFT treated with polymer only.

The testing program and modelling were completed in 2017 and the project report was finalized in 2018.

LESSONS LEARNED

The results of this work confirm that treating FFT with a combination of coagulant and polymer leads to more rapid strength gain, and therefore could accelerate final reclamation of treated FFT deposits. The coagulant and dosages chosen for this project were as mild as possible to avoid any confounding chemical reactions; stronger coagulants may have more significant effects on FFT strength gain. The laboratory test methods developed in this study provide a relatively rapid means to screen a wide range of additives and dosages.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

D. Hockley & H. Rourke 2018. Limitations to the Geotechnical Properties of Polymer-Amended Tailings, Presentation to 2018 Oil Sands Innovation Summit, Calgary, June 2018.

Reports & Other Publications

SRK Consulting (Canada) Inc. 2018. Limitations to the Geotechnical Properties of Polymer-Treated FFT, Report 1CC047.001 prepared for Canada's Oil Sands Innovation Alliance (COSIA) Tailings Research Working Group, April 2018.

RESEARCH TEAM AND COLLABORATORS

Institution: SRK Consulting (Canada) Inc.

Principal Investigator: Daryl Hockley, 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)
Holly Williams (Rourke)	SRK Consulting (Canada) Inc.			
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Tailings Consolidation Mechanisms

COSIA Project Number: TE0031, RWG (IOSI 2015-05)

Research Provider: University of Calgary

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Imperial, Suncor Energy Inc., Syncrude Canada Ltd. Teck Resources Limited

Status: Completed

PROJECT SUMMARY

The oil sands bitumen extraction process generates large volume of tailings, consisting of a matrix of sand, clay, water, and fine particles below 44 µm (Boger et al. 2013). In a tailings pond, partial settlement of coarse solids leads to the formation of mature fine tailings (MFT). MFT generally consists of 30 wt% fine clay, 60 wt% to 70wt% water, and mostly with 1 wt% - 5 wt% residual bitumen. Without treatment, MFT may take up to 150 years to fully dewater and settle out. As of August 2012, approximately 800 million m³ of fluid tailings were held in above-grade containment dams (OSTC and COSIA 2012). Managing, stewarding and limiting the accumulation of fluid tailings are consistent with the goals of progressive reclamation and closure (OSTC and COSIA 2012), as well as decreasing liability and environmental risk resulting from the accumulation of fluid tailings on the landscape.

This project examined tailings consolidation mechanisms through a combination of X-ray computed tomography (CT), nuclear magnetic resonance spectroscopy (NMR and one-dimensional [1-D] magnetic resonance imaging [MRI]), and dielectric properties measurements through electromagnetic (EM) sweeps.

The major objectives included:

- 1) To screen the potential for CT, NMR, 1D MRI, EM to characterize settling properties of original (unsettled and untreated) MFT.
- 2) To characterize raw (untreated by chemical additives such as flocculants or coagulants) MFT by several analytical techniques: Dean-Stark extraction, methylene blue index (MBI), particle size distribution (PSD,) and water chemistry.
- 3) To utilize CT, NMR, 1-D MRI, and EM technologies to characterize raw MFT and treated MFT samples.
- 4) To develop test protocols and technology that can be used to characterize the settling and transitional stages of original MFT.
- 5) To develop a modelling approach for the settlement behaviours of raw tailings and treated tailings.

Measurements were taken for original untreated, and treated with flocculant and coagulant additives MFT samples from two sources. Untreated MFT samples were considered as control cases. CT, NMR, MRI and EM techniques were used in the experiments. CT measurements are based on density profiles, while NMR is based on amplitudes and relaxation times of free water and bound water. While the CT and NMR measurement techniques are completely independent, both were able to measure a similar rate ($\pm 0.5\%$) of free water phase separation

over time, and thickness of the water phase over time. This is significant because if only the NMR system was available when monitoring MFT settlement, the data would be expected to be similar to using CT.

The data of porosity versus depth and location were used in modelling to predict the settling rate of an original MFT over a longer period of time, and to predict the permeability of the MFT region over time.

The characterization of raw MFT properties was carried out to determine water content, solids content, particle size distribution, MBI, and properties of MFT process water. It should be noted that the MFT properties are in agreement with experimental results from CT, NMR, and MRI. For example, the solid density at 2.650 g/cm^3 and water content and solids content are consistent with the density profile of MFT from CT measurement.

In the second phase, experimental work replicated these measurements in treated MFT samples, and the same output parameters were acquired and compared against the original MFT. During the investigation, it was observed that treatment with a polymer flocculant was more effective compared to the sole use of coagulant. Combined coagulant and flocculant additives (Malikova, et al. 2016) are able to both significantly accelerate the settling behaviour as well as decrease water content in the final settled material.

Finally, the results of the experiments were analyzed using kinetic reaction and 1-D spatial particle models. The rates and ultimate dilution parameters for the MFT samples were estimated using statistical analysis of the data. The estimated parameters can be used for both simulating settlement behaviour and evaluating the additive efficiency. One-dimensional spatial particle settling models were used for estimating spatial settling parameters and simulating MFT settlement behaviour.

The results of the measurements are very significant for industrial applications. Firstly, measurement procedures were developed for evaluating MFT settlement using x-ray CT, NMR and MRI (Kantzias 1994, Wright, et al. 2004, Motta Cabrera et al. 2009, Motta Cabrera, et al. 2010, Manalo, et al. 2003, Kantzas, 2003, Hum and Kantzas, 2007). It was shown that all three approaches are able to evaluate settling behaviour and provide statistically similar conclusions. This observation is very important for developing efficient field settlement monitoring equipment. NMR is the best candidate for such equipment due to its relative low cost, fast measurements and the possibility of on-line data processing. On the other hand, x-ray CT is a more appropriate laboratory measurement technique that is capable of providing information about two-dimensional (2-D) density distribution of MFT samples. However, this technique is more expensive and difficult to implement under field conditions.

Secondly, the experiments enabled development of a workflow for evaluating and analyzing the effect of different additives on the settling behaviour of MFT samples. This workflow could be very important for industrial applications when estimating the optimum concentrations of different additives. Such estimation is possible in laboratory conditions using relatively small MFT samples. The example with coagulant and flocculant additives illustrates the importance of such analysis. In the case of the additives, the combined treatment provides better settling behaviour for two criteria, including the rate of settlement and the amount of residual water in the settled samples.

Finally, the modelling approaches developed and applied in this project make it possible to estimate settlement parameters as well as to simulate settlement.



The application of the research results into mine and tailings management plans would require two major stages; including laboratory estimates of the optimum concentrations of additives for tailing samples, and field monitoring of settlement using optimum treatments.

PROGRESS AND ACHIEVEMENTS

The project work is completed. All objectives of the project are achieved. Summary of project achievements is presented in the previous section.

LESSONS LEARNED

X-ray CT, NMR, MRI and EM techniques are effective monitoring approaches for evaluating MFT settlement behaviour. These techniques provide consistent results for optimizing tailing pond treatments with coagulant and flocculant additives. Estimating the optimum concentration of additives is necessary for efficient and economical MFT settlement. Both coagulant and flocculant additives are required for optimum settling treatment. Concentrations of these additives are field dependent but can be estimated in laboratory conditions using one of the developed techniques. Field monitoring can be conducted using the NMR on-line tool.

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Motta Cabrera, S.C., Bryan, J. and Kantzas, A., "Estimation of Bitumen and Solids Content in Fine Tailings Using Low-Field NMR Technique", *CIPC 2007-074, SPE138973, J. Can. Pet. Tech.*, 49(7), 8-19, 2010.

