ecoENERGY Innovation Initiative

Research and Development Component

Public Final Report

Project: [UOSE 034 and Understanding Oil Sands Tailings Treatment at Nano, Micro and Macro-Scales with Increased Water Recycling/Reuse]

1 What was the R&D gap and why was this project needed?

Canada has vast natural resources, and has the largest oil sands deposit in the world. In a typical water-based oil sands extraction process, the production of one barrel of bitumen requires approximately two to four barrels of water. Unfortunately, after the bitumen is recovered, significant amount of tailing sludge is left, which has to be discharged into tailing ponds. Once being deposited, the coarse particles in the tailings would settle down to form beaches, while it is very difficult to settle and consolidate the fine solids. After days, weeks, months and even a few years of settling, the fine solids may still remain suspended in the form of mature fine tailings (MFT). Although part of the water in the original tailings could be released at the initial stage of settling, no further noticeable densification of MFT could occur for several decades. This is one of the most challenging issues technically and environmentally faced by the industry today: how to settle and consolidate tailings, reclaim the affected land, and to further recycle/ reuse the water trapped in the tailings for oil sands processing. Although much efforts has been devoted to developing oil sands tailings management solutions, there is no single commercial technology capable of economically and ultimately resolving the challenges posed by mature fine tailings.

This project focuses on developing novel low-cost and environmentally friendly polymers that are able to increase the settling rate of the fine solid particles with high efficiency. The as-developed polymers have been incorporated into a newly designed coacervate flocculation procedure, through which more clarified water can be generated for recycling in oil sands extraction. The settling rate for oil sands tailings, especially for extraction tailings, is significantly increased using the polymers developed in this project, and the quality of recycled water is also significantly improved. Meanwhile, a new dewatering process has been developed based on the sandcastle-inspired flocculation procedure, followed by a two-step compression. This process allows us to reclaim most of the water from MFT for reuse in the oil sands production and the treatment of MFT with high mechanical strength would meet the requirement of Alberta government on oil sands tailings. The project well aligns well with ecoENERGY Innovation Initiative's objectives of conducting R&D to improve tailings management by reducing tailings inventories, and reducing the volume of tailings produced.

2 Project objective:

The objective of this Project is to better understand the basic interaction mechanisms among clay particles, water and bitumen in oil sands tailings at the nano, micro and macro scales, and to develop high-efficiency, economical and environmentally friendly polymer flocculants based on natural macromolecules (i.e. natural polysaccharide derivative, and biomimetic polymers inspired by marine bio-adhesive systems such as mussels). Polymer flocculants are a kind of chemical that would cause suspended particles in a suspension to aggregate (aggregated particles are called flocs) and become heavier and bigger. The flocs developed from fine particles could significantly increase the settling rate of fine tailings and allow more water to be released for recycling. The research addresses the oil sands tailings treatment and associates water management initiatives and contributes to the continuing and sustainable development of the oil sands and other mineral resources in Canada.

3 Project evolution:

3.1 Identification and securing partners, permits etc.

A number of stakeholders can be identified for tailings management including water reuse/ recycle from the oils sands sector:

a) Oil and gas companies that are involved in the production/extraction of bitumen from oil sands resources;

b) Local communities and aboriginal communities;

c) Non-governmental environmental organizations;

d) Governments (all levels).

All of these stakeholders would benefit from the development of novel, high-efficiency, cheap and environmentally friendly polymers for improved tailings pond remediation and water treatment. The major mineral companies (oil sands, base metals, and coal) could also be the potential receptors of the results as these would enhance their mine tailings management and recovery/recycling of water from their extraction and processing operations. Also, by supporting the sustainable development of the oil sands industry, the local communities including aboriginal groups would benefit from ongoing employment and trade opportunities. Governments, at all levels, will benefit from the increased development and production from oil sands resources, with attendant capital investment and employment.

3.2 R&D Activities performed

Multiple techniques have been employed for the detailed characterization of the water chemistry and solids in the oil sands tailings samples provided by the oil sands industry. The results obtained have guided us to design and synthesize efficient, economical and environmentally-friendly polymer flocculants based on natural macromolecules (i.e.

