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COSIA TAILINGS EPA

2019 Tailings Research Report

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Introduction

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

Tailings deposits can have very different properties: from sand-dominated deposits to thin and thick lift fines-dominated deposits; deposits that will underlie the water column in pit lakes; and tailings mixed with other materials like overburden. Reclamation of most tailings deposits occurs some time after deposition, so understanding the desired properties of treated tailings requires an understanding of the factors that affect the time for consolidation after the deposit is placed. 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.

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).

This report was prepared and funded by:

Canadian Natural Resources Limited
Imperial
Suncor Energy
Syncrude Canada Ltd.
Teck

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TAILINGS CAPPING

Conversion of Oil Sands Byproducts to Closure Landforms

COSIA Project Number: TE0045

Research Provider: BGC Engineering Inc.

Industry Champion: Suncor

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 2 of 2

PROJECT SUMMARY

Oil sands mining generates a variety of both low-volume and high-volume byproducts. These byproducts may be deposited for permanent storage within an operator's mineral surface lease following mine plans approved under Alberta's *Environmental Protection and Enhancement Act*. Some byproducts are good landform construction materials whereas others require containment or encapsulation due to their geotechnical and geoenvironmental properties. However, many of the byproducts have not been fully characterized or evaluated for use in construction of the reclaimed landscapes, or for their long-term performance in the reclaimed landscape.

The Landform Conversion Project (the Project) was initiated by Canada's Oil Sands Innovation Alliance (COSIA's) Land/Tailings Cross-Environmental Priority Area Working Group (X-EPA WG). The intent of the Landform Conversion Project is to collect high-level design and environmental information on oil sands mining byproducts to guide their use in the construction of landforms or landform elements within the reclaimed landscape. This includes highlighting geotechnical and geoenvironmental considerations related to the handling and long-term storage of these byproduct materials.

The Landform Conversion Project was comprised of three phases:

- Phase 1 identified key byproducts of interest to COSIA and included a data gap analysis of operator-provided data (BGC, October 30, 2019).
- Phase 2 sought to improve understanding of the evolution of landforms in the reclaimed landscape: how to predict landform evolution processes, design for them, and communicate them in discussions with others (BGC, September 23, 2019).
- Phase 3 characterized selected byproducts from Phase 1, based on their geotechnical and geoenvironmental properties, and used that information to assess the ways in which each byproduct might be used, re-used, or stored in the reclaimed landscape (i.e., conducts a Byproduct Use Assessment) (BGC, November 29, 2019).

The final deliverable from Phase 3 provided guidance, based upon geotechnical and geoenvironmental considerations, on the suitability of major byproducts for placement in standard oil sands mining landforms and landform elements. It is anticipated to be a useful industry-wide screening level tool for oil sands landform design teams (i.e., planners, designers, technical experts), Research and Development teams, and management.

PROGRESS AND ACHIEVEMENTS

The majority of Phase 1 work was completed in 2018. A list of byproducts 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 geoenvironmental properties of the byproducts to inform the Byproduct Use Assessment. Data from the oil sands operators were assessed to determine if sufficient information was available to characterize the byproducts for the Byproduct Use Assessment, or alternately, if additional sampling and laboratory testing are required to address the data gaps. Five byproducts were identified as having sufficient information to proceed to Phase 3: tailings sand, fluid tailings, centrifuged mature fine tailings, petroleum coke, and froth treatment tailings.

Phase 2, the Landform Evolution Concept Review, was completed in 2019 and was indirectly related to Phases 1 and 3. Key outcomes from this work included the definition of the term “landform evolution” in the context of oil sands mining. This definition allows for clear communication of the concept of landform evolution with stakeholders, regulatory bodies and communities. In addition, six categories of landform evolution processes and many specific processes were identified as applicable to the oil sands mining post-closure landscape setting. The identified processes can be used when setting landform design goals and objectives as part of a design basis, as a checklist for landform design projects, and to guide risk assessments for long-term performance.

The deliverable from Phase 3, the Byproduct Use Assessment, includes a framework for evaluating mining byproducts for use in the reclamation landscape. It also presents the results from BGC’s assessment of use or storage options for thirteen oil sands byproducts in the reclaimed landscape. These byproducts are: Syncrude Coke, Suncor Coke, Froth Treatment Tailings, Froth Cake, Centrifuged Mature Fine Tailings, Fluid Tailings, dried mature fine tailings, tailings sand, composite/consolidated tailings, flue gas desulphurization waste, fly ash, along with warm water lime softener, produced water and salt waste from *in situ* operations. The byproduct use assessment presents each byproduct and their qualitative suitability ratings for each of the twenty use options along with comments explaining the rating for each byproduct.

LESSONS LEARNED

This work has provided an important reference for planners and engineers tasked with closure design and storage of oil sands mining byproducts.

Phase 2 identified that the evolution of landscapes and landforms over time through geomorphic processes is an inherent part of natural systems. The landforms created by oil sands reclamation activities will become part of the natural systems and will evolve over time predominantly through these natural processes. The science discipline of geomorphology provides a framework to communicate the processes that will be active. Using natural processes as a baseline should allow operators, designers, regulators, Indigenous Peoples, and local communities to evaluate performance over time.

Lessons learned from Phase 3 included that, in general, there are many uses for byproducts having sufficient shear strength and density to be used as construction material for landforms. However, full consideration needs to be given to the various aspects of a given byproduct to predict how it will perform in the long-term landscape. For a few byproducts, geoenvironmental properties limit the range of suitable uses. Designers should take care to place materials that have elevated concentrations of constituents in locations where the potential effects on the receiving environment can be appropriately managed.

LITERATURE CITED

BGC Engineering Inc. (2019, November 29). Landform conversion project – Phase 3 assessment of oil sands byproducts for use in the reclaimed landscape [Report]. Prepared for Canada's Oil Sands Innovation Alliance.

BGC Engineering Inc. (2019, October 30). Summary of activities, results and recommendations associated with Phase 1 of COSIA's Landform Conversion Project – Final [Memorandum]. Prepared for Canada's Oil Sands Innovation Alliance.

BGC Engineering Inc. (2019, September 23). Landform conversion project - Landform evolution concept review [Report]. Prepared for Canada's Oil Sands Innovation Alliance.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Holden A, Provost H, Pollard J, McKenna G, & Wells PS. (2019). Evolution of landforms in reclaimed landscapes in the surface mineable Athabasca oil sands. In J. Goodwill, D. Van Zyl, & M. Davies (Eds), Proceedings of Tailings and Mine Waste 2019 (pp. 739-754). Vancouver, BC: Norman B. Keevil Institute of Mining Engineering and C3 Alliance Corp.

Abstract submitted to Tailings and Mine Waste 2020: Provost H, Holden A, Scully K, McKenna G, & Wells PS. Assessment of oil sands byproducts for use in the reclaimed landscape. BCG Engineering Inc. plans to present in November 2020, if accepted.

RESEARCH TEAM AND COLLABORATORS

Principal Investigators: BGC Engineering Inc.

Research Collaborators:

Canadian Natural, Imperial, Syncrude, Teck

From Slurry to Soil: Creating Soil from Oil Sands Tailings

COSIA Project Number: TE0052 – RWG (IOSI18)

Research Providers: Northern Alberta Institute of Technology (NAIT) and InnoTech Alberta

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 1 of 1 (Complete)

PROJECT SUMMARY

Background:

The production of synthetic crude oil in Northern Alberta results in large volumes of waste material known as oil sands tailings. In 2015, new policy direction was issued by the Government of Alberta under the *Lower Athabasca Region: Tailings Management Framework for the Mineable Athabasca Oil Sands*[1] and implemented beginning in 2016 under *Directive 085*[2]. *Directive 085* specified, among other requirements, that new fluid fine tailings (FFT) deposits must be ready to reclaim ten years after the end of mine life, and that all legacy tailings[3] must be ready to reclaim by the end of mine life. Current deposits of treated fine tailings are difficult to cap and reclaim for upland ecosystems (COSIA, 2017). Large time and cost savings would be achieved if the treated tailings could both meet the designated reclaimed strength and be integrated into the surrounding environment directly without capping. The integration of plants has the potential to enhance dewatering of treated tailings (Silva, 1999; Silva, Naeth, Biggar, Chanasyk, and Sego, 1998), improve both stability and strength, and enable progressive reclamation. Untreated and treated FFT are often devoid of critical nutrients required to support and sustain the physical and chemical functions and processes of plants, though previous studies have shown that FFT is able to support certain native species when sufficient nutrients have been provided (Wu, Sego, Naeth, & Wang, 2011a, 2011b, 2010). Furthermore, the low hydraulic conductivity of clay-dominated FFT makes it difficult for adequate moisture flow to occur around roots, resulting in water logging or drought conditions. Adding sand to FFT to mimic naturally-occurring soils in the Athabasca region is expected to improve moisture transfer and facilitate plant establishment.

Project Description:

This project aims to create an artificial soil prototype material by enhancing tailings with the goal of creating a surface that promotes plant growth and development similar to regional soil conditions, to achieve improved surface consolidation, soil structure development, soil stability, and early boreal forest plant succession. The ideal artificial soil will begin as a pumpable tailings slurry that will rapidly evolve into sediment with the appropriate sand-to-fines

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[1] *Lower Athabasca Region: Tailings Management Framework for mineable Athabasca oil sands*, Government of Alberta, 2015.

[2] *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects.* Alberta Energy Regulator, 2017.

[3] Legacy tailings are defined in *Directive 085* as fluid tailings in storage before January 1, 2015.

ratio (SFR) for optimal water permeability and nutrients to support plant growth without continued site maintenance.

In this study, polymer A3338-treated FFT was blended with sand to form tailings with three sand-to-fines ratios (SFR) – namely SFR 0.0, SFR 1.5, and SFR 3.0, with SFR 1.5 as a close representation of a Luvisolic soil. This soil order commonly occurs in the Athabasca oil sands region and throughout northern Alberta. In addition, three potential sources of supplemental nutrients were incorporated into the treated FFT; two were from organic materials (compost and alfalfa) and the third was an inorganic nitrogen source (urea). These amendments were evaluated against a no-amendment condition as a control group. The protocols of flocculation were investigated and determined based on the Net Water Release (NWR), release water quality, and the repeatability of the tests. Plant establishment and survival over the six-week growth trial was assessed based on above-ground biomass and maximum plant height.

PROGRESS AND ACHIEVEMENTS

Phase 1:

This study was carried out in two phases over 2019, with the final report submitted in November 2019. In phase 1, a mixing study demonstrated the reproducibility of developed protocols to produce an artificial soil prototype using FFT with sand addition at three SFRs (0.0, 1.5, and 3.0). The tailings with SFR 0.0 had the highest NWR but exhibited little geotechnical stability. The tailings with SFR 3.0 resembled wet sand rather than sand-filled flocs, were difficult to produce and had poor release water quality. Consequently, neither SFR 0.0 nor SFR 3.0 emulated the targeted Luvisolic soil. Furthermore, complications in flocculation arising from the excessively sandy nature of FFT at SFR 3.0 made it undesirable for further scale up. The SFR 1.5 sample produced a well-flocculated product with a higher solids content though lower NWR value when compared to SFR 0.0. Tailings with SFR 1.5 behaved as an optimal middle-ground of sand and FFT and more closely emulated a Luvisolic soil type. The protocols of flocculation for SFR 1.5 were repeatable. Therefore, the upscaling of the protocol should also be feasible. The NWR, water clarity and required polymer dosage were not negatively impacted by any of the nutrient amendment conditions, indicating that in-line addition of an amendment may be feasible.

Phase 2:

Phase 2 examined the ability of three native plant species (slender wheatgrass [*Elymus trachycaulus*], sandbar willow [*Salix interior*] and western dock [*Rumex occidentalis*]) to germinate, survive and grow in these substrates. After the preparation of all SFR and nutrient amendments, seed was sown (slender wheatgrass) or seedlings (sandbar willow and western dock) were established into 1 L containers of these substrates. Seedlings were measured before and after a six-week growth period to evaluate plant response to each SFR/nutrient amendment combination. Compost was the only amendment used in this study that contained a wider range of macro/micronutrients, including phosphorous (which can increase nitrogen uptake by plants), and significantly improved the growth of slender wheatgrass and western dock at all tested SFR levels. Sandbar willow grew taller in urea or compost-amended tailings regardless of the SFR but accumulated larger biomass in tailings with SFR 1.5 amended with urea. In general, compost appeared to be the most consistent of all three amendments in terms of improving plant growth. Based on results of the mixing study, SFR 1.5 is likely the optimum SFR level required to provide a more stable soil structure for improved species growth. These results should however be taken with some caution as compost contains a wider range of macro/micronutrients. Conversely, urea and alfalfa only provide a source of nitrogen, and nitrogen and carbon, respectively. A secondary fertilization blend of macro/micronutrients, shown to improve plant growth in related greenhouse studies (Collins et al., 2019), was not added in this trial. Therefore, a longer-term trial with an addition of secondary fertilization blend of macro/micronutrients should be undertaken to test the limitation of a secondary nutrient and understand nutrient fluxes over longer time periods. The addition of alfalfa inhibited the seed emergence of slender wheatgrass in tailings with SFR 3.0. As the inhibitory effects of alfalfa have previously been observed to dissipate with time, a full evaluation of this nutrient amendment is necessary, as the six-week period of this study is only useful in providing information on short-term growth trends and may not necessarily be a reasonable representation of multi-year plant growth in field conditions. It is speculated that the nitrogen contained in urea and alfalfa was also less readily available to plants initially due to a slower process of breaking down, which would have further contributed to the differences observed. A longer growth trial may also demonstrate greater growth improvements with alfalfa.

LESSONS LEARNED

- All nutrient amendments tested in this study had no significant adverse impact on the key flocculation performance characteristics of the artificial soils. This serves as a good indication that the addition of nutrients can be achieved through in-line mixing, which would be beneficial to industry from an ease of access perspective. By creating a final substrate that is reclamation ready, this approach could be applied as a surface capping technique over top of already existing soft tailings deposits; further study would be required to validate this suggestion as the present trial was conducted at the bench-scale.

- While the SFR 1.5 condition exhibited good flocculation characteristics and supported plant growth, an SFR of 3.0 severely decreased flocculation performance. Emergence rate of slender wheatgrass was severely hindered by a combination of high SFR and alfalfa amendment.

- It should be emphasized that sand contributes no nutritional value to the artificial soils, and in fact serves to dilute the existing nutrient content of FFT with amendments. Addition of sand to tailings in this study elevated the electrical conductivity of the mixtures from approximately 3.5 dS/m when the SFR was 0.0 to over 7.0 dS/m at an SFR of 3.0. Plants struggle when the electrical conductivity is above 4, and the presence of extra salt in the sand is a source of stress to the tested species. This may explain why no significant benefit to sand addition alone was found in the growth study. Therefore, it would be worthwhile for future studies to consider the addition of nutritional amendments that may compensate for the elevated electrical conductivity in the artificial soils.

- Compost was consistently the best performing nutrient amendment for all plant species, as it was the only amendment which provided a range of macro/micronutrients. Urea was also observed to improve the growth of sandbar willow, especially at an SFR of 1.5. As compost is likely to be the most costly (due to weight) and difficult amendment to procure operationally, future studies should evaluate the incorporation of amendment treatments that will emulate the blend of macro and micronutrients observed in the compost in this study.

- The inhibitory effects of alfalfa pellets have been observed to lessen with time in previous greenhouse studies; the six-week period of this trial was insufficient to allow for a full evaluation of this amendment and may benefit plants with a greater "resting" period prior to plant establishment to allow for adverse chemical effects to dissipate. Therefore, there is a need to test the suggestion that the inhibitory effect of alfalfa pellets is short-lived and can be corrected with pre-planting irrigation to dilute the effects of the allelopathic chemicals. The chemistry of release water from different combinations of amendments and SFR needs to be further studied to understand if there are any impacts on species growth.

LITERATURE CITED

Alberta Energy Regulator. (2017). *Directive 085 Fluid Tailings Management for Oil Sands Mining Projects.* Retrieved from https://www.aer.ca/documents/directives/Directive085.pdf

Collins, V., Chigbo, C., Schoonmaker, A., Kaminsky, H., Sedgwick, A., & Mussone, P. (2019). *"Bugs and Veggies" as Tailings Management Tools.* Edmonton, Alberta.

COSIA. (2017). Soft Tailings Capping Technology. Retrieved October 24, 2019, from https://www.cosia.ca/sites/default/files/attachments/COSIA Challenge Tailings - Soft Tailings Capping Technology_1.pdf

Silva, M. J. (1999). Plant Dewatering and strengthening of mine waste tailings. In *ProQuest Dissertations and Theses.* Retrieved from http://exlibproxy.unisa.edu.au/login?url=http://search.proquest.com/docview/304554265?accountid=14649%0Ahttp://www.library.unisa.edu.au/applications/findit/ ?ctx_ver=z39.88-2004&ctx_enc=infor:ofi/enc:UTF-8&rfr_id=info:sid/ProQuest+Dissertations+&+Theses+Full

Silva, M.J., Naeth, M.A., Biggar, K.W., Chanasyk, D.S., & Sego, D.C. (1998). Plant selection for dewatering and reclamation of tailings. *Annual Meeting of the American Society for Surface Mining and Reclamation.*

Wu, S., Sego, D., Naeth, A., & Wang, B. (2011a). Responses of Wheatgrass Species to Composite/Consolidated Oil Sands Tailings. *Tailings and Mine Waste.*

Wu, S., Sego, D., Naeth, A., & Wang, B. W. (2011b). A Greenhouse Study of Grass Response on Composite Tailings Discharged from Alberta Oilsands Mine. *Proceedings of the 5th Mining and the Environment International Conference.*

Wu, S., Sego, D., Naeth, M. A., & Wang, B. W., (2010). Evapotranspiration Dewatering Effect on CT Deposits by Grasses. *Proceedings of the 63rd Canadian Geotechnical Conference and 6th Canadian Permafrost Conference.*

RESEARCH TEAM AND COLLABORATORS

Institution: Northern Alberta Institute of Technology (NAIT)

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

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Dr. Amanda Schoonmaker	NAIT	Research Chair		
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Dr. Chibuike Chigbo	NAIT	Research Associate		
Dr. Yunhui Li	NAIT	Research Associate		
Kaela Walton-Sather	NAIT	Research Technician		
Patric McGlashan	NAIT	Student research assistant Diploma in Chemical Technology	September 2017	May 2020
Catalina Romero Calducho	NAIT	Student research assistant Diploma in Chemical Technology	September 2018	May 2020

Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings

COSIA Project Number: TE0059 – RWG (IOSI18)

Research Provider: Barr Engineering and Environmental Science Canada Ltd

Industry Champion: Canadian Natural

Industry Collaborators: Imperial, Suncor, Syncrude, Teck

Status: Year 2 of 2

PROJECT SUMMARY

Hydraulically-placed sand caps are potentially cost-effective and practical for use in the oil sands. The project evaluated the technical feasibility of hydraulically placing a sand cap over treated fine tailings. The project comprised three main steps:

1. Develop a two dimensional (2D) numerical model (Fast Lagrangian Analysis of Continua – FLAC) to assess tailings failure modes as a cap is placed over soft tailings;
2. Conduct bench-scale tests to confirm numerical model results; and
3. Use the model and bench-scale test to identify critical factors when considering scale-up for possible pilot or commercial scale implementation.

Two hydraulic capping methods were evaluated in the numerical (FLAC) model:

1. Subaqueous advancement of a uniform lift (“sand raining”); and
2. Subaerial advancement of a sloped cover (“deltaic capping”).

A matrix of material parameters and physical configurations was established for the FLAC model to examine a range of placement scenarios possible in the oil sands. The bench test was conducted to evaluate sand cap support mechanisms and compare with the FLAC model results. Modelling prior to testing established the test size and tailings strength ranges that would allow failure mechanisms to develop. A glass-walled tank was half-filled with about 600 L of centrifuged fluid fine tailings (about 100 Pa shear strength). The tank was instrumented to monitor pore pressures and displacements during subaerial sand cap placement (by hand) in nine successive lifts.

PROGRESS AND ACHIEVEMENTS

The FLAC 2D model was developed to predict potential failure mechanisms during cap advance on soft tailings. The physical test was used to calibrate/validate the model results and demonstrate that a cap could be placed on soft tailings. Factors were identified for the development of larger-scale tests or commercial applications.

Key conclusions from the FLAC analyses were:

1. The front slope of the cap and deposit solids content (i.e., strength variation with depth) are key factors, and cap advance rate was found to be a minor contributor to cap stability;
2. Rotational sliding at the leading edge of the cap was the dominant failure mechanism, and a flat front slope was more stable than a steep front slope (lower shear stress and smaller bow wave); and
3. Small-strain models may not appropriately capture the large displacements that can occur during failure.

The bench-scale test, in conjunction with additional FLAC 2D large-strain modelling, showed:

1. The sand cap initially displaced the tailings downward and the onset of rotational failure occurred before the total cap thickness was placed;
2. The experiment and numerical model showed large displacements in the same general areas: downward displacement below the cap, horizontal displacement beneath the cap slope, and upward displacement beyond the cap toe;
3. Excess pore pressure generation in the experiment generally matched the FLAC model;
4. A subaerial sand cap could be placed on tailings of about 100 Pa undrained shear strength at bench scale (see below regarding tailings strength scale-up);
5. FLAC modelling prior to physical test was valuable for planning of instrumentation and monitoring; and
6. Large-strain deformation modelling could reasonably represent tailings response to cap placement, even for tailings above the liquid limit.

Key considerations and factors for scale-up were evaluated by reviewing the FLAC and physical test findings in conjunction with available literature. These included geometry, time dependence (e.g., shear-strain softening), environmental exposure (e.g., wetting), heterogeneity, gas production, temperature and water levels. An approximate analysis showed the importance of accounting for scale-up when translating bench scale results to full scale application: at full scale, to support the cap placed during the bench scale capping demonstration, tailings would need to be approximately 1 kPa, nearly 10 times stronger than the bench test tailings.

LESSONS LEARNED

The project contributed to understanding the potential for hydraulic capping of treated fine tailings deposits. Areas of further study could include:

1. Deposition method (sand slurry behaviour) and dynamics of cap placement;
2. Analysis of the bench test boundary effects to understand scale up;
3. Assessing the strain-dependent behaviour of the tailings;
4. Assessing the impact of surface strengthening and cap/tailings heterogeneity; and

5. Improved understanding of the process of achieving conditions needed to support reclamation activities, such as placement of multiple lifts of cap, the time needed between lifts, and potential resultant limitations on reclamation constructions.

LITERATURE CITED

Beier, Nicholas, et al., 2012. "Geotechnical Aspects of Flocculation-based Technologies for Dewatering Mature Fine Tailings," Proceedings, 65th Canadian Geotechnical Conference, Winnipeg, Manitoba, September 30 –October 3, 2012.

Canada's Oil Sands Innovation Alliance, 2017. COSIA Challenge, Soft Tailings Capping Technology, Appendix 1, September 28, 2017.

De Leeuw, H. A., Smits, E. P. T., Mathijssen, F. A. J. M., and Estourgie, A. L. Ph., 2002. "Reclamation on Soft Subsoil by Spraying Thin Layers of Sand: the 'Ijburg' Project near Amsterdam," International Association of Dredging Companies, Terra et Aqua International Journal on Public Works, Ports & Waterways Developments, Number 89 – December 2002.

Dunmola, Adedeji, et al., 2013. "Geotechnical Benefits of Flocculation in Dewatering Oil Sands Mature Fine Tailings," Proceedings, 66th Canadian Geotechnical Conference, Montreal, September 29 – October 3, 2013.

Hockley, Daryl, 2018. "Clay Effects on Tailings Geotechnical Properties," Workshop Lecture Series, volume 22, Introduction to Oil Sands Clays, chapter 9, Clay Minerals Society, January 1, 2018.

Nidal, Jerard, 2016. "Temperature impact on the consolidation and creep behaviour of compacted clayey soils." Mechanics of materials [physics class-PhD]. Université de Lorraine, PhD Thesis, 2016.

Scott, J.D., 2003. Multiphase Mass Volume Relationships for Tailings, Department of Civil and Environmental Engineering, University of Alberta, Revised April 14, 2003.

Smith, Will, et al., 2018. "Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Deposit," Proceedings, 6th International Oil Sands Tailings Conference, Edmonton, December 9 – 12, 2018.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings. Nav Dhadli. International Oil Sands Tailings Conference (IOSTC), December 2018.

Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings, 2D FLAC Modelling of Subaerial Sand Capping of Treated FFT. Jed Greenwood. COSIA Oil Sands Innovation Summit. June 2019.

RESEARCH TEAM AND COLLABORATORS

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

Principal Investigator: Philip Solseng

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Ebi Meshkati	Deltares	Ph.D.		
Branko Damjanac,	Itasca Consulting Group	Ph.D.		

Modelling the Cap Placement with Tailings Deformation and Consolidation

COSIA Project Number: TE0073 (IOSI19)

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 1 of 2

PROJECT SUMMARY

This research is exploring the feasibility of deltaic capping to place a cap on soft, fines-dominated treated tailings. Deltaic capping is subaerial[4] placement of a cap using hydraulic transport and deposition of a sand (or other granular) slurry, applying the processes that nature uses to build river deltas. The 2018-2019 project, "Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings," (COSIA project number TE0059) demonstrated that deltaic capping held promise.

The current research is exploring potential limits of applicability of deltaic capping by considering strain softening[5] of the tailings as they are capped. The focus is on tailings weaker than those that could normally be capped using mechanical methods (conventional practice limits mechanical sand cap placement to tailings that have already achieved trafficable strengths, i.e., 25 kPa). By incorporating strain softening of the underlying tailings and infilling of the resulting depression in the cap, this work accounts for the effects of deformation due to the increasing load with increasing cap thickness. The concept and key assumptions are illustrated in the figures below.

[4] subaerial placement or subaerial deposition means deposited above water with exposure to the atmosphere

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

1. When the cap is placed, the tailings will settle under the loading from the cap, as shown in Figure 1. The water level shown is to make these illustrations universal; for the current research, the water level is assumed to be at the tailings surface, so the tailings are always saturated.

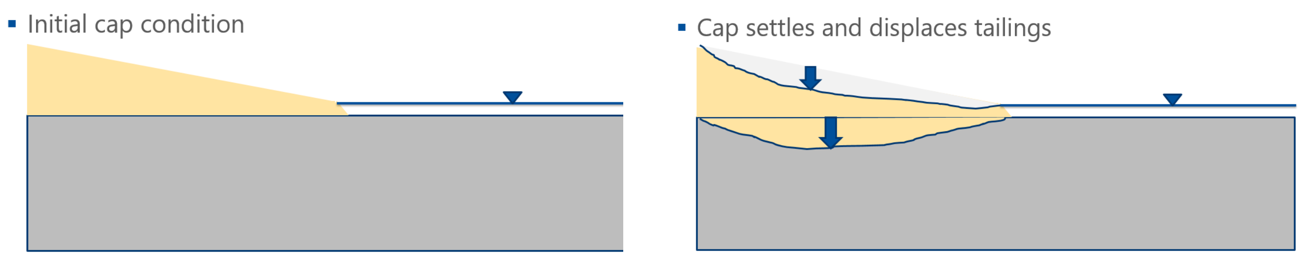

Figure 1. Initial Cap Condition and Initial Cap Settlement

2. The cap (delta) slope is restored by infill of sand, meaning the cap becomes thicker and the load increases due to cap settlement, setting up a cycle of cap infilling and settlement, as shown in Figure 2 below.