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Kantzias, A., "Investigation of Physical Properties of Porous Rocks and Fluid Flow Phenomena in Porous Media Using Computer Assisted Tomography", *In Situ*, 14(1), 77-132, 1990.

Hum, F.P. and Kantzas, A., "Clarifying the Contribution of Clay Bound Water and Heavy Oil to NMR Spectra of Unconsolidated Samples", CIM 2003-100, *J. Can. Pet. Tech.*, 46(7), 30-36, 2007.

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

PRESENTATIONS AND PUBLICATIONS

Journal Publications

Two journal publications are in preparation.

Conference Presentations/Posters

Babak, P., Kantzas, A., Li, F., Motta, S. 2018. Laboratory and Field Monitoring of Efficiency of Flocculant and Coagulant Additives on Settling Behaviour in Solid Liquid Suspensions. Suncor Academic Forum on Transformational Technology for Energy Systems. October 10-12, 2018.

Babak, P., Kryutchkov, S., Bryan, J., Kantzas, A. 2017. Tailings consolidation mechanisms. Institute for Oil Sands Innovation (IOSI) May 10-11, 2017 Stewardship. Edmonton, Canada.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Calgary

Principal Investigator: Professor Apostolos Kantzas

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Apostolos Kantzas	University of Calgary, PERM Inc.	Ph.D., Professor		
Petro Babak	University of Calgary	Ph.D., Research Associate		
Feng Li	PERM Inc.	Ph.D. Researcher		

In Situ Real Time Measurements of Solids Content in Settling Tailings

COSIA Project Number: TE0041

Research Provider: University of Alberta, NAIT

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Syncrude Canada Ltd., Suncor Energy Inc., Imperial, Teck Resources Limited

Status: Year 1 of 3

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 will be 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 will be used as the calibration standard for the optical sensors. The technology will be validated in laboratory scale systems. Numerical models will be developed for both the scattering and x-ray measurement techniques to allow easy extension to systems with different material constituents. The technology will be developed in such a way that it can be implemented at remote oil sands tailing ponds to measure settling of tailings in real time with lateral and depth spatial resolutions. This technology can be used by the oil sands industry to incorporate into the design of their oil sands projects to deliver a more effective process and improved environmental performance.

Milestones include:

1. Testing of scattering techniques with simple clays in suspension such as kaolinite.
2. Testing of scattering techniques with FFT samples.
3. Development of a low activity x-ray source and demonstration of ability to measure solids content.
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 fluid fine tailings (FFT) samples.
7. Demonstration of low level x-ray measurements in test columns with FFT samples.
8. Demonstration of calibration of optical scattering detectors with low level x-ray detectors in test columns.
9. Develop a modelling code for light scattering from kaolinite and FFT.
10. Develop a modelling code for x-ray transmission through kaolinite and FFT.

PROGRESS AND ACHIEVEMENTS

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

1. Lab bench measurements of the scattering of laser light at various angles and at various wavelengths have been carried out.
2. A test column and detector mounting tube has been developed.
3. Scattering measurements of the settling of tailings in a test column have been started over periods of up to one month.
4. Fouling tests have been carried out on various plastic and glass windows.
5. The ability to measure inorganic solids content in test samples of kaolinite and FFT has been demonstrated using a low level x-ray source.
6. The development of a first principles modelling code has been started 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 principles modelling code based on GEANT4 has been developed for the low level x-ray scattering measurements and compared to the measurements obtained in kaolinite and FFT.

LESSONS LEARNED

The lessons learned thus far include:

1. The scattered light versus angle from kaolinite samples behave to a large extent as a diffuse scattering medium.
2. Preliminary measurements of the dependency of scattered light versus wavelength from FFT samples indicate both short wavelength and long wave sources are advantageous for detection of solids content.
3. It is possible to monitor solids settling in a test column measuring backscattered light with a multiple detector array.
4. Accurate measurement of solids content can be made with low level x-ray transmission diagnostics.
5. Modelling of x-ray diagnostic response requires incorporation of both absorption and scattering in the x-ray model.

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

R. Fedosejevs, Y.Y. Tsui, M. Gupta and A. Sedgwick. 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.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Ying Y. 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)
Manisha Gupta	University of Alberta	Assist. Professor		
Andrea Sedgwick	Northern Alberta Institute of Technology	Applied Research Chair		
Robert Fedosejevs	University of Alberta	Professor		
Felipe Goncalves	University of Alberta	Undergrad Student	2015	2019
Yu Wan	University of Alberta	MSc student	2016	2018
Priyesh Dhandharia	University of Alberta	Post Doctoral Fellow		
Bo Yu	University of Alberta	MSc Student	2017	2019
Wei Wang	University of Alberta	MSc Student	2017	2019

Research Collaborators: NSERC

Conversion of Oil Sands By-products to Closure Landforms

COSIA Project Number: TE0045

Research Provider: McKenna Geotechnical Inc. and BGC Engineering Inc.

Industry Champion: Suncor Energy Inc.

Industry Collaborators: Syncrude Canada Ltd., Teck Resources Limited, Imperial, Canadian Natural Resources Limited

Status: Year 1 of 2

PROJECT SUMMARY

Oil sands operations produce several types of by-products, some of which need to be used to construct permanent landforms that must integrate into the final closure landscape and support a self-sustaining, boreal ecosystem. Typically, these materials are placed in location-specific, designed storage facilities or repositories that may either be temporary or permanent.

The objective of this project is to obtain and document environmental information on mining by-products for their use in the selection and design of landforms and landform elements in the closure landscape. This will be done for each operator while highlighting any geotechnical or geo-environmental issues related to handling or long-term storage.

The project is a collaborative effort of COSIA's Tailings Environmental Priority Area (EPA) and Land EPA. Phase I and Phase II will be led by the Tailings EPA. The project includes:

- a systematic review of key by-products from the operations (Phase I);
- examining their properties through developed testing standards (Phases I and II); and
- analysing their suitability for placement in standard landform structures such as overburden structures, stockpiles, specialized containment areas within overburden structures (i.e., slop cells) (Phase III).

The final document (Phase III) will be a technical guideline identifying best practices for material evaluation and design analysis, general suitability analysis of major by-products for placement in standard landforms, and recommendations and identification of further opportunities to refine the best practice basis.

PROGRESS AND ACHIEVEMENTS

The majority of Phase I work was completed in 2018. A list of by-products produced during surface mining at the various oil sands operations was compiled. The list included materials such as gypsum, fly ash, and froth treatment tailings. A methodology was also developed to systematically characterize the geotechnical and geo-environmental properties of the by-products to inform the assessment of landform conversion; that is, the progression from



standard to closure landforms. Data from the oil sands operators were assessed to determine if sufficient information was available to characterize their by-products for landform conversion, or if sampling and laboratory testing are required to address the data gaps. This latter work will be completed in 2019.

Project participants identified a new concept, adaptive landform, as a potentially new type of landform that will be defined and explored in Phase II.

LESSONS LEARNED

This project is in its early stages and therefore, results are too preliminary to be included as lessons learned. This work will form an important reference for planners and engineers tasked with the design and storage of oil sands by-products. The primary use will be for COSIA operating members. Any public release will require review and approval by COSIA members as a separate activity.

RESEARCH TEAM AND COLLABORATORS

Principal Investigators: McKenna Engineering Inc. and BGC Engineering Inc.

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 Resources Limited, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Year 1 of 2

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 cohesive deposits in the oil sands and explore different types of capping strategies to the deposits in a timely manner to a terrestrial landform (with wetlands). Deep cohesive tailings deposits are fines-dominated cohesive materials with associated depositional and consolidation behaviour that is 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 fine tailings (FFT) into in-pit disposal sites between 20 and 140 metres (m) thick.