chitosan derivative, and biomimetic polymers inspired by marine bio-adhesive systems such as mussels) with special adhesive interactions with clay particles, water and bitumen in oil sands tailings. The developed polymer flocculants have been adopted in treating oil sands tailings including extraction tailings, mixed tailings of extraction tailings and mature fine tailings, diluted mature fine tailings and original mature fine tailings, demonstrating unique flocculation performance in terms of water quality and settling speed. Combined with some of the existing commercial consolidation technologies in oil sands industries, a new process has been developed based on the sandcastle-inspired flocculation procedure, followed by a two-step compression. This process allows us to reclaim most of the water from MFT for reuse in oil sands production and the treatment of MFT with high mechanical strength would meet the requirement of Alberta government on oil sands tailings. The as-developed sandcastle-inspired coacervation flocculation process can be possibly integrated into several commercial (on-line) tailings processes, such as the tailings reduction operation (TRO) process of Suncor Energy, and the flocculation-centrifugation process of Syncrude Canada Ltd. The R&D Activities performed during the whole project could be divided into the following three main parts: (1) developing suitable methodologies to characterize the complex water chemistry of oil sands tailings and the basic interaction mechanisms among clay particles, water and bitumen in oil sands tailings and polymer flocculants; (2) Designing and synthesizing novel bioinspired polymer flocculants and incorporating them in a newly-developed coarveration flocculation procedure for treating different oil sands tailings; (3) developing a novel dewatering process through the combination of a sandcastle-inspired coacervation flocculation followed by a two-step compression to efficiently dewater and consolidate pure mature fine tailings.

Developing comprehensive methodologies to characterize the basic interaction mechanisms among clay particles, water and bitumen in oil sands tailings and polymer flocculants: To optimize and succeed in the design and synthesis of functional polymer flocculants and improve their flocculating performance on oil sands tailings including extraction tailings and mature fine tailings, the basic interaction mechanisms among clay particles, water and bitumen in oil sands tailings and polymer flocculants have been investigated by using surface forces apparatus (SFA), quartz crystal microbalance with dissipation monitoring (QCM-D) and focused beam reflectance measurement (FBRM) at the nano, micro and macro scales, respectively. The results demonstrated that a single polymer flocculant usually cannot perform well in treating mature fine tailings as the complicated water chemistry and complex interfaces severely undermine the adhesive interactions between the polymer flocculant and tailings particles, so that insufficient flocculation occurs, especially when the polymer flocculants adopted are polyelectrolytes (viz. charged polymers).

Novel flocculation procedures by using two complementary flocculants or additives have been developed and validated for treating extraction tailings, mixed tailings of extraction tailings and mature fine tailings or dilute mature fine tailings: Inspired by marine organisms such as mussel and sandcastle, we have developed a novel flocculation procedure by using two complementary flocculants or additives. Using two oppositely charged polyelectrolytes as polymer flocculants via electrostatic interaction and catechol chemistry, this methodology has been validated to be an efficient flocculation strategy in settling extraction tailings, mixed tailings of extraction tailings and mature fine tailing and dilute mature fine tailings, as well as in the recycling water from these tailings. As shown in Figure 1, the developed flocculation procedure on extraction tailings demonstrated a better flocculation performance in terms of ISR and turbidity of released water when compared with the commonly adopted flocculation procedure with a commercial polymer flocculant, magnofloc 1011 (MF). At optimal dosages of MF and chitosan, a comparable settling rate like that with MF alone. Hog the clarity of the supernatant is dramatically enhanced: the turbidity of the resultant supernatant is extremely low with a value of 71 NTU while the ISR value was maintained as high as 7.7 m/h. The whole two-step flocculation process was also explored by using FBRM and found that the enhanced settling performance of the developed two-step flocculation process is due to the sequential destabilization: (1) bridging of fine solids by anionic polyacrylamide polymer (i.e. MF), and (2) further aggregation and flocculation mediated by charge neutralisation of the cationic polymer (i.e. chitosan).

Although the two-step flocculation process performs well in treating extraction tailings, mixed tailings of extraction tailings and mature fine tailing in terms of initial settling rate (ISR) and clarity of the released water, it showed quite limited performance on consolidating diluted mature fine tailings even after extra operation efforts such as filtration. To confer this coacervation procedure with the ability to treat diluted mature fine tailings, we have designed and developed an environmentally friendly polymer flocculant based on a natural polysaccharide, chitosan, which possesses thermo-responsiveness and adopts a bottle-brush polymer architecture. The developed thermo-sensitive polysaccharide, poly(2-(2-Methoxyethoxy)ethyl methacrylate) grafted chitosan (CgM), could be switched from hydrophilic to hydrophobic when increasing the temperature above its lower critical phase separation temperature, around 27 ^{o}C. We have demonstrated that this polymer flocculant together with anionic polymer flocculants in coacervation flocculation procedure shows outstanding flocculation performance on treating extraction tailings, mixed tailings of extraction tailings and mature fine tailings as well as diluted mature fine tailings. With the assistance of heat treatment, sequential destabilization on the remaining fine solids in the supernatant could be induced and in turn further improve the clarity of the released water, which could be concluded from higher transmittance of supernatants at 50 ^{o}C as compared to that at 4 ^{o}C (Figure 2). Despite a better flocculation performance on diluted mature fine tailings was achieved by using the two-step flocculation process with the assistance of the cationic thermo-responsive polymer developed (see Figure 2), CgM, it showed very limited consolidation on the mature fine tailings. To further dewater and consolidate the flocculated tailings, filtration was applied on the flocculated tailings, and it was found that the CgM polymer endowed the flocculated tailing cake with better filterability after treated with optimal polymer dosage of CgM and MF, that is, 0.83 g/L CgM followed by 0.2 g/L MF when compared to that treated by 0.2 g/L MF (see Figure 2D). In addition, treatment of dilute mature fine tailing at a higher temperature above LCST, for example, 50 ^{o}C, ensured a faster filtration rate when compared with that at 4 ^{o}C. With a suitable heating treatment and filtration, we were able to further dewater the flocculate MFT tailings and consolidate the tailings to a physical form for direct deposition with a solid content >60%.