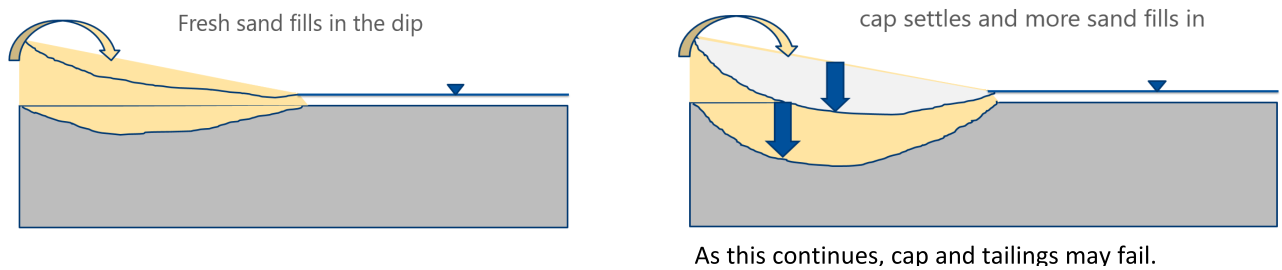

Figure 2. Cap Slope Restored with Fresh Sand Filling the Depression and Further Settlement

3. The shear strain in the tailings will increase with increasing shear stress. After the peak shear strength is mobilized, the strength will decrease with increasing shear strain, towards a remoulded (residual) shear strength. For strains beyond the peak shear strength, increased load and decreased tailings strength can result in cap failure.

This research is a step toward better understanding the feasibility of deltaic capping, or potential fatal flaws, by considering failure mechanisms associated with having the tailings settle/deform and increasing the cap thickness. If successful, deltaic cap construction might be safer, faster, and have a lower environmental impact and lower cost than other potential cap construction methods. This could enable more rapid reclamation of tailings deposits and the ultimate return of the land to a boreal forest landscape.

Design and Methodology

This work builds on the subaerial results from the previous 2018-2019 project, “Evaluation of Granular Cap Success Conditions and Failure Potential on Treated Fine Tailings,” where a cap of 1 m thickness with a long front slope (8H:1V) and a 1-percent top slope could be supported on tailings of 1 kPa peak undrained shear strength. The 2018-2019 project modelling assumed the tailings were covered by a water cap equal to the nominal cap thickness (1 m), and the tailings increased in solids content and strength with depth. For the current research, there is no water cap and tailings properties were held constant with depth to focus on the role of tailings shear strain in potential cap failure. This work uses a wedge-shaped cap, initially using cap slopes of 0.5, 1, and 2 percent, representative of typical oil sands hydraulic deposition conditions. Other slopes may be considered based on modelling results.

The research uses the advanced geomechanics program FLAC® (Fast Lagrangian Analysis of Continua) for numerical simulation of the behaviour of the tailings and the interaction between tailings and cap. The modelling is carried out using FLAC 2D in large strain mode. The modelling assumes that effective stresses have been developed within the fine tailings, so that the material is in the "soil mechanics regime" and not the "fluid mechanics regime." Modelling will include cases both with and without strain softening in order to reveal the importance of this phenomenon.

The tailings are assumed to be generally similar to Accelerated Dewatered Tailings[6], a flocculated, high-fines content, low-strength material that undergoes slow consolidation in deep deposits. Tailings peak undrained shear strengths of 1, 2, and 5 kPa were modelled initially. Other strengths may be considered based on modelling results. The strain softening constitutive model embedded in FLAC is used along with field vane data to estimate the relevant tailings properties. The elastic behaviour of the materials is calculated using stiffness moduli; while the plastic behaviour is modelled based on predefined input tables accounting for strain softening occurring in the post-peak shear strength regime.

The cap is assumed to consist of sand. However, in order to remove complications associated with modelling granular material behaviour in a large-strain FLAC model, the cap is treated as a surcharge load. Thus, the only relevant property of the cap material is its density, represented as 1,935 kg/m^3 saturated density for sand at 45 percent porosity.

The study will determine which cases produce tailings failures, the type of failure observed, and the importance of including infilling of cap settlement during cap placement and strain softening in the tailings constitutive model. The results will provide guidance on the practical cap thickness and cap slope angle for different tailings strengths. The expectation is that operators will be able to define requirements for tailings properties to support successful subaerial hydraulic capping and ultimately better plan their reclamation programs.

PROGRESS AND ACHIEVEMENTS

The research is not yet complete, but preliminary results indicate that adding strain softening to the model is decisive in characterizing the potential for success or failure of a cap on soft, fines-dominated tailings deposits. Cases from simpler modelling that suggested a cap with a 1% slope could be supported on 1 kPa tailings are shown to fail when accounting for infilling of cap settlement and tailings strain softening.

LESSONS LEARNED

Initial work on deltaic capping focussed on simplified modelling of a small representative section of tailings and cap to see if the concept had potential for successful capping of soft tailings. The current work has used a 300-m-long

[6] Accelerated dewatering is described in this report, as well as in the *2018 Tailings Research Report* available on Canada's Oil Sands Innovation Alliance (COSIA) website (www.cosia.ca)

cap on a 400-m-long tailings deposit. The longer extent allows failures to manifest that would not have appeared in the much-smaller dimensions of the initial work.

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

Modelling of capping over soft tailings requires consideration of strain softening, and there may be other constitutive model elements that should be considered when modelling soft, fines-dominated tailings.

Capping soft tailings will require integration of the cap geometry as it progresses over the tailings, as well as tailings strength and behaviour in order to find combinations for successful cap placement.

RESEARCH TEAM AND COLLABORATORS

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

Principal Investigator: Jim Langseth

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Farzaan Abbasy	Barr Engineering and Environmental Science Canada Ltd.	Geotechnical Engineer		
Philip Solseng	Barr Engineering and Environmental Science Canada Ltd.	Vice President, Sr. Geotechnical Engineer		
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Research Collaborators: Deltares

Surface Strengthening of a Soft Deposit

COSIA Project Number: TJ0090

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

Industry Champion: Canadian Natural

Status: Year 4 of 5

PROJECT SUMMARY

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 fully-lined 5m deep, 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 centrifuged fluid fine tailings (CFFT) in January 2016. The initial solids content of the CFFT after deposition was on average 47% by weight.

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 included: 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

Principal Investigator: Gavin Freeman

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Gavin Freeman	Canadian Natural	Lead Process Innovation Principal Investigator		
Erin Olauson	BGC Engineering Inc.	Senior Geotechnical Engineer		
Will Smith	BGC Engineering Inc.	Geotechnical Engineer-in-Training		
Amanda Schoonmaker, PhD	NAIT Boreal Research Institute	NSERC Industrial Research Chair for Colleges in Boreal Reclamation and Reforestation		

TAILINGS TREATMENT TECHNOLOGIES

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

COSIA Project Number: TE0006 and TE0036

Research Provider: Carleton University

Industry Champion: Teck

Industry Collaborators: Canadian Natural, Imperial, Suncor, Syncrude

Status: Year 3 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 (fFFT) (creep and thixotropy/structuration) that potentially influence long-term consolidation predictions;

c) Incorporating such behaviours into our research group's consolidation-desiccation model UNSATCON;

d) Extending UNSATCON from a one dimensional (1D) to two dimensional (2D) model;

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

f) Studying changes in pipeline rheology and linking to post-pipe dewatering behaviour to optimize polymer dosage and to assisting operators develop improved technologies for on-spec and off-spec detection.

PROGRESS AND ACHIEVEMENTS

Progress up to 2019

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

We developed three candidate methods to rapidly estimate the hydraulic conductivity-void ratio (or k-e) relationship. These methods are described in a number of papers, including a paper presented at the International Oil Sands Tailings Conference (IOSTC) 2018. These methods range in time and cost from single point measurement of hydraulic conductivity coupled with database learning, to column tests involving *ex situ* measurement of density using non-gamma ray techniques. 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 performed in industry using a large couette rheometer to simulate pipeline transport. We are now progressing to understand how material changes and recovers after shearing during pipeline transport, using optical microscopy and advanced rheometry. We plan to generate tailings exposed to different flow regimes and test them in our specialized column experiment to measure consolidation properties.

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.

Progress in 2019

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

Using data from large strain consolidation (LSC) tests at the University of Alberta (UA) (co-principal investigator (co-PI), Beier), we have been further verifying the three methods to rapidly estimate k-e. These tests include data on novel polymer-fFFT mxitures, the new polymers created in co-PI Soares (UA Chemical Engineering) laboratory. We have developed a column test to rapidly estimate the k-e function using a combination of the three methods previously documented in IOSTC 2018. The column test uses a high rate of non-destructive measurement of density and pore-water pressure measurements to directly calculate fluxes and gradients in pressure, therefore allowing for a high density of direct k-e measurements. The column test can be designed to measure k-e in the high range of void ratio, where the greatest uncertainty lies, in less than two weeks. This can be combined with other methods to estimate the full k-e function. Preliminary comparisons with the UA LSC data using replicate samples are very good to date.

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

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

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, through our ongoing modelling work of COSIA member pilots and field trials, we will determine if creep and structuration are net positives or negatives to the performance of their deposits. If negative, there are ways of depositing tailings that would minimize the negative aspects of structuration, and we can assist member companies with those decisions. For some reclamation strategies, such as water-capped tailings, structuration may be positive, as it will affect consolidation and therefore reduce contaminant flux to the overlying water body. The results that indicate a lower polymer dose is more optimal for long-term dewatering in the field has obviously, large financial implications.

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. We are very confident now that the very specific methods we are currently developing can be used by industry to rapidly estimate k-e, removing either slow or expensive consolidation testing as a barrier to innovation.

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

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

PRESENTATIONS AND PUBLICATIONS

Theses

Salam, Muhammad. 2019. Effects of polymers on short- and long-term dewatering of oil sands tailings, Ph.d. thesis, January 2019.

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

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

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

Journal Publications

Qi, S.; Chen, X., Simms, P., Zhou, J., Yang, X. 2020. Determination of permeability under coupled sedimentation-large strain consolidation conditions. Submitted to ASCE Journal of Geotecnical and Geoenvironmental Engineering.

Salam, M., Ormeci, B., Simms, P. 2020. Determination of optimum polymer dosage for dewatering of oil sands tailings using torque rheology. Submitted to Journal of Petroleum Science and Engineering.

Babaoglu, Y., Simms, P. 2020. Improving hydraulic conductivity estimation for soft clayey soils, sediments, or tailings using predictors measured at high void ratio**.** Under re-review by AE only, ASCE Journal of Geotecnical and Geoenvironmental Engineering.

Qi, S., Simms, P. 2019. Robust methods to estimate consolidation properties from column experiments. Canadian Geotechnical Journal, Published on the web ahead of Print https://doi.org/10.1139/cgj-2018-0870

Qi, S., Simms, P., Vanapalli, S., Daliri, F. 2019. Coupling elasto-plastic behaviour of unsaturated soils with piecewise linear large strain consolidation. Geotechnique, Published on the web ahead of print. https://doi.org/10.1680/jgeot.18.P.261

Qi, S., Simms, P. Vanapalli, S. 2018. Discussion of "From saturated to unsaturated conditions and vice versa" by Martí Lloret-Cabot, Simon J. Wheeler, Jubert A. Pineda, Enrique Romero, and Daichao Sheng. Acta Geotechnica, 13: 489. https://doi.org/10.1007/s11440-017-0625-2.

Conference Presentations/Posters

Parent, E. Simms, P. 2019. 3D modelling of tailings flows using viscosity bifurcation rheology. Proceedings of Tailings and Mine Waste '19, Vancouver, B.C, Nov. 17-20, 2019.

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

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

Igbinedion, D. , Salam, M. & Simms, P. 2019. Creep and structuration in centrifuge cake oil sands tailings. Proceedings of GeoSaintJohn's 2019. September 27-30, 2019, Saint John's, NL.

Aldaeef, A.A., Simms, P. 2019. Influence of pipeline transport on sedimentation and consolidation of flocculated Fluid Fine Tailings (fFFT). Proceedings of GeoSaintJohn's 2019. September 27-30, 2019, Saint John's, NL.

Babaoglu, Y., Qi, S., Simms, P. 2018. Rapid Estimation of Hydraulic Conductivity for Fluid Fine Tailings. Proceedings of Sixth International Oil Sands Tailings Conference 2018. December 9-12, 2018. Edmonton, Alberta.

Babaoglu, Y., Simms, P. 2018. Estimating Hydraulic Conductivity from Compressibility Curves for Fluid Fine Tailings. GeoEdmonton, 71st Canadian Geotechnical Conference, Edmonton, Alberta, September 23 -26, 2018.

Baboaglu, Y., Simms, P. 2017. Estimating Hydraulic Conductivity from Simple Correlations for Fine Grained Soils and Tailings. In Proceedings of GeoOttawa 2017, Canadian Geotechnical Conference, October 2-4, 2017, Ottawa, Ontario. Electronic proceedings.

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

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

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

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

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

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

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

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

Salam, A., M., Simms, P., Ormeci, B. 2018. Structuration in Polymer Amended Oil Sands Fine Tailings. GeoEdmonton, 71st Canadian Geotechnical Conference, Edmonton, Alberta, September 23-26, 2018.

Salam, A.M., Simms, P., Ormeci, B. 2018. Evidence Of Creep & Structuration In Polymer Amended Oil Sands Tailings. Proceedings of IOSTC 2018.

Salam, M, Simms, P. Ormeci, B. 2017. Thixotropy and dewatering in polymer amended oil sands tailings In Proceedings of GeoOttawa 2017, Canadian Geotechnical Conference, October 2-4, 2017, Ottawa, Canada. Electronic proceedings.

Simms, P., Qi, S. 2018. Pore-size distributions measured by mercury intrusion porosimetry:implications for functional relationships in hydromechanical models. UNSAT2018, International Conference on Unsaturated Soils, Hong Kong, August 4-8, 2018.

RESEARCH TEAM AND COLLABORATORS

Institution: Carleton University / University of Alberta

Principal Investigator: Paul Simms, P.Eng.

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Joao Soares	University of Alberta	Professor		
Sunchao Qi	Carleton University / Sichuan University China	Postdoctoral Fellow/ Professor at Sichuan University	2017	Completed PostDoc December 2018
Amin Esmaelizadeh	Carleton University	Postdoctoral Fellow	2019	2022

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Arazooben Patel	Carleton University	PhD Candidate	2019	2023
Oswaldo Hurtado	Carleton University	MSc Candidate	2016	2018
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Vahid Vajinejad	University of Alberta	Postdoctoral Fellow	2017	2019
Yunhai Zhang	University of Alberta	PhD Candidate	2019	2023
Kwaku Amoako	University of Alberta	M.A.Sc. Candidate	2018	2020

Microbiological and Vegetation for Tailings Management (Bugs and Veggies)

COSIA Project Number: TE0039 RWG (IOSI)

Research Provider: Northern Alberta Institute of Technology

Industry Champion: Canadian Natural

Industry Collaborators: Imperial, Suncor, Syncrude, Teck

Status: Completed

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 if plants were 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 which 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 naturally-occurring selected bacterial 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. The plants will in-turn dewater the tailings through evapo-transpiration, thereby increasing shear strength of the materials for deposition.

The current work is the first to attempt growing native boreal plant species supplemented with naturally-occurring 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 representative of 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 natural 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

This project was completed in 2019 and the final report submitted in June 2019. The project comprised two phases of study where Phase 1 optimized the production of bacteria grown on solid carriers, with the capability of growing in tailings and able to achieve one or more of the following: degrade hydrocarbons, fix nitrogen, and improve rhizosphere environment to enhance plant development and growth. In Phase 2, an outdoor column study evaluated plant growth and changes in tailings physical structure through inclusion of organic amendments and bacteria (based on phase 1 findings). Key methodology and findings from each phase of study are further described below.

Phase 1:

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 N_2 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:

- Sample A MFT from a COSIA member company's tailings deposition area;
- Sample B MFT from another COSIA member company's tailings deposition area; and
- Two in-house enrichments using thickened tailings and tailings centrifuge cake[7] also provided by COSIA member companies.

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 Sample B MFT and Sample A MFT enrichments producing significantly more methane than centrifuge cake or thickened tailings cultures. Hydrocarbon degradation results are considered inconclusive due to changes in surface chemistry from microbial growth across different substrates. Sample A MFT 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, Sample A MFT 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; this culture was scaled up during the period between March 2018 and May 2018.

[7] Both thickened tailings and centrifuge cake are produced from treatment processes to dewater tailings fluid fine tailings

Phase 2:

During Phase 2, slender wheatgrass (*Elymus trachycaulus*) and sandbar willow (*Salix interior*) were grown in 1 metre length (10 cm diameter) columns filled with either centrifuge cake or thickened tailings and inoculated with the scaled up bacterial cultures as well as other organic amendments (hydrochar and peat). The column study was conducted outdoors in an enclosed growing space from the beginning of June 2018 and then destructively harvested in September 2018. The bacterial community, plant measurements including leaf and root biomass, and leaf area index (LAI), and geotechnical measurements including solids content, consolidation, evapo-transpiration and undrained shear strength were evaluated. Key findings from these measurements are detailed below.

Microbial community

Microbial community analysis revealed a large bacteria population with Archaea only contributing < 1% of the population. Methanogens are known to abound in mature fine tailings (Penner and Foght, 2010; Fowler et al., 2012); however, the absence of Archaea both in the day 0 centrifuge cake sample and other samples from this experiment suggests that either the tailings were too fresh to have allowed for community development of a methanogenic population, or that the homogenization process combined with observed algal growth in the clear columns severely reduced the population of the strictly anaerobic Archaea (Rother, 2010). The possibility of primer bias (Eloe-Fadrosh et al., 2016; Raymann et al., 2017) and the presence of other, more energetically-favourable electron acceptors are also possible explanations that will require additional investigation. Of the remaining Archaeal sequences, Crenarchaeota and Thaumarchaeota were the dominant groups.

The bacterial population was diverse, with the top four richest samples containing peat from the top of the column. Peat is known to contain an array of microorganisms (Dedysh et al., 2006), including bacteria known to colonize plant rhizospheres and fix nitrogen (Belova et al., 2006). The composition of peat also likely would affect the microbial population by providing a different physicochemical environment from the tailings (Andersen et al., 2010). These combined factors likely accounted for the increased richness observed in these treatments.

Proteobacteria were dominant in all treatments ranging from 46-77% of the total population. These were primarily from the groups Betaproteobacteriales, now within the Gammaproteobacteria, and Pseudomondaceae. Many of these species are known to promote plant growth through nitrogen fixation and other functions (Chen et al., 2003). Of the amendments evaluated, the inclusion of hydrochar appeared to alter the microbial population overall in the top of the columns as compared to unamended columns in the absence of plants.

Overall, the community composition was statistically different between centrifuge cake and thickened tailings. This observation was supported in a study by Yergeau et al. (2012), which found microbial communities varied between tailings pond sediment and other sediment in the Athabasca region due to the composition of the material. The microbial communities from the middle section of the columns were also different from the top of the columns in both tailings types and may be explained by the potential for oxygen infiltration, which would have reduced the presence of strict anaerobes such as Desulfuromonadaceae. Columns where *S. interior* was present also contained a substantially different microbial population in the top of the column compared to non-vegetated treatments across both tailings types, suggesting that roots exhibited stronger selective pressures on the community than amendments or inoculum. Roots are known to secrete organic acids, sugars, amino acids, and other desirable molecules, many of which benefit the microbial community in proximity to the roots (Ahemad and Kibret, 2014).

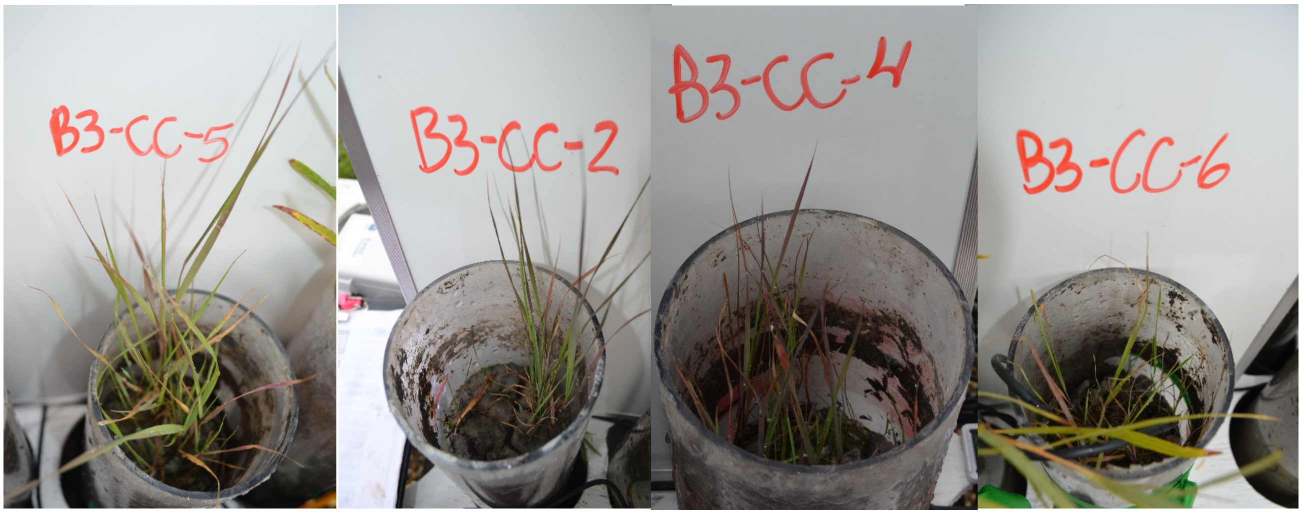
Plant growth

Both species evaluated in this study demonstrated some level of persistence when grown on either centrifuge cake or thickened tailings, regardless of the organic amendment or bacterial treatment incorporations (refer to Figure 1 showing examples of *Elymus trachycaulus* and *Salix interior* seedlings in columns following one season of growth in centrifuge cake (plants grew similarly in thickened tailings) at the conclusion of the trial). Seedlings were grown in 10 cm diameter by 1 m deep columns. Treatments included bacteria (a, e), hydrocar (b, f), peat (c, g), and no amendment (d, h).

However, total aboveground biomass and root biomass of *E. trachycaulus* were substantially lower than sandbar willow experiment-wide. *E. trachycaulus* was hand seeded into the columns. Warm and windy conditions were recorded during initial week of the experiment when *E. trachycaulus* was sown, resulting in the tailings surface drying out and inhibiting seed germination. The hard, crusted surface was subsequently broken up with a fork and seeds were re-sown a second time approximately 3 weeks later, but this delay resulted in a ~ 4-week lag in growth. As such, interpretation of the growth response of *E. trachycaulus* in this study should be taken with some caution.

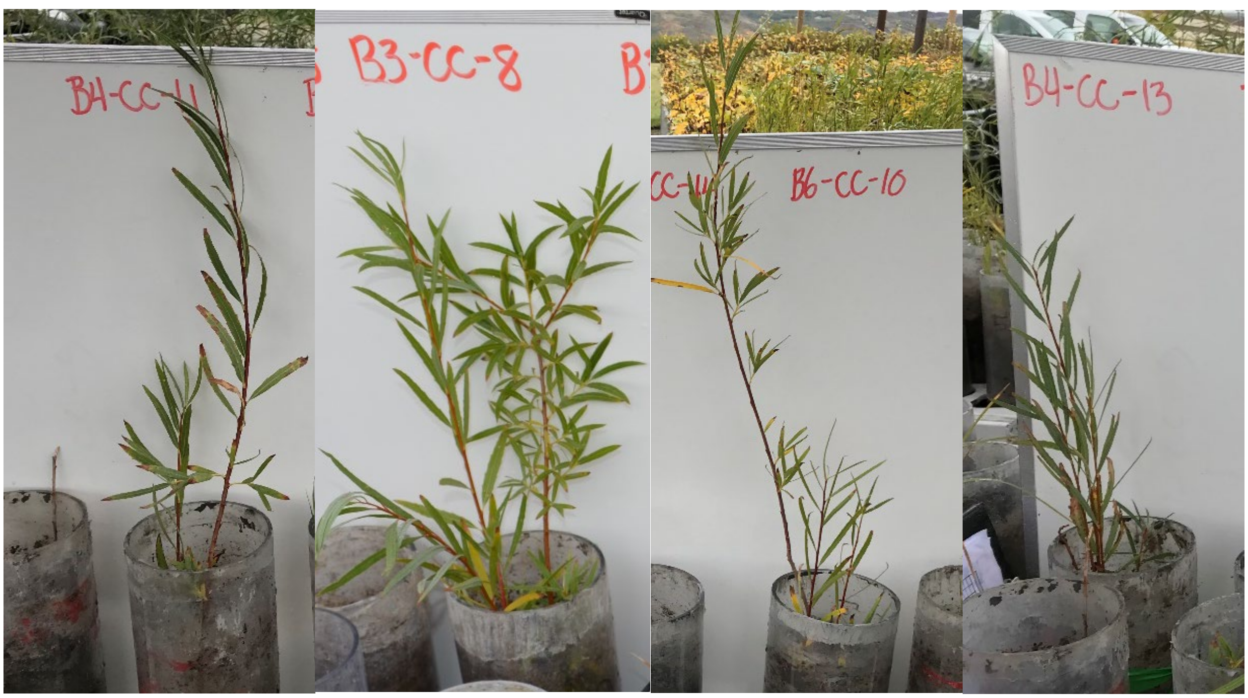
Incorporation of peat or hydrochar did not significantly improve growth (maximum height, leaf or root biomass, leaf area and leaf area index (LAI)) of *E. trachycaulus* relative to the control treatment; in fact, growth appeared to be inhibited by the presence of hydrochar and this was largely attributable to poor emergence and slower initial growth in the hydrochar treatment. Others have also found that hydrochars can be inhibitory to initial germination of plants and have suggested that depending on the type of feedstock used for production, hydrochar may contain compounds that inhibit seed emergence (Fang et al., 2015; Puccini et al., 2018).

Leaf biomass and leaf area index of *S. interior* increased with the application of hydrochar, corresponding with an increase in total nitrogen pool (%) in leaves, but peat did not have any effect on leaf biomass or LAI compared to un-amended treatments. With the addition of bacteria, the leaf biomass of *S. interior* did not differ significantly and there was no difference in any growth parameters between centrifuge cake and thickened tailings except that the average height of *S. interior* was significantly higher in centrifuge cake compared with thickened tailings. *S. interior* root biomass and root:leaf ratio were significantly highest in treatments with bacteria but were otherwise unaffected by amendment type or tailings type.



(a) (b) (c) (d)

Elymus trachycaulus **in Centrifuge Cake Amended with Bacteria (a), Hydrocar (b), Peat (c), No Amendment (d)**



(e) (f) (g) (h)

Salix interior **in Centrifuge Cake Amended with Bacteria (e), Hydrocar (f), Peat (g), No Amendment (h)**

Figure 1. Images of *Elymus trachycaulus* (a-d) and *Salix interior* (e-h) on September 6, 2018

Tailings properties

In this study, *E. trachycaulus* was grown outdoors and in columns with small surface area (10 cm diameter), which together resulted in surface crusting due to warm and windy conditions in the first week of the trial. Seeds caught in the crust failed to germinate and the crust had to be broken and reseeded three weeks after initiation of the study (in late June). This substantially reduced growth period (2.5 months) in combination with anticipated slower growth in outdoor conditions are the primary reasons for limited aboveground growth observed for this species. As such, there was no significant increase in solids content, shear strength or consolidation in columns planted with *E. trachycaulus* relative to columns without plants in this study. Despite the limited leaf area development, there were some modest indications that seasonal water use was on average higher for columns with grasses relative to those without, and significantly so for the hydrochar + bacteria treatment. Nevertheless, the limited growth observed in this trial should not eliminate this species as a candidate as *E. trachycaulus* has been grown on oil sands tailings in greenhouse studies (Wolter and Naeth, 2014; Noah, 2017; Wu 2009; Wu et al., 2010), and has been used successfully in tailings dewatering studies at NAIT (Yucel et al., 2016 and, Schoonmaker et al., 2018). In Yucel et al. (2016), individual grass plants were found to remove up to 70 mL of water from centrifuge cake per day through evapotranspiration in a 5-month greenhouse trial.