A guide describing 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 is under development as part of the DDWG mandate. The proposed guide will use existing data, experience and knowledge to describe the current state of practice for deep cohesive tailings deposits in the oil sands and their expected performance during design, placement, reclamation and closure. The guide will be a technical manual and reference 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 50% complete at the end of 2018 with completion targeted for the first half of 2019. A communication and implementation plan will be developed in conjunction with guide preparation and completion.

The guide is a compendium of deep deposit planning, placement, management, and reclamation knowledge and experience accumulated through several decades by the oil sands industry. Two COSIA workshops in particular: the 2017 Deep Deposit Capping Workshop; and the 2018 Deep Deposit Consolidation Workshop provided valuable



case histories, research data, and design information that form the basis of the guide. A wealth of other oil sands and international literature augments information from the workshops.

LESSONS LEARNED

The project was initiated in 2017 with a target completion date in 2019; therefore it is too preliminary to present lessons learned.

Observations and knowledge from the accumulated design, research and execution effort on deep deposits in the oil sands, including an assessment of gaps and opportunities for additional research and investigation, are planned for inclusion in the guide. Guidance in the application and use of deep cohesive deposits in mining and tailings planning schemes is included.

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

Institution: McKenna Geotechnical Inc.

Principal Investigator: Gordon McKenna

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Gordon McKenna	McKenna Geotechnical Inc.	Geotechnical Engineer		
David Wylyntko	West Hawk Associates	Communications		
James Hrynyshyn	West Hawk Associates	Communications		
June Pollard	J Pollard Consulting	Engineering Geologist		
Bill Shaw	WHS Engineering	Tailings Engineer		
Derrill Shuttleworth	N/A	Illustrator		

Effects of Shearing on Dewatering and Compressibility of Treated Tailings

COSIA Project Number: TE0058

Research Provider: Coanda Research & Development Corporation

Industry Champion: Suncor Energy Inc., Imperial, Canadian Natural Resources Limited

Industry Collaborators: Syncrude Canada Ltd., Teck Resources Limited

Status: Year 1 of 1

PROJECT SUMMARY

The ultimate goal of treating oil sands tailings is to remove water within a reasonable time frame to enable reclamation and closure. Several technologies have been proposed for dewatering of tailings including flocculation, filtration, centrifugation, thickening, atmospheric drying, and sedimentation. Many of the treatment methods involve the addition of polymeric flocculants and subsequent transport to deposition sites using pipeline transport systems.

Treated tailings experience a range of shear conditions during transport and deposition. It is generally presumed that shearing adversely affects the water release and compressibility of treated tailings. Accordingly, shear rate is considered a constraint when designing processing equipment, pipelines, and deposition strategies used in tailings treatment facilities. A preliminary study was conducted on measuring the pipelining impact on dewatering and material strength of flocculated fine tailings at Coanda using a Couette device to mimic the shearing conditions [1]. However, despite its importance, the effects of shearing on dewatering and long-term consolidation characteristics of treated tailings have not been studied in detail. Additionally, the impact of processing variables such as flocculant type, dosage, and mixing conditions on the shear-dewatering relationship is not fully understood.

This project aims to study these effects through a series of laboratory experiments on two selected types of tailings: fluid fine tailings and thickened tailings. Flocculants were blended with the tailings using an in-line pipe mixer and characterized before undergoing varying levels of shear in a custom shear-cell. Additional characterization measurements were performed post-shear and samples are undergoing geotechnical testing, including large strain consolidation, seepage-induced consolidation, and beam centrifugation. The data collected from the experiments will be used to model the consolidation behaviour of the samples at field scale, providing a link between pipeline shear conditions and deposit performance.

PROGRESS AND ACHIEVEMENTS

The project is still in progress and final results are not yet available. All of the flocculation experiments were completed in 2018 and the materials are now undergoing geotechnical testing.



The materials produced in the laboratory with varying levels of shear had different properties that were quantified through various metrics. As expected, shearing reduced the yield strength of the material in all cases, but under some conditions, low levels of post-flocculation shearing appeared to improve dewatering characteristics. High levels of shear had an impact on the immediate material performance, but long-term performance remains to be quantified. Some initial results suggest minimal impact on the compressibility of some samples, with small differences in permeability noted at higher void ratios.

The final results available in 2019 will provide insight into the effects of shear on treated tailings characteristics, allowing operators to tailor treatment strategies to their particular requirements.

LESSONS LEARNED

Experiments are still in progress so it is too early to discuss lessons learned.

LITERATURE CITED

- [1] Effects of Shearing and Shearing Time on Dewatering and Yield Characteristics of Oil Sands Flocculated Fine Tailings, Babak Derakhshandeh, Abu Junaid and Gavin Freeman. 2016. International Oil Sands Tailings Conference Proceedings, Lake Louise: December 2016.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigator: Scott Webster, Clara Gomez (on leave)

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	Research Scientist		
Clara Gomez	Coanda Research & Development Corporation	Research Scientist		
Amarebh Sorta	Coanda Research & Development Corporation	Geotechnical Engineer		
Tayfun Aydin	Coanda Research & Development Corporation	Research Scientist		
Pravic Komal	Coanda Research & Development Corporation	Laboratory Tech		
Mariana Cruz	Coanda Research & Development Corporation	Laboratory Tech		
Ashley Gonzalez	Coanda Research & Development Corporation	Laboratory Tech		

Soft Soil Settlement and Strength as Applied to Oil Sands Fine Tailings

COSIA Project Number: TE0077 and TX0131

Research Provider: Argila Enterprises Inc.

Industry Champion: Canadian Natural Resources Limited (Canadian Natural)

Industry Collaborators: Imperial, Suncor Energy Inc., Syncrude Canada Ltd., Teck Resources Limited

Status: Year 2 of 2

PROJECT SUMMARY

The purpose of this project is to document previous efforts, experience and understanding of consolidation and settlement analyses of soft soil as applied to fine tailings in the oil sands. The development of the document was initiated through various correspondence and reports supporting several oil sands tailings pilots between 2013 and 2016 at Shell Canada (now Canadian Natural), building off of previous work by Dr. Carrier of Argila Enterprises, Inc. in the oil sands as early as the 1980s and at other mines. Active development and preparation of the document was started in 2017 and completed in 2018.

The resulting document provides an overview of consolidation theory and practice, with practical explanations, to help users understand the fundamental concepts that are often clouded by easy-to-use computer programs. The goal of the guide is to clarify and bring greater consistency, accuracy and repeatability to consolidation assessments and settlement calculations of deep cohesive tailings deposits in the oil sands.

The contents of the document were applied to develop a relatively easy-to-use Microsoft Excel spreadsheet to calculate consolidation and settlement. The guide and spreadsheet formed the basis of a Consolidation Workshop (March 2018) attended by COSIA member company employees and research partners. The document may be updated periodically to include research advances and review feedback, as appropriate.

PROGRESS AND ACHIEVEMENTS

The guide and workshop were structured to promote greater consistency, accuracy and repeatability of consolidation and settlement calculations and evaluations for deep cohesive deposits in the oil sands. The knowledge and benefits of the guide and the workshop were:

- Review sedimentation and consolidation theory for deep tailings deposits (>2 m) and summarize sedimentation, consolidation and input functions to the model.