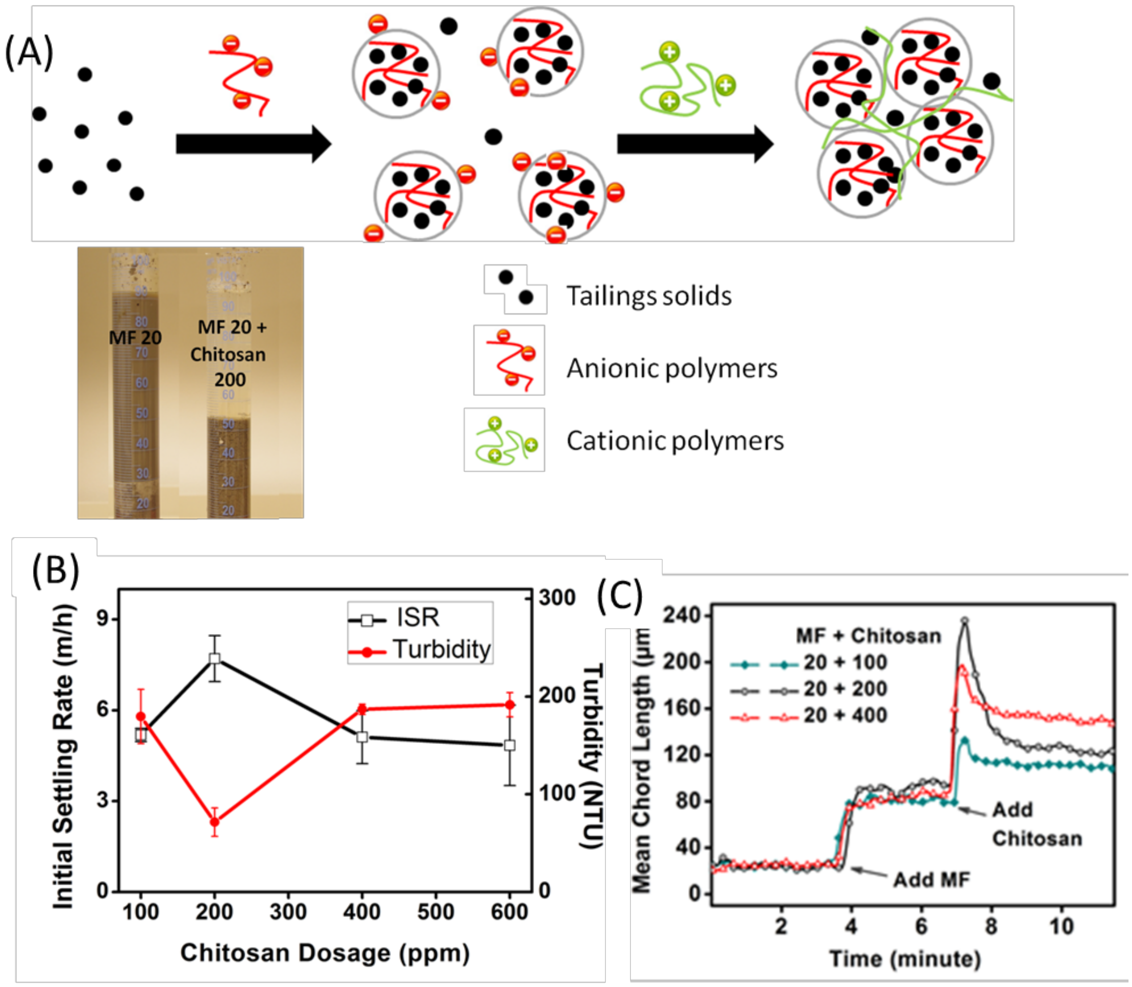

Figure 1. The flocculation performance and related mechanism of the developed flocculation procedure on extraction tailings exempted with two oppositely-charged polymer flocculants: (A) A schematic illustrates proposed flocculation mechanism involved in the two-step flocculation process. The inset is an image showing a significant improvement in clarity of the released water after the two-step flocculation process by using 20 ppm MF followed by 400 ppm Chitosan when compared to that treated by an optimal dosage of MF, which is a commonly adopted flocculant in oil sands industry. (B) ISR and turbidity of supernatants of oil sands extraction tailings settled using a two-step flocculation process with 20 ppm of MF followed by different dosages of chitosan. (C) Square weighted mean chord length versus time measured using FBRM in two-step flocculation using a fixed dosage of MF at 20 ppm with varied chitosan dosage (100, 200, 400 ppm) on the treatment of oil sands tailings. The mixing speed was fixed at 300 rpm.