S. interior growth consistently increased the solids content in the top 35 cm of the centrifuge cake columns across all treatments compared to columns without plants. Even in the middle measurement point (35-65 cm), there was a consistent and often significant increase relative to unplanted columns. Similarly, solids content for *S. interior* grown in thickened tailings followed the same general trend as that observed for centrifuge cake, although the difference between planted and non-planted columns (within an amendment treatment) was not always significant. One explanation for the difference in solids content between the two tailings types may be increased water infiltration due to the higher sand content of the thickened tailings material. The coarser nature of the thickened tailings makes them easier to re-wet, whereas the centrifuge cake does not allow for substantial water infiltration due to the high density of the fine particulates.

Consolidation increased, on average, in the presence of *S. interior* although there was no statistically significant effect in centrifuge cake. Consolidation improved significantly in thickened tailings columns. On average, *S. interior* improved consolidation by ~5.3cm (58%) and decreased water levels by ~19.1 cm (24%) compared to non-vegetated columns. These results should be treated conservatively however, as several precipitation events preceded final measurements, which may have decreased the apparent efficacy of willow treatments in both tailings types. Evapotranspiration and seasonal water usage were also significantly higher in centrifuge cake columns with willows reducing tailings column water by an additional ~21% compared to columns without plants. *S. interior* grown in thickened tailings followed a similar pattern in evapotranspiration and water use though the results were not significantly different from unplanted.

Mean undrained shear strength was consistently higher, for both types of tailings, in columns planted with *S. interior* compared with unplanted columns and this difference was measurable to a depth of 50 cm or more. The highest mean undrained shear strength was found in the centrifuge cake treatment with *S. interior* and both hydrochar and bacteria, which exceeded predicted shear strength based on solids content. In general, there was good agreement between predicted and measured shear strength, for both types of tailings suggesting the gain in strength was largely attributable to increased solids content. When the measured strength exceeded predicted strength, this indicated that root stabilization might have further contributed to strength gain. This was observed in centrifuge cake planted with willow for the hydrochar + bacteria, peat + bacteria and no-amendment treatments; it was also observed in thickened tailings with willow for the hydrochar, peat + bacteria and no amendment treatments. Root-induced soil stabilization is a well-documented phenomenon (Wu and Watson, 1998) and the technique is utilized for hill slope stabilization (Xu et al., 2009). Modelling of this behaviour for river bank stabilization has suggested that the greatest gains in shear strength come from a small number of larger roots rather than an abundance of small roots, though the authors also suggested that grasses with strong, dense roots may also offer equally effective stabilization (Simon and Collison, 2001).

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) of the substrates examined.

- Sample A MFT and Sample B MFT enrichment cultures had significantly higher metabolism than other culture inoculum (235 µmol and 188 µmol methane (CH_4)), respectively as compared to ~20 µmol CH_4 in thickened tailings and tailings centrifuge cake cultures. Sample A MFT 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 sample (Sample A MFT) and one tailings culture (thickened tailings) were selected for evaluation in the scale-up phase.

- During the scale-up phase, Sample A MFT cultures degraded toluene to methane significantly more effectively than thickened tailings and sterile cultures. By day 41, ≤ 2 µmol CH_4 were detected in thickened tailings and sterile control cultures whereas 123 µmol CH_4 was produced in Sample A MFT enrichment cultures. Sample A MFT 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.

- In this study, *S. interior* demonstrated reasonable levels of growth and persistence throughout the trial, this species was planted as a rooted seedling, which provided a growth advantage over the *E. trachycaulus* that was established by hand seeding. Although *E. trachycaulus* is certainly capable of growth and persistence on these tailings, the primary limitation in this study was the initial rate of surface drying (hard crust formed) at the onset of the study. Only after the crust was manually broken up did we have successful levels of seed germination, but the delay in germination resulted in substantially smaller plants and therefore less marked effects on tailings geotechnical properties. In a field situation, this is less likely to be as much of an issue as there would invariably be greater surface heterogeneity (cracking) that could provide appropriate microsites for seed germination.

- Actively incorporating bacteria did not clearly translate into improved plant growth aboveground but there was a significant effect on root growth. Amending tailings with hydrochar does appear to improve plant aboveground leaf growth though not root growth. Although neither of these treatments translated into significant additional benefit to tailings dewatering during this study, there were some indications in improved shear strength. In a longer-term trial, however, it is logical to assume that any amending treatments to tailings that result in growth improvements in plants will likely benefit geotechnical properties of tailings.

- Inoculation with naturally occurring bacteria did not ultimately impact the bacterial community; other factors were found to be more critical to modifying bacterial groups. Numerous reasons why this may have occurred but the most likely was simply due to the inoculated community being overwhelmed by the bacteria present in the columns. Future work could build on this and take the 'amending' approach but with the purpose of understanding how to enhance certain desirable bacterial groups.

- Plants use more water, above that expected from atmospheric evaporation, and they correspondingly make tailings stronger both from improved solids content and root-mediated strengthening. In future, focused efforts in setting up multi-year studies, in the field, will provide the best demonstration of plant potential to dewater and strengthen tailings. This is due to growth rates of native plants which will increase exponentially over time; therefore, leaving plants in the ground for three years continuously should be more impactful than reseeding an area with an annual species for three years.

LITERATURE CITED

Andersen, R., Grasset, L., Thormann, M.N., Rochefort, L., and Francez, A.J. (2010) Changes in microbial community structure and function following Sphagnum peatland restoration. *Soil Biol. Biochem.* **42**: 291–301.

Ahemad, M. and Kibret, M. (2014) Mechanisms and applications of plant growth promoting rhizobacteria: Current perspective. *J. King Saud Univ. - Sci.* **26**: 1–20.

Belova, S.E., Pankratov, T.A., and Dedysh, S.N. (2006) Bacteria of the genus Burkholderia as a typical component of the microbial community of Sphagnum peat bogs. *Microbiology* **75**: 90–96.

Chen, W., Moulin, L., Bontemps, C., Vandamme, P., Bena, G., and Boivin-Masson, C. (2003) Legume Symbiotic Nitrogen Fixation by Β-Proteobacteria Is Widespread in Nature. *J. Bacteriol.* **185**: 7266–7272.

Collins, C.E.V., J.M. Foght, and T. Siddique. 2016. Co-occurrence of methanogenesis and N_2 fixation in oil sands tailings. Sci. Total Environ. 565, 306–312.

Dedysh, S.N., Pankratov, T.A., Belova, S.E., Kulichevskaya, I.S., and Liesack, W. (2006) Phylogenetic Analysis and In Situ Identification of Bacteria Community Composition in an Acidic Sphagnum Peat Bog. *Appl. Environ. Microbiol.* **72**: 2110–2117.

Eloe-Fadrosh, E.A., Ivanova, N.N., Woyke, T., and Kyrpides, N.C. (2016) Metagenomics uncovers gaps in amplicon-based detection of microbial diversity. *Nat. Microbiol.* **1**: 1–11.

Fang, J., Gao, B., Chen, J., and Zimmerman, A.R. (2015) Hydrochars derived from plant biomass under various conditions: Characterization and potential applications and impacts. *Chem. Eng. J.* **267**: 253–259.

Fowler, S.J., Dong, X., Sensen, C.W., Suflita, J.M., and Gieg, L.M. (2012) Methanogenic toluene metabolism: Community structure and intermediates. *Environ. Microbiol.* **14**: 754–764.

Noah, M. (2017) Biogeochemical process studies on oil sand tailings used for land reclamation in Alberta, Canada. Doktor der Naturwissenschaften, der Technischen Universität Berlin zur, Berlin.

Penner, T.J. and Foght, J.M. (2010) Mature fine tailings from oil sands processing harbour diverse methanogenic communities. *Can. J. Microbiol.* **56**: 459–70.

Puccini, M., Ceccarini, L., Antichi, D., Seggiani, M., Tavarini, S., Latorre, M.H., and Vitolo, S. (2018) Hydrothermal carbonization of municipal woody and herbaceous prunings: Hydrochar valorisation as soil amendment and growth medium for horticulture. *Sustain.* **10**: 1–16.

Raymann, K., Moeller, A.H., and Goodman, A.L. (2017) Unexplored Archaeal Diversity in the Great Ape Gut Microbiome. *Am. Soc. Microbiol.* **2**: 1–12.

Rother, M. (2010) Methanogenesis. *Handb. Hydrocarb. Lipid Microbiol.* 481–499.

Silva, M.J. 1999. Plant dewatering and strengthening of mine waste tailings. PhD thesis, University of Alberta.

Schoonmaker, A., Degenhardt, D., and Floreani, T. (2018) Evaluating the potential to establish plants to aid in dewatering of an atmospheric fine drying tailings deposit at Muskeg River Mine. In, *International Oil Sands Tailings Conference*. Edmonton, AB.

Simon, A. and Collison, A.J.C. (2001) Quantifying Root Reinforcement of Streambanks for Some Common Riparian Species: Are Willows As Good As It Gets? In, *Wetlands Engineering & River Restoration*., pp. 1–13.

Wolter, G.L.L. and Naeth, M.A. (2014) Dry Mature Fine Tailings as Oil Sands Reclamation Substrates for Three Native Grasses. *J. Environ. Qual.* **43**: 1510–1516.

Wu, S. (2009) A Greenhouse Study of Selected Native Plant Species for Dewatering CT. MSc Thesis, University of Alberta, Edmonton.

Wu, S., Sego, D., and Naeth, M.A. (2010) Evapotranspiration Dewatering Effect On CT Deposits By Grasses. In, *Canadian Geotechnical and Canadian Permafrost Conference*. Calgary, pp. 1371–1378.

Wu, T.H. and Watson, A. (1998) In situ shear tests of soil blocks with roots. *Can. Geotech. J.* **35**: 579–590.

Xu, Q.J., Zhang, L.M., Wang, W.C., and Zhang, Y. (2009) Biotechnical means of soil stabilization using willow cuttings. *J. Soil Water Conserv.* **64**: 105–119.

Yucel, K., Schoonmaker, A., Degenhardt, D., Kaur, J., and Khadka, B. (2016) Evaluating the potential to establish plants to aid in dewatering of an atmospheric fine drying tailings deposit at Muskeg River Mine. In, *International Oil Sands Tailings Conference*. Lake Louise, AB.

PRESENTATIONS AND PUBLICATIONS

Collins, V., A. Schoonmaker, H. Kaminsky, A. Sedgwick, C. Chigbo, and P. Mussone. 2018. Development of Bacterial Inoculum for the Promotion of Plant Growth on Tailings Material. International Oil Sands Tailings Conference 2018, Edmonton, Alberta. Accepted October 2018.

Collins, V., C. Chigbo, A. Schoonmaker, H. Kaminsky, A. Sedgwick, and P. Mussone. 2019. "Bugs and Veggies" as a plant mediated tailings dewatering technology. COSIA Innovation Summit June 2019, Calgary, Alberta.

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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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Andrea Sedgwick	Northern Alberta Institute of Technology	Ledcor Applied Research Chair in Oil Sands Environment Sustainability		
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Optimizing the Use of Oligochaete Worms 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

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 2 of 3

PROJECT SUMMARY

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

1. Optimize Oligochaete worms survival and reproduction in tailings environment;
2. Quantify the ultimate solids content and shear strengths achieved by adding Oligochaete worms 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 Oligochaete worms.

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

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

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

PROGRESS AND ACHIEVEMENTS

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

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

Task 2: Complete – A series of beaker tests were performed to study the effects of several "feeding strategies" on reproduction and survival of Oligochaete worms. These included low quality organic matter, high quality organic matter, and inorganic nutrients (two concentrations). Results showed that low quality organic matter applied at a 3% of the dry weight of tailings result in a factor 3 reproduction after 4 months. In all other cases worms population slowly decays with time, reaching zero at approximately 4 months as well.

Experiments in tasks 1 and 2 were repeated for the new worm, obtaining consistent results.

Task 3: Near finalization – When added in combination with low quality organic matter (see Task 2 results), Oligochaete worms produced the largest dewatering rates measured to date. So not only had we managed to give the worms an environment where they can survive and reproduce, but also when given this environment the enhanced dewatering and strengthening discovered in Task 1 was maximized. Final worm count to be performed once the experiments are finished will confirm that the consistency of the reproduction results as well (e.g., if results from beaker testing hold for larger scales as well).

Task 4: Test Matrix being currently finalized and discussed within the research team.

LESSONS LEARNED

The results of the project show that Oligochaete worms improve dewatering properties of oil sands tailings in a laboratory environment to a very competitive range (factor 2 relative increase in solid contents, factor 1.5 to 3 higher strengths), and that Oligochaete worms can live and reproduce in oil sands tailings when combined with the correct amendment. Finally, it appears that adding the amendment to provide worms survival also has a positive effect in the enhancement of the dewatering properties. The project has also provided practical knowledge that needs to be considered when designing a follow-up pilot.

REFERENCES

Brinkhurst, R.O. 1976. Aquatic *oligochaeta* recorded from Canada and the St. Lawrence great lakes. Pacific Marine Science Report 76-4. Downloaded 9-8-18 from www.dfo-po.gc.ca/Library/54831.pdf

Brinkhurst, R.O. 1996. On the role of *Tubificid oligochaetes* in relation to fish disease with special reference to the *Myxozoa.* Annual Review of Fish Diseases, Vol. 6, pp. 29-40.

Granath, W.O. Jr., M.A. Gilbert. 2002. The role of *Tubifex tubifex* (Annelida: Oligochaeta: Tubificidae) in the transmission of *Myxobolus cerebralis* (Myxozoa: Myxosporea: Myxobolidae). In: Bartholomew J.L. and Wilson, J.C. (eds.) Whirling disease: Reviews and current topics. Am. Fish. Soc. Symp. 29. American Fisheries Society, Bethesda, MD, pp. 79–85.

Marchese, M.R., M.R. dos Santos, J.C. dos Santos Lima, and P.A. Zaitune Pamplin. 2015. First record of introduced species *Lumbriculus variegatus* Müller, 1774 (*Lumbriculidae, Clitellata*) in Brazil. BioInvasions Records 4: 81–85. doi http://dx.doi.org/10.3391/bir.2015.4.2.02.

Pickavance, J.R. 1971. The ecology of *Lumbriculus variegatus* (Müller) (*Oligochaeta, Lumbriculidae*) in Newfoundland. Canadian Journal of Zoology, 1971, 49(3): 337-342, https://doi.org/10.1139/z71-049.

Özer, A. and R. Wootten. 2000. The life cycle of *Sphaerospora truttae* (*Myxozoa: Myxosporea*) and some features of the biology of both the actinosporean and myxosporean stages. Dis. Aquat. Org. 40: 33-39.

Özer, A., R. Wootten, and A.P. Shinn. 2002. Survey of actinosporean types (*Myxozoa*) belonging to seven collective groups found in a freshwater salmon farm in Northern Scotland. Folia Parasitologica 49: 189-210.

Urawa, S., M.A. Freeman, S.C. Johnson, S.R.M. Jones, and H. Yokoyama. 2011. Geographical variation in spore morphology, gene sequences, and host specificity of *Myxobolus arcticus* (*Myxozoa*) infecting salmonid nerve tissues. Dis. Aquat. Org. 96: 229–237.

PRESENTATIONS AND PUBLICATIONS

Sittoni, L., M. De Lucas Pardo, and J. Hanssen. 2018. Enhancing densification and strength of Oil Sands Tailings deposits by using Tubifex worms. Successes so far. Oil Sands Innovation Summit 2018, Calgary, Alberta.

de Lucas Pardo, M., X. Yang, M. Ibanez, and L. Sittoni. 2016. Tubifex: a biological method for enhancing dewatering oil sands tailings. Latest results and next steps. Conference proceedings International Oil Sands Tailings Conference 2016, 280-286.

Yang, X., Pardo, M. D. L., Ibanez, M., Deng, L., Sittoni, L., Ulrich, A., & Chen, Q. (2019). Improving Engineering Properties of Mature Fine Tailings using Tubifex. Canadian Journal of Civil Engineering, (ja).

Yang, X., M. de Lucas Pardo, M. Ibanez, L. Deng, L. Sittoni, A. Ulrich, and Q. Chen. 2016. Addition of Tubifex accelerates dewatering of oil sands tailings. Canadian Journal of Civil Engineering, 43(12), 1025-1033.

Yang, X., M. de Lucas Pardo, L. Deng, L. Sittoni, A. Ulrich, and Q. Chen. 2015. Tubifex: a biological method for dewatering oil sands tailings. Conference proceedings Tailings and Mine Waste 2015, 499-507.

RESEARCH TEAM AND COLLABORATORS

Institution: Deltares and University of Alberta

Principal Investigator: Migues de Lucas, Deltares

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Miguel de Lucas	Deltares, the Netherlands	Principal Investigator Research Scientist		
Alex Kirichek	Deltares, the Netherlands	Research Scientist		
Peter Herman	Deltares, the Netherlands	Senior Advisor		
Luca Sittoni	Deltares, the Netherlands	Program Manager		
Ania Ulrich	University of Alberta, Canada	Professor		
Peter Kuznetsov	University of Alberta, Canada	Assistant Professor		

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

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 1 of 1

PROJECT SUMMARY

A new sludge filtration technology named the Volute Screw Press (VSP) filter was tested at proof-of-concept scale to assess its feasibility on dewatering fluid fine tailings (FFT). One of the advantages of the VSP is that it continuously filters feed sludge as opposed to intermittent/batch operation as in a conventional filter press.

Previously, in the Phase 1 work performed with the new VSP filter, the capability of continuously producing a filter cake of more than 60 weight percent (wt%) solids and a filtrate of less than 1 wt% solids from 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 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. 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, coagulants, and collectors from different chemical vendors were evaluated using the VSP filter in Phase 2.

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 installation 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. Additional sample analyses at Syncrude Research, data analyses, and report preparation were completed on March 2019.

The final project report was submitted to COSIA on April 15, 2019. As well, a project presentation was given to the COSIA Annual Project Update Meeting on May 1, 2019.

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 currently 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 VSP 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

The following are the lessons learned from this project:

- The Volute Screw Press (VSP) filter is capable of continuously producing ≥ 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;
- The CVST was found to be a good tool for screening the chemical schemes before the VSP tests;
- The PAM flocculant + polymeric coagulant outperformed the PAM flocculant + collector in the VSP tests; and,
- However, the current VSP equipment has a limited dry solids throughput, which is good for proof-of-concept tests. It is proposed to utilize a larger and newer generation of VSP named Swingmill to investigate FFT processability, equipment reliability, dry solids throughputs, and scale-up factors at a pilot scale.

PRESENTATIONS AND PUBLICATIONS

Published Theses

Wang, C., 2017. Flocculation-assisted dewatering of fluid fine tailings using a volute screw press. Ph.D. thesis, Department of Chemical and Materials Engineering, University of Alberta.

Journal Publications

Wang, C. et al, 2018. Flocculation-assisted dewatering of fluid fine tailings using a volute screw press. Can. J. Chem. Eng., https://doi.org/10.1002/cjce.23227

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, Principal Investigator		
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		

Treating Mature Fine Tailings Using Environmentally Safe Engineered Bacteria

COSIA Project Number: TE0065 (IOSI19)

Research Provider: Larry Unsworth, University of Alberta

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 1 of 3

PROJECT SUMMARY

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

PROGRESS AND ACHIEVEMENTS

Good progress has been made in preparing the DNA which will direct the biopolymer production and cell surface localization. Appropriate tailings bacterial strains have been identified from the literature and a compatible anchor system for generating the biopolymers and transporting them to the bacterial cell surface was defined. The DNA sequences for this anchor system and biopolymers to be tested were designed and synthesized. The biopolymer DNA sequences were concatemerized to create numerous highly-repetitive sequences which were then inserted into the anchor/display sequences. DNA sequencing has confirmed the final biopolymer products are correct and ready for production.

LESSONS LEARNED

There is no information that can be disclosed due to the recent initiation of the project.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Larry Unsworth

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Larry Unsworth	University of Alberta	Principal Investigator		
Markian Bahniuk	University of Alberta	Post-Doctoral Fellow		
Xiaoli Tan	University of Alberta	Research fellow		
Simon Yuan	Syncrude	Senior Associate – Chemical		

Pipeline Transport of Flocculated Tailings Materials

COSIA Project Number: TE0066 (IOSI19)

Research Provider: Coanda Research & Development Corporation

Industry Champions: Canadian Natural, Imperial, Suncor

Industry Collaborators: Syncrude, Teck

Status: Year 1 of 1

PROJECT SUMMARY

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

A previous project between Coanda Research & Development Corporation (Coanda) and COSIA member companies (COSIA project number TE0058 – RWG (IOSI18)[8]) explored the effects of shearing on the dewatering and compressibility of treated tailings. Flocculated fluid fine tailings (FFT) and re-flocculated thickened tailings (TT) tailings were produced using an in-line dynamic mixer. A large-scale Couette device was used to shear the samples. The material rheology, dewatering and consolidation performance characteristics were measured before and after shearing. Geotechnical measurements including seepage induced consolidometers (SICT), beam centrifuge and large strain consolidometers (LSC) were conducted on identical samples that only differed in the level or shear experienced. The project found that low levels of shear sometimes had beneficial effects for dewatering and consolidation, and that higher levels of shear degraded immediate performance, and possibly had a minor negative influence on long-term geotechnical performance.

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

[8] The research summary for COSIA project number TE0058 – RWG (IOSI18) Effects of Shearing on Dewatering and Compressibility of Treated Tailings, is included in this report.

PROGRESS AND ACHIEVEMENTS

Following a planning period, a tailings flow loop was constructed at Coanda's Burnaby, B.C. laboratory, leveraging existing tailings treatment infrastructure co-owned by several COSIA member companies. Initial commissioning experiments were performed by treating FFT with two types of polymer and recirculating the material around a closed-pipe loop. Samples of the same material were collected prior to entering the pipe loop and sheared in the Couette shear device that was used in the previous project (described above). The pipe flow and Couette shear conditions were determined based on expected field pipeline transport parameters, in particular a nominal laminar flow wall shear rate of 8 U/D, where U is the fluid velocity and D is the pipe diameter.

During the initial experiments, data were collected from a variety of instruments, including differential pressure transducers, video via transparent pipe sections, a particle vision and measurement (PVM) *in-situ* microscope, and a focused beam reflectance measurement (FBRM) *in-situ* particle size analyzer. Samples collected before and after shearing were evaluated for index tests for dewatering and material strength; i.e., capillary suction time, yield stress, permeability by vacuum filtration, net water release, and column settling. Analysis of the data has recently started to enable planning of the next set of experiments, including additional tests with FFT and evaluation of TT in the same apparatus.

LESSONS LEARNED

As the project is still in progress, there are no lessons learned available at this time.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigators: Clara Gomez, Scott Webster

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Scott Webster	Coanda Research & Development Corporation	Principal Investigator Research Scientist		
Clara Gomez	Coanda Research & Development Corporation	Principal Investigator Research Scientist		
Tayfun Aydin	Coanda Research & Development Corporation	Research Scientist		
Pravic Komal	Coanda Research & Development Corporation	Laboratory Technician		

Effect of Dispersants on Dispersion and Flocculation of Oil Sands Tailings

COSIA Project Number: TE0068 (IOSI19)

Research Provider: University of British Columbia

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Ongoing

PROJECT SUMMARY

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

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

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

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

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

Table 1. Characteristics of Various Types of Lignosulfonate

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

These reagents are mainly different in their levels of anionicity and molecular weights. Therefore, they would illustrate lignosulfonate capabilities as dispersants of oil sands tailings. Lignosulfonate is a by-product of the pulp and paper industry and is considered non-toxic (LD_{50}=5 g/kg). This reagent is a very strong dispersant and is typically used in oil well drilling muds as a mud thinner and as a water reducer for concrete.

PROGRESS AND ACHIEVEMENTS

Milestone	Activities	Methods	Status
1. Assessment of partition of dispersants between the solids and the solution phase. Determination of adsorption characteristics of dispersants on tailings.	• Characterization of tailings samples, mineralogy by X-RAY diffraction, particle size distribution, BET surface area, chemical assay including residual bitumen content. • Adsorption experiments with the measurement of equilibrium dispersant concentration in the aqueous phase. • Analysis of dispersant concentration in the aqueous phase using total organic carbon content. • Determination of the adsorption density of the dispersants on the solids from tailings.	X-RAY Diffraction, X-RAY Fluorescence, Brunauer-Emmett-Teller (BET) analysis, Cations & Anions analysis, Dean Stark, Total Carbon, Methylene Blue Index (MBI) characterization	100% Completed
2. Determination of the dispersing capabilities of the tested dispersants.	• Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage. • Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions. • Selection of dispersant dosages for flocculation studies.	Ultraviolet (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	80% Completed
3. Determination of the dispersing capabilities of the tested dispersants.	• Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage. • Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions. • Selection of dispersant dosages for flocculation studies.	Ultraviolet (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	80% Completed

Milestone	Activities	Methods	Status
4. Determination of the dispersing capabilities of the tested dispersants.	• Measurement of suspension turbidity and solids content in the supernatant as a function of dispersant dosage. • Comparison with the adsorption results to establish correlations between the surface coverage by the dispersant and the extent of dispersion of tailings suspensions. • Selection of dispersant dosages for flocculation studies.	Ultraviolet (UV) Spectrophotometry, Zeta potential, Total Carbon, Turbidity, Particle size distribution (PSD)	80% Completed
5. Effect of dispersants on flocculation of tailings suspensions.	• Flocculation experiments to determine settling rates, sediment volumes, solids contents, and turbidity in the supernatant. • Characterization of flocculated sediments using laser light backscattering in terms of root-mean square scattering, signal mean, and aggregation index to quantify the extent of aggregation/flocculation of the sediment. • Measurement of residual polymer concentrations in the aqueous phase after flocculation through analysis of Total Nitrogen content (for polyacrylamide-based flocculants). • Assessment of flocculant-dispersant interactions in solution through intrinsic viscosity measurements.	Laser light backscattering, Total Nitrogen content, Turbidity, Net water release, Yield stress, Solids content of deposit, Pressure filtration	Ongoing

LESSONS LEARNED

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

1. Based on laser backscattering measurements, D-619 is the strongest dispersant, releases the most amount of water, and causes fine particles to settle.

2. Based on partition analysis, most of the reagent gets adsorbed onto solid particles. UV-Vis spectrophotometry analysis indicates the amount of reagent remaining in the aqueous phase is the least when D-750 is used, followed by D-648 and D-619. Specifically, in the case of D-750, 100% of the reagent is adsorbed to the solids until the dosage is 500 g/t. This is important for water recycling purposes, as less effort would be required for decontamination of the recycled water.

3. Based on zeta potential experiments, adsorption of the reagent onto particles is the most when D-648 is used, followed by D-619 and D-750. This means that particles are more negatively charged when D-648 is the reagent, in comparison with the other two reagents. This is important for flocculation tests since the target is to enhance bitumen extraction while minimizing the impact on subsequent flocculation.

RESEARCH TEAM AND COLLABORATORS

Institution: University of British Columbia

Principal Investigator: Dr. Marek Pawlik

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Marek Pawlik	University of British Columbia	Professor, Principal Investigator		
Givemore Sakuhuni	Imperial	Research Scientist		
Atoosa Zahabi	Imperial	Research Scientist		
Hamid Alizadeh	University of British Columbia	Student	May, 2019	May, 2020

Accelerated Fluid Fine Tailings Consolidation with Electrokinetics

COSIA Project Number: TJ0016

Research Provider: ElectroKinetic Solutions Inc. (EKS)

Government and Industry Collaborators: Alberta Innovates, Sustainable Development Technology Canada, Natural Resources Canada, Canadian Natural, InnoTech Alberta

Academic Collaborators: University of Alberta, University of Calgary, University of Guelph, Western University

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 EKS–Dewatering Technology or the 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 m^3 and 25 m^3) at the C-FER Technologies (C-FER) facility in Edmonton. Canadian Natural (previously Shell Canada) and Suncor provided financial support for these lab-scale pilot tests.

The C-FER tests assessed the scalability of the technology and produced significant insights for the ongoing development of this technology. The results demonstrated that the EKS-DT process 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 to optimize the design and operation of the technology. This research resulted in significant innovations that improved dewatering performance allowing higher achievable final solids content with greater energy efficiency.