- Interpret compressibility and hydraulic conductivity functions, and review strength and the importance of input functions.
- Greater consistency, accuracy and repeatability in calculating the final settlement of deep deposits with an easy-to-use Microsoft Excel spreadsheet.
- Interpret results using case histories and more recent data and information from tailings research initiatives and projects.
- Each company received copies of the guide and the Microsoft Excel spreadsheet for calculating and assessing consolidation and settlement of deep cohesive deposits.

LESSONS LEARNED

The document and spreadsheet are based on generally accepted geotechnical formulae and principles of consolidation theory, case histories and research information. They provide systematic guidance in estimating consolidation and settlement of deep cohesive deposits in mining and tailings planning schemes. The document, procedures and spreadsheet bring greater consistency, accuracy and repeatability to consolidation and settlement estimates in the oil sands. The guide provides insight into various input parameters, calculation methodology, expected results and the implications of consolidation settlement for tailings plans and tailings planning.

RESEARCH TEAM AND COLLABORATORS

Institution: Argila Enterprises, Inc.

Principal Investigator: David Carrier

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
David Carrier	Argila Enterprises, Inc.	Geotechnical Engineer		
Robert Mahood	Imperial	Technical Support		
Monica Ansah-Sam	Canadian Natural Resources Limited	Technical Support		
Gavin Freeman	Canadian Natural Resources Limited	Technical Support		

Mature Fine Tailings Drying (MFTD) Research

COSIA Project Number: TJ0028

Research Provider: Coanda Research & Development Corporation

Industry Champion: Suncor Energy Inc.

Status: Ongoing

PROJECT SUMMARY

The purpose of this project is to evaluate and develop techniques to understand flocculation fundamentals of mature fine tailings (MFT) using a multi-phase approach. MFT is a subset of fluid fine tailings with sand-to-fines ratio of less than 1 and solids content greater than 30%, nominal. MFT is very difficult to dewater and so advances in dewatering of MFT will accelerate tailings pond reclamation and closure. The two most recent goals of the project are the application of focused beam reflectance measurement to MFT floc size measurement and the development of a population balance model for slurry flocculation.

Focused Beam Reflectance Measurement Application in MFT Floc Size Measurement:

Optical measurement techniques are becoming more widespread in various industrial applications. In particular, focused beam reflectance measurement (FBRM) is utilized as a monitoring tool for particle size distribution (PSD) in slurries. At the same time, limited information is available on how flow parameters, such as velocity and particles volume fraction, may affect FBRM measurements. In this work, we attempted to close this gap by examining water suspensions of well-characterized particles (glass beads and plastic) of different diameter, opacity and shape under variety of conditions.

Population Balance Model Development for Slurry Flocculation:

Suspensions of very fine particles tend to exhibit resistance to settling due to their size and electrical charge. One of the methods to facilitate settling and its accompanying water release is the addition of a polymer to the slurry. The polymer binds fine particles of the slurry into larger flocs that then become more amenable to separation. This process is called flocculation and is commonly used in the treatment of oil sands tailings. Due to its importance in environmental and operations performance and cost reduction, much effort is directed to bettering understand the flocculation phenomenon. Numerical modelling is part of this effort as it reveals the internal structure of the flow, along with complex multi-phase interactions.

PROGRESS AND ACHIEVEMENTS

It was observed that the distribution of the glass beads appears significantly wider than the corresponding PSD. It is likely due to the lower opacity of glass beads. At the same time, the shape, which is spherical for the glass beads and random for the plastic particles, does not appear to play a role. It was shown that the influence of the material velocity on the measurement results is relatively small for most of the range of parameters considered. The

influence of the volume fraction appears to be very significant. For most of the considered particle concentrations, the increase of the volume fraction of particles leads to the decrease of the measured FBRM size.

The developed Population Balance Model considers floc formation, fractal growth and breakage, influence of polymer concentration, rheological changes associated with polymer mixing and flocculation progress, and flow regime changes. Eulerian multi-fluid representation is adopted for liquid and floc phases with the poly-dispersed floc size distribution being represented through the population balance approach. The model was tested and adjusted based on available experimental data for different flocculation conditions.

LESSONS LEARNED

- For most of the considered particle concentrations, the increase of the volume fraction of particles leads to the decrease of the measured FBRM size.
- Eulerian multi-fluid representation is an important tool for MFT flocculation modelling.

PRESENTATIONS AND PUBLICATIONS

Hosseini, M., Pougatch, K., Delfel, S., Moyls, B., Revington, A., Sadighian, A. 2018. FBRM Application to Evaluate Particle Size in Suspensions, presented at XXIX Interamerican Congress of Chemical Engineering Incorporating the 68th Canadian Chemical Engineering Conference, October 28-31, Toronto, ON.

Hosseini, M., Pougatch, K., Delfel, S., Moyls, B., Revington, A., Sadighian, A. 2018. Population Balance Model Development for Slurry Flocculation, presented at XXIX Interamerican Congress of Chemical Engineering Incorporating the 68th Canadian Chemical Engineering Conference, October 28-31, Toronto, ON.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor Energy Inc.

Principal Investigator: Adrian Revington

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Adrian Revington	Suncor Energy Inc.	Team Lead		
Ardalan Sadighian	Suncor Energy Inc.	Project Lead		
Benny Moyls	Coanda Research & Development Corporation	Process Engineer		
Konstantin Pougatch	Coanda Research & Development Corporation	Researcher		

Research Collaborators: Coanda Research & Development Corporation

Deep Cohesive Deposit Modelling

COSIA Project Number: TJ0045

Research Provider: Syncrude Canada Ltd.

Industry Champion: Syncrude Canada Ltd.

Status: Ongoing

PROJECT SUMMARY

Deep deposits of cohesive treated fluid fine tailings (FFT) have the advantages of minimizing the footprint requirement for tailings management and avoiding the multiple material re-handling requirements of thin-lift deposit operations. The long-term dewatering and densification of these deep deposits are expected to be primarily driven by large-strain consolidation. However, in the intervening periods during and after deposition, other dewatering mechanisms (such as sedimentation, atmospheric drying and under-drainage) may be important. It is important to accurately predict the long-term performance of these deep deposits so that optimum decisions related to deposition, deposit management, capping, reclamation and closure operations can be made. One cost-effective way of predicting this long-term performance is through numerical modelling. However, available numerical models are limited in that they are unable to couple most or all of the aforementioned dewatering mechanisms to large-strain consolidation. The purpose of this project was to develop a numerical model that can integrate all these dewatering mechanisms in a single platform. The numerical model was successfully developed and benchmarked against other numerical models and publicly available data for oil sands and non-oil sands tailings materials. The numerical model was also successfully calibrated against a field deposit of 10m deep in-line flocculated FFT at the Syncrude Canada Ltd. site.

PROGRESS AND ACHIEVEMENTS

The numerical model was developed, with the capability for coupling large-strain consolidation to sedimentation, atmospheric drying (evaporation and freeze-thaw dewatering) and under-drainage. The numerical model was successfully benchmarked against other numerical codes for cases involving coupling sedimentation to consolidation, for a variety of materials such as sand, natural sediments, clay slurries and oil sands tailings. The benchmarking exercise covered a variety of deposition (instantaneous and staged filling), capping (cap and no cap) and initial condition (homogenous and heterogeneous initial profile) scenarios. In particular, the long-term behaviour of the University of Alberta standpipe # 1 was reasonably predicted with the numerical model when sedimentation was implemented in addition to large-strain consolidation. Also, the numerical model was successfully calibrated to Syncrude Canada Ltd.'s 10 m deep accelerated dewatering (ADW) deposit. Implementing large-strain consolidation alone in the numerical model grossly under-predicted the field performance of the ADW deposit. However, when all the mechanisms observed in the field (sedimentation, atmospheric drying and under-drainage) were included with consolidation in the model, the predictions agreed with field performance data.