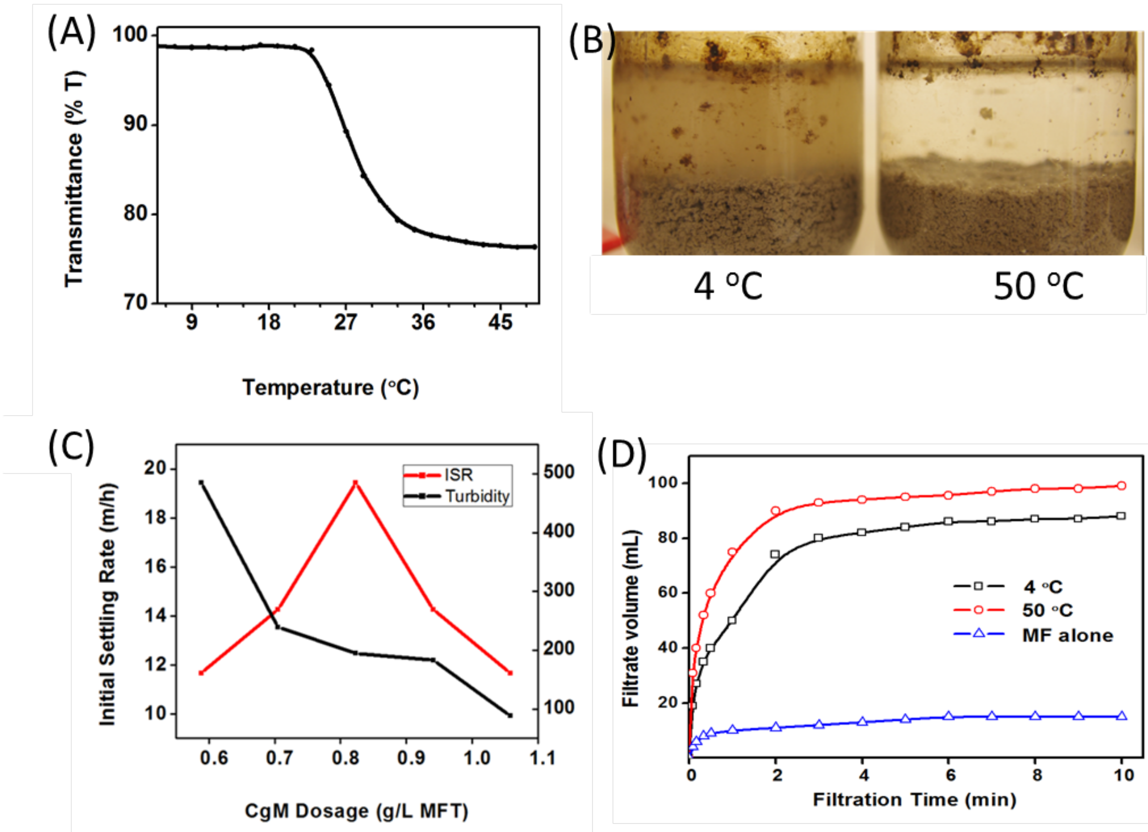

Figure 2. The properties of the developed thermo-sensitive polysaccharide focculant and its flocculation performance on the diluted mature fine tailings by using the developed two-step flocculation process: (A) Determination of the lower critical solution temperature (LCST) for the developed thermo-sensitive polysaccharide, poly(2-(2-Methoxyethoxy)ethyl methacrylate) grafted chitosan (CgM) , in an aqueous solution (10 mg/mL), based on change in transmittance (at 700 nm) of aqueous solutions against the temperature change. (B) The temperature effect on final clarity of the released supernatant after flocculation with MF and CgM, which clearly demonstrated that increasing temperature to 50 ^{o}C (above LCST) could significantly improve the clarity of the released supernatant. (C) Initial settling rate (ISR) and turbidity of supernatants of oil sands extraction tailings settled using a two-step flocculation process with 20 ppm of MF followed by different dosages of CgM. (D) Filterability of the flocculated cakes (viz. volume of filtrated water as a function of time) after treated with 0.83 g/L CgM followed by 0.2 g/L MF at 4 ºC and 50 ºC as well as 0.2 g/L MF alone at room temperature.