Building on these developments, a field demonstration program was initiated in 2019. A purpose-built test cell was constructed in spring 2019 at the InnoTech Alberta Vegreville research facility. The test cell measured 20 m x 25 m x 6 m deep. The test cell was filled in June 2019 with FFT sourced from Canadian Natural's Albian operations.

The electrode arrays were fabricated on site by EKS and deployed in October 2019. A power supply unit and automated control system were installed in a retrofitted sea can. The field test was commissioned in October 2019.

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 in a relatively short period of time. The field test is expected to run for at least one year. During and after the dewatering process, geotechnical and chemical analyses will be undertaken.

The field tests results will be used to address the following issues that are important for the commercialization of the technology:

1. The practicability of fabricating, installing and operating the EKS-DT process at a commercial scale;
2. The capital and deployment costs of an installation (including electrode arrays, power supply system, control system, instrumentation);
3. The operating costs to achieve different levels of dewatering/consolidation (the operating costs are almost exclusivity electricity costs);
4. The dewatering rate and energy consumption at operating costs to different levels of applied power and at different stages in the dewatering/consolidation process;
5. The maximum power requirements over the course of the dewatering process;
6. The vertical movement of the electrodes during the dewatering process;
7. The vertical and horizontal density gradients formed during the dewatering process;
8. The formation of cracks during the later stages of the dewatering process and their impact;
9. Power attenuation along the length of the electrodes; and
10. The amount and pattern of anode corrosion over the duration of the dewatering process.

PROGRESS AND ACHIEVEMENTS

The following milestones have been achieved:

- The test cell was filled with FFT in June 2019.
- The electrodes arrays were fabricated on site and deployed.
- The instrumentation system, power supply and the control systems were installed and commissioned by October 2019.
- The field demonstration program was fully operational in October 2019.

Concurrently, a comprehensive research lab program is underway in collaboration with the Universities of Alberta and Guelph. The results of these experiments will inform the operation of the field test and the design of commercial installations.

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 for the engineering of commercial-scale installations, including:

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

- final solids content; and
- anode corrosion.

The data from the field test and the lab tests will be used to calibrate the forecasting system.

PRESENTATIONS AND PUBLICATIONS

A series of Microsoft PowerPoint™ presentations, research reports and question-and-answer documents have been prepared. As well, a peer-reviewed comparative life cycle analysis has been prepared that analyzes 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)
Dr. Tinu Abraham	EKS	Researcher		
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 Funding Partners (2011 – present): Alberta Innovates; Shell Canada (up until June 2017); Canadian Natural; Natural Resources Canada; Suncor; Sustainable Development Technology Canada

Clay Removal from Fluid Fine Tailings

COSIA Project Number: TJ0031

Research Provider: Syncrude

Industry Champion: Syncrude

Industry Collaborators: Teck

Status: Year 5 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 Research & Development 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 dewaters 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 has successfully conducted laboratory proof-of-concept tests, small pilot tests for clay flotation, and field pilot test for FFT clay treatment. Both Processes A and B can be conducted in situ or near a tailings pond.

The main objective of the project is to develop alternative technologies for deployment that would augment current commercial technologies such as composite tailings, 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 bench scale.

The pilot clay flotation tests were conducted in a continuous mode using the same chemical recipe as that in the laboratory 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 cell. 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.

The clay flotation concept is also applied for selective flotation of clay from fresh oil sand tailings such as Composite Tailings (CT) cyclone overflow and flotation tailings from bitumen extraction. The preliminary laboratory test data showed that it is feasible to float out the problematic clay minerals from the CT cyclone overflow and flotation tailings from bitumen extraction. In addition, a new concept of in-line clay frothing of FFT treated with the flocculant-collector recipe is being tested. Moreover, the Large Strain Consolidation (LSC) tests and the geotechnical beam centrifuge tests of FFT treated with different collectors are ongoing.

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 laboratory 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 in-line dynamic mixer and then mixed with a collector in another in-line dynamic mixer in sequence. The treated FFT stream was pipelined to fill the deposition cell. The clear water was rapidly 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.

The concept-proof tests of in-situ treatment of FFT were conducted with a submerged mixer traversing through the FFT, and at the same time mixing the flocculant solution with the FFT in a flume. The systematic studies on the types of impellers, impeller rotation speeds, mixer traversing speeds along the flume, with and without the use of a shroud around the impeller, and the rheological effect on the mixing patterns and efficiency were conducted using transparent Carbopol fluids with varying yield stresses. Under the optimal test conditions obtained from the tests with Carbopol, FFT was tested with the in-situ test facility. The test results demonstrated that it was feasible to effectively treat FFT in situ in the flume.

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.

The concept-proof tests of in-situ treatment of FFT were successfully conducted with a submerged mixer. The test results demonstrated that it was feasible to effectively treat FFT in situ in the flume. It is expected that the in-situ treatment of FFT in a tailings pond should also be feasible. The selective clay flotation from fresh tailings, in-line clay frothing of treated FFT, LSC and beam centrifuge tests are still ongoing.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigator: Simon Yuan

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Weibing Gan	Teck	Section Leader		
David Lin	Teck	Principal Metallurgist		
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Mike Di Marco	Teck	Manager, Mine Engineering		
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Amarebh Sorta	Coanda Research & Development Corporation	Geotechnical Engineer		
Gonzalo Zambrano	University of Alberta	Research Director		

Engineered Tailings Research

COSIA Project Number: TJ0033

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Year 5 of 7

PROJECT SUMMARY

Engineered Tailings Research is seeking new technology options for tailings treatment aimed at reducing capital and operating 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 activities were the scope of Engineered Tailings Research:

1) Geotechnical property measurements of the low sand-to-fines ratio (SFR) products resulting from co-processing of fresh tailings directly from the extraction process and FFT using modern paste 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.
3) More fines capture from composite tailings (CT) cyclone overflow.

Following the successful lab and small pilot tests of co-processing of fresh tailings from bitumen extraction and legacy FFT (as per D085[9]) using modern paste tailings technology, the geotechnical properties of the low SFR co-processed 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. The hypothesis of co-processing of fresh tailings and FFT is that the dewatering rate could be accelerated with the increase in SFR in the polymer treated co-processed deposit. The objective of this activity is to prove the hypothesis and provide the technical foundation to further develop the co-processing technology in a field scale, and eventually implement this technology at a commercial scale.

For the polymer evaluation, laboratory 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.

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[9] D085 – *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects* issued by the Alberta Energy Regulator (2017)

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

PROGRESS AND ACHIEVEMENTS

The geotechnical property measurements of the low SFR co-processed products demonstrated that the Atterberg limits; i.e., liquid limit, plastic limit and plasticity index, decrease with the increase in SFR in the co-processed products. The hydraulic conductivities increase significantly with the increase in SFR in the co-processed products at the same void ratio. The compressibility of the co-processed products under the same effective stress is also increased when the SFR in the co-processed 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-processed 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.

Characterization of the Aurora site's CT cyclone overflow showed that it was comprised of more than 90% fines (solid particles with diameters less than 44 µm). The flocculation test results demonstrated that it is feasible to treat the CT cyclone overflow with the polymeric flocculant in the pipeline before it is discharged into the deposition cell.

LESSONS LEARNED

The geotechnical property measurements showed that the hydraulic conductivities significantly increased with the increase in SFR in the co-processed products at the same void ratio. These data proved the hypothesis and provided the technical foundation to further develop the co-processing technology in a field scale and implement this technology at a commercial scale. The potential benefit of co-processing of fresh tailings and FFT is that this technology not only treats the legacy[10] 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.

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

[10] legacy tailings, as defined in *Directive 085*, are fluid tailings in storage before January 1, 2015

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

Principal Investigator: Simon Yuan

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Fluid Tailings Removal Optimization

COSIA Project Number: TJ0076

Research Provider: Suncor and Tetra Tech

Industry Champion: Suncor

Status: Completed 2015

PROJECT SUMMARY

Fluid tailings treatment processes benefit from stability in supply and material properties. Harvesting oil sands fluid tailings from a settling basin requires consideration of numerous aspects, including material density, rheology, clay content, debris and operational logistics. These aspects inform the selection of the appropriate hydraulic dredger.

This field pilot project investigated the hydraulic characteristics of fluid tailings removal with the goals of stabilizing material properties for fluid tailings feed treatment operations and improving operational logistics.

In 2014 the field pilot was initiated to:

1. Validate the hydraulic characteristics using a generated data set;
2. Determine the effectiveness of surface mounted pumps for removing high density and yield stress fluid tailings material;
3. Improve the effectiveness of fluid tailings selectivity for treatment operations; and
4. Avoid debris dispersal throughout the settling basin.

PROGRESS AND ACHIEVEMENTS

The field pilot was completed in the fourth quarter of 2014.

LESSONS LEARNED

The key outcomes from the field pilot included:

1. Hydraulic calculations for high density and yield stress material were validated;
2. Selectivity of fluid tailings from the settling basin was improved over current practices;
3. The ability to avoid debris was unsuccessful as particle passing size of the trial pump was restricted during the field pilot; and
4. Lift pumps were made workable during the field pilot; however, they are not ideally suited for this service.

PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

Internal reports highlighting the field pilot were generated; however, there is no direct commercial application.

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor

Permanent Aquatic Storage Structure for Fluid Fine Tailings

COSIA Project Number: TJ0082

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

Industry Champion: Suncor

Industry Collaborators: Teck

Status: Year 4 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 principal parameters to levels that meet federal and provincial guidelines for freshwater lakes shortly after the end of deposition. The water expressed from the substrate during the deposition period must also meet the criteria for use in bitumen production, as the water is recycled to the process water loop.

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

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

The PASS FFT treatment solution leveraged decades of research and development in oil sands and mineral mine fluid tailings, bitumen extraction processes and waste water treatment to simultaneously create a geochemically and geotechnically stable aquatic reclamation substrate. And given the long deposition periods and variability of the FFT feed, performance models were also developed to predict the deposit geochemical and geotechnical trajectories. These models are supported and validated by bench and pilot scale geocolumns that would be monitored over several years.

PROGRESS AND ACHIEVEMENTS

- Research hypothesis: Long-term immobilization of material of potential concern (principal parameters) in a PASS deposit
    - Ongoing monitoring of the 5-m geocolumns simulating several treatment variables indicate that the principal parameters remain immobilized and in line with the design basis. However, as the deposits become anoxic, the solubility of several parameters may change, which in the long run could inform the type of immobilization chemistry used in future implementations of the technology. The research also indicates that both aluminum and iron (III) based coagulants (beyond a threshold dosage) are effective at immobilizing the principal parameters in the short-term while minimizing the impact on rapid water release after flocculant addition.
- Research hypothesis: Rapid dewatering of treated FFT through flocculant addition
    - A new static polymer injector was designed to maximize the flocculation efficiency in high throughput operations, with FFT feed flows ranging from laminar to turbulent. The injector design, coupled with modelling of the pipe shear experienced by the flocculated FFT during transport over several kilometers, ensures that the treated FFT floc sizes at the deposition point could be "dialed in" to satisfy competing objectives of rapid dewatering and very low stacking angles in the mined-out pit.
    - A bench top geotechnical centrifuge was developed to simulate treated-FFT settlement in a deep deposit. The geotechnical centrifuge can be used for rapid monitoring of short- and long-term geotechnical behaviour, with feedback to the process within a day.

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. In addition to the long-term objective, a more efficient static polymer injector also improves the dewatering rates of the treated FFT to further support water use in the extraction process.

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 treated FFT placed in-pit.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

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

RESEARCH TEAM AND COLLABORATORS

Institution: Suncor

Principal Investigator: Oladipo Omotoso

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Adrian Revington	Suncor	Lead Technology (extraction/tailings)		
John Diep	Coanda Research and Development	Process Engineering		
Benny Moyls	Coanda Research and Development	Process Engineering		
Matt Lindsay	University of Saskatchewan	Associate Professor		
Macoura Kone	SRK Consulting	Senior Geochemist		
Daryl Hockley	SRK Consulting	Corporate Consultant		

Outotec PSI500i® Instrument Field Test

COSIA Project Number: TJ0094 and TJ0115

Research Providers: Teck CESL test facility/ Teck (TJ0094) and ExxonMobil Research/Imperial (TJ0094)/Canadian Natural (TJ0115)

Industry Champions: Teck (TJ0094), Canadian Natural (TJ0115)

Industry Collaborators: Imperial, Suncor, Outotec

Status: Year 4 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 the Outotec PSI500i® 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 completed for this scope of work.

Phase 1: The existing Outotec PSI500® oil sands units were removed from site and transported to the Teck CESL test facility in Richmond, BC. One of the units was commissioned and put 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 instrument 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 COSIA Joint Industry Project (JIP), TJ0094, longer-term testing in the field was conducted 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 in-line tailings treatment process control. This work includes 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 during one week.

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

The instrument key performance was evaluated on-line through:

- Accuracy – the accuracy was 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 sand-to-fines ratios (SFR) and solids content range of flotation tailings.
- Maintenance requirement (with/without automatic wiper) – how often the instrument maintenance and manual cleaning was required 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 the Outotec PSI500i® particle size analyzer on oil sands samples from different operations were conducted. Tests were performed by recirculating the slurry in closed circuit to simulate real plant conditions. This JIP, led by Teck, 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 and 2019 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.

In 2019, we were successful at developing an alternative feed system that is able to provide a slurry feed to the instrument continuously. The original feed system design was to have a continuous slurry feed rate of 50-100 L/minute, with the continuous feed flow going through a sample cutter and an appropriate amount of slurry—enough for a subsample—into the measurement dilution tank. Controlling the feed flow rate was challenging because of the presence of petrified wood in the analyzer feed which resulted in plugging when throttling changes were attempted. Several potential solutions were tested to achieve 50L-100 L of continuous slurry feed, however, all appeared to be unsuccessful.

An alternative feed system was designed and tested. An auto-sampler was synchronized with the Outotec PSI500i® to obtain the appropriate amount of sample. The sample volume per cycle was 25 mL. A sample receiver was made and placed under the auto-sampler outlet, and the water flush line originally used for the cutter wash were re-located to the sample receiver. A screen with the opening of 2.38 mm was placed inside of the sample receiver to collect any trash. A 19 mm (¾'') hose with Teflon liner was used to transfer the tailings sample from the sample receiver into the dilution tank. The main advantage of using an autosampler is that the slurry volume to be handled is small. For each measurement, only 50-100 mL slurry is needed and no slurry return is needed. We believe that the sample from the auto-sampler is representative as the auto-sampler is located near the pump outlet where mixing is good. The auto-sampler was successfully synchronized with the Outotec PSI500i®. When the analyzer is requesting the sample, a signal was sent to the PLC and the autosampler will be triggered to take one stoke sample. The number of stokes can be set up by Outotec PSI500i® sample cut numbers. The rule of thumb for the recommend sample volume is to have the lowest transmission around 50%. Depending on the solids and fine content in the slurry feed, the flotation tailings sample cut numbers were in the range of 2-4, which means 50-100 mL flotation tailings. During the over 200 h of continuous testing, the auto-sampler worked well with no concerns with regards to its robustness.

With the success of the new feed system, the instrument was tested with live flotation tailings. The accuracy of the instrument was thoroughly evaluated by comparing the instrument reading and the lab results for over 100 samples. It was found that measured fines content (<44 µm, <11 µm and <1.9 µm) was strongly correlated with lab data and measured particle size distributions D90, D50 & D10 which are the intercepts for 10%, 50% and 90% of the cumulative mass was correlated to lab analysis; however, not as strongly as measured fines content. Although the instrument constantly reported higher fines content, the trending well reflected the feed PSD change, which is good for process control.

Lens fouling was successfully mitigated by using cold dilution water, an automated chemical wash, and window wiper. No lens fouling was observed within the 90 h of continuous operation. The manual cleaning interval could be a month or longer. The sample receiver and dilution tank need to be cleaned weekly with the automation strategies applied.

The effectiveness of hot flush water to mitigate bitumen fouling was also studied. The flush water temperatures were set up at 40°C, 60°C and 80°C. Using warm flush water resulted in the reporting of more larger particle sizes, which was problematic as—based on the lab results—they did not actually exist in the sample. The analysis showed that using warm/hot water for flushing with cold dilution water is not recommended. If the hot water flush was chosen for the tank cleaning, both dilution and flush water needs to be hot and the reading during that period needs to be discarded.

Various qualities of dilution water were also tested to investigate the impact of dilution water quality on the accuracy of the instrument. Raw water with turbidity between 8.6-43.2 NTU was used to investigate the impact of the dilution water quality on the measurement. Using raw water did not affect the correlation strength of the fines percentage, D90, D50, D10 between the lab measurement and the PSI500i® analyzer reading. It was concluded that using raw water with turbidity less than 50 NTU could be used for trending.

The new 200 mm laser head performed well. The laser head alignment was stable and no detectors required disabling, resulting in the wide measurement range of up to 742 µm.

Testing of the instrument was completed in 2019. A procedure has been developed to successfully trend the fines content in the flotation tailings.

LESSONS LEARNED

COSIA Project TJ0094

The lessons learned from the initial lab and pilot testing included:

The on-stream analyzer performed well at detecting different size fractions accurately. There was good agreement between lab and analyzer for fine fractions <44 µm, and clay <10 µm and < 2 µm. 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 field test are outlined below:

It was difficult to obtain 50-100 L/min representative flotation tailings because of the existence of large pieces of petrified wood in the slurry. Using the auto-sampler at the right location can provide the required sample and avoid handling the slipstream sample.

For the light scattering system to measure the particle size, warm/hot dilution water should be avoided. The water's optical properties and the existence of tiny air bubbles will affect the PSD measurement.

For oil sands tailings, the application of Outotec PSI500i® resulted in the level switch for the dilution water surface detection quickly becoming fouled. A non-direct contact level switch is recommended when used for oil sands tailings.

The fines in water settled in the water storage tank, which gave inconsistent dilution water quality. It was better to interlock the dilution water quality with the background measurement. If the dilution water quality changes to some extent, the background should be re-measured to reflect the changes to the dilution water quality.

The chemical wash and wipe sequence can also be interlocked with the background signal so it will only be triggered when the lenses become fouled.

A pilot test with live feed is necessary for on-line instrument development.

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

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In-line Flocculation: Instrumentation and Control Support Work and Field Pilots

COSIA Project Number: TJ0106

Research Provider: Coanda Research and Development

Industry Champion: Canadian Natural

Industry Collaborators: None in 2019 (Syncrude in 2017 and 2018)

Status: Ongoing since 2017

PROJECT SUMMARY

The purpose of this project is to develop the different elements of an instrumentation and control system for In-line flocculation (ILF) of tailings. Chemical amendments such as polymeric flocculants are widely considered for use in a number of tailings treatment technologies. ILF offers one of the most effective and simple ways to introduce chemical amendments for tailings treatment.

Typically, polymeric flocculants such as polyacrylamides (PAMs) are used to dewater oil sands mature fine tailings (MFT). Although this process has shown promising results at a laboratory scale (i.e., in a controlled environment), there are numerous challenges when using PAMs on a field scale. These challenges include:

- the constant variation in feed characteristics (of the MFT); and
- the limited control of chemical (flocculant) dosage during in-line flocculation.

The challenges of feed variability and control of chemical dosage may affect the flocculation process and hence, consolidation of the tailings deposit. The process is also shear sensitive; i.e., the quality of the treated tailings (with PAMs) can deteriorate or may not achieve the desired target without the appropriate shear environment.

In order to maintain the right intensity and process conditions for chemical treatment, the ability to control and mix high density and high viscosity streams needs to be developed. Laboratory studies were conducted to understand the effects of:

- variability of the raw (untreated) tailings (e.g., solids and clay contents);
- process fluctuations on the chemical treatment;
- the delivery mechanism of the chemical amendment to the tailings stream; and
- polymeric treatment on the end product performance; i.e., whether the treatment generates products with the required properties allowing effective long-term dewatering and consolidation of tailings and land reclamation.

However, accounting for these variations while building an effective and robust control system to produce on-spec flocculated materials from a dewatering perspective, material strength and long-term consolidation properties was a relatively uncharted territory until a previous COSIA project was specifically targeted to do so. A small-scale, conceptual prototype was constructed and pilot-tested in a laboratory at the Saskatchewan Research Council (SRC). The system used in-line dynamic mixing with instruments for feed characterization and product quality assessment. However, with our evolving understanding of the above technological uncertainties, the different elements of the control system need to be modified and field-tested on an ongoing basis. Also, since the prototype is at a conceptual state largely built with laboratory instruments, significant continuing effort is required to develop these to a field-ready state.

The technological objective of this project is to continue developing the different elements of an automated and continuously operable in-line system for chemical treatment of tailings. An effective control system would ensure on-spec flocculation of tailings, enabling rapid dewatering and consolidation, and ultimately leading to effective water recovery and land reclamation.

PROGRESS AND ACHIEVEMENTS

In 2017, a Joint Industry Project (JIP) was created with Syncrude. The field scale ILF prototype was tested at a limited capacity at the Syncrude Mildred Lake Accelerated Dewatering Phase 2 pilot with commercial-scale flow rates. Performance of the prototype, during a limited test period, focused on the ability to react and properly control flocculant dosing of various tailings feed and consistency conditions. The Syncrude test program addressed operational issues, which resulted in the design of new tools and accessories. Mathematical techniques and programming were also improved.

In 2018, the design of these new tools, accessories and mathematical techniques/programming continued along with additional testing and data analysis of the Syncrude field test program. Laboratory testing of newly designed instrument accessories to prevent fouling and damage of instruments from harsh process conditions and handling was performed. New methods and software for improved prediction and control of the flocculation process were studied. Other key 2018 activities included continuation of laboratory-scale development of a feed-forward mapping for the control system as a function of process variabilities (density and clay contents, etc.) for polymers other than the widely used PAMs for better dewatering and consolidation performance of treated tailings.

In 2019 more effective mathematical prediction methods for flocculation control was explored. This is intended to construct a more effective predictive tool for the control system that uses a different logic compared to the current model, which had some overlap in differentiating between different classes of flocculated tailings.

A laboratory project to improve the performance of clay content prediction in tailings was also launched. The current model is based on limited data and is applicable to tailings of certain characteristics. The new project involves rebuilding the model based on analyses of a large number of samples collected from different depths of various tailings ponds. The revised model is expected to be much more robust.

Field-testing of the newly designed (2018) tools and accessories (spool pieces, cleaning system) was also performed in 2019. One of the concerns of using optical instruments is fouling from use in a bitumen-containing environment, which can ultimately result in sub-optimal performance. Online cleaning systems designed to eliminate fouling without interruption of the process were tested for more than two months of continuous operating time. Also, better methods for data acquisition, transfer and storage and modifications of the control software were tested.

LESSONS LEARNED

The technological advancement sought from this project was to develop an automated and continuously operable in-line system for chemical treatment of tailings, allowing rapid dewatering and consolidation of the tailings, ultimately leading to effective water recovery and land reclamation.

Between 2017 and 2019 the project had identified and tested the individual components required for characterization of the various streams in the inline flocculation process as well as the overall control scheme utilizing these components at the field environment at a limited capacity.

A key focus of the work in 2019 was to understand the limitations of the current prediction method for the variations within the flocculated tailings. Passive post-analyses of data generated from past pilots demonstrated that a novel approach can potentially be used as a more efficient and accurate alternative. This would result in an improvement of the overall performance of the control system.

A preliminary finding from the ongoing work on the clay content prediction—based on models from site samples—appears to be a robust tool. However, the model is still in its infancy and will require integration of additional data from the ongoing work.

Field-testing of the hardware improvements demonstrated the advances made in 2019 to eliminate/reduce fouling of the optical instruments in a bituminous and harsh environment. Also, better data acquisition, transfer and storage systems tested in the field resulted in improved performance of the control system as a whole.

RESEARCH TEAM AND COLLABORATORS

Institutions: Coanda Research & Development Corporation and Canadian Natural

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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Scott Webster	Coanda Research & Development Corporation			

Accelerated Dewatering / Rim Ditching

COSIA Project Number: TJ0109

Research Provider: Syncrude

Industry Champion: Syncrude

Status: Ongoing

PROJECT SUMMARY

Accelerated dewatering (ADW) or rim ditching is a tailings treatment process that involves the in-line mixing of a chemical amendment with fluid fine tailings (FFT), followed by prompt removal of the initial water release, and subsequently, 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. Further dewatering and densification of the treated FFT is accomplished through a combination of self-weight consolidation, atmospheric drying and under-drainage. To date, three sets of pilot deposits have been created, 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 field 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. Each of these pilot deposits was approximately 10 m deep with a volume of 60,000-70,000 m^3. Long-term dewatering and consolidation trajectories for the pilot deposits are tracked through in-situ monitoring, testing and sampling. Analysis showed that the initial dewatering and geotechnical performance of the two 2017 ADW deposits are superior to that of the 2009 ADW deposit. This confirms that the process improvements implemented for the newer ADW deposits are effective in significantly improving the deposit performance. All three ADW deposits are being continuously monitored to assess their long-term geotechnical performance.

PROGRESS AND ACHIEVEMENTS

All three ADW deposits had similar geotechnical index properties. However, the average initial solids content for the 2017 ADW deposits was ~10% higher compared to the 2009 deposit. Correspondingly, the fines-over-fines plus water (FOFW) for the two new ADW deposits was also higher compared to the 2009 deposit. This behaviour confirms that the improved ADW process was successful in creating tailings product that has superior initial dewatering properties compared to the 2009 ADW deposit. Also, the initial profiles of undrained shear strength for the newer ADW deposits were significantly higher compared to the 2009 ADW deposit. The year-over-year comparison of the percentage solids content, FOFW and undrained shear strength of both newer ADW deposits showed a full-depth increase, a pattern that was not observed at any time over the 10-year monitoring period for the 2009 ADW deposit.

The consolidation material properties of the 2017 ADW deposits are currently being assessed to confirm the impact of the improved ADW process on the intrinsic fabric properties of the new ADW.

LESSONS LEARNED

The process improvements implemented for the ADW in 2017 were very effective in terms of both the initial dewatering performance as well as the geotechnical properties of the treated FFT. Efficient in-line mixing and the pre-conditioning of the FFT using gypsum prior to flocculation and making the FFT hydrophobic after flocculation produced on-spec material. The protocols and effective process control strategies developed to achieve flocculation and hydrophobic treatment of FFT on a continuous basis represents a significant improvement for the ADW technology. It has been demonstrated that the improved ADW process is capable of producing geotechnically-competent material that is on a trajectory to becoming integrated into the closure landscape.

RESEARCH TEAM AND COLLABORATORS

Institution: Syncrude

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)
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Robertino Hertanto	Syncrude	Senior Associate- Chemical		
Barry Bara	Syncrude	Senior Associate - Mechanical		
Simon Yuan	Syncrude	Senior Associate - Chemical		
Chris Schroeter	Syncrude	Senior Technologist		
Randy Mikula	Kalium Research	Consultant		

Geobags Pilot Study

COSIA Project Number: TJ0112

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Industry Collaborators: Teck

Status: Pilot Completed; Deposit Monitoring Year 2 of 3

PROJECT SUMMARY

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

The goal of the pilot was to collect all 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 m^3 of storage. The FFT was pumped from the pond through a system where it was treated with chemical amendments and exposed to a variety of mixing and shear regimes prior to flowing into the bags. A site was prepared that enabled drainage while maximizing the use of the bag volume. Bags of different sizes were used to test the effects of scaling. Bags were stacked one on top of the other. Run-off water from the bags was collected for analysis. Much attention was paid to operational issues as well. Safety and efficiency were principal operational considerations for the pilot study. Lessons learned from the pilot study will be valuable for future commercial evaluation of the technology.

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

PROGRESS AND ACHIEVEMENTS

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

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

- Chemical amendment (treatment) recipes tested included commercially available polymers (flocculants) and alum. The polymers included Dow XUR, SNF 3338, and BASF 1047; and
- Operational lessons learned will inform the design for a viable commercial operation.

The bags are expected to continue dewatering over time. The impact of freeze-thaw was evaluated in 2019. Two geotechnical sampling campaigns were completed in June and September of 2019. The solids content and strength numbers increased between original deposition in 2018 and the sampling in 2019.