LESSONS LEARNED

A large-strain consolidation model was developed that was able to couple all the relevant dewatering mechanisms for deep cohesive deposits. Such a coupled large-strain consolidation model is required to accurately predict the long-term performance of deep cohesive deposits where other dewatering mechanisms, in addition to self-weight consolidation, are relevant. For tailings deposits with initially low solids content, implementing sedimentation, in addition to large-strain consolidation, is important to accurately predict the long-term behaviour of the deposit. This was illustrated in the case of the ADW deposit where field deposit performance was substantially underpredicted by the model, even when all the other mechanisms were coupled to large-strain consolidation, unless sedimentation was included.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude Canada Ltd.

Principal Investigator: Adedeji Dunmola

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Jim Lorentz	Syncrude Canada Ltd.	Team Leader		
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Murray Fredlund	SoilVision Systems Ltd.	President/CEO		

Evaluation of Vertical Strip Drains in Oil Sands Tailings

COSIA Project Number: TJ0049

Research Provider: SNC Lavalin Inc. Centre for Advanced Testing and Research, formerly MDH Engineered Solutions Corp.

Industry Champion: Suncor Energy Inc.

Industry Collaborators: Teck Resources Limited

Status: Year 5 of 5

PROJECT SUMMARY

In 2010, Suncor Energy Inc. began construction of a floating cover over the soft tailings of Pond 5. This was intended to provide a trafficable surface on which reclamation activities could ultimately lead to the closure of Pond 5. A key component of this approach was that the surface of tailings be strengthened sufficiently to support reclamation activities. A network of vertical strip drains (VSD) was installed to speed consolidation by providing seepage paths for water to drain from the tailings.

An experimental setup was devised of a 0.5 m diameter column filled with 3 m height of mature fine tailings (MFT), which was fully instrumented and allowed to consolidate with a wick drain down the centre of the column. The project was separated into different phases of work:

1. **Phase 1 (2011 – 2012)** involved a measuring the consolidation under self-weight conditions (no external load) to evaluate the effectiveness of VSD in dewatering MFT. This column was also dismantled with samples taken for testing after eight months of consolidation.
2. **Phase 2A (2013 – 2014)** followed in which the MFT from Phase 1 was homogenised and placed into the same wick drained vessel under a 40 kPa surcharge load (representing approximately 2 m of soil cover). This surcharging continued for 11 months, after which the settlement slowed down so the surcharge was increased to 60 kPa.
3. **In Phase 2B (2014 – 2016)**, a 60 kPa surcharge was applied to the column and the effect on speeding up the rate and magnitude of consolidation was measured. The column was dismantled and tested after approximately two and a half years of consolidation. This involved sampling and testing in nine layers, working downward from the top by cutting and removing layers of the test column, to provide access for testing lower levels. The testing of each of the layers involved measuring water/solids content, strength, bitumen content, clay content, and specific gravity.

This laboratory program was intended to provide baseline data on which future studies on the effectiveness of adding surcharge load, changing VSD depths, and spacing could be evaluated.

PROGRESS AND ACHIEVEMENTS

All phases of the project were completed by 2017, with the final report completed in 2018. The results of the test program found that the loading system was capable of simulating the effects of surcharge loading on the MFT inside the test column. It demonstrated the effectiveness of the VSD and surcharge loading in increasing the rate of settlement and the build-up of effective stress. It also found that higher levels of surcharge were required to lower the water content below the liquid limit (i.e., increase the solids content above 70%). See the lessons learned section for further information.

LESSONS LEARNED

Throughout the five years of testing, the VSD Evaluation in Oil Sands Tailings project yielded the following lessons learned:

- Increased loading was found to significantly increase the rate of settlement in the test column without measuring a bitumen migration, which may blind off the wick.
- Large strain consolidation (LSC) derived compressibility values were consistent with the moisture contents and effective stresses measured in the column.
- Consolidation analysis using the LSC derived parameters was able to match the measured self-weight consolidation performance of the wick-drained column.
- Strengths measured in the casing were consistent with those measured as part of another Suncor Energy Inc. study, Slurry to Soil.
- A surcharge greater than 60 kPa will be required to get this MFT to a moisture content lower than its corresponding liquid limit.

The settlement data, pore pressures and measured solids content profiles have also been preserved for further future analysis in other consolidation simulations.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Haug, Moir D. and Gan, Julian 2018. Test column study in VSD aided self-weight consolidation of oil sands tailings. GeoEdmonton 2018, Paper 330.

Haug, Moir D., Gan, Julian and Al-Mamun, Mohammad 2018. Impact of surcharge loading on VSD performance in dewatering oil sands tailings. GeoEdmonton 2018, Paper 347.

Haug, Moir D., Gan, Julian, Kaminsky, Heather and Al-Mamun, Mohammad 2016. Permeability of oil sands tailings – a comparison of direct constant head measurements with back calculated hydraulic conductivity measurements from large strain consolidation test. International Oil Sands Tailings Conference 2016, Lake Louise, AB, Canada. pp. 340 - 347

RESEARCH TEAM AND COLLABORATORS

Institution: SNC Lavalin Inc. Centre for Advanced Materials Testing and Research, Saskatoon, SK

Principal Investigator: Moir D. Haug

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Deep Deposit Modelling, Atmospheric Fines Drying Test Cells

COSIA Project Number: TJ0058

Research Provider: Canadian Natural Resources Limited (Canadian Natural)

Industry Champion: Canadian Natural

Status: Completed

PROJECT SUMMARY

The objective of this project is to develop reclamation technology for oil sands mines. The main goal for oil sands mining reclamation is to build reclaimed landforms that are capable of supporting a self-sustaining, locally common boreal forest. There are a number of key requirements related to landform design, including: strength of the surface of tailings deposits to allow cap placement and contouring, long-term settlement of the tailings and its impact on upland areas, reclaimed wetlands, and the quantity and quality of water.

The project was a field study using Canadian Natural's atmospheric drying (AFD) process for fluid fine tailings (FFT) management at its Muskeg River Mine. The AFD process consists of thin-life dewatering of in-line flocculated mature fine tailings (MFT). The study's goal was to assess the short-term (one- to two-year) dewatering and resultant strength gain performance of thin-lift layering versus deep stacking depositional approaches. The study systematically evaluated whether using multiple lifts, including both thin and thick lifts, or a single deep deposit was a better tailings management strategy to pursue using the AFD process. The objectives were to:

- Compare the amount of fines processed per unit area to peak shear strength of 5 kPa in one year;
- Quantify and assess the relative contribution of evaporative drying and consolidation towards deposit dewatering; and
- Compare the potential for freeze-thaw dewatering.

Three tailings depositional approaches—thin lifts (Thin ML), thick lifts (Thick ML), and deep stacking (Deep Stack)—were investigated.

For the Thin ML deposit, seven thin lifts of treated MFT were deposited over the course of one year (August 2012 to August 2013), on an approximate 30-day cycle. Each lift averaged approximately 0.6 m in thickness.

Three thick lifts of treated MFT were deposited over the same time period on an approximate 90-day cycle, and averaged 1.4 m in thickness for the Thick ML deposit.

The Deep Stacking consisted of one 4.5-metre-thick lift of treated MFT placed in a continuous pour on October 4, 2012.