A novel process combining a sandcastle-inspired coacervation flocculation followed by a two- step compression has been developed for dewatering and consolidating mature fine tailings: It should be noted the developed polymer flocculants only show limited ability in treating non-diluted mature fine tailings. Therefore, another flocculation strategy has been developed based on a self-healable coacervation procedure by endowing polymer flocculants/additives with abilities to form dynamic Schiff base bonds and adhere to tailing particles even in non-diluted mature fine tailings. Two adhesive polymer components have been developed and synthesized to replace the oppositely charged polyelectrolytes used in the previously developed coacervation procedure, of which one is a cationic polymer with a hyperbranched architecture branched poly(ethyleneimine) (BPEI), a weak polybase and not sensitive to ionic strength, and the other one is a delicately-designed functional crosslinker, difunctional polyethylene oxide (DFPEO), for BPEI. This flocculation procedure could greatly enhance the mechanical property of the flocculated MFT and feasibly reclaim inbound water from MFT, which has been validated by measurements using rheometer and capillary suction timer. To facilitate recycling the inbound water from MFT and dewatering/consolidating flocculated MFT for direct deposition, a two-step consolidation procedure was developed on flocculated MFT by applying two different pressures, i.e., low pressure (e.g. 0.15 bar) and high pressure (10 bar) in sequence. The consolidation setup as shown in Figure 3(A) is an in-house built equipment combining two steel plates and a table clamp. The pressure conditions adopted here are quite low, which can be easily achieved in the real industrial tailings treatment. After treating 120 g MFT with 0.5 g BPEI and 0.5 g DFPEO, we could easily reclaim 30 wt% inbound water from the MFT. After further sequentially applying 0.15 bar (<1hr) and 10 bar pressure (<1 h), a total water release of 70 wt% was finally achieved. More importantly, the solid content in the pressed MFT could be significantly enhanced from 30 wt% to around 75 wt%, which can be directly deposited for land reclamation. Figure 3(B) and 3(C) show compressed cakes of mature fine tailings after being treated with BPEI and DFPEO followed by 0.15 bar (<1hr) and 10 bar pressure (1 h), respectively. It is noted that the compressed cake of mature fine tailings even only after 0.5 bar for 0.5 hr appear to be quite dry and has high mechanical strength. This cake could be further consolidated to be a soil with solid content above 70 wt% by 10 bar pressure (<1 h). Through these compression tests, the volume of the cake is decreased by 5 times. To explore the mechanism of the process developed and the excellent performances on dewatering and consolidating MFT, surface forces apparatus (SFA) was utilized here to investigate the interactions among these synthesized polymers and tailing solid particles. The SFA measurements clearly indicate that BPEI could strongly adhere to clay particles to cause primary aggregations which could be bridged by forming crosslinks of Schiff base bonds between BPEI and

DFPEO. Meanwhile, these crosslinks of Schiff base bonds are highly reversible. Under external force or pressure such as shearing, the bond could be easily damaged but could be totally recovered. Therefore, all of these results have validated that the developed process combining a sandcastle-inspired coacervation flocculation followed by a two-step compression is a promising method in consolidating mature fine tailings and could be easily integrated into the existing technologies for oil sands tailings.