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

LESSONS LEARNED

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

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural, Chevron

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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Monica Ansah-Sam	Canadian Natural	Engineer, Tailings Support		
Brittany Skinner	Canadian Natural	EIT, Tailings		
Jason Hill	Canadian Natural	Engineer, Process Innovation		
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Pressure Filtration for Fluid Fine Tailings Treatment

COSIA Project Number: TJ0113

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Industry Collaborators: Teck

Status: Year 7 of 7 (Site pilot completed)

PROJECT SUMMARY

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

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

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

PROGRESS AND ACHIEVEMENTS

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

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

LESSONS LEARNED

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

Solids content achieved in the filter press cakes ranged from 50-70% by weight throughout the project. An average of 63% by weight was achieved over the ~215 runs performed over the course of July and August 2019. There is a strong strength to solids content correlation.

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

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigator: Gavin Freeman

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Gavin Freeman	Canadian Natural	Lead Process Innovation Principal Investigator		
Peter Stapleton	Canadian Natural	Tech. Dev. Lead		
Jason Hill	Canadian Natural	Tech. Dev. Engineer		
Madelaine De Guerre	Teck	Mine Engineer, EIT		
Sreekumar Nair	Canadian Natural	Tech. Dev. Engineer		
Cynthia Cote	Canadian Natural	Tech. Dev. Engineer		

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

Non-segregating Tailings Hydraulic Infrastructure Analysis

COSIA Project Number: TJ0116

Research Provider: Barr Engineering and Environmental Science Canada Ltd.

Industry Champion: Canadian Natural

Status: Completed

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 is an engineered, fines-water-sand slurry that is conveyed to and deposited in tailings deposition areas. NST results in a tailings deposit where the fines (particles less than 44 microns in size) primarily stay within the sand matrix. The NST mixture of coarse sand and fines can be pumped, settles rapidly, densifies, and becomes trafficable upon consolidation. The current method for producing NST is to use thickener underflow combined with a sand stream from a cyclone underflow, which is then treated with carbon dioxide.

The current project is a high-level hydraulic analysis that informs the next design phases of Canadian Natural's transition to depositing non-segregating tailings (NST) in Dedicated Disposal Area 2 (DDA2), which is within a previously mined portion of the Horizon mine. Using previously mined lands for tailings deposition is positive from an overall land disturbance perspective. Currently, NST is deposited in the Horizon mine External Tailings Facility (ETF). Canadian Natural will begin to deposit NST in DDA2 during 2020.

This study had two primary objectives. The first study objective was to determine the number and preliminary location of NST booster pumps along the planned five NST delivery pipelines. The second study objective was to develop energy management concepts to minimize negative impacts on NST performance resulting from the NST being conveyed between the crest and floor of the Horizon mine pit, a vertical distance of about 95 metres. The NST pipelines will be placed on soil ramps at about a 7% grade between the mine pit crest and floor of DDA2. The primary NST performance concern is that without energy management mitigations, air will likely being entrained in the NST and it is believed that this will result in increased segregation of the fines from the sand matrix when the NST is deposited.

The study generally applied existing oil sands tailings slurry flow knowledge including the use of the Saskatchewan Research Council's SRC PipeFlow 10.2 software. The study was performed between November 2017 and November 2018.

PROGRESS AND ACHIEVEMENTS

The study concluded that:

- 36 booster pumps (some of which are existing) will be required along the about 41 kilometres of 26-inch outside diameter NST pipeline during the life of DDA2. Booster pump location guidance was also provided.
- Energy management will be an issue for about the first two years on three of the five NST pipelines and that three energy management concepts should be advanced to the next design phase. These concepts are:
    - the use of smaller (21 +/- inch inside) diameter pipe along a portion of the ramps;
    - the use of about six, 19-inch diameter eccentric orifices or the use of venturi sections in the pipelines along the ramps; and
    - the need for special energy management measures should be re-evaluated given that there is a relatively short time period during which energy management is an issue and given that there is no known research to validate the NST sand-fines segregation concern due to air-entrainment in the NST. As part of the next design phase, Canadian Natural will also conduct experiments on the impact to NST deposit performance resulting from air-entrainment into NST flowing in a pipeline.

LESSONS LEARNED

The NST energy management study and its conclusions regarding preserving NST performance may be valuable to other oil sands operators that use the NST technology and have a similar physical disposal situation (e.g., in-pit disposal resulting in the need to convey NST down steep ramps).

The high-level hydraulic analysis of our new NST pipeline system applied existing industry knowledge and concepts as part of our design process and did not advance industry knowledge.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

Principal Investigator: Barr Engineering and Environmental Science Canada Ltd.

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Lisa Dueck	Canadian Natural			
Connor Merkel	Canadian Natural			
Alan Fandrey	Barr Engineering and Environmental Science Canada Ltd.			

Enhanced In-line Flocculation of Fluid Fine Tailings Field Pilot

COSIA Project Number: TJ0118

Research Provider: Imperial

Industry Champion: Imperial

Status: Year 1 of 2

PROJECT SUMMARY

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

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

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

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

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

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

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

PROGRESS AND ACHIEVEMENTS

The lab scale study of the enhanced chemistry project showed improvement in the KPIs of treated FFT when compared to the single polymer treated FFT. Data analysis of the results from the field pilot is ongoing; however, the available data show that the eILF field pilot performed better than the single polymer; i.e., having higher solids content and strength, and the released water from the eILF deposit was clearer compared to the single polymer treated deposit. The final results will be shared in subsequent COSIA tailings research reports.

The variability of the eILF treatment feed; in particular, its higher solids content range (30-35 wt%) compared to 25-30% wt % solids content range for the single polymer treatment, affected its flocculation efficacy. These ranges of solids content were higher than the original FFT treatment design of 16-25 wt% solids content. However, the eILF treatment field pilot demonstrated its robustness to handle a wide range of solids content. This can be beneficial for handling feed fluctuations inherent in oil sands deposits and processing, and to significantly improve the efficacy of the eILF treatment process when compared to the single polymer treatment process.

LESSONS LEARNED

The main lesson learned from the field pilot was the FFT dredging challenges from the TT panels. The pump was plugged continuously and a consistent flow of FFT was not achievable. The plugging challenge was addressed by using a larger pump, as setting up a screen on the smaller pump did not resolve the problem.

RESEARCH TEAM AND COLLABORATORS

Institution: Imperial

Principal Investigator: Atoosa Zahabi

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
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Givemore Sakuhuni	Imperial	Research Scientist		
Jennifer Haverhals	Imperial	Senior Regulatory Advisor		
Reza Moussavi Nik[1]	Imperial	Tailings Advisor		

[1] Previously with Shell Canada Limited

Modified Atmospheric Fines Drying (MAFD)

COSIA Project Number: TJ0120

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Lab scale testing and field scale pilot complete

PROJECT SUMMARY

Atmospheric Fines Drying (AFD) is a method to treat fluid fine tailings (FFT). The technology is applied by focusing on using flocculation with anionic polymers to treat FFT that is then deposited in close-ended drying cells. Modified Atmospheric Fines Drying (MAFD) expanded on the typical AFD process by using a dual treatment strategy of coagulation, followed by flocculation with anionic polymers, to treat FFT that would then be deposited in thin layers on the beach of a tailings pond (open-ended beach drainage). This was the first field application of open-ended beach drainage at the Canadian Natural Jackpine Mine (JPM).

The new treatment process is based on decreasing the surface charge density by coagulation, or simply the repulsive forces of the fine particles, allowing for more efficient flocculation. Furthermore, the deposition strategy on the beach of a tailings pond, versus close-ended drying cells, is intended to provide a positive drainage towards the tailings pond. This is also expected to promote rapid dewatering and strength gain. Similar to typical AFD projects, dewatering is expected to occur over time through consolidation, under-drainage, evaporation and freeze-thaw effects. The main uncertainties associated with the MAFD process were related to the unidentified effects of coagulation on release water chemistry and the ability of the treated tailings to form a beach deposit.

MAFD performance was tested at a laboratory scale before testing at a field scale to address the associated uncertainties. A rigorous experimental program was conducted from April to May 2018, testing various combinations of anionic polymers and a coagulant to treat FFT for a beach deposition application—to analyze the initial water release—and the effect on release water chemistry.

It was found that using higher dosages of coagulant (4,500 and 6,500 g/t of solids) led to a higher dissolved calcium content in the release water. Additionally, using the lowest tested dosage of coagulant at 2,500 g/t of solids led to the highest initial solids content upon discharging the mixture. It is recommended to repeat the testing using the lowest dosage of coagulant to confirm the results.

The testing then proceeded to a field scale trial carried out at JPM from August to October 2018. The total volume of FFT treated by MAFD was 0.21 Mm^3. Treated tailings were deposited in thin layers, on the coarse sand tailings (CST) containing beaches of the tailings pond Sand Cell 2 (SC 2) at JPM. The project consisted of 39 spigot locations, across four cells. Prior to deposition, the majority of the beach was relatively flat and extended approximately 200 m from the spigot locations to the edge of the tailings pond. Flocculation, with two different anionic polymers, was examined. Coagulation could not be tested during the field trial due to the unavailability of the required chemical skid. Different deposition methods were explored at numerous locations using different spigot configurations. It was found that using spigots extended deep into the cell were effective in providing better coverage of the deposit.

PROGRESS AND ACHIEVEMENTS

Deposit samples were collected to evaluate the solids content, thickness, strength and performance. Analyses of trial results showed that MAFD was effective at producing relatively thin layers of treated tailings.

MAFD deposit samples at several locations were collected:

- In November 2018, the average solids content was 50.7% and the average thickness was 0.45 m
- In June 2019, the average solids content was 70.3% and the average thickness was 0.27 m
- In September 2019, the average solids content was 69.6% and the average thickness was 0.26 m

The decrease in average solids content from June to September is likely due to rewetting from precipitation.

Thin deposits with approximately 0.30 m thickness would dry to:

- 55% average solids content (approximately 20 cm thickness) within two months
- 70% average solids content (approximately 10 cm thickness) within a year

Deposit profiles were thicker at the discharge locations in comparison to the edges of the deposit.

LESSONS LEARNED

Several practical lessons learned were derived from the lab and field investigations:

- Higher dosages of coagulant led to higher calcium concentration in the release water in the lab
- Using the lowest coagulant dosage of 2,500 g/t of solids led to the highest initial dewatering in the lab
- Over time, thinner deposit thickness resulted in high solids content

Depositing treated tailings onto an existing beach with a positive drainage is a feasible drying method.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

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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Centrifuge Optimization Trials

COSIA Project Number: TJ0121

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Status: Lab scale testing and field scale pilot complete

PROJECT SUMMARY

Treating tailings using the centrifuge technology is a method to speed the separation of water from fluid fine tailings (FFT) and is currently being used at Canadian Natural's Jackpine Mine (JPM). The technology applies centrifugal force to the contents in the centrifuge and separates them based on varying densities. The process is implemented by injecting FFT with a flocculant before feeding it into the centrifuges, producing a centrifuge product (cake) and process water (centrate), which are then deposited. It was desired to optimize the centrifuge process to achieve improved dewatering post-deposition in order to support closure and reclamation plans in a sufficient timeframe. It was desired to optimize the centrifuge process to achieve improved dewatering post-deposition, in order to support closure and reclamation plans in sufficient timeframes. As such, a field trial at JPM was completed to evaluate the impact of using different chemical formulations as well as evaluating deposition strategies to improve centrifuge deposit performance.

The optimization efforts consisted of specific adjustments made to the current configuration by using different chemical amendments (three flocculants and one coagulant) and centrifuge modes:

I. Treating FFT with flocculant 1;

II. Treating FFT with flocculant 2;

III. Treating FFT with coagulant + flocculant 3;

IV. Treating FFT with flocculant 3 and bypassing the centrifuge; and

V. Treating FFT with coagulant + flocculant 3 and bypassing the centrifuge.

These adjustments were based on different aspects to evaluate the centrifuge deposit performance such as the impact of using different flocculants, and adding a coagulant to decrease the repulsive forces of the fine particles and promote more effective flocculation. The centrifuge was utilized under different modes to investigate if bypassing the centrifuge could result in a better maintained floc structure and improved dewatering performance. Although the centrifuge bypass mode is not typically used as a part of the centrifuge technology, it allowed various chemical amendments to be analyzed without the significant amount of shear imparted from centrifugation that may be breaking floc structures. Furthermore, the centrifuge product was deposited onto a beach rather than directly to a tailings pond, to determine the drying performance and evaluate the deposition strategy.

Laboratory testing of the various chemical amendments was done prior to a field trial. The chemical solutions were mixed with FFT in a graduated cylinder and then deposited onto a sloped metal tray. Measurements for key variables including solids content, yield stress, water release and chemistry were then taken. From the lab study, the two most promising chemical amendments were found to be flocculant 2 and coagulant + flocculant 3. Field testing was then conducted at JPM, from May to June 2018. The cake from the different testing conditions were poured into five separate sloped and open-ended cells on a beach under different operational conditions. Each cell was poured three times with each pour being eight days apart. The influence of the different testing conditions on the previously mentioned key variables along with floc cohesiveness, rheology, deposit thickness and dewatering were measured and analyzed.

PROGRESS AND ACHIEVEMENTS

The trial results from field testing of each modification made is summarized in Table 1. Using flocculant 2 with the normal centrifuge mode resulted in the best drying performance after three months, where the deposit reached 70.2% solids content with a 0.5 m average deposit thickness. The dissolved calcium content of streams at different points in the process was measured; however, not all streams could be sampled (represented in the table as "-"). In general, the use of a coagulant in either normal or bypass centrifuge mode led to higher calcium content and overall water consumption compared to the other conditions tested. High calcium content is undesirable as it can be detrimental to the bitumen extraction process, which reuses the release water. Furthermore, the considerable amount of water consumption is deemed unfavourable from an operations perspective.

Table 1. Summary of Trial Results from Field Testing

Key Variables	Trial Conditions				
	I	II	III	IV	V
Target FFT feed solids content (%)	26.0	20.0	20.0	20.0	20.0
End of pipe cake solids content (%)	47.6	38.5	43.1	14.7	8.30
Deposit solids content after 24 hours (%)	50.8	38.9	42.7	43.9	47.1
Deposit solids content after 48 hours (%)	51.2	39.4	43.8	56.0	51.2
Deposit solids content after 3 months (%)	61.5	70.2	67.0	66.8	-
Average deposit thickness (m)	1.1	0.5	0.7	0.4	0.2
Dissolved calcium content in cake pore (mg/L)	72.7	78.7	164.0	-	-
Dissolved calcium content in release water (mg/L)	-	-	92.2	45.0	94.7
Water consumption (m^3 per tonne of solids)	0.35	0.62	7.80	0.90	7.90

The yield stresses of centrifuge product samples at the discharge and the end of pipe were measured to observe rheological reduction due to shear. It was observed that there were reductions in the yield stresses in all chemical amendments, by hundreds of Pascals between the centrifuge discharge and at the end of pipe due to the length of the pipeline transport.

LESSONS LEARNED

The findings from the trial indicate that it is favourable to use flocculant 2 with the normal centrifuge mode for the best possible results in terms of dewatering and currently this is what is being used at JPM. It is also recommended to maintain the use of the centrifuge technology, without bypassing it, regardless of the chemical amendments. Future testing should consider placing the flocculant injection point at a closer distance to the discharge point or minimize the piping discharge length, as it was observed that yield stresses were lowered during transport through a long distance of pipeline.

RESEARCH TEAM AND COLLABORATORS

Institution: Canadian Natural

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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Michael Graham	Canadian Natural	Lead Geotechnical Operations Support		

FROTH TREATMENT TAILINGS

Froth Treatment Tailings Evaluation

COSIA Project Number: TE0050 and TJ0110

Research Provider: Golder Associates Ltd., Innotech Alberta, SRK Consulting (Canada) Inc.

Industry Champion: Imperial, Suncor

Industry Collaborators: Canadian Natural, Syncrude, Teck

Status: Year 3 of 4

PROJECT SUMMARY

Froth Treatment Tailings (FTT), the stream that forms during contacting of bitumen froth from primary extraction with a light hydrocarbon mixture in the froth treatment process step, is known to be unique in composition compared to water-based tailings materials. FTT is generally enriched in oleophilic minerals, since these tend to associate with the bitumen froth in primary extraction. A fraction of these minerals (*e.g.*, pyrite) are known to be Acid Rock Drainage (ARD) precursors, and may include Naturally Occurring Radioactive Materials (NORM). Further, trace light hydrocarbons (either paraffinic or naphthenic, depending on the operator) will be present in this stream. Light hydrocarbons are more readily bio-available and will support microbial activity in the tailings sediment. It was recognized in 2017 that better insight into the complex bio-geochemical effects within the FTT sediments was required in order to fully manage the *life cycle* tailings needs for the operations.

The Froth Treatment Tailings Evaluation project was initiated in 2017. The primary intent of the project was to identify and close the knowledge gaps around *post-placement* environmental performance of FTT material. Industry-wide sampling campaigns were executed in 2017 and 2018 (Imperial and Suncor conducted additional sampling in 2019), in which materials from different operators with differing deposit age, deposition environment and light hydrocarbon type were collected. Gas, water, oil and solid phase compositions were determined, and detailed microbiological information was gathered. This characterization was used then to develop a more predictive conceptual model for the long-term bio-geochemical effects that could be expected in such deposits. These fundamental insights are now used to inform site-specific closure plans, as well as to develop dedicated mitigation strategies, where required.

PROGRESS AND ACHIEVEMENTS

Several insights have been gathered from the sampling campaigns to date. Results have been shared at the 2018 and 2019 Oil Sands Innovation Summits (OSIS). Key findings include:

- The existence of a free gas phase in some FTT affected tailings sediments. This has led to specific studies around bubble-mature fine tailings (MFT) interaction (COSIA project number TJ0127 summary is included in this report), which has shed new light on the mechanisms for greenhouse gas (GHG) and odour release from tailings deposits.

- Significant lateral and vertical variability, as well as variability among operations. FTT does not exhibit a single behaviour, but was found to be site-specific with operational history playing an important role within the deposits. This indicates that site-specific management will be necessary. Indications were further found that sediment behaviour is dominated by *placement method* (*i.e.*, sub-aerial beach versus sub-aqueous pond placement), rather than light hydrocarbon type (*i.e.*, paraffinic versus naphthenic solvent).

- A core micro-biome is present within all sediments studied. This micro-biome is capable of light hydrocarbon degradation. Gas composition analysis, aqueous phase isotope analysis and data on microbiology are starting to paint a picture of the light hydrocarbon bioconversion processes that occur within the sediments. These data are expected to support estimates for kinetic rate expressions, which will in turn provide insight in the timescales for full degradation of the light hydrocarbon components.

Work is continuing on data interpretation. Information collected to date is currently being used to enhance the understanding of the various bioconversion processes that are occurring in the sediments. Further, information is used to commence development of potential mitigation strategies (*e.g.*, COSIA project numbers TJ0124 and TJ0125—both summaries are included in this report).

LESSONS LEARNED

Preliminary insights have been shared with the "Fort McKay Air Quality and Odour Recommendations Program" (FMAQO – recommendation 9[12][13]), in order to ensure that recent findings around microbiological activity in FTT-affected tailings areas were incorporated in that program.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations

Innovation Summit 2019, June 3-4, 2019, Hyatt Regency, Calgary, Alberta:

- S. Fawcett *et al.*, "COSIA Froth Treatment Tailings Sampling Project: An overview of the 2018 program"

- K. Budwill and J. Birks, "Regional Assessment of Diluent Degradation in Tailings: Insights from Microbiology and Hydrocarbon Analyses"

- S. Fawcett *et al.,* "Pre-Treatment of Oil Sands Tailings for Geochemical Testing"

- K. Budwill, "Methanogenic Diluent Microcosm Study: Insights Into Diluent Degradation in Tailings Material"

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

[13] The report is *Recurrent Human Health Complaints Technical Information Synthesis Fort McKay Area,* September 2016. Prepared by the Alberta Energy Regulator and Alberta Health. (https://www.aer.ca/documents/reports/FortMcKay_FINAL.pdf, accessed 2020-02-13)

- M. Neuner *et al.* "COSIA Froth Treatment Tailings Sampling Project: Gas Generation and Composition"

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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Matt Neuner	Golder Associates Ltd.	Senior Hydrogeochemist		
Mackenzie Bromstad	Golder Associates Ltd.	Geochemist		
Ajinkya Koleshwar	Golder Associates Ltd.	Water Quality Modeller		
Jean Birks	InnoTech Alberta	Principal Researcher, Water Research		
Karen Budwill	InnoTech Alberta	Senior Researcher, Processing Technologies		
Tatiana Sirbu	InnoTech Alberta	Researcher, Water Management		
Stephen Day	SRK Consulting (Canada) Inc.	Corporate Consultant, Geochemistry		

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

COSIA Project Number: TE0055 - RWG (IOSI18)

Research Provider: Queen's University

Industry Champion: Suncor

Industry Collaborators: Canadian Natural, Imperial, Syncrude, Teck

Status: Year 2 of 3

PROJECT SUMMARY

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

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

1. Evaluate the impact of the concentration of different TEA (such as sulphate and nitrate), of diluent (e.g., naphtha) and of nutrients such as phosphate (PO_4^{3-}) and ammonium (NH_4^+) on biogenic gas production from tailings obtained from different types of tailing ponds (impacted by froth treatment tailings [FTT]) at different depths and lateral locations on the rates of biogenic gas production, consumption of TEA, and hydrocarbon degradation in laboratory microcosm studies.

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

3. Develop a first generation model coupling mass transfer and reaction rates to provide basic information on CO_2 and CH_4 emissions based on pond chemistry, and to use the model to potentially identify dominant

mechanisms which may aid in developing strategies for minimizing CH_4 emissions *in situ* or for manipulating the biodegradation rate of the diluent (naphtha).

PROGRESS AND ACHIEVEMENTS

Objective 1 – Effect of TEA, Phosphate, Ammonium etc. on Greenhouse Gas Production:

Results from preliminary experiments, with mature fine tailings (MFT) samples suggest that phosphate (PO_4^{3-}) may be a key nutrient limiting degradation rates. This is consistent with high performance liquid chromatography HPLC/ Ion chromatography analysis of the pore water, which was below detectable levels (PO_4^{3-} < 1.0 mg/L). Initial experiments examined the addition of ammonium and phosphate nutrients.

Unamended biotic controls represent baseline conditions in the tailing ponds under methanogenic conditions. Typically for a tailings pond with diluent-affected MFT initial methane production was ~5 µmol CH4/100 mL MFT/day in the first 20 days after which it declined to 2.5 µmol CH4/100 mL MFT/day as the residual naphtha concentration in the MFT decreased. Addition of NH4+ and/or PO43- enhanced biological activity; e.g., as phosphate concentration increased methane production increased under methanogenic conditions.

With increasing naphtha concentration under methanogenic conditions, in the presence or absence of ammonium or phosphate nutrients, methane production increased until about 0.5% naphtha and did not increase further at higher concentrations even when sufficient ammonium and phosphate were present. From experiments with diluent-affected MFT, a yield of gram (g) CH4 produced per g naphtha consumed was experimentally determined. This value will also be determined for other MFT samples and will help predict how much total methane might be expected from the residual naphtha in the pond.

Under sulphate-reducing conditions, in the presence of sufficient sulphate (SO42-), methanogenesis is inhibited and sulphate reduction occurs producing hydrogen sulphide (H2S). It is anticipated that once the sulphate is exhausted, methanogenesis would resume unless the level of H2S produced is inhibitory. For diluent affected MFT, about 1060 mg/L of sulphate inhibited methanogenesis for at least 20 days while 2240 mg/L inhibited methanogenesis for at least 38 days. The amount of SO42- needed to degrade 1 g of naphtha was determined.

Under nitrate-reducing conditions, concentrations above 585 mg/L nitrate inhibited methanogenesis in diluent affected MFT. In nitrate reduction, nitrate can be reduced through a series of intermediates (nitrate NO_3^- → nitrogen dioxide NO_2^- → nitric oxide NO → nitrous oxide N_2O → nitrogen gas N_2) to nitrogen gas. We did not anticipate any measurable N_2O production since Holowneko et al. (2000) had found that nitrate concentrations ≤ 1800 mg/L did not result in N_2O accumulation using tailings from another pond. However, at the highest nitrate concentration tested (1165 mg/L), N_2O levels persisted indicating that the N_2O to N_2 step was a rate-limiting step and that the N_2O level was either toxic to the cells or totally inhibited the enzyme, N_2O reductase, at this step. At the intermediate level (584 mg/L), N_2O was transient indicating that although there was a bottleneck of N_2O → N_2, the N_2O reductase enzyme was still functional. N_2O is undesirable because it has a global warming potential 265 to 298 times that of CO_2 over 100 years. Our results indicate that it might be possible to find a nitrate concentration to inhibit methanogenesis without forming N_2O. Once that nitrate is exhausted, it would have to be replenished to maintain the inhibition of methanogenesis. For diluent-affected MFT, the amount of NO_3− needed to consume 1 g of naphtha was determined.

Although experiments are still in progress, recent results indicate that there is an initial rapid loss of phosphate and ammonium upon their addition to MFT. A preliminary examination of the dried solids by X-Ray diffraction (XRD) did not reveal any potential precipitates that would explain their removal. When the pore-water chemistry for the tailings pond at 5 m was entered into the PHREEQC software (llnl database) (U.S. Geological Survey), the model did not predict precipitation of these species indicating another mechanism of removal. Ammonium and phosphate ions may be adsorbing onto the MFT solid phase - perhaps on the clays. Furthermore, the addition of phosphate produced experimentally-measured abiotic CO_2 which was supported by the PHREEQC software. The model predicts that as the phosphate concentration is increased, the pH decreases with a corresponding increase in abiotic CO_2 generation. These ponds are known to have high levels of bicarbonates and a decrease in pH may shift the carbonate/bicarbonate/carbonic acid/CO_2 equilibrium to release CO_2. Determining the biologically produced CO_2 is further complicated because a portion of the gaseous CO_2 is removed by the carbonate/bicarbonate/carbonic acid/CO_2 equilibrium and CO_2 can also be used as a terminal electron acceptor by methanogens or as a carbon source by autotrophic organisms.

Objective 2 – Effect of Bitumen on Naphtha Biodegradation:

In developing an appropriate protocol to meet this objective, initial sacrificial experiments in triplicate were performed 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 were sacrificed to measure naphtha components in the aqueous phase. We are in the process of independently repeating this experiment. Future experiments will involve evaluating the biodegradation of these components in the model system using an enrichment culture from MFT.

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. In the coming year, we will test the diffusion model with our experimental results obtained from Objective 2 and will focus more on the biological component of the model.

LESSONS LEARNED

1. Phosphate, nitrogen as well as the carbon and energy sources, all limit microbial activity.
2. Addition of terminal electron acceptors; e.g., NO_3 and SO_4 effectively suppresses CH_4 production.
3. Yields of how much electron acceptor is required for a given amount of naphtha degradation and the yield of methane from naphtha were determined but must be further refined.

LITERATURE CITED

Holowneko, F.M. and P.M. Fedorak. 2000. Methanogens and sulphate-reducing bacteria in oil sands fine tailings waste. *Canadian Journal of Microbiology*, 2000, 46(10): 927-37, http://doi.org/10.1139/w00-081

RESEARCH TEAM AND COLLABORATORS

Institution: Queen's University

Principal Investigator: Juliana Ramsay

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Sreemoyee Ghosh Ray	Queen's University	Postdoctoral Fellow (part-time)		
Mara da Silva	Queen's University	Postdoctoral fellow		
Mickel Tawadrous	Queen's University	MSc Candidate	September 2017	Completed Nov 2019
Avery Ling	Queen's University	BSc student	September 2018	April 2019
Avery Ling	Queen's University	MSc student	January 2020	December 2021
Alison Holman	Queen's University	BSc student	September 2018	April 2019

Managing Tailings from the Creating Value from Waste Process

COSIA Project Number: TJ0114

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

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

Status: Year 2 of 2

PROJECT SUMMARY

Titanium Corporation Inc. has developed a process called Creating Value from Waste (CVW™) 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 CVW™ 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. The thickened tailings samples were characterized and then subjected to geotechnical tests in order to provide information required to develop a deposition and reclamation strategy for CVW™ tailings.