PROGRESS AND ACHIEVEMENTS

All three deposits had similar amounts of dewatering, increasing from an initial average solids content of approximately 38% to a final average solids content of 62% after two years. However, their rates of dewatering differed, and the magnitude of dewatering attributed to flocculation, sedimentation, consolidation phenomena, and evaporative drying differed between deposits. The results of the test program suggest that producing material meeting design specifications and deep stacking—to exploit the enhanced drainage attributed to a larger driving head and initially higher permeable material—is a superior approach to multiple layering for deposits focused on short-term (one year or less) dewatering and strength gain performance.

None of the depositional approaches achieved material with high enough solids content or strength meaningful enough to achieve stable, soil-like material for incorporation into a terrestrial reclamation landscape after two years. Enhanced dewatering methods consisting of surcharging/capping, sand layering, wick drains, rim ditching, or others were then considered to advance these materials toward reclamation readiness.

In 2016 and 2017 a series of trafficability, capping and drainage studies were conducted on the deep stack test cell. The 2018 activities included a comprehensive sampling and analysis campaign to determine the response of the cell subsequent to capping and the placement of wick drains. The cell was mined through shortly after the sampling was completed and this project will be completed with a final report in early 2019.

LESSONS LEARNED

The three deposit configurations ended with a similar average solids content of 62%, but the profiles are different as the result of variable dewatering. The Deep Stack has a characteristic 'C' shape as the result of self-weight consolidation and evaporation impact in the upper one metre of the deposit. By comparison, the ML deposits have both higher solids content crusts and densified layers and lower solids content regions that resulted from incomplete consolidation or drying prior to subsequent lift placement.

Solids contents in the crust approached 75% with peak shear strengths over 20 kPa prior to subsequent lift placement. The buried crusts in the ML cells rewetted but retained relatively higher solids content intervals within the deposit profile as stacking continued. The buried crusts in the ML cells, though relatively thin, had low permeability zones that impeded drainage and relief of excess pore water pressure generated by progressive layering. Over time, the buried crusts became less distinguishable, and the deposit began to behave as a more uniform deposit.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Kolstad, D., Dunmola, A., Dhadli, N., O'Kane, M., Song, J., and Masala, S. 2012. *Towards the Improvement in Geotechnical Performance of Atmospheric Fines Drying (AFD) at Shell's Muskeg River Mine*. IOSTC 2012: Presented at the Third International Oil Sands Tailings Conference, Edmonton, Canada, December 2-5, 2012.

Dunmola, A., Cote, C., Freeman, G., Kolstad, D., Song, J. and Masala, S. 2013. *Dewatering and Shear Strength Performance of In-line Flocculated Mature Fine Tailings Under Different Field Depositional Schemes*. Presented at Tailings and Mine Waste '13, Banff, Canada, November 3-6, 2013.

Adedeji Dunmola, A. and Nag, 2013. *Shell's Atmospheric Fines Drying Technology for Dewatering Mature Fine Tailings – Past, Present and Future*. Presented at Tailings and Mine Waste '13, Banff, Canada, November 3-6, 2013.

Masala, S., Nik, R.M., Freeman, G. and R. Mahood, R. 2014. *Geotechnical Insights into Deposition, Dewatering and Strength Performance of Thickened and Paste Tailings Deposits at Shell Canada Tailings Test Facility*. IOSTC 2014. Presented at the Fourth International Oil Sands Tailings Conference, Lake Louise, Canada, December 7-10, 2014.

Kolstad, D., Borree, B., Song, J. and Mahood, R. 2016. *Field Pilot Performance Results for Flocculated Fluid Fine Tailings Under Three Depositional Variations*. IOSTC 2016. Presented at the Fifth International Oil Sands Tailings Conference, Lake Louise, Canada, December 4-7, 2016.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural Resources Limited

Principal Investigator: Gavin Freeman

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Robert Mahood	Imperial			

Consolidation of Fluid Fine Tailings

COSIA Project Number: TJ0059

Research Provider: Canadian Natural Resources Limited

Industry Champion: Canadian Natural Resources Limited

Industry Collaborators: Suncor Energy Inc.

Status: Year 5 of 10

PROJECT SUMMARY

The objectives of the fluid fine tailings (FFT) consolidation project are to understand the long-term consolidation behaviour of FFT and to evaluate the performance of various flocculants and process treatments for FFT.

The project began with a series of laboratory trials using geocolumns to compare different types of FFT treatments. Geocolumns are large instrumented clear cylinders (3 m high) that are used in the laboratory to measure tailings consolidation (density differentials) and to visually observe changes in tailings consolidation. The FFT treatments included different flocculants, varying dosage rates of flocculants, and centrifugation. It was hypothesized that comparing a large number of different treatments in the laboratory would be indicative of the most promising tailings treatments for further testing. Both visual and density observations were made over time, with the lessons learned from the laboratory trials applied to the development of the subsequent tailings consolidation casing experiment.

Following the laboratory trials, the Tailings Consolidation Casing Experimental Project Pilot (TCCEPP) was initiated. The TCCEPP is a field scale pilot designed to conduct consolidation experiments using eight instrumented columns or casings (3 m wide x 10 m deep) filled with various FFT treatments. The casings are at a scale that approaches the expected geotechnical stresses anticipated in field scale tailings deposits and are considered analogues to deep, fines-dominated tailings deposits. Seven casings were filled at the Albian Sands Sharkbite mine in 2015 with the final casing filled in 2016. The treatments consist of various combinations of centrifuged and flocculated FFT. Casing 1 and Casing 7 were filled with Muskeg River mine (MRM) and Jack Pine mine (JPM) untreated FFT, respectively. They serve as the experimental controls for parameters such as settling rates, densification and shear stress. Casings 2 to 4 were filled with MRM FFT treated with various dosages of flocculants added in an in-line process. Casings 5 and 6 were filled with FFT from Suncor Energy Inc. treated with different flocculants at various dosages. Casing 8 was filled with JPM centrifuged flocculated tailings. Once the casings were filled, instrumentation was installed, and FFT samples were collected to determine per cent (%) solids content, % water, yield strength, void ratio and density changes. Monitoring and sampling were conducted over time and depth.

The geotechnical information from these projects will assist in planning and scheduling tailings deposition to meet closure landform objectives for deep fines-dominated tailings deposits.



PROGRESS AND ACHIEVEMENTS

Knowledge from this project will:

- enhance the industry's understanding of cohesive deposit consolidation in oil sands;
- provide confidence in meeting closure and reclamation plans and final landform objectives;
- provide industry with the basis for decision-making regarding centrifuged FFT placement, capping and drainage management options to create targeted landforms; and
- offer insight into fines-dominated deposit performance variables that, in turn, may initiate new fundamental geotechnical research work.

In each year since filling, monitoring of the deposit performance continued and samples were taken to determine % solids content, % water, yield strength, void ratio and density changes over time and depth. Results are influencing subsequent evaluation as well as optimizing current FFT treatment technologies. Modelling is in progress to evaluate consolidation properties for each casing and to determine the potential for scale-up.

LESSONS LEARNED

This project seeks to advance the oil sands industry's understanding of cohesive deposit consolidation in oil sands. The effect of different treatments on consolidation behaviour is studied.

Preliminary results show that tailings treated with flocculant settle quicker and contain higher shear stress capabilities than untreated or centrifuged tailings. Identification of a MFT chemical amendment resulting in improved consolidation performance was achieved. This performance included higher deposit permeability at lower void ratios; i.e., at higher per cent solids content and further consolidation. Ultimately, this information will be used to further develop tailings technology for full-scale implementation.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

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

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

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural Resources Limited

Principal Investigator: Gavin Freeman

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Cynthia Cote	Imperial			

Seepage Induced Flocculation Testing of Mature Fine Tailings

COSIA Project Number: TJ0068

Research Provider: University of British Columbia, University of Colorado Boulder, Coanda Research & Development Corporation

Industry Champion: Suncor Energy Inc.