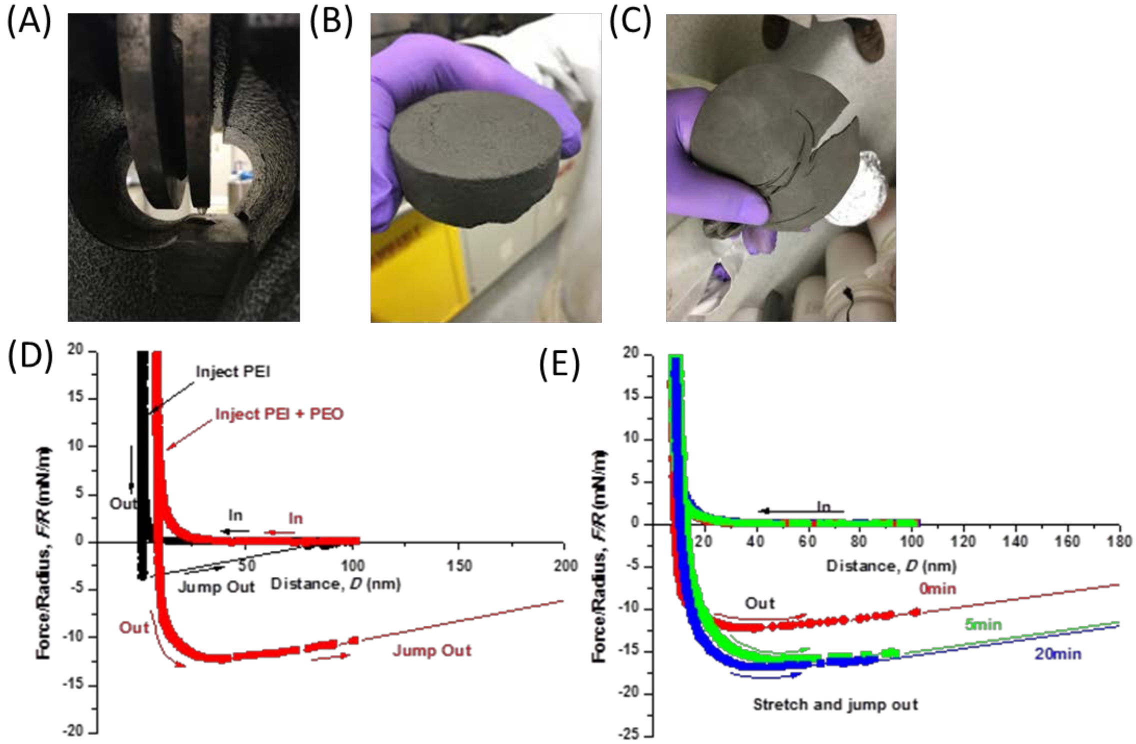

Figure 3. The consolidation properties of the developed novel process combining a sandcastle-inspired coacervation flocculation followed by a two-step compression on mature fine tailings with branched poly(ethyleneimine) (BPEI) and difunctional polyethylene oxide (DFPEO) as well as surface force measurements for exploring its related consolidation mechanism by using SFA: (A) The in-house setup using a table clamp consolidates flocculated mature fine tailings. Due to high cohesion and high mechanic strength of cakes of flocculated mature fine tailings, the cake can stay integral and continue dewatering under external pressure. (B) and (C) show the consolidated cakes pressed after 0.15 bar for 0.5 hr and 10 bars for 1hr. SFA results showing the interactions among mica (a model clay), BPEI and DFPEO, and the reversibility on force magnitude of Schiff-base bonds formed between amine and benzylaldehyde groups of BPEI and DFPEO: (D) force-distance profiles between two mica surfaces associated with

approaching and separation after injecting BPEI (black line) followed with the injection of DFPEO (the red line) (E) Force-distance profiles of two mica surfaces associated with approaching and separation after injecting BPEI and DFPEO.

3.3 Challenges encountered:

Industrial and academic societies have devoted tremendous efforts to developing different technologies to deal with the challenging issues related to mature fine tailings in order to effectively and efficiently recycle large amounts of inbound water and reclaim the land occupied by the gigantic tailings ponds, including the composite tailings (CT) technology, the thickened tailings (TT) technology, the tailings reduction operation (TRO) and the flocculation-centrifugation process. However, none of these can effectively dewater MFT directly. To achieve a better dewatering performance, the existing methods usually require additional pre-treatment steps such as dilution or adding coarse sands. Other methods like freeze-thaw cyclic treatment demonstrated its effectiveness in dewatering MFT at small scale. However, this method might be difficult to scale up and its final performance is highly dependent on weather and seasonal variations. It is also noted that all of these existing technologies are highly dependent on process conditions such as the ways to add and mix chemicals with MFT, and the natural drying conditions via evaporation.

Due to the complex water and colloid chemistry involved in mature fine tailings, it is still a great challenge to effectively flocculate, swiftly dewater and consolidate pure mature fine tailings to produce depositable soil of high solid content of above 70 wt%. Inspired by sandcastle, we have developed a self-healable coacervation procedure for treating mature fine tailings, by using the developed cationic polymer flocculant with a hyperbranched architecture, branched poly(ethyleneimine) (BPEI), which is a weak polybase and not sensitive to ionic strength, and difunctional polyethylene oxide (DFPEO), a specific adhesive to BPEI. This new process and methodology has been verified to be able to greatly enhance the mechanical property of flocculated MFT and ensure feasible reclamation of inbound water from MFT in a short period of time by combining with a two-step compression. Our settling tests on real mature fine tailings have shown that this new process/technology could effectively consolidate flocculated MFT for direct deposition. To the best of our knowledge, this is the first method in the field of mature fine tailings treatment that could efficiently reclaim 30 wt% of water from MFT in less than 1 hr and achieve a total water releasing rate of 70 wt% in ~1 hr via mild compression (e.g. 10 bar pressure), significantly enhancing the solid content of pressed MFT from 30 wt% to ~75 wt% that allows direct deposition and land reclamation.

The developed process by combining the coacervation flocculation procedure and a two-step compression is compatible with and can be possibly incorporated into some of the existing commercial processes, such as the tailings reduction operation (TRO) process of Suncor Energy, and the flocculation-centrifugation process of Syncrude Canada Ltd. All these commercial tailings treatment technologies use a significant amount of polymer flocculants and they enhance the dewatering process via different methods (e.g. centrifugation) which are generally energy-intensive and time-consuming. The novel polymer flocculants developed in this project can be used individually or combined with commercial flocculants for the treatment of oil sands tailings, which can more efficiently dewater the oil sands tailings and facilitate the land reclamation for oil sands industry.