PROGRESS AND ACHIEVEMENTS

Three types of model tailings were prepared, spanning the range that could potentially be seen from the CVW™ 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 thickened tailings samples were subjected to a hindered sedimentation test and large strain consolidation (LSC) test in order to measure the compressibility and hydraulic conductivity as a function of effective stress. Routine water chemistry was performed on the water evolved during the sedimentation test. A vane shear test was also performed on the materials in the LSC following each loading step. One dimensional (1D) oedometer tests were also performed on the consolidated samples in order to extend the data set to higher effective stresses than those capable in the LSC.

In general, all thickened tailings samples were classified as clay of intermediate plasticity (as per the Unified Soil Classification System[14] [USCS]) or as Fine Tailings (F-2, sand-to-fines ratio [SFR]< 1 as per the Unified Oil Sands Tailings Classification System[15] [UOSTCS]). The sedimentation, LSC, and 1D oedometer tests revealed that, at a fixed total solids content, the clean thickened tailings and the as-is thickened NRU tailings establish the boundary (upper and lower) material properties, with the CVW™ thickened tailings falling in between. This information can be used in modeling and predicting the consolidation behaviour of CVW™ Thickened Tailings (with varying composition) when deposited in a tailings disposal facility.

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

Principal Investigator: Danuta Sztukowski

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[14] Unified Soil Classification System (USCS) is used to describe soil grain size and soil plasticity

[15] Unified Oil Sands Tailings Classification System (UOSTCS) is illustrated in Figure 2-1 of the *Guidelines for Performance Management of Oil Sands Fluid Fine Tailings Deposits to Meet Closure Commitments*. COSIA. 2014. Available on the COSIA website https://cosia.ca/sites/default/files/attachments/FFT%20Performance%20Management_Feb2014.pdf

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Peter Stapleton	Canadian Natural	Lead Engineer, Process Innovation		
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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 Affected Mature Fine Tailings Light Hydrocarbon Removal

COSIA Project Number: TJ0124

Research Provider: Coanda Research and Development Corporation

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

In the froth treatment of oil from mined oilsands, naphtha is added as a process aid to assist in the process of separating the extracted bitumen from the solids and water phases. Although most of the diluent is recovered, the tailings rejected from this process contain trace naphtha. In recent years there has been increased environmental motivation to recover this residual diluent from the tailings ponds in which they reside.

The purpose of the current research was to evaluate the potential for conventional air stripping to remove naphtha from the tailings material in which it resides. This problem is not straight forward, since there is no chemical definition for naphtha, the tailings do not exhibit Newtonian rheology, and the distribution and length scales of the bitumen entities in which the naphtha resides are not known. As such, there is no framework available through which to estimate the potential performance of this approach, either at laboratory or field scale.

To address these knowledge gaps a program was carried out to:

1. quantify the rates of naphtha release that could be realized through air addition; and
2. develop scaling relationships from which commercial performance could be estimated.

PROGRESS AND ACHIEVEMENTS

An apparatus was first developed in which to evaluate the potential stripping rates. The design consisted of an acrylic vessel, with ports located at equal intervals along the height of the vessel, to facilitate sampling and for instrumentation. A sparger was constructed of sintered ceramic, in a geometry that produced a bubble field that covered the cross section of the vessel.

Major challenges were encountered with the primary analytical elements of the project. For the gas phase, two techniques were used in parallel to quantify the naphtha. An ionization detector was calibrated to produce a continuous signal that was proportional to the overall flux of hydrocarbon leaving the vessel. Periodically, the off-gas was routed through a bed of charcoal for a fixed period of time. The naphtha adsorbed onto the solid was then extracted using a solvent, and injected into a gas chromatograph (GC), where a complete speciation of the stripped hydrocarbons was quantified. The combination of these techniques permitted the stripping of subfractions of interest in the naphtha to be tracked. An analytical method was also developed that allowed quantification of the naphtha in small quantities of the tailings.

Using the stripping apparatus, it was determined that air stripping could indeed recover considerable amounts of naphtha (> 70%) in commercially relevant time frames (~6 hours). A mathematical model was developed for scaling purposes. The framework contained a single adjustable parameter, which was correlated to the process conditions. Excellent agreement was obtained between the model and the experimental data.

For scaling purposes, the model was then non-dimensionalized in order to collapse the dimensionality of the problem. Through this exercise, the natural scaling variables were elucidated, identifying a non-dimensional time. Using this variable, the recovery of all species in the naphtha, at all process conditions were found to collapse on a single universal curve. Using this relationship, the effectiveness of air stripping can be determined at any scale.

LESSONS LEARNED

Air sparging has been demonstrated to be a feasible method of light hydrocarbon removal from tailings. The performance of the unit as measured by the transient concentrations of the various species in the naphtha can be captured with high fidelity using a mathematical model. There exists a characteristic time of the process that allows the transient curves from all species to collapse onto a universal line. This curve can be used for design purposes, allowing the performance to be predicted at commercial scales. The current work enables a commercial solution for the recovery of naphtha from oil sands tailings. The scaling relationships address a primary development gap that existed and enables an engineered sparging solution to be designed.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Cedric Laborde-Boutet, Wayne Brown, Daniel Hood, Elco Hollander and Babak Derakhshandeh, "Diluent Removal from Froth Treatment Tailings by Air Sparging". Oilsands Innovation Summit, Calgary AB June 3-4, 2019.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research and Development Corporation

Principal Investigator: Cedric Laborde-Boutet

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Wayne Brown	Coanda Research and Development Corporation	CTO		
Derek Hood	Coanda Research and Development Corporation	Engineer in Training		

Froth Treatment Tailings Affected Mature Fine Tailings Total Hydrocarbon Removal

COSIA Project Number: TJ0125

Research Provider: Coanda Research and Development Corporation

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

In the secondary extraction of bitumen from many of the mined oil sands in Northern Alberta, naphtha is added as a diluent to facilitate bitumen separation from solids and water. Although most of the diluent is recovered, a small amount is retained in the tailings rejected from froth treatment. The microorganisms that exist naturally in the tailings ponds digest the light hydrocarbons that exist in the diluent and generate methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S). Gas bubbles produced from the biodegradation of light hydrocarbons attach to bitumen and fines, release them to the surface water and could negatively impact the performance of pit lakes, recycled water from the ponds, and the aquatic systems used to reclaim tailings. If gas generation is inhibited, it is reasonable to assume that risks associated with release of bitumen and fine solids to the surface water are eliminated or minimized.

Light hydrocarbons are primarily dissolved in the bitumen phase. Therefore, bitumen removal would result in proportional light hydrocarbon removal. Using this concept, this project was focused on developing a flotation technology for removal of bitumen (and light hydrocarbons) from tailings. The product of flotation, in this case, was a “cleaned” tailings stream with residual light hydrocarbon contents below a critical threshold to ensure on spec performance of aquatic systems.

The overall objectives of this project were to:

a) evaluate the overall performance of conventional flotation in removal of bitumen from tailings;

b) measure the kinetics of flotation, ranges of recovery and process requirements; and

c) develop scale-up relationships for designing commercial scale flotation units.

PROGRESS AND ACHIEVEMENTS

A range of experiments was performed in 5 L and 250 L flotation cells with tailings collected from Suncor tailings ponds. The impact of tailings dilution, temperature, agitation, and aeration on the bitumen recovery and kinetics of flotation was studied. Flotation of bitumen was found to follow a first-order kinetic equation. The rate constant was found to be a strong function of the power input into the cell and temperature, whereas air flow rate had a small impact on the kinetics of bitumen removal. Additionally, feed tailings had to be diluted with water for successful removal of bitumen. With no dilution, the recovery of bitumen was essentially zero. However, once the feed tailings (at ~30 wt% initial solids content) were diluted with process effluent water (PEW) to ~13 wt%, recoveries up to ~70% was achieved within ~18 minutes.

Aeration of the flotation cell was characterized by the superficial gas velocity, gas holdup, and bubble size. Gas holdup (ε_G) was found to correlate with rotor speed (N) and airflow rate (Q_g) as $\varepsilon_G \propto N^{1.49} {Q_g}^{0.57}$. Bubble diameter was well-described by an empirical correlation from the literature as a function of aeration number (Q_g/ND^3). Based on these findings, a kinetic scale-up framework was developed for geometrically similar flotation cells. These scaling relations, which were developed based on data collected from the 5 L cell, were able to predict the performance of the 250 L cell (50× larger scale) indicating that the same relationships could be used to design commercial scale units.

LESSONS LEARNED

Flotation technology could be used as an effective method of hydrocarbons removal from tailings. When varying feed compositions are encountered, the level of hydrocarbon recovery could be adjusted by controlling the agitation intensity, temperature or feed dilution.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Javed Ally, Wayne Brown, Daniel Palys, Elco Hollander and Babak Derakhshandeh, "Bitumen Flotation to Remove Naphtha from Froth Treatment Tailings Affected Ponds". Oilsands Innovation Summit, Calgary AB June 3-4, 2019.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research and Development Corporation

Principal Investigator: Javed Ally

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Javed Ally	Coanda Research and Development Corporation	Engineering Scientist		
Wayne Brown	Coanda Research and Development Corporation	CTO		
Daniel Palys	Coanda Research and Development Corporation	Engineer-in-Training		
Derek Hood	Coanda Research and Development Corporation	Engineer-in-Training		

Diluent Measurement in Tailings

COSIA Project Number: TJ0126

Research Providers: Coanda Research & Development Corporation, Bureau Veritas Canada, InnoTech Alberta

Industry Champion: Suncor

Status: Year 1 of 1

PROJECT SUMMARY

In order to predict the long-term bio-geochemical activity of diluent-containing tailings sediments, it is critical to have robust data on the residual light hydrocarbon content of these materials. Only if concentrations are known can an estimate be given for *e.g.*, time to complete biodegradation and expected gas production remaining within these deposits. Unfortunately, reliable diluent measurement was proven to be difficult for Mature Fine Tailings (MFT) samples. MFT is a complex mixture of water, bitumen, low concentrations of diluent (nominally 10-1000 ppm), and a variety of hydrophilic and hydrophobic solids. Recent Vapour-Liquid Equilibrium measurements on naphtha containing MFT have shown that the light hydrocarbons behave as being mostly dissolved in the bitumen phase. For accurate measurement, it is necessary to access *all* light hydrocarbons inside the bitumen. Due to a variety of reasons related to mass transfer, solubility and potential for stable emulsion formation, this has shown to be experimentally challenging. As a result, it was found that results could vary by as much as a factor of five between lab protocols.

This project aimed at identifying the root cause of the observed variability and developing an updated protocol that was capable of reliably measuring diluent content in MFT samples.

PROGRESS AND ACHIEVEMENTS

A detailed experimental protocol review between Coanda Research & Development, Bureau Veritas Canada, and InnoTech Alberta revealed a critical sample preparation step that was prone to systematic error. All protocols require the samples to be contacted with an 'extraction medium', *i.e.*, a solvent that is used to transfer all light hydrocarbons from the sample to a solids-free dissolved phase. This medium is subsequently analyzed through conventional gas chromatography (GC) methods. An extraction method is required because the MFT samples cannot be analyzed directly with GC due to its solids content. It was shown that the choice of the type of extraction solvent was critical. Standard organic solvents (highly compatible with bitumen and diluent) showed a high tendency to form emulsions with the sample material upon contacting, likely due to the presence of clay-like particulate matter. The emulsions are not suitable for GC analysis, which meant that from a practical point of view lower mixing intensities need to be used. While this mitigated the emulsion formation, it also made it less likely that all diluent was transferred to the extraction medium.

By switching to methyl-ethyl-ketone (MEK) as an extraction agent, a different approach was taken to resolve this issue. MEK is an amphiphilic solvent, capable of solubilizing both water and bitumen/diluent. MEK avoided emulsion formation altogether. Since all water and oil will be transferred to the extraction medium, complete diluent capture is guaranteed. The interpretation of the chromatograms required extra attention due to contaminants in the MEK itself, but appropriate baseline correction procedures were developed for this. The improved method was tested by analyzing samples at the three participating labs. Results typically came back to within 10% relative error. This is considered to be well within acceptable limits for the purpose of this analysis.

LESSONS LEARNED

The protocol has been made available to all operators and can be used by the participating labs as an alternative to earlier diluent measurement methods.

Suncor would like to acknowledge Coanda Research & Development, Bureau Veritas Canada and InnoTech Alberta for their willingness to collaborate on the development of the updated protocol.

PRESENTATIONS AND PUBLICATIONS

- W. Brown *et al.*, "Thermodynamic Limit for the Recovery of Naphtha from Oilsands Tailings", 2018 Oil Sands Innovation Summit.
- C. Laborde-Boutet *et al.*, "Light Hydrocarbon removal from Froth Treatment Tailings by Air Sparging", 2019 Oil Sands Innovation Summit.
- Analytical Protocol for Naphtha Content in Tailings. Coanda Research & Development, Bureau Veritas Canada, InnoTech Alberta.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigator: C. Laborde-Boutet

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
C. Laborde-Boutet	Coanda Research & Development Corporation			
W. Brown	Coanda Research & Development Corporation			
J. Hay	Bureau Veritas Canada			
A. Gatzke	Bureau Veritas Canada			
A. Pereira	InnoTech Alberta			

Froth Treatment Tailings Affected Mature Fine Tailings Failure Mode Assessment

COSIA Project Number: TJ0127

Research Provider: Coanda Research and Development Corporation

Industry Champion: Suncor

Status: 1 of 1

PROJECT SUMMARY

In the secondary extraction of bitumen from mined oil sands, naphtha is added as a process aid to assist with separation of the extracted bitumen from the solids and water phases. Although most of the naphtha is recovered, the froth treatment tailings (FTT) rejected from this process contains trace residual naphtha. The light hydrocarbon content of FTT affected mature fine tailings (MFT) deposits can be digested by the microorganisms in the tailings pond leading to generation of methane (CH_4), carbon dioxide (CO_2), and hydrogen sulphide (H_2S). Initially, these molecules dissolve in the pore water, but once the solubility limit is reached a population of bubbles will form in the deposit. The size of the gas bubbles increase over time as the bioactivity continues. The variation in bubble size, their population and the yield stress of the deposit could result in a range of gas release mechanisms from the deposit. Some release mechanisms could result in the possibility of elevated gas concentrations at the pond surface and the potential for uncontrolled free surface dynamics in the event of sudden releases of large quantities of biogas in localized areas.

The aim of this research was to develop a more fundamental understanding of the behaviour of gas bubbles in tailings ponds with a focus on quantifying the conditions required for:

a) individual bubble rise;

b) maximum gas fractions attainable in tailings ponds prior to release; and

c) layer inversion and development and rise of buoyant zones.

PROGRESS AND ACHIEVEMENTS

It was found that the critical radius (R_c) required for a bubble to rise in tailings is a function of the yield stress (τ_y). The correlations available from past studies on similar systems were only able to predict the critical bubble size for yield stresses <~34 pascals (Pa). At higher yield stresses bubbles were found to rise at much smaller diameters compared to predictions. It was found that the critical radius can be described by $R_c = \frac{\tau_y{}^B}{A\rho g}$ where ρ is the tailings density, g is gravitational constant, and A=0.025-0.04 and B=0.28-0.44 are constants. Experiments were also performed to estimate the maximum void fraction that can be achieved in tailings when bubbles are smaller than the R_c. At yield stresses between 40 Pa to 680 Pa, tailings were able to hold up to ~85% by volume gas. Given the non-homogeneous distribution of gas and rheology in the ponds, such high void fractions could lead to development of localized buoyant zones. A bubble-rich zone may form consisting of individual bubbles trapped due to their small size and a local yield stress. This zone can rise in a manner similar to a gas bubble, once its overall size and density difference relative to the surround region are sufficiently high due to continuous bio-gas release. Experiments performed in this work indicate that buoyant zones are formed in tailings when $\frac{\tau_y}{\Delta\rho_z g R} = \sim 0.2$ where Δρz denotes the density difference between buoyant zone and surrounding deposit and R is the hydraulic diameter of the buoyant zone.

LESSONS LEARNED

The knowledge gained from this work helps identifying/quantifying the various risks associated with presence of a gas phase in ponds. Some of the observations made in the laboratory need to be evaluated further in order to assess the extent of consequences at pond scales. However, the results collected to date indicate that the low density zones could form and rise in the ponds potentially imposing risks to the activities on the pond surface. The knowledge gained from this work would help assessing the short term operational and long term closure risks and assists in developing mitigation plans.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Babak Derakhshandeh, Darwin Kiel, and Ricky Chong, "Impacts of Biogas on the Dynamics of FTT affected MFT Ponds". Oil Sands Innovation Summit, Calgary AB June 3-4, 2019.

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research and Development Corporation

Principal Investigator: Darwin Kiel

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Darwin Kiel	Coanda Research and Development Corporation	PhD		
Ricky Chong	Coanda Research and Development Corporation	BSc.		

CONSOLIDATION MODELLING

NSERC/COSIA Industrial Chair in Oil Sands Tailings Geotechnique

COSIA Project Number: TE0010

Research Provider: University of Alberta (UofA)

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 5 of 5

PROJECT SUMMARY

In 2013, the COSIA Tailings Environmental Priority Area (EPA), the Natural Sciences and Engineering Research Council of Canada (NSERC) and the University of Alberta (UofA) partnered to establish the NSERC/COSIA Industrial Research Chair (IRC) in Oil Sands Tailings Geotechnique to address the challenges of managing oil sands tailings. Four themes for innovation and research were developed in consultation with industry partners:

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.

The individual project objectives were initially aimed at assisting industry to achieve the requirements of regulatory Directive 074[16]. In 2015, new policy direction was issued under the *Lower Athabasca Region: Tailings Management Framework for the Mineable Athabasca Oil Sands*[17] and implemented beginning in 2016 under *Directive 085*[18], which specified (among other requirements) that new FFT deposits must be ready to reclaim ten years after the end of mine life and that all legacy[19] tailings must be ready to reclaim by the end of mine life. Adjustments to individual project scopes and objectives within the IRC were made to accommodate this shift in research priorities.

The collaborative research and field investigations resulted in the development of new field investigation techniques, tailings simulation models and unsaturated soil mechanics models, many now in use in Canada's oil sands tailings industry. The collaboration between the COSIA and the UofA resulted in fundamental discovery and

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[16] *Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes*. Energy Resources Conservation Board, 2009.

[17] *Lower Athabasca Region: Tailings Management Framework for mineable Athabasca oil sands*, Government of Alberta, 2015.

[18] *Directive 085: Fluid Tailings Management for Oil Sands Mining Projects*. Alberta Energy Regulator, 2017.

[19] Legacy tailings are defined in Directive 085 as fluid tailings in storage before January 1, 2015.

adaptation of tailings behaviour, further enabling the development and refinement of new tailings management, geotechnical engineering and mining reclamation methods and approaches. Collaboration and feedback was fostered through a COSIA IRC Research Advisory Committee.

The IRC commenced in 2013 and was completed in 2019. A new research and funding partnership between COSIA, NSERC and the UofA has been established, in part, to build off the success and results of this IRC and to collaborate with the Northern Alberta Institute of Technology (NAIT) through a similar college research funding arrangement.

PROGRESS AND ACHIEVEMENTS

The IRC program provided COSIA members with novel technologies to measure the effectiveness of tailings remediation, reduce the amount of post-production tailings, understand the long-term geotechnical behaviour of fluid fine tailings, and tailings simulation models for planning and management, which increased the research capacity for the UofA and industry partners.

Examples of novel technologies and approaches that were developed are:

- Empirical correlations between total suction and hyperspectral imagery to provide non-intrusive, cost-effective surveys of tailings deposits;
- Coupling freeze-thaw and desiccation dewatering codes into one common modelling platform, which is being trialed in industry;
- Completing studies to better understand the engineering and behaviour of the tailings co-mixed product;
- Blending and mixing of FFT with the overburden Clearwater Shale to form ready-to-reclaim deposits which, had been piloted and commercialized by industry collaborators;
- Unmanned systems to reduce the risk and cost of deploying standard geotechnical tools on soft oil sands tailings deposits) using robots and automated sampling and data collection techniques, and new tools to estimate soil parameters from robot-terrain interactions; and
- Multidisciplinary collaboration between engineering and science faculties to develop novel designs for high-resolution field-deployable vane shear test tools.

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

This project investigated the potential of hyperspectral imagery to monitor the flocculation performance of tailings. The study showed 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: Remote estimation of moisture content, evaporation rate, and total suction would help to assess the drying and optimize tailings management. The project provides the potential for low-risk, cost-effective surveys to manage large volume tailings and accelerate conversion to reclaimable landscapes.

ii. Using ECV to Measure and Predict Dewatering Performance

Evaporation rates were measured using a micrometeorological technique known as eddy covariance (ECV). Evaporation rates in field trials were found to be lower than expected, which suggested that current drying models might overestimate dewatering due to evaporation.

Benefits: Optimized drying, tailings management and reclamation of ponds and deposits.

iii. Tailings Characterization Using an Unmanned Ground Robot

Novel technologies for characterizing soft ground terrains, such as tailings deposits, were developed, including automated vane shear tools and new tools to estimate soil parameters from robot-terrain interactions to reduce the risk and cost of deploying payloads and tools in challenging soft tailings. The robots successfully collected samples and deployed the instruments in tailings deposits with low bearing capacity.

Benefits: The new technologies will enable characterization of deposits that are not available using conventional geotechnical approaches. This new information will aid in the understanding of how tailings change over time, and in decision-making on process control and post-deposition assessments.

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

This project focused on the development and verification of a revised methodology for estimating the coefficient of permeability and the water storage functions for unsaturated soils by taking saturation and void ratio into account for high volume change materials (oil sands tailings).

Benefits: The revised theory could be applied in numerical modelling to facilitate an improved design of tailings disposal and in reducing potential engineering costs.

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

The research focused on investigating fundamental soil mechanics principles (e.g.; stress–strain) relationships to predict the FFT behaviours using commercially available numerical modelling software. This project investigated whether fluid fine tailings (FFT), when subjected to a variety of enhanced dewatering treatments, adhere to the principles of soil mechanics: stress-strain; compressibility; and hydraulic conductivity curves.

Benefits: The research program provided a laboratory data set and analyses that narrowed the existing knowledge gap of tailings behaviours and provided a basis to establish constitutive relations of deposited FFT in relation to the stress–strain state using independent variables.

1.4 Modelling of Pore Fluid in the Computation of Actual Evaporation

This research project investigated the effects of cyclic freeze-thaw on the suction behaviour of centrifuged tailings through an experimental filter paper laboratory study. The work investigated the effectiveness of multiple cycles of the freeze and thaw in increasing the osmotic suction capable of leading to crust formation and gaining strength at the surface. The following conclusions were made:

- At temperatures of 15°C, 10°C, and 3°C, the filter paper method was not applicable. At a temperature 0°C, the filter paper test was applicable. The results could not be extrapolated from the ASTM calibration curve because the calibration curve was produced at room temperature (20°C).
- The filter paper method appears to be applicable to soil samples with very high solids content. It does not appear that this method can be used for suction measurements of this sample under study.

Benefits: 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 and the evaluation of 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

This research was focused on sedimentation and consolidation processes governing the transition of mature fine tailings to a soil, consolidation and creep in MFT to enhance understanding of soft soil behaviour. The data collected during the experiment clearly demonstrated that the majority of volumetric deformation observed in the tailings was associated with creep rather than with consolidation. A creep theory proposed by Vermeer et al. (2014) resulted in an adequate fit with the data.

Benefits: A consolidation model that incorporates creep was used to explain a settlement profile for MFT. This will improve the assessment, management and closure of oil sand tailings facilities.

2.3 Modelling MFT Consolidation with a Geotechnical Centrifuge

The objective of this research was to model continuous and layered tailings deposition in the geotechnical centrifuge. Laboratory characterization of the chosen test materials and two rounds of centrifuge tests were completed. Results from the different test procedures included settlement curves, void ratio profiles, compressibility parameters and segregation (for oil sands tailings test materials).

Benefits: This research provides the opportunity to improve understanding of the consolidation behaviour of oil sands tailings through testing in a geotechnical centrifuge.

Theme 3: Assessing and Improving Deposition of Tailings

3.1 Deep Fines-Dominated (Cohesive) Deposits

This laboratory testing and numerical simulation research evaluates the effect of natural conditions (multiple freeze-thaw cycles, summer drying and precipitation) on the strength of treated centrifuged tailings deposits and deposit crust development prior to reclamation.

Benefits: 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 and the time required for developing a crust.

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 Formation (Kc) shale overburden. Analysis of the testing is still underway with possible next steps that include comparing the measured results to theoretical values using an unsaturated soil mechanics model. Field trials consisting of test piles of blended Kc and tailings are currently in progress.

Benefits: 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. Coupled Freeze-thaw and Desiccation Dewatering Code in One Modelling Program 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. 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. Investigate Alternative Design and Operating Strategies to Improve Thin Lift Dewatering

This research aims to demonstrate the feasibility of using System Dynamics (SD) to develop a transparent, open-source and reproducible model capable of simulating long-term soil water dynamics in a tailings-cap system subject to upward flux from a consolidating tailings substrate. The model explores various feedback mechanisms in self-weight consolidation and unsaturated soil water movement under climatic influence and uses Causal Loop Diagramming (CLD) techniques to identify key feedback structures, promote system thinking and facilitate shared understanding of the inter-related behaviour between the reclamation cap and the tailings substrate.

Benefits: The integrated model improves a previous model and provides a quick method to test hypotheses and gain insights into the interaction between capping material and tailings substrate. It is an analytical tool for due diligence; builds a common qualitative language for interdisciplinary collaboration; fosters a culture of participatory modelling; and brings transparency and flexibility to the modelling process.

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

This work investigated the effect of increased floc size on geotechnical properties of chemically-treated FFT. A method was developed to determine floc size distribution of a treated FFT sample. Two of the treatments were analyzed for compressibility, hydraulic conductivity, and vane shear strength. Compressibility and vane shear strength were found to be sensitive to changes in floc size while hydraulic conductivity did not appear to be largely impacted by floc size.

Benefits: This research contributes to industry's goals of accelerating the process of converting tailings deposits 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. In the laboratory testing program samples were cured to degrade the flocculant and the microstructure of the tailings before and after treatment was assessed.

Benefits: 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. Based on the results of the testing, a number of key conclusions can be made:

1. The method appears to be applicable to metal tailings that have large proportions of sand sized particles;
2. This estimation technique requires a soil classification of colloidal or non-colloidal, which can be difficult, so the method is useful for screening;
3. It does not appear that this method can be used to estimate the SWCC from the SFCC for oil sands tailings.

Benefits: This method may be used 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

Using an existing tailings storage facility (TSF) in the oil sands as a study site, this research included five components:

1. Geomorphic design;
2. Identification, classification, and quantification of erosion on an active TSF;
3. Integration of geomorphic stability with tailings dams design processes;
4. Assessment of long-term geomorphology with three future climate change scenarios; and
5. Assessment of five erosion mitigation design options.

Erosion due to wind and water as well as areas at risk was identified on the TSF dam slopes using light detection and ranging (LiDAR) and 'PurVIEW' software. The results confirmed a concept that long-term stability of these landforms is best achieved by designing with nature rather than against it.

Benefits: The remote methods tested in this project provided a relatively efficient method for evaluating landscape erosion and performance during active and passive reclamation stages.

LITERATURE CITED

Vermeer, P.A., L. Beuth, and C. Dykstra. 2014. Creep-consolidation Analyses of Standpipe Test. Presentation to University of Alberta, 08 May.

PRESENTATIONS AND PUBLICATIONS

Published Theses

Elias, J. 2019. Measurement of Floc Size and the Influence of Size Distribution on Geotechnical Properties of Oil Sands Fluid Fine Tailings. MSc Thesis, Department of Civil & Environmental Engineering, UofA, Edmonton, Alberta.