Status: Year 2 of 2

PROJECT SUMMARY

Effective stewardship of mature fine tailings (MFT) is important for oil sands mining, reclamation and closure. MFT treated with flocculants has been shown to settle quicker than untreated tailings, improving consolidation and release of water. Aspects of the flocculation or MFT treatment process such as the quality of the resulting flocs (i.e., the clumps of fine particles formed during flocculation) and the associated release of water influence the rapidity of dewatering and consolidation behaviour. Up until 2015 the question of how the importance of floc structure to long-term dewatering of treated MFT (tMFT) had not been investigated; however, with advancements in MFT flocculation precision (i.e., dosage and mixing conditions) implications to long-term behaviour for a leave in-place stacked deposit or deep deposit can now be examined. The purpose of this project was to determine the impact of flocculation efficiency on long-term consolidation by using seepage induced consolidation testing (SICT).

In 2015, Suncor Energy Inc. partnered with the University of British Columbia and the University of Colorado Boulder to conduct SICT on different tMFT treatments to investigate the effects of flocculation on consolidation. SICT is a relatively rapid method to determine the consolidation parameters of a soil subject to large strains. Consolidation parameters of interest are the hydraulic conductivity and compressibility relationships, where compressibility determines the volume change of the soil when a given load is applied, and hydraulic conductivity determines the duration for the volume change to occur. SICT has been used in other consolidation testing on untreated MFT with some success, and is quicker at one to two months versus the year required for Large Strain Consolidation (LSC) testing.

An experimental setup was devised which included a SICT test to determine the consolidation parameters for five different flocculent treatments and one untreated MFT. A single trained individual obtained samples of the treated and untreated MFT through multiple hand flocculations in a 10 cm cup. In addition to the tMFT in the SICT cell, six 60 cm columns were constructed for each of the different treatments. The columns were destructively sampled after one, three, eight, 14, 30 and 60 days to provide validation data for the consolidation modelling predictions.

The SICT predictions were then compared with the measured values to show agreement and where consolidation theory applied, as well as where it did not.

PROGRESS AND ACHIEVEMENTS

The project was completed in 2016. A final report and conference presentation were prepared. In summary, the SICT approach was valid for the rapid dewatered tMFT tested and clear improvement of the optimal dosed and optimally mixed tMFTs was evident.

Further details are discussed in the Lessons Learned section.

LESSONS LEARNED

Throughout the testing, the following was learned about SICT of MFT and tMFT:

- Seepage induced consolidation testing is an appropriate methodology for determining consolidation characteristics for both treated and untreated MFT. The hydraulic conductivity of the flocculated MFT increases by up to one order of magnitude when compared to the untreated MFT.
- The flocculation process has less effect on the compressibility characteristics of the treated MFT. It also does not negatively affect the final storage volume. There may, however, be a significant impact of the difference during the initial fill.
- Treated MFT exhibit random compressibility behaviour at low effective stresses. Consolidation modelling in this zone is not appropriate, as the slurry does not have soil-like characteristics. Determining the effective stress or void ratio at which the material transitions from an open and random structure to a more slurry-like homogeneous mixture is a critical step in any modelling effort.
- For the tested material and treatment methods that transition is taking place at about 1 kPa effective stress or a void ratio of about 2.5, depending on the treatment process.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Znidarcic, D., Van Zyl, D., Ramirez, M., Mittal, K., Kaminsky, H. 2016. Consolidation Characteristics of Flocculated MFT – Experimental Column and SICT Data. Fifth International Oil Sands Tailings Conference 2016, Lake Louise, AB, Canada. pp. 408 - 515

RESEARCH TEAM AND COLLABORATORS

Institution: Norman B. Keevil Institute of Mining Engineering, University of British Columbia, Vancouver B.C.; University of Colorado at Boulder, Department of Civil Engineering; Coanda Research & Development Corporation

Principal Investigator: Dirk Van Zyl

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Dobroslav Znidarcic	Department of Civil Engineering, University of Colorado, Boulder, CO	Co-Principal Investigator		
Kushagra Mittal	Coanda Research & Development Corporation	Senior Researcher		

Deep Deposit Filling, Monitoring and Modelling

COSIA Project Number: TJ0072

Research Provider: Golder Associates Ltd.

Industry Champion: Imperial

Status: Year 4 of 8

PROJECT SUMMARY

The objective of this project is to develop a database of consolidation parameters for a commercial scale deep thickened tailings deposit. The consolidation parameters will be used to model long-term consolidation behaviour of the deposit. The actual performance of the deep commercial scale deposit will be monitored annually and compared with the predicted performance of the model to validate (and calibrate) consolidation parameters.

Currently, the oil sands industry lacks a suite of consolidation parameters that are calibrated against a commercial scale deposit. Most existing consolidation models are based on sand-to-fines ratio (SFR). This project aims to close that gap by providing a set of consolidation modelling parameters—including clay content—applicable to new and existing deep deposits. It is anticipated that the model will validate or require changes to current operational practices so that long-term closure of the deep deposit can be achieved.

Thickened tailings (TT) are usually produced by combining fresh tailings with aged fluid fine tailings removed from a tailings pond. If the thickener underflow is hydraulically transported to the depositional area, shearing of the thickened material occurs. This is unavoidable. Re-flocculation of sheared material at the end of the pipe is an option to rebuild the sheared material floc structure, enhance dewatering of thickened tailings and accelerate water release at the deposition area.

Hydraulic placement of TT tends to create different zones within the tailings deposit based on the hydraulic migration capabilities of the TT layers. These naturally created zones consolidate differently due to the composition (clay content, fines content, initial void ratio, etc.) of each zone. In addition, thickener feed variability also results in deposits with varying composition and consolidation properties. Thus, a suite of consolidation parameters rather than one set of parameters or averages are required to model the entire deposit and its different TT zones.