4 Conclusions:

Through our proposed project, the research has built up an improved and profound fundamental understanding of settling of fine solids and removal of hazardous components in the oil sands tailings, which helps reduce the environmental footprint of fossil energy exploration, extraction and processing. We have also developed novel flocculants and settling strategies for the treatment of oil sands tailings. Understanding the interfacial properties and settling of tailings at the macro, micro, and nano scales and even at the molecular level is crucial for solving the challenging tailings issues to allow increased water recycling/reuse in mineral engineering and industry. Our project developed innovative flocculants, new knowledge, and technologies to address the challenging issues on tailings treatment and water recycling/re-use, which is critical to the continuing and sustainable development of the vast oil sands resource in Canada and can be also extended to other mineral tailings and water treatment industries.

In principle, all the oil sands and mineral industries can be the potential receptors of the proposed work. The oil sands industry is currently using the conventional water-based extraction processes, which causes an increase in the salinity of the recycled release water and produces tailings with poor settling and consolidation properties. Fine tails volume increases at a rate of about 0.1 m^3 per ton of processed oil sand, and the growth of mature fine tails is about 0.06-0.15 m^3 per ton of processed oil sand. There are more than 170 square kilometers of tailings ponds in the oil sands production region. As the capacity of existing plants is increasing and new plants are being constructed, the existing MFT inventory of 800 million m^3 will grow at a much faster rate and reach one billion m^3 in a few years. The demand for water is becoming a bottleneckfor the future oil sands development. All the major mineral companies (oil sands, base metals, and coal) such as CNRL, Syncrude, Imperial Oil, Shell, Suncor, Teck, and TOTAL would all be the potential receptors ofthis work. Our research findings have helped to develop innovative, highly efficient, economical and more environmentally friendly technologies to treat oil sands tailings and improve the dewatering processes, enhancing Canada's ability to sustainably develop important unconventional oil and gas resources and reduce the adverse environmental impacts.

4.1 Benefits and outcomes of the project

Canada has the largest oil sands reservoir in the world. While enjoying a healthy economic growth based on the abundant natural resources, the Canadian oil sands and mining industry is facing great technical and environmental challenges. The oil sands industry is currently using the conventional Clark Hot Water Extraction process, which operates at elevated pH, causes an increase in the salinity of the recycled release water and produces tailings with poor settling and consolidation properties. Fine tails volume increases at a rate of about 0.1 m^3 per ton of processed oil sand, and the growth of mature fine tails is about 0.06-0.15 m^3 per ton of processed oil sand. Currently, there are more than 170 km^2 of tailings ponds in the oil sands region. As the capacity of existing plants is increasing and new plants are being constructed, the existing mature fine tailings inventory of 800 million m^3 will grow at a much faster rate and reach one billion m^3 in a few years. Water represents a major component of oil sands and mineral processing operations, and the demand for water is becoming a bottleneck for the future oil sands development. Water management is critical to the continuing and sustainable development of the vast oil sands resource in Canada, which has been the main focus of this project.

This research project has addressed the challenging issue on oil sands tailings treatment and associated water management, and the research outcomes contribute to the continuing and sustainable development of the Athabasca Oil Sands resources. The research findings have improved the fundamental understanding of the settling of oil sands tailings and water management, which helps to reduce the environmental footprint of fossil energy exploration, extraction and processing. The outcomes of this project can also help develop innovative, highly efficient, economical and more environmentally friendly ways and technologies to extract bitumen and improve the dewatering processes, enhance Canada's ability to sustainably develop important unconventional oil and gas resources and reduce environmental impacts. The benefits and outcomes generated through this project could be detailed as follows:

Better understanding the settling of oil sands tailings and water management and developing innovative, highly efficient, economical and more environmentally friendly ways and technologies to improve the dewatering processes: Polymer flocculants have been widely used in industrial water treatment and in some of the commercial processes for the treatment of the oil sands tailings. For example, the tailings reduction operation (TRO) combines polymer flocculation with thin lift deposition. Nevertheless, none of the commercial processes/technologies can effectively dewater MFT to meet the government's regulations, and these commercial processes usually require additional pre-treatment steps such as dilution or adding coarse sands to achieve acceptable outcomes so that the MFT could be suitably dewatered and consolidated to a certain point, which is generally energy-intensive and time-consuming. Therefore, it is of both fundamental and practical importance to understand the interaction mechanisms among clay particles, water, ions and bitumen in oil sands tailings and polymer flocculants at the nano, micro and macro scales and to develop highly efficient, economical and environmentally-friendly polymer flocculants for effectively dewatering, consolidating and densifying mature fine tailings. This research project has built up a unique library of methodologies to characterize the basic interaction mechanisms among solid particles, water and bitumen in oil sands tailings and polymer flocculants, which revealed that the complicated water chemistry in oil sands tailings could significantly affect the interfacial interactions among solid particles and the polymer flocculants added. Based on these fundamental understandings, we have designed and developed some bio-inspired effective polymer flocculants and coacervation flocculation process, which suits the treatment of different oil sands tailings ranging from extraction tailings to mature fine tailings. For example, based on the developed cationic polymer flocculant with a hyperbranched architecture, branched poly(ethyleneimine) (BPEI), which is a weak polybase and not sensitive to ionic strength, and difunctional polyethylene oxide (DFPEO), we have developed a self-healable coacervation procedure for treating mature fine tailings. This new process and methodology have been verified to be able to greatly enhance the mechanical property of the flocculated MFT and ensure feasible reclamation of inbound water from MFT in a short period of time by combining with a two-step compression. Our settling tests on real mature fine tailings have shown that this new process/technology could effectively consolidate flocculated MFT for the direct deposit. To the best of our knowledge, this is the first method in the field of mature fine tailings treatment that could efficiently reclaim 30 wt% of water from MFT in less than 1 hr and achieve a total water releasing rate of 70 wt% in ~1 hr via mild compression (e.g. 10 bar pressure), significantly enhancing the solid content of pressed MFT from 30 wt% to ~75 wt% that allows the direct deposition and land reclamation.