Owusu, P. 2019. Laboratory study of the effects of repeated freeze-thaw cycles on the suction behavior of centrifuged tailings. Masters of Engineering Report, Department of Civil & Environmental Engineering, UofA, Edmonton, Alberta.

Slingerland, N. 2019. Geomorphic landform design and long-term assessment of tailings storage facilities in the Athabasca oil sands. PhD Thesis, Department of Civil & Environmental Engineering, UofA.

Zheng, X. 2019. Development of a tailings simulation model using System Dynamics. MSc Thesis, Department of Civil & Environmental Engineering, UofA, Edmonton, Alberta.

Schafer, H. 2018. Freezing Characteristics of Mine Waste Tailings and their Relation to Unsaturated Soil Properties. MSc Thesis, Department of Civil & Environmental Engineering, UofA, Edmonton, Alberta.

Ogloza, J. 2017. Measuring Actual Evaporation Rates from a Tailings Pond. MSc Thesis, Department of Civil & Environmental Engineering, UofA, Edmonton, Alberta.

Entezari, I. 2016. Applications of remote hyperspectral sensing in the characterization of Alberta's oil sands tailings. PhD Thesis, Department of Earth and Atmospheric Sciences, UofA.

Zabolotnii, E. 2016. Roadmap to Finalizing the 30-Year Settlement Column Experiment. MEng Report, Department of Earth and Atmospheric Sciences, UofA.

Zhang, F. 2016. Unsaturated Soil Property Functions for High Volume Change Materials. PhD Thesis, Department of Civil & Environmental Engineering, UofA.

Journal Publications

Beier N., Zheng T., and Sego D. (Accepted) Tailings Management Simulation Model - Part I: Model Development. Environmental Geotechnics.

Beier, N., Zheng, T., and Sego, D. (Accepted) Tailings Management Simulation Model: Part II – Model Validation. Environmental Geotechnics.

Entezari, I., Rivard, B., Lipsett, M.G. (Accepted) Predicting the abundance of clays and quartz in oil sands using hyperspectral measurements. International Journal of Applied Earth Observation & Geoinformation.

Schafer, H., and Beier, N.A. 2020. Estimating the SWCC from the SFCC for mine waste tailings using TDR. Accepted. Canadian Geotechnical Journal. 57(1): 73-84.

Entezari, I., Rivard, B., Vajihinejad, V., Wilson, G.W., Soares, J., Fisseha, B., and Beier, N. 2019. Monitoring Tailings Flocculation Performance Using Hyperspectral Imagery. Canadian Journal of Chemical Engineering. 97:2465-2471.

Slingerland, N., Beier, N.A. and Wilson, G.W. 2019. Oil sands tailings dam design considerations for ease of closure. Submitted. Canadian Institute of Mining, Metallurgy and Petroleum Journal. 10(2), 29 pages.

Slingerland, N., Sommerville, A., O'Leary, D., Beier, N.A. 2018. Identification and measurement of erosion on an oil sands tailings dam. Geomorphology. doi: 10.1080/12269328.2018.1538823

Kabwe, L.K., Scott, J.D., Beier N.A. and Wilson, G.W. 2018. Environmental Implications of End Pit Lakes at Oil Sands Mines. Environmental Geotechnics, ICE Journal. 6(2): 67-74.

Kabwe, L.K., Wilson, G.W., Beier N.A. and Scott, J.D. 2018. Effects of Atmospheric Drying and Consolidation of Flocculated Thickened Tailings and Centrifuged Cake on Near-Surface Shear Strength. Special article of The Second Pan-Am Conference on Unsaturated Soils, Dallas, 2017, Published in the Journal of ASCE June 20, 2018.

Slingerland, N., Beier N.A. and Wilson, G.W. 2018. Enhanced geomorphic design for reclamation of rural waste-scapes. Detritus Journal, Vol 1(2): 170-179.

Zhang, F., Wilson, G.W. and Fredlund, D.G. 2018. Estimation of permeability functions for Bulyanhulu Tailings. Geotechnical Testing Journal. doi: 10.1520/GTJ20170303.

Zhang, F., Wilson, G.W. and Fredlund, D.G. 2018. Permeability function for oil sands tailings undergoing volume change during drying. Canadian Geotechnical Journal, 55(2): 191-207.

Jeeravipoolvarn, S., Miller, W., Scott, J.D., Kabwe, L.K. and Wilson, G.W. 2017. Modeling Effect of Bitumen Extraction Processes on Oil Sands Tailings Ponds". Journal of Civil Engineering & Architecture, 11: 48-59.

Wilson, G.W., Kabwe, L.K., Beier N.A. and Scott, J.D. 2017. Effect of various treatments on consolidation of oil sands fluid fine tailings. Canadian Geotechnical Journal. 55(8): 1059-1066. (Winner of NRC Editor's Choice Paper 2018).

Beier, N.A., Kabwe, L.K., Scott, J.D., Pham, N.H. and Wilson, G.W. 2016. Modeling the effect of flocculation, thickening and desiccation on oil sands tailings. Geotechnical Special Publication No. 270: Geotechnics for

Sustainable Energy – Selected Papers from Sessions of Geo-Chicago 2016. Eds. A. Farid, A. De, K.R. Reddy, N. Yesiller and D. Zekkos.

Entezari, I., Rivard, B., Lipsett, M.G. and Wilson, G.W. 2016. Prediction of Water Content and Normalized Evaporation from Oil Sands Soft Tailings Surface Using Hyperspectral Observations. Canadian Geotechnical Journal, 53(10): 1742-1750.

Olmedo, N.A. and Lipsett, M.G. 2016. Design and field experimentation of a robotic system for tailings characterization. Journal of Unmanned Vehicle Systems, 4(3): 169-192.

Zhang, F., Fredlund, D.G. and Wilson, G.W. 2016. Water permeability function for soils that undergo volume change as suction changes. Indian Geotechnical Journal, 46(3): 210-227.

Zhang, F. and Fredlund, D.G. 2015. Examination of the estimation of relative permeability for unsaturated soils. Canadian Geotechnical Journal, 52(12): 2077-2087.

Edited Conference Proceedings

UofA Geotechnical Centre (2018). The Sixth International Oil Sands Tailings Conference, December 9-12, 2018, Edmonton, Alberta, Canada. Edited by Beier, N.A., Wilson, G.W., and. Sego, D.C.

UofA Geotechnical Centre (2016). The Fifth International Oil Sands Tailings Conference, December 4-7, 2016, Lake Louise, Alberta, Canada. Edited by Sego, D.C., Wilson, G.W., and Beier, N.A.

UofA Geotechnical Centre (2017). The Fifth International Oil Sands Tailings Conference, December 4-7, 2016, Lake Louise, Alberta, Canada. Edited by Sego, D.C., Wilson, G.W., and Beier, N.A.

UofA Geotechnical Centre (2014). The Fourth International Oil Sands Tailings Conference, December 7-10, 2014, Lake Louise, Alberta, Canada. Edited by Sego, D.C., Wilson, G.W., and Beier, N.A.

UofA Geotechnical Centre (2013). The 13th International Conference on Tailings and Mine Waste, November 3-6, 2013, Banff, Alberta, Canada. Edited by Sego, D.C., Wilson, G.W., and Beier, N.A.

Conference Presentations/Posters

Slingerland N., Beier NA, Wilson, GW. 2019. Stress-testing geomorphic and traditional tailings dam designs for closure using a landscape evolution model. International Mine Closure Conference. Perth, Australia. Australian Centre for Geomechanics.

Slingerland, N., Sommerville, A., O'Leary, D., Beier, N.A., & Wilson, G.W. 2019. Erosional processes on an oil sands tailings dam and implications for reclamation. Canadian Dam Association Annual Conference. Calgary, Canada.

Wilson, G.W., Beier, N.A. and Giang, V. 2019. An introduction to oil sands tailings: Innovations and challenges. Tailings 2019. 10-12 July, Santiago, Chile.

Burden, R.N. and Wilson, G.W. 2018. Simulating deposition of Clearwater shale – FFT blends using a novel consolidation test. Presentation at the COSIA Innovation Summit, Calgary, AB: June 7-8, 2018.

Entezari, I., Rivard, B., Vajihinejad, V., Wilson, G.W., Soares, J., Fisseha, B., and Beier, N. 2018. Assessment of the Tailings Flocculation Performance Using Hyperspectral Imagery. Sixth International Oil Sands Tailings Conference (IOSTC 2018).

Hall, T., Beier, N. and Chalaturnyk. R. 2018. Influence of Fill Scheme on Oil Sands Tailings Consolidation Modelling in a Geotechnical Centrifuge. Sixth International Oil Sands Tailings Conference (IOSTC 2018).

Fisseha, B.T., Wilson, G.W., and Simms, P.H. 2018. Assessment of self-weight consolidation of flocculated fluid fine tailings under various environmental conditions. Proceedings of the 21st international seminar of paste and thickened tailings, Perth, WA, April 11-13, 2018.

Olmedo, N.A., Lipsett, M.G., Zhang, H. and Wilson, G.W. 2018. Robotic Systems for Environmental Monitoring - Applications for terrain characterization in oil sands tailings. Poster presentation at the COSIA Innovation Summit, Calgary, AB: June 7-8, 2018.

Olmedo, N.A., Lipsett, M.G., Zhang, H. and Wilson, G.W. 2018. Tailings monitoring using low-cost science stations. Poster presentation at the COSIA Innovation Summit, Calgary, AB: June 7-8, 2018.

Rima, U. and Beier, N. 2018. Effects of Surficial Seasonal Weathering on Centrifuged Oil Sands Tailings. Sixth International Oil Sands Tailings Conference (IOSTC 2018), December 9-12, 2018.

Rima, U. and Beier, N. 2018. Evaluation of Temperature and Multiple Freeze-Thaw Effects on the Strength Properties of Centrifuged Tailings. Poster presentation at the COSIA Innovation Summit, Calgary, AB: June 7-8, 2018.

Schafer, H.L., Beier, N.A., Slingerland, N. and Macciotta, R. 2018. Overview of Current State of Practice for Closure of Tailings Dams. Sixth International Oil Sands Tailings Conference (IOSTC 2018), December 9-12, 2018.

Slingerland, N., Beier N.A. and Wilson, G.W. 2018. Landscape evolution modelling of large sand dams. International Mine Closure Conference. Leipzig, Germany.

Slingerland, N., Isidoro, A., Fernandez, S., Beier, N.A. and Wilson, G.W. 2018. Geomorphic analysis for tailings dam design in consideration of a 1000-year closure design life. Planning for Closure conference. Santiago, Chile.

Zheng, T. and Beier, N. 2018. System Dynamics Approach to Tailings Management. Presentation at the COSIA Innovation Summit, Calgary, Alberta, June 7-8, 2018.

Zheng, T. and Beier, N. 2018. Stochastic Simulation of Tailings Consolidation Process. Canadian Geotechnical Conference. Edmonton AB.

Zheng, T. and Beier, N. 2018. System Dynamics Approach to Tailings Management Simulation. Tailings and Mine Waste. Keystone, Colorado.

Burden, R.N. and Wilson, G.W. 2017. Co-deposition: Blending of FFT and overburden materials. Proceedings of the 2017 Tailings & Mine Waste Conference, Banff, AB: November 5-8, 2017.

Elias, J. and Beier, N.A. 2017. Effect of floc size on geotechnical properties of oil sands fluid fine tailings: Experimental study. Proceedings of the 2017 Tailings & Mine Waste Conference, Banff, AB: November 5-8, 2017.

Fisseha, B., Wilson, G.W. and Fredlund, D. 2017. Large-Strain Consolidation Column with Applied Negative Water Pressure. Proceedings of the Pan-Am-UNSAT 2017: Second Pan American Conference on Unsaturated Soils, Dallas, TX: November 12-15, 2017.

Fisseha, B. and Fredlund, D. 2017. Assessment of Large-strain Consolidation and Shear Strength of Saturated/Unsaturated Fluid Fine Tailings. Proceedings of GeoOttawa: 70th Canadian Geotechnical Conference, Ottawa, ON: October 1-4, 2017.

Fredlund, D.G., and Zhang, F. 2017. Effect of initial conditions on the interpretation of soil-water characteristic curves (SWCCs) in geotechnical engineering. Proceedings of the Second Pan-Am Conference on Unsaturated Soils, Dallas, TX., Nov. 12-15.

Kabwe, L.K., Wilson, G.W., Beier, N.A., Cunningham, K.A. and Scott, J.D. 2017. Geotechnical characterization of a two-year old thick centrifuge product deposit subjected to one cycle of freeze & thaw treatment under laboratory controlled conditions. Proceedings of the 2017 Tailings & Mine Waste Conference, Banff, AB: November 5-8, 2017.

Kabwe, L.K., Wilson, G.W., Beier, N.A. and Scott, J.D. 2017. Evaluation of various drying processes to further increase solids content and shear strength of treated fluid fine tailings. Proceedings of the Canadian Geotechnical Conference, Ottawa, ON.

Kabwe, L.K., Wilson, G.W., Beier N.A. and Scott, J.D. 2017. Oil Sands Tailings Centrifuge Cake Subjected to Freeze/Thaw. Proceedings of the Tailings & Mine Waste Conference, Banff, AB: November 5-8.

Olmedo, N.A., Lipsett, M.G., Zhang, H. and Wilson, G.W. 2017. Design and field experimentation of a robotic system for tailings characterization. Poster presentation at the COSIA Innovation Summit, Calgary, AB: March 21-22, 2017.

Schafer, H., Beier, N. 2017. Development of Soil Freezing Characteristic Curves for Fluid Fine Tailings using TDR. In Proceedings of the 70th Canadian Geotechnical Conference, Ottawa, Ontario, 2-4 October 2017.

Schafer, H. and Beier, N. 2017. Freezing Characteristics of Fluid Fine Tailings and their Relation to Unsaturated Soil Properties. Poster presentation at the COSIA Innovation Summit, Calgary, AB: March 21-22, 2017.

Slingerland, N. and Beier, N.A. 2017. Enhanced geomorphic design for rural waste-scapes. Proceedings of the 16th International Waste Management and Landfill Symposium. Cagliari, Italy. International Waste Working Group.

Zhang, F., Fredlund, D.G., and Wilson, G.W. 2017. Hydraulic properties for Bulyanhulu tailings during drying. Proceedings of the Second Pan-Am Conference on Unsaturated Soils, Dallas, TX., November 12-15, 2017.

Zhang, F., Wilson, G.W., and Fredlund, D.G. 2017. Hydraulic properties for Devon silt considering volume change during drying. Proceedings of Geo-Ottawa 2017, Ottawa, ON, October 1- 4.

Beier, N., Kabwe, L., Scott, J.D., Pham, N. and Wilson, G.W. 2016. Modeling the effect of flocculation and desiccation on oil sands tailings. GEO-CHICAGO 2016: Sustainability, Energy, and the Geoenvironment, Chicago, United States.

Burden, R.N. and Wilson, G.W. 2016. Co-deposition: Blending of FFT with overburden. Proceedings of the Fifth International Oil Sands Tailings Conference, Lake Louise, AB: December 4-7, 2016.

Entezari, I., Rivard, B., Lipsett, M.G. and Wilson, G.W. 2016. Hyperspectral Sensing in Support of Oil Sands Tailings Operation and Management. Proceedings of the Fifth International Oil Sands Tailings Conference, Lake Louise, AB: December 4-7, 2016.

McKenna, G., Mann, V., Fisseha, B., Beier, N. and Olmedo, N. 2016. The geotechnical vane shear strength of mine tailings compared to soft foods. Fifth International Oil Sands Tailings Conference. Lake Louise, Alberta, Canada. December 4-7, pp. 329-339.

Olmedo, N., Lipsett, M.G. and Wilson, G.W. 2016. Advanced robotic payloads for measuring properties of tailings deposits. Proceedings of the Fifth International Oil Sands Tailings Conference, Lake Louise, AB: December 4-7, 2016.

Schafer, H. and Beier, N. 2016. Freezing Characteristics of Fluid Fine Tailings and their Relation to Unsaturated Soil Properties. Proceedings of the 5th Canadian Young Geotechnical Engineers & Geoscientists Conference, Whistler, British Columbia, 29 September-1 October 2016.

Slingerland, N. and Beier, N.A. 2016. A regional view of site-scale decisions. Proceedings of the Fifth International Oil Sands Tailings Conference, Lake Louise, AB: December 4-7, 2016.

Entezari, I., Rivard, B., Lipsett, M.G., and Wilson, G.W. 2015. Application of Hyperspectral Technology for the Estimation of Methylene Blue Index in Oil Sand Tailings. Proceedings of the COSIA/PTAC Oil Sands Clay Workshop and Conference, Edmonton, AB: April 28-29, 2015.

Kabwe, L.K., Scott, J.D., Beier N.A. and Wilson, G.W. 2015. Environmental Implications of End Pit Lakes at Oil Sands Mines. Proceedings of the Geo-Environmental Engineering Conference, Montreal, PQ, May 21-22.

Kabwe, L.K., Wilson, G.W., Scott, J.D., Sorta, A. and Beier, N.A. 2015. Effect of flocculent treatments on consolidation of oil sand fluid fine tailings. Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, Quebec City, September 20-23, 2015.

Leigh, A., Pineau, J., Olmedo, N. and Zhang, H. 2015. Person Tracking and Following with 2D Laser Scanners. Proceedings of the IEEE International Conference on Robotics and Automation 2015, Seattle, WA: May 26-30, 2015.

Slingerland, N. and Wilson, G.W. 2015. End land-use as a guide for integrated mine planning and closure design. In Fourie, A., Tibbett, M. (eds). Mine Closure 2015. Proceedings of the 10th International Mine Closure Conference, Vancouver, BC. Australian Centre for Geomechanics, Western Australia.

Sorta, A., Beier, N.A., Kabwe, L.K., Scott, J.D. and Wilson, G.W. 2015. The case for using fines void ratio. Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, Quebec City, September 20-23, 2015.

Wilson, G.W. 2015. Innovations in Oil Sand Tailings Geotechnique for Fluid Fine Tailings Management. Keynote at Symposium 2015 Mines and the Environment, Rouyn-Noranda, QC.

Wilson, G.W., Kabwe, L.K., Beier, N.A. and Scott, J.D. 2015. Effect of various treatments on consolidation of oil sands fluid fine tailings. Proceedings of the Canadian Geotechnical Conference, Quebec, PQ.

Zhang, F., Fredlund, D.G., Fredlund, M.D. and Wilson, G.W. 2015. Role of air-entry value and choice of SWCC in the prediction of the unsaturated permeability. Proceedings of the 68th Canadian Geotechnical Conference and 7th Canadian Permafrost Conference, Quebec City, September 20-23, 2015.

Zhang, F., Fredlund, D.G. and Wilson, G.W. 2015. Hydraulic properties for soils that undergo volume change as soil suction is increased. AP-UNSAT 2015, Guilin, China: October 23-26, 2015.

Anglow, W., Wilson, G.W., Sego, D.C., Kabwe, L.K. and Kan, J. 2014. Field and laboratory geotechnical properties of oil sands tailings beach deposits in flume tests. Proceedings of the Canadian Geotechnical Conference, Regina, SK.

Entezari, I., Rivard, B., Lipsett, M., Feng, J. and Wilson, G.W. 2014. Deployment of Hyperspectral Imaging Instruments for Remote Monitoring of Soft Tailings Water Content. Proceedings of the Fourth International Oil Sands Tailings Conference, Lake Louise, AB: December 7-10, 2014.

Entezari, I., Rivard, B., Lipsett, M.G. and Wilson, G.W. 2014. Estimation of Moisture Content and Activity of Oilsands Tailings Using Hyperspectral Techniques. IEEE International Geoscience and Remote Sensing Symposium (IGARSS 2014), Quebec City, QC: July 13-18, 2014.

Kabwe, L.K., Wilson, G.W. and Scott, J.D. 2014. Influence of an Underlying Sand Beach on Drainage and Desiccation of Fine Tailings. Fourth International Oil Sands Tailings Conference, Louise Lake, AB: December 7-10.

Kabwe, L.K., Wilson, G.W., Scott, J.D., Donahue, R. and Lahaie, R. 2014. Field and laboratory measurements of centrifuge cake deposits for oil sands reclamation. Proceedings of the Canadian Geotechnical Conference, Regina, SK.

Lipsett, M., Olmedo, N., Rivard, B. and Wilson, G.W. 2014. Robotic systems for measuring properties of tailings deposits and collecting samples. Proceedings of the Fourth International Oil Sands Tailings Conference, Lake Louise, AB: December 7-10, 2014.

Olmedo, N. and Lipsett, M. 2014. Soil parameter estimation and sample collection using an unmanned ground vehicle. Proceedings of the Fourth International Oil Sands Tailings Conference, Lake Louise, AB: December 7-10, 2014.

Olmedo, N., Zhang, H. and Lipsett, M. 2014. Mobile robot system architecture for people tracking and following applications. IEEE International Conference on Robotics and Biomimetics, Bali, Indonesia: December 5-10, 2014.

Pham, N.H. and Sego, D.C. 2014. Modeling Dewatering of Oil Sands Mature Fine Tailings Using Freeze Thaw. Proceedings of the Fourth International Oil Sands Tailings Conference, Lake Louise, AB: December 7-10, 2014.

Scott, J.D., Kabwe, L.K., Wilson, G.W. and Sorta, A. 2014. From Fluid to Solid: Oil Sands Fluid Fine Tailings. Proceedings of the 7ICEG Conference, Melbourne, Australia.

Slingerland, N., Baida, M. and Wilson, G.W. 2014. The great divide between mine closure goals and outcomes, and potential solutions. In Fourie, A., Tibbett, M., (eds.). Mine Closure 2014. Proceedings of the 9th International Mine Closure Conference, Johannesburg, South Africa: October 1-3, 2014.

Wilson, G.W, Kabwe, L.K. and Scott, J.D. 2014. Closure options for oil sands fluid fine tailings ponds. Proceedings of the International Mine Closure Conference, Johannesburg, South Africa.

Zhang, F., Fredlund, D.G., Wilson, G.W. and Sedgwick, A. 2014. Determination of the permeability function for drying oil sands tailings undergoing volume change and desaturation. Proceedings of the Fourth International Oil Sands Tailings Conference, Lake Louise, AB: December 7-10, 2014.

Entezari, I., Rivard, B., Lipsett, M.G. and Wilson, G.W. 2013. Application of Hyperspectral Remote Sensing In Estimation of Oilsands Tailings Water Content. IEEE WHISPERS 2013, Gainesville, FL: June 25-28, 2013.

Entezari, I., Rivard, B., Lipsett, M.G. and Wilson, G.W. 2013. Water Content Estimation of Oilsands Tailings Using Remote Hyperspectral Sensing. 34th Canadian Symposium on Remote Sensing, Victoria, BC: August 27-29, 2013.

Fredlund, D.G. and Zhang, F. 2013. Combination of shrinkage curve and soil-water characteristic curves for soils that undergo volume change as soil suction is increased. Proceedings of the 18th International Conference on Soil Mechanics and Geotechnical Engineering, Paris.

Kabwe, L.K., Kone, M., Sorta, A., Wilson, G.W., Scott, J.D. and Ulrich, A.C. 2013. Measurements of unsaturated soil properties of old and new mature fine tailings. Proceedings of the International Mine Closure Conference, Cornwall, UK.

Kabwe, L.K., Scott, J.D., Sorta, A., Wilson, G.W., Jeeravipoolvarn, S. and Kone, S. 2013. Geotechnical Characteristics of the Mature Fine Tailings in the 30-Year 10-m Standpipe. Proceedings of the Canadian Geotechnical Conference, Montreal, QC.

Kabwe, L.K., Wilson, G.W. and Donahue, R. 2013. Determination of Geotechnical Properties of In-Line Flocculated Fine Fluid Tailings for Oil Sands Reclamation. Proceedings of the Tailings and Mine Waste Conference, Banff, AB: November 3-6.

Olmedo, N. and Lipsett, M. 2013. Active soil parameter estimation using a UGV. Unmanned Systems Canada Conference, Vancouver, BC: November 11-15, 2013.

Scott, J.D., Kabwe, L.K., Wilson, G.W., Sorta, A. and Jeeravipoolvarn, S. 2013. Properties which affect the consolidation behaviour of Mature Fine Tailings. Proceedings of the Tailings and Mine Waste Conference, Banff, AB: November 3-6.

Reports, Invited Presentations & Other Publications

Beier, N. 2019. Summary of the impact of the NSERC/COSIA Industrial Research Chair in Oil Sands Geotechnique program (2013-2019). COSIA Oil Sands Innovation Summit. Calgary, Alberta, June 2-4, 2019.

Slingerland, N. 2018. Invited presentation to Northern Alberta Institute of Technology. Leduc, AB. Geological Technology Program. April 11.

Slingerland, N., Schafer, H., and Eaton, T. 2018. Long-term Performance of Tailings Dams in Alberta. Geotechnical News. March, 2018.

Wilson, G.W. 2018. Advances in the NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique. Presentation at the COSIA Oil Sands Innovation Summit, Calgary, AB: June 7-8, 2018.

McKenna, G., Mann, V., Fisseha, B., Beier, N. and Olmedo, N. 2017. This tailings has the consistency of chocolate pudding: a formal comparison of the geotechnical vane shear strength of food and soft tailings. Geotechnical News, 35(1): 28-33.

Wilson, G.W. 2017. The NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique: An Update. Presentation at the COSIA Oil Sands Innovation Summit, Calgary, AB: March 21-22, 2017.

Brown, J. 24 January 2016. CBC Radio Interview: The 180. Seeing mines as blank canvases.

Cairney, R. 18 January 2016. PhD student wants mining industry to take a long, long, long view on impact. U of A News.

Slingerland, N. 2016. Introduction to Mine Reclamation for Landscape Architects. Invited presentation. University of Guelph. Landscape Architecture Department. 24 October 2016.

Slingerland, N. 2016. Geomorphic landform design for the Athabasca oil sands. Invited presentation. Golder Associates. Mississauga, ON. 26 September 2016.

Slingerland, N. 2016. Landscape architectural approach to mine closure. Invited presentation. Golder Associates. Edmonton, AB. 26 April 2016.

Slingerland, N. and Beier, N.A. 2016. An industry self-evaluation on geotechnical mine closure objectives and planning teams. Geotechnical News. June 2016.

Wilson, G.W. 2016. The Need for Designer Wastes. Keynote address presented at MINExpo 2016, Las Vegas, NV, 26 September.

Beier, N. 2015. How To Improve Fluid Fine Tailings Management In Order To Efficiently Increase Solids Content And Improve Trafficability Of The Tailings For Reclamation. Presentation at the Global Tailings Management Congress, Denver, CO: March 17-18, 2015.

Beier, N. 2015. Research Update for the NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique. Presentation to the COSIA Tailings EPA, Calgary, AB: April 20, 2015.

Beier, N. 2015. Tailings Management Simulation and Technology Evaluation Tool. CIM Symposium 2015, Mines and the Environment, Rouyan-Noranda, Quebec, June 14-17, 2015.

Beier, N.A., Sego, D.C. and Morgenstern, N.R. 2015. Tailings management simulation and technology evaluation. Geotechnical News. 33(3).

Slingerland, N. 2015. Landscape Architecture and Engineering Design for Mined Earth Structures and Reclamation. Invited presentation. Shell Canada. Calgary, AB. 19 March 2015.

Slingerland, N. 2015. The Architecture of Landforming for Mine Closure. Invited presentation. COSIA Land Reclamation Group. Syncrude Research Facility, Edmonton, AB. 9 January 2015.

Slingerland, N., Landman, K. and Kelly, S. (2015, Nov). Post-mining landscapes as habitat conservation hubs? Canadian Reclamation, 15(2), 18-22.

Wilson, G.W. 2015. "Innovations in Oil Sand Tailings Geotechnique for Fluid Fine Tailings Management", Keynote address presented at Symposium 2015 Mines and the Environment, Rouyn-Noranda, QC, 14-17 June.