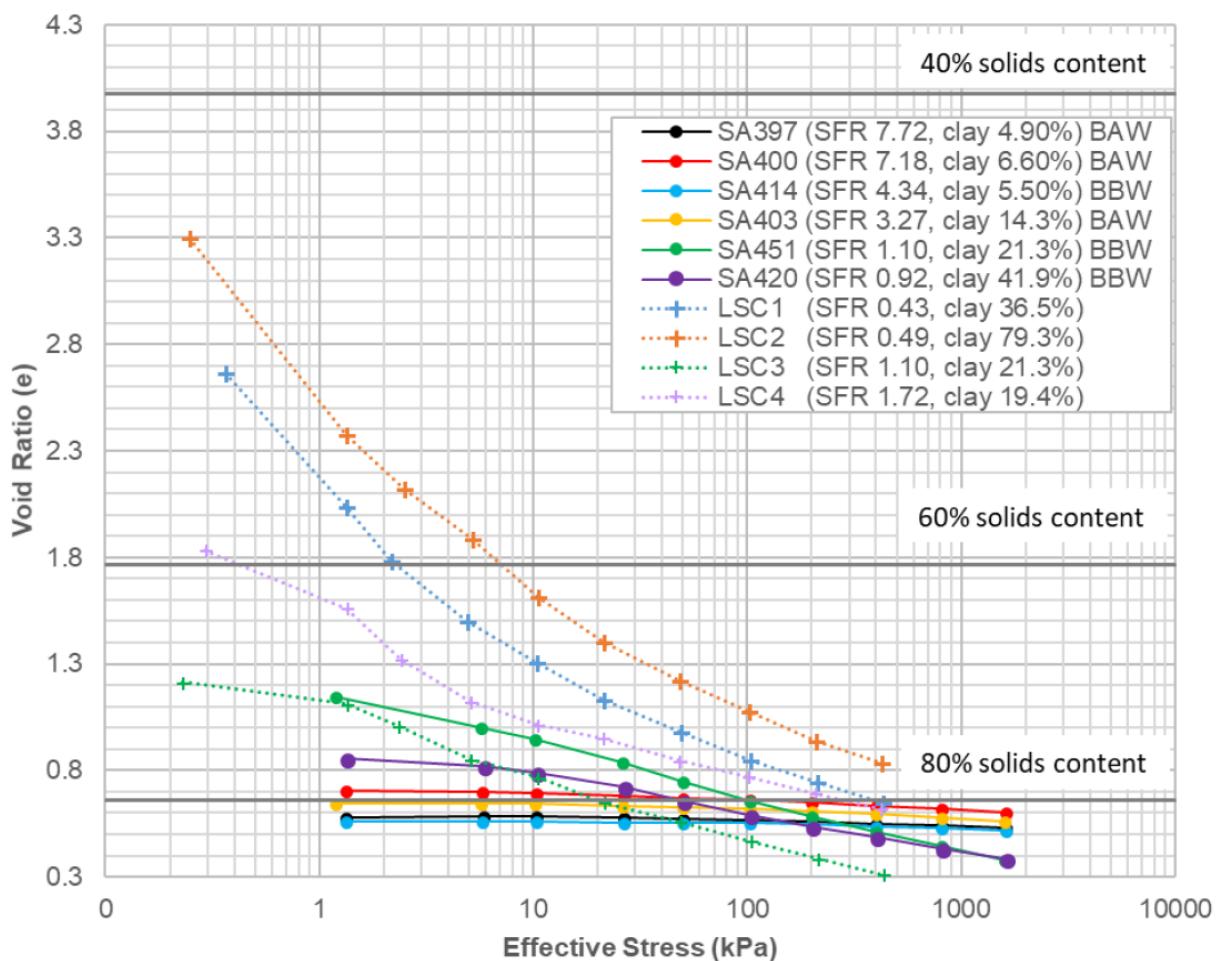
In phase one of the project, laboratory scale testing was carried out to simulate and produce samples with potentially different composition. Different ratios of fresh tailings and fluid fine tailings were mixed to simulate the thickening process as well as the secondary re-flocculation treatment process. Materials with different composition and varying the feed range were tested in large strain consolidation (LSC) cells (or oedometer cells) to measure compressibility and hydraulic conductivity of the tailings mixtures.

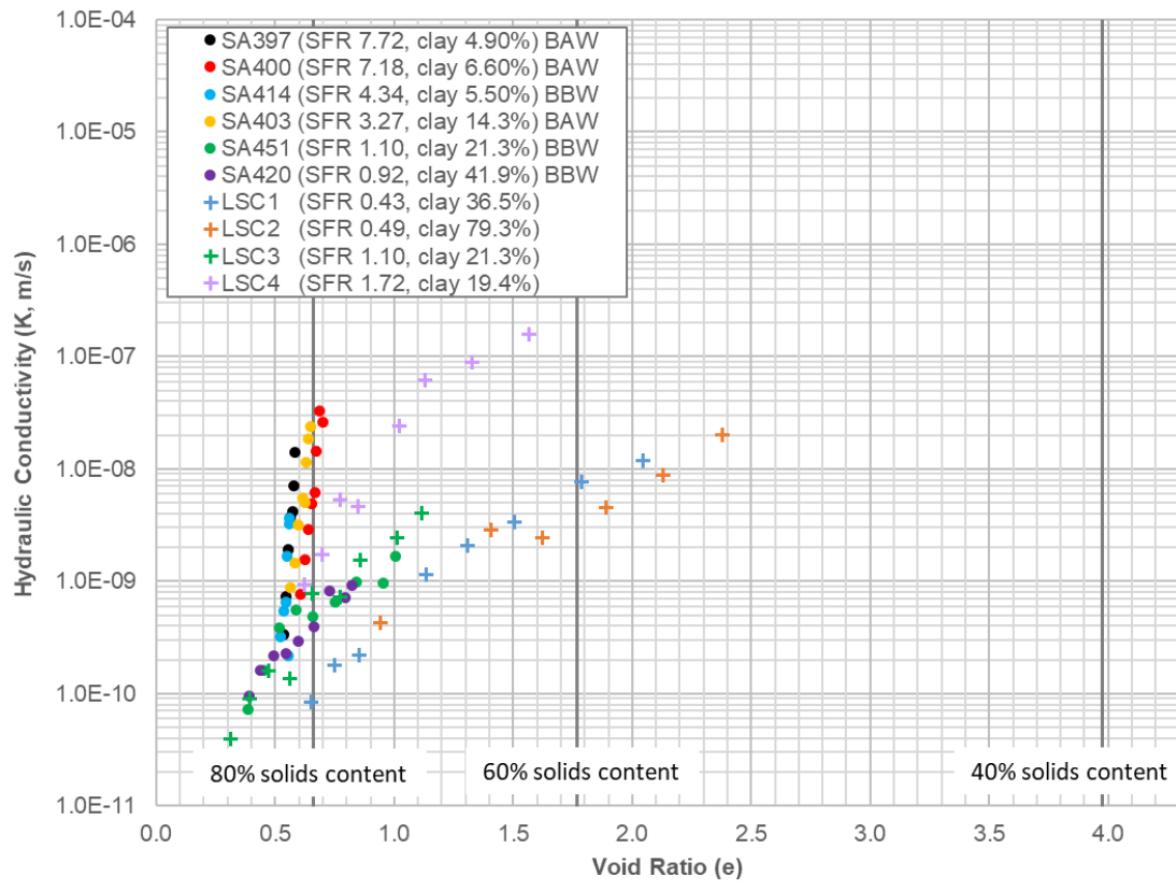
In phase two of the study, *in situ* samples were collected from the commercial scale tailings deposit and tested to determine the same properties as in phase one, such as compressibility and hydraulic conductivity. These

properties will be used to model consolidation behaviour of the commercial scale deposit. Deposit behaviour will be determined through annual *in situ* sampling and testing and will be compared to the modelled predictive consolidation behaviour. The predictive consolidation model will be calibrated accordingly with the annual sampling and testing results.

PROGRESS AND ACHIEVEMENTS

Large strain consolidation (LSC) tests were conducted to determine compressibility and hydraulic conductivity parameters for samples with different composition. Samples fabricated in the lab and *in situ* samples were used to measure those parameters. The following two figures illustrate some of the measured parameters (effective stress, void ratio, hydraulic conductivity) at various SFR, clay content, location (beach above water [BAW], beach below water [BBW], or LSC).





LESSONS LEARNED

It is recognized that subsampling errors and other laboratory errors are unavoidable in measuring index properties such as hydraulic conductivity. Therefore “engineering judgment” should be used in selecting ranges for consolidation properties.

LITERATURE CITED

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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		
Jason Stianson	Golder Associates Ltd.	Associate – Geotechnical Engineer		

Acronyms and Glossary

ADW	accelerated dewatering
AER	Alberta Energy Regulator
AFD	atmospheric fines drying
behaviour of fluid fine tailings	measured response of the fluid fine tailings in a tailings deposit over time
BAW	beach above water
BBW	beach below water
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 074	<i>Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes</i>
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.
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%
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 ≤44 µm
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)
TRO™	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)