All of these accumulated information and acknowledge could be taken up and used by the stakeholders of the oil sands industry. The developed tailings settling technologies and water management strategies will significantly add further values to the extensive work which has been done in the tailings field in both oil sand industry and research institutes in Canada. The research project helps to advance Canada's commitment to reduce the environmental impacts of energy production, conversion, and use, including responding to the Government of Canada's commitment, contributing to the reduction of other air emissions as well as other environmental benefits, such as clean water and land. The research outcomes help to solve the challenging tailings water issues in oil sands extraction and support the development of next-generation technologies that target and respond to Canada's energy profile and needs. The new flocculants and processes/technologies developed in this project contribute to Canadian prosperity and competitiveness, and in particular, to support and enhance the competitiveness of Canada's clean tech sector, building on Canada's strengths and competitive advantage.

Training opportunities provided to Highly Qualified Personnel for future hiring for the mineral and energy industry of Canada: The research project addresses the oil sands tailings treatment and associated water management initiatives and contributes to the continuing and sustainable development of the oil sands and other mineral resources in Canada. This project focused on the interdisciplinary area of chemical engineering, materials engineering, nanotechnology, energy, petroleum engineering and environmental engineering. The highly qualified personnel had the opportunity to be trained on various unique and state-of-the-art and advanced techniques and experimental methodologies such as surface forces apparatus (SFA), quartz crystal microbalance with dissipation monitoring (QCM-D) and focused beam reflectance measurement (FBRM) to investigate the basic interaction mechanisms among clay particles, water, ions and polymer flocculants at the nano, micro, and macro scales. Through the proposed research, the highly trained personnel have mastered how to apply these techniques and methodologies to solve a practical industrial challenge faced by oil sands industry via the development of novel bio-inspired polymer flocculants to support the sustainable development of natural energy resources in Alberta. The highly trained personnel were co-supervised by the PI and co-PIs, and have the opportunity to publish their research results in the top journals in the field and present their results at national and international conferences and workshops, interacting with researchers from different fields. The highly trained personnel (HQP) in this project has extensive experience working in multidisciplinary research environment within the synergy of collaboration between academic and industrial research, which has made them a great asset for future hiring for the mineral and energy industry of Canada. They are capable of integrating knowledge across disciplines, working in teams, understanding industrial needs, and addressing problems from an engineering system's perspective.

4.2 What are the next steps for R&D in this area?

The project has systematically characterized the properties of oil sands tailings (i.e., types of salts and concentrations, pH, solid particles), and investigated the interfacial interactions of the particles in the tailings and polymer flocculants. The fundamental knowledge generated, together with the data available in the literature, can serve as a useful database for the academic and industrial researchers/engineers in the field to develop improved technologies for better water use and water management in Canadian industries in nature resources within the medium term (5-10 years, and even longer). The environmentally friendly and bio-inspired polymer flocculants developed in this project, such as polysaccharides (e.g., based on functionalized chitosan and chitosan derivatives), can be used individually or combined with commercial flocculants for the treatment of oil sands tailings, which can more efficiently dewater the oil sands tailings and facilitate the land reclamation for oil sands industry. The developed process by combining the coacervation flocculation procedure and a two-step compression is compatible with and can be possibly incorporated into some of the existing commercial processes for oil sands tailings treatment, such as the tailings reduction operation (TRO) process of Suncor Energy, and the flocculation-centrifugation process of Syncrude Canada Ltd. The successful development and application of th novel, environmentally friendly and biomimetic polymers have stimulated us to develop more innovative technologies for mature fine tailing treatment in the future. For the next steps of this project, we will work with the industry to further investigate how the developed flocculants and flocculation process can be effectively integrated with the current commercial flocculants and tailings treatment processes used by the oil sands industry.