Wilson, G.W. 2015. The NSERC/COSIA Industrial Research Chair in Oil Sands Tailings Geotechnique. Presentation at the COSIA Innovation Summit, Banff, AB: March 31-April 2, 2015.

Cairney, R. 2014. Grad students' startup company is making waves, UofA Engineer. Fall 2014 issue.

Howell, D. 2 December 2014. Transforming waterscapes into landscapes focus of new U of A research program. The Edmonton Journal.

Olmedo, N. 2014. Poster presentation on IRC students' research presentations at IOSTC 2014 for the Shell Enhanced Learning Fund Symposium, Edmonton, AB: November 17, 2014.

Pratt, S. 19 November 2014. U of A's 'game-changing' sensors revolutionize methods of monitoring climate science data. The Edmonton Journal.

Slingerland, N. 2014. Landscape Architectural Approach to Mine Closure. Invited presentation. Golder Associates. Burnaby, BC, and Calgary, AB. 26-27 November 2014.

Slingerland, N. 2014. Why Closure Plans Fail. Presentation at the 17th Mining Industry Learning Seminar. Surface Mining Association Research and Technology (SMART). 7 October 2014.

Slingerland, N., Baida, M. and Wilson, G.W. 2014. New teams for new schemes: Diversification in mine closure. Canadian Reclamation, 14(2): 22-28.

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Dr. G. Ward Wilson

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Development of Restricted-Flow Consolidation Test Method Applicable to Oil Sands Tailings

COSIA Project Number: TE0029

Research Provider: Thurber Engineering Ltd.

Industry Champion: Canadian Natural – Albian Sands (Previously Shell Canada)

Industry Collaborators: Imperial, Suncor, Syncrude, Teck

Status: Complete

PROJECT SUMMARY

Conventional large strain consolidation test methods for oil sands tailings require a long testing time for practical purposes. These conventional tests include the step-loading large strain consolidation test (LSC) and the seepage induced consolidation (SIC) test. They are known to take several months to complete depending on test configurations and specimen properties. In search for a faster consolidation test technique, COSIA retained Thurber Engineering Ltd. (Thurber) to investigate the application of restricted flow consolidation (RFC) test for oil sands tailings. The objectives of this study were to:

1) Develop a new rapid consolidation test method by adapting the RFC test by Sills et al. (1986) at the University of Oxford, UK.
2) Evaluate the performance of the RFC test method by comparing it with the LSC tests on oil sands fluid fine tailings (FFT).

The main tasks in the proposed scope for this research program included:

- Literature review with focus on the RFC and LSC methods;
- Development of an RFC apparatus;
- Laboratory investigation (running RFC and LSC tests on the same reference and tailings materials);
- Comparative analysis of the RFC and LSC test data; and
- Numerical modeling to evaluate the design parameters for an RFC apparatus.

For development of the Thurber RFC apparatus, certain aspects of the Oxford RFC equipment required modification prior to its use with very soft materials like oil sand tailings.

PROGRESS AND ACHIEVEMENTS

This research project developed an RFC apparatus and the associated test procedure for running faster consolidation tests on fluid fine tailings. Initially several reference materials (e.g., glass beads, kaolinite, etc.) with known properties were tested using the RFC apparatus and then the results were compared with step-loading LSC test results on the same materials. After this phase an RFC test was run on treated fluid fine tailings and these results were compared with LSC test results. In general, test results were in good agreement and likely within the repeatability limits for LSC tests. The speed of the RFC with the current test configuration was found to be 2.5 times faster than the LSC for oil sands tailings.

The project deliverables consisted of:

- Literature review summary memorandum.
- Laboratory test plan memorandum.
- Update reports to COSIA.
- Final report and presentation to COSIA.

LESSONS LEARNED

This study showed that the RFC apparatus and test procedure allows obtaining compressibility and permeability functions in a more efficient way compared to LSC test:

- The total testing time can be reduced.
- The compressibility and hydraulic conductivity relationships can be resulted as continuous functions from a single test.
- The RFC testing procedure requires only one load application followed by monitoring of the pore pressure dissipation to track the development of effective stress in the specimen.
- Interpretation of the results does not require a theoretical model or simulation or a curve fitting.

Additional development and optimization of the test is required to confirm assumptions regarding the uniformity of pore pressure, effective stress and void ratio profiles for the test specimen. Such work is also an opportunity to enhance the accuracy, control and speed of the test for practical applications. Finally, the repeatability limits for RFC testing need to be defined for this method as well as other large strain consolidation test methods.

LITERATURE CITED

ASTM D2435 / D2435M-11, 2011. Standard Test Methods for One-Dimensional Consolidation Properties of Soils Using Incremental Loading, ASTM International, West Conshohocken, PA, www.astm.org

ASTM E177 ‐ 14, 2014. Standard Practice for Use of the Terms Precision and Bias in ASTM Test Methods. Book of Standards 14.05, Standard Practice, ASTM International, West Conshohocken, PA, www.astm.org.

Caughill, D.L. 1992. Geotechnics of non-segregating oil sand tailings, M.Sc. thesis, Department of Civil and Environmental Engineering, University of Alberta, Edmonton, AB, CANADA, 262p.

Jeeravipoolvarn, S. 2010. Geotechnical behaviour of in-line thickened oil sands tailings. Ph.D. Thesis, University of Alberta, Edmonton, AB, CANADA, 431p.

Sills, G.C., Hoare, S. D. L. and Baker, N. 1986. An Experimental Assessment of the Restricted Flow Consolidation Test. Consolidation of Soils: Testing and Evaluation, ASTM STP 892, R.N. Yong and F.C. Townsend, Eds. American Society for Testing and Materials, Philadelphia, 1986, pp. 203-216.

PRESENTATIONS AND PUBLICATIONS

Reports & Other Publications

Thurber Engineering Ltd. (2017) "Development of Restricted Flow Consolidation Test Method Applicable to Oil Sands Tailings". Delivered to COSIA Tailings EPA.

RESEARCH TEAM AND COLLABORATORS

Institution: Thurber Engineering Ltd.

Principal Investigator: Srba Masala, M.Sc., P.Eng. Senior Geotechnical Engineer

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Srba Masala	Thurber Engineering Ltd.	P.Eng., M.Sc., Senior Geotechnical Engineer		
Samuel Proskin	Thurber Engineering Ltd.	P.Eng., Ph. D., Project Engineer		
Silawat Jeeravipoolvarn	Thurber Engineering Ltd.	P.Eng., Ph. D., Project Engineer		
Trempess Moore	Thurber Engineering Ltd.	P.Eng., M. Eng., Review Principal		

Enhancing Prediction of Depositional Flow and Segregation of non-Newtonian Slurries (Phases II & III)

COSIA Project Number: TE0048

Research Provider: Deltares

Industry Champion: Syncrude

Industry Collaborators: Canadian Natural, Imperial, Suncor, Teck

Status: Year 2 of 2 (Project Completed)

PROJECT SUMMARY

Downstream of the bitumen extraction process, oil sands tailings—a diluted mixture of sand, fines (silt and clay), residual bitumen, and process water—are produced. Depending on the tailings treatment technology implemented, tailings are deposited in tailings basins or dedicated disposal facilities as slurry mixtures with different densities, rheology and sand-to-fines ratios (SFR). The characteristics of the deposit (i.e., sand or fines distribution) dictate reclamation performance: consolidation rates, strength development, ability to be capped, etc.

This project continued the development of the numerical tool Delft3D-Slurry (D3Ds – a special module of Delft3D dedicated to non-Newtonian slurries deposition) to improve prediction of tailings depositional flow behaviour and the distribution of sand and fines in a tailings basin as a function of tailings densities, rheology, SFR and discharge rate, location and time variation.

Since the end of 2014, COSIA, Deltares, Delft University of Technology, Carleton University and the University of Alberta have collaboratively worked on enhancing the numerical software Delft3D to include tailings specific processes; i.e., rheology and sand settling and thixotropic behaviour. As at the end of 2019, D3Ds is proven capable of computing non-Newtonian tailings flow and sand settling behaviour along a cross-section of tailings beach and pond for a various range of tailings rheology and SFR, and to initiate morphological features in 3D. During the last three years the model was also utilized in various industry projects to evaluate sand settling and fines capture and co-mixing (Talmon *et al*., 2018). In February 2020, a workshop was organized by COSIA to evaluate opportunities to apply and further develop the model, based on industry needs. During the workshop two hands-on sessions were organized during which industry staff were trained for basic use of the model.

This project is partially supported by Dutch Public Grants dedicated to development of innovative tools and technologies in collaboration with industry partners. This project is also aligned with the strategic research ambitions of Deltares.

PROGRESS AND ACHIEVEMENTS

This project achieved:

1. Upgrading D3Ds to the standard version of Delft3D, with access to the Graphical User Interface of Delft3D and embedding of outputs specific to D3Ds;
2. Development of an analytical thixotropy model suitable to be embedded in D3Ds; and
3. Testing of D3Ds in three-dimensional mode, with application to concept case studies.

This project delivered:

1. A new version of D3Ds that includes three-dimensional simulation capabilities, a Graphical User Interface;
2. An analytical thixotropy model;
3. A presentation to the November 2018 IOSI knowledge exchange workshop and to the December 2018 International Oil Sands Tailings Conference (IOSTC); and
4. A COSIA-supported workshop in Calgary in February 2020.

LESSONS LEARNED

This study showed that D3Ds could simulate fundamental flow and sand settling behaviour according to analytical and experimental observations. D3Ds also produced the development of morphological features similar to what was observed in the field, even if not yet capturing the full morphological evolution.

A critical point that necessitates further verification and possibly development is the interaction between the flowing tailings and the beach that develops as tailings are deposited or erodes in response to variable deposition conditions. The flow / beach interaction is likely responsible to create a stable channel and lobes, and therefore to develop a tailings deposit as observed in the field. Mixing of tailings with equal or different properties (i.e., centrifuge cakes and coarse tailings) is also an important point of attention, especially in relation to current industry applications (e.g., co-mixing).

A further important development to capture the behaviour of oil sands tailing is the embedding of the thixotropy model in D3Ds. An analytical model was developed in this study, which showed good prediction capabilities of rotoviscometer tests. When embedded in D3Ds, this model should capture the strengthening (or vice versa remoulding) behaviour of flocculated dewatering tailings, as observed in various flume tests. Differential tailings strength is likely leading to the development of morphological features, as sand settling does. Thixotropy modelling required specific data. As always, consistency between data and model is extremely important. Measuring the rheological parameters should be consistently done to capture and interpret thixotropy processes; for example, changes to structure with shear and time. While not included in this study, a protocol should be developed to accurately measure rheological parameters that can be most accurately used for deposition studies of flocculated (i.e., time-dependent) tailings.

Finally, D3Ds has so far utilized uniform tailings properties at the discharge point. Plunge-pool or other near-field depositional features were not considered. It may be therefore desirable to couple D3Ds with near-field observation (or models) and test the effect of specific near-field implementation on depositional behaviour.

D3Ds is not yet perfect and it probably necessitates further development. The current version of D3Ds proved to provide valuable information for concept as well as actual oil sands industry applications to predict sand segregation and co-mixing. Only by using D3Ds in various industry applications will the actual performance and utility of the model be revealed, which will help determine development priorities. We recommend using D3Ds critically by knowing its capabilities and limitations. But also importantly, we recommend not to use D3Ds (i.e., a numerical model) alone, but always in combination with field and laboratory data, and critical understanding of the physical processes observed in the field. A model is not only useful to extrapolate field or flume observations and to evaluate different (operational) scenarios, but it also offers insight to help explain and interpret field data, especially when these are limited or spatially sparse. Indeed, it is always important to achieve good alignment between field observation, to understand physical processes, and model results.

LITERATURE CITED

Talmon, A.M., Hanssen, J.L.J, van Maren, D.S., Simms, P.H., Sittoni, L. and van Kester, J.A.Th.M. (2018) “Numerical modelling of tailings flow, sand segregation and sand co-depositions. Latest developments and applications”. 6th Int. Oil Sand Tailings Conference, IOSTC, Edmonton, Canada.

PRESENTATIONS AND PUBLICATIONS

Published Thesis

Parent, E., (2018) “Validation of Delft3D Slurry in 2D and investigation of 3D behaviour”. MSc-thesis, Carleton University.

Journal Publications

Conference Presentations/Posters

Talmon, A.M., Hanssen, J.L.J, van Maren, D.S., Simms, P.H., Sittoni, L. and van Kester, J.A.Th.M. (2018) “Numerical modeling of tailings flow, sand segregation and sand co-depositions. Latest developments and applications”. 6th Int. Oil Sand Tailings Conference, IOSTC, Edmonton, Canada.

Sittoni, L., Talmon, A.M., Hanssen J.L.J, van Es, H.E., van Kester, J.A.Th.M., Uittenbogaard, R.E., Winterwerp, J.C. and van Rhee, C., (2017) “One step further towards prediction of tailings deposition flow and sand segregation. Where we are, and what comes next.”. COSIA Innovation Summit, Calgary, Canada.

Reports & Other Publications

Deltares (2019) “A research trajectory towards improving fines capture prediction with Delft3D-slurry”. Delivered to IOSI in February 2019. IOSI contract #: IOSI 2017-08; TKI reference #: DEL072; Deltares Project #: 11201392;

Deltares (2020) "Delft3D-slurry Workshop Report". Delivered to COSIA on April 10th, 2020.

RESEARCH TEAM AND COLLABORATORS

Institution: Deltares

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)
Dr. Arno Talmon	Deltares	Principal Investigator		
Luca Sittoni	Deltares	Sr. Advisor		
Dr. Bas van Maren	Deltares	Sr. Advisor		
Jill Hanssen	Deltares	Jr. Advisor		
Jan van Kester	Deltares	Sr. Advisor		
Vincent van Zelst	Deltares	Jr. Advisor		
Prof. Paul Simms	Carleton University	Professor		
Etienne Parent	Carleton University	Student (M.Sc)	March 2017	September 2018

Research Collaborators:

Prof. Han Winterwerp , Technical University of Delft

Dr. Rob Uittenbogaard , Deltares

Prof. Sean Sanders , University of Alberta

Dr. Ben Sheets , Barr Engineering

In Situ Real Time Measurement of Solids Content in Settling Tailings

COSIA Project Number: TE0041 – RWG (IOSI)

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

Industry Champion: Canadian Natural

Industry Collaborators: Syncrude, Suncor, Imperial, Teck

Status: Year 2 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 are being explored for both techniques, including different wavelength lasers and detection geometries for the optical technique and different sources and geometries for the low level x-ray detector. The x-ray technique is used as the calibration standard for the optical sensors. The technology is being validated in laboratory-scale systems. Numerical models are being developed for both the scattering and x-ray measurement techniques to allow easy extension to systems with different material constituents. The technology is being developed in such a way that it can be potentially implemented at remote oil sands tailing ponds to measure settling of tailings in real time with lateral and depth spatial resolutions.

Milestones include:

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

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

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

PROGRESS AND ACHIEVEMENTS

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

2018

Results from 2018 were reported in the *2018 Tailings Research Report*, available on COSIA's website at: https://cosia.ca/sites/default/files/attachments/2018%20Tailings%20Research%20Report_FINAL%2003Jun2019.pdf (page 131 of 164 of the PDF document).

2019

1. Building on the 2018 activities, lab bench measurements of the scattering of laser light at various angles and at various wavelengths have been completed and an optimum wavelength for measuring solids content has been determined.

2. Building on the 2018 activities, fouling tests have been completed on various plastic and glass windows and the best "anti-fouling" optical material has been determined.

3. Building on the 2018 activities, the ability to measure inorganic solids content at few percent accuracy in test samples of kaolinite and FFT has been demonstrated using two low-level x-ray sources.

4. A specially designed compact, portable, and economical gamma ray detector has been fabricated. The custom-made gamma ray detector can be fabricated at a significantly lower cost than a typical commercial gamma ray detector.

5. Building on the 2018 activities, a first principle 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 for different setups. The calculations accurately model the x-ray source and measurement system giving good agreement with the experimental results to within a few percent.

6. Scattering and low-level x-ray measurements were used to track the temporal change of solids content in a settling column filled with a Kaolin and water mixtures and shown consistent results.

LESSONS LEARNED

The lessons learned thus far include:

1. Long wavelength Near Infrared laser sources are advantageous for the detection of solids content.

2. Accurate absolute measurement of solids content can be made with low-level x-ray transmission diagnostics.

3. Compact, portable, and economical custom-designed gamma ray detector can be fabricated.

4. Accurate modelling of x-ray diagnostic response requires incorporation of both absorption and scattering in the x-ray model.

5. It is possible to monitor solids settling in a test column measuring backscattered light with a multiple detector array and low-level x-ray transmission diagnostics.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

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

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

Reports & Other Publications

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.

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

RESEARCH TEAM AND COLLABORATORS

Institution: University of Alberta

Principal Investigator: Ying Tsui

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

Research Collaborators: NSERC

Planning and Design of Deep Cohesive Tailings Deposit Guide

COSIA Project Number: TE0046

Research Provider: McKenna Geotechnical Inc.

Industry Champion: Imperial

Industry Collaborators: Canadian Natural, Suncor, Syncrude, Teck

Status: Year 2 of 3

PROJECT SUMMARY

The mandate of COSIA's Deep Deposit and Soft Deposit Capping Working Group (DDWG) is to identify and develop approaches and technologies for designing and implementing deep fines-dominated deposits in the oil sands and explore different types of capping strategies to convert the deposits in a timely manner to a terrestrial landform (including wetlands). Deep fines-dominated deposits are 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 tailings with a sand-to-fines ratio (SFR) <1.

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 is proposed to be a technical manual and reference document for mine and tailings planners, geotechnical engineers, technical specialists and closure landform design teams.

PROGRESS AND ACHIEVEMENTS

Work on the project commenced in 2018 with preparing a work plan, assembling relevant technical and process inputs, and beginning the task of drafting the guide. Work was about 90% complete at the end of 2019 with completion targeted for the first half of 2020. A communication and implementation plan will be developed in conjunction with preparation and completion of the guide.

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

LESSONS LEARNED

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. 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 Wylynko	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 – RWG (IOSI18)

Research Provider: Coanda Research & Development Corporation

Industry Champions: Canadian Natural, Imperial, Suncor

Industry Collaborators: Syncrude, Teck

Status: Year 1 of 1

PROJECT SUMMARY

The ultimate goal of treating oil sands tailings is to remove water within a reasonable timeframe to reclaim a tailings deposition site. Several technologies have been proposed for dewatering tailings including flocculation, filtration, centrifugation, thickening and natural drying. Many of the treatment methods involve the addition of a polymeric flocculant 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 to measure the pipelining impact on dewatering and material strength of flocculated fine tailings at Coanda Research & Development Corporation (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 (FFT) and thickened tailings[20] (TT). 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 (Couette device). Additional characterization measurements were performed post-shear and samples are currently 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.

[20] Thickened tailings (TT) are tailings treated through thickeners and in-line flocculation

PROGRESS AND ACHIEVEMENTS

The flocculation and shearing experiments were completed in 2018 and the materials subsequently underwent geotechnical testing which was completed in 2019. The work was presented at the Tailings and Mine Waste 2019 conference in Vancouver, B.C. and the project concluded on December 1, 2019. The materials produced in the laboratory with varying levels of shear had obviously 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 a negative impact on the immediate material performance.

Samples of the optimally dosed low and high shear samples for each tailings type were also evaluated geotechnically by means of large strain consolidation (LSC) and seepage induced consolidation (SIC) testing. These tests provided the compressibility (relationship between effective stress and void ratio) and permeability (relationship between hydraulic conductivity and void ratio) that govern the consolidation process. The results of these tests were not greatly different for the low and high shear levels. However, the low shear sample had either better compressibility or permeability at high void ratios than the high shear sample for all materials except TT treated with Dow XUR (XUR), a polymeric flocculant, which had no differences.

The implications of the small compressibility and permeability differences seen in the testing results for commercial tailings deposits were investigated by modelling using large strain consolidation software. The simulations showed that the material that had experienced low levels of shear consolidated somewhat more rapidly than the high-shear material for all materials except the XUR-treated TT, consistent with expectations based on the LSC data. The magnitude of the differences in modelled bed height was up to 11% during the pond filling period and less than 7% during the quiescent consolidation period. The differences diminished to negligible levels at long time scales.

LESSONS LEARNED

The optimal amount of shear likely depends on the specific deposition or processing strategy selected for final tailings disposal. Certain methods could be less tolerant to shear, but deep deposits might benefit from some shear experienced in pipelines downstream of the flocculation process. Generally, we did not see evidence that shear caused long-term deterioration of consolidation performance to a significant extent, which should help alleviate concerns regarding floc damage during post-treatment processing and transport.

LITERATURE CITED

[1] Derakhshandeh, B., Junaid, A., and Freeman, G. 2016. Effects of Shearing and Shearing Time on Dewatering and Yield Characteristics of Oil Sands Flocculated Fine Tailings. International Oil Sands Tailings Conference Proceedings, Lake Louise, December 2016.

PRESENTATIONS AND PUBLICATIONS

Conference Presentations/Posters

Webster, S.E., Aydin, T., Gomez, C., Sorta, A., Derakhshandeh, B., Junaid, A., Mousavi Nik, R., and Sakuhuni, G. 2019. Effects of Shear on Dewatering and Compressibility of Treated Oil Sands Tailings. *in: Proceedings of Tailings and Mine Waste 2019,* Vancouver, B.C., 2019. (oral presentation at *Tailings and Mine Waste 2019)*

RESEARCH TEAM AND COLLABORATORS

Institution: Coanda Research & Development Corporation

Principal Investigators: Scott Webster, Clara Gomez

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Scott Webster	Coanda Research & Development Corporation	Research Scientist Principal Investigator		
Clara Gomez	Coanda Research & Development Corporation	Research Scientist Principal Investigator		
Amarebh Sorta	Coanda Research & Development Corporation	Geotechnical Engineer		
Tayfun Aydin	Coanda Research & Development Corporation	Research Scientist		
Pravic Komal	Coanda Research & Development Corporation	Laboratory Technician		
Mariana Cruz	Coanda Research & Development Corporation	Laboratory Technician		
Ashley Gonzalez	Coanda Research & Development Corporation	Laboratory Technician		

cosia

Deep Deposit Modelling, Atmospheric Fines Drying Test Cells

COSIA Project Number: TJ0058

Research Provider: 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-lift dewatering of in-line flocculated mature fine tailings (MFT). This 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 (Thin ML) and thick (Thick ML) lifts, or a single deep deposit (Deep Stack) 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
- Evaluate freeze-thaw dewatering for each depositional method.

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 2020.

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.

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 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

Principal Investigator: Gavin Freeman

Name	Institution or Company	Degree or Job Title	Degree Start Date (For Students Only)	Expected Degree Completion Date or Year Completed (For Students Only)
Gavin Freeman	Canadian Natural	Lead Process Innovation Principal Investigator		
Adedeji Dunmola[1]	Syncrude			
Reza Moussavi Nik[2]	Imperial			
Cynthia Cote	Canadian Natural			
Robert Mahood[3]	Imperial			

[1] Formerly with Shell Canada

[2] Formerly with Canadian Natural

[3] Formerly with Shell Canada

Consolidation of Fluid Fine Tailings

COSIA Project Number: TJ0059, TJ0123

Research Provider: Canadian Natural

Industry Champion: Canadian Natural

Industry Collaborators: Suncor

Status: Year 6 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 × 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 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 should assist in planning and scheduling tailings deposition to meet closure landform objectives for deep fines-dominated tailings deposits.

PROGRESS AND ACHIEVEMENTS

Knowledge from this project will help to:

- enhance the industry's understanding of cohesive deposit consolidation in oil sands;
- provide confidence in meeting closure and reclamation plans and final landform objectives;
- provide 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

Principal Investigator: Gavin Freeman

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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Adedeji Dunmola[1]	Syncrude			
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Robert Mahood[3]	Imperial			
Cynthia Cote	Canadian Natural			

[1] Formerly with Shell Canada

[2] Formerly with Canadian Natural

[3] Formerly with Shell Canada

Deep Deposit Filling, Monitoring and Modelling

COSIA Project Number: TJ0072

Research Provider: Golder Associates Ltd.

Industry Champion: Imperial

Status: Year 5 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 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 (FFT) removed from a tailings pond. If the thickener underflow is hydraulically transported to the depositional area, shearing of the thickened material occurs. Re-flocculation of sheared material at the end of the pipe is an option that could 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 due to thickener feed variability, flow parameters and segregation during deposition. These naturally created zones consolidate differently due to the composition (clay content, fines content, initial void ratio, etc.) of each zone. Thus, a suite of consolidation parameters rather than one set of parameters or averages are required to model the deposit.

PROGRESS AND ACHIEVEMENTS

In phase one of the project, laboratory scale testing was carried out on samples with different compositions by varying the ratio of fresh tailings and FFT. 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 deposit and tested to determine the properties, as was done in phase one, and were used to model consolidation behaviour of the commercial deposit. Deposit behaviour was assessed through the annual *in situ* sampling and testing program and compared with modelled predictive consolidation behaviour, which was calibrated with the annual sampling data. Large strain consolidation (LSC) tests and tests on *in-situ* samples were conducted to determine compressibility and hydraulic conductivity parameters for samples with different composition.

The deposit was divided into three zones based on solids content, SFR and clay content. Consolidation parameters were applied to each zone of the deposit using one-dimensional (1-D) consolidation models at ultimate deposit height assuming current deposit characteristics and distribution of properties, and double drainage boundary conditions due to sandy original ground conditions.

The modelling results indicated that the 60 m thick deposit will take up to 250 years for complete settlement, most of the surface can be capped before the end of mine life, and most of the deposit will undergo between 15 and 30 m of settlement by completion. Significant capping volumes will be required based on residual settlements of up to 45 m in some parts of the deposit. The results also indicated that deposition strategy may need to change and mitigations may need to be applied to achieve final reclamation objectives and outcomes.

LESSONS LEARNED

It was recognized that variability in laboratory and field-derived parameters is unavoidable and that a range of consolidation properties need to be evaluated and considered to understand the sensitivity of the results to the inputs, and to flesh out appropriate closure schemes.

LITERATURE CITED

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

Canada's Oil Sand Innovation Alliance (COSIA). 2015. Guideline for Tailings Deposit Sampling and Measuring Tools. Prepared by COSIA Geostatistical and Deposit Sampling Working Group. April 27, 2015.

Gibson, R. E., England, G., Hussey, M. J., 1967. The Theory of one-dimensional consolidation of saturated clays. 1. Finite non-linear consolidation of thin homogeneous layers. Geotechnique 17, 261-273.

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

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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Wei Ren	Imperial	Senior Advisor, Mineral Processing		
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
centrifuge cake	clay material produced following centrifuging (spinning) polymer-treated fluid fine tailings
CFT	centrifuge fine tailings
coagulation	The agglomeration of fine particles in a tailings slurry, usually by the addition of a chemical agent that alters the electrical charge on those particles, thereby reducing inter-particle repulsive forces
COSIA	Canada's Oil Sands Innovation Alliance
CST	capillary suction time
Directive 074	*Directive 074: Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes*
Directive 085	*Directive 085: Fluid Tailings Management for Oil Sands Mining Projects*
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%
LAI	leaf area index is the leaf area per unit of ground area
Liquid Limit	The geotechnical water content defining the boundary between a liquid and a solid in soil mechanics. This state is defined by a standard laboratory test modified for use in oil sands tailings containing bitumen. It can also be described in terms of an equivalent FOFW (fines over fines + water ratio) or solids content. This test results in an equivalent remoulded shear strength of 1 to 2 kPa.
MFT	mature fine tailings – fluid fine tailings with a low sand-to-fines ratio (<0.3) and a solids content greater than 30% (nominal)

PSD	particle size distribution
SC	solids content – mass of solids divided by mass of (solids + bitumen + water) x 100%
SFR	sand-to-fines ratio – the mass ratio of sand-to-fines; i.e., the mass of mineral solids with particle size >44 µm divided by the mass of mineral solids with particles ≤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)
TMF	*Lower Athabasca Region: Tailings Management Framework for the Mineable Athabasca Oil Sands*
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)