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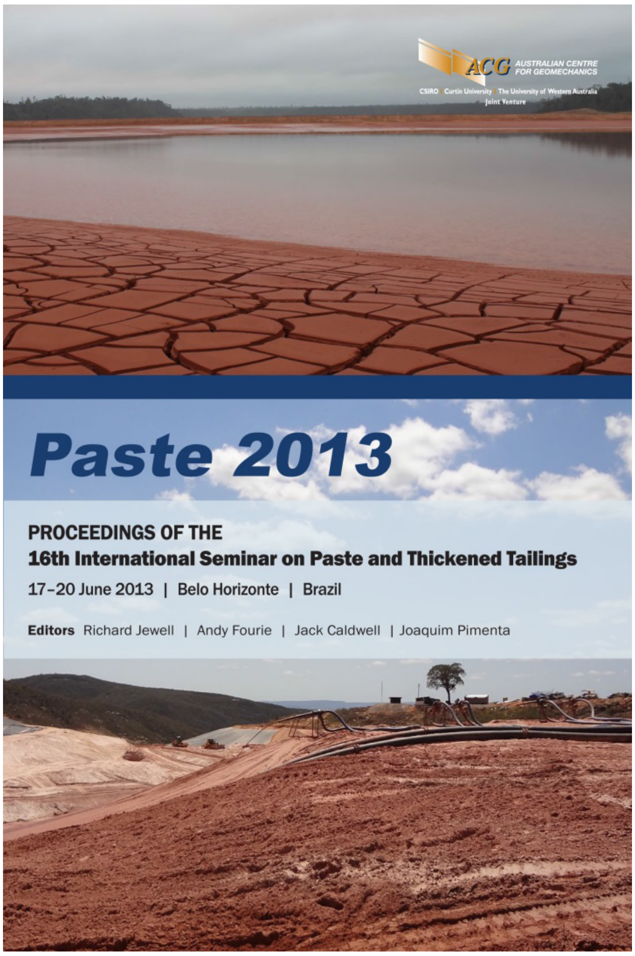

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# Developments in treating and dewatering oil sand tailings

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## Abstract

*Alberta's oil sand mining industry has embarked on a number of initiatives to develop novel ways of dewatering oil sand tailings so that they can be reliably and responsibly stored in a closure landscape. This has included the production of paste tailings (by various means) and the production of dry, stackable tailings. The technical challenges are significant and the pressure (both regulatory and stakeholder) for quick solutions has resulted in a tremendous concentration of research and development effort (and dollars spent).*

*Challenges to the success of this initiative include: a) the very real technical difficulties with dewatering and fines capture for this type of tailings, b) the long research and development cycles, c) late-breaking issues that only surface during the large scale-up required to handle typical oil sand tailings flow rates, d) the impediments resulting from less than full and timely industry collaboration, e) unexpected environmental implications, and f) the changes introduced by an evolving regulatory environment.*

*This paper will give a short overview of some of these issues and then will focus on recent industry research and development initiatives. This includes a discussion of promising dewatering methods under development, including future roles for thickeners, in-line thickening with polymers (resulting in a variety of possible tailings deposits), treatment with silica-based technologies, novel additives, and non-conventional applications of filtering technologies. Part of the equation is also the treatment and discharge of water released by these processes.*

*The paper ends with a discussion of the impact this work is having on the planning for future oil sand mines, and due to the large accumulation of high water content, low strength tailings deposits, how tailings dewatering technologies have become an important determinant in the overall mine plan. This serves to emphasise the importance of the old adage to 'begin with the end in mind'.*

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## 1 Introduction

### 1.1 The problem: fluid tailings

Fluid tailings, sometimes called fluid fine tailings, are defined in the oil sand mining industry as any tailings in a fluid state, with a solids content greater than 1% and a remoulded undrained shear strength of less than 1 to 2 kPa. At the end of 2010, 830 million m$^3$ of fluid tailings had accumulated on all of the open pit mining leases in the Athabasca Oil Sand area, in northern Alberta, Canada (Alberta Environment and Sustainable Resource Development). The containment structures cover an area of close to 180 km$^2$ (18,000 ha) and are easily visible on Google Earth or recent satellite photographs.

It has been technologically difficult to reclaim oil sands tailings ponds in a manner that would produce trafficable deposits and a geotechnically stable closure landscape, without the use of an intervening tailings treatment technology that would speed up the settlement of fines in the fluid tailings or otherwise separate the fines from the process water. Various technologies have been in development for several years now (Sobkowicz, 2010), but remain expensive to deploy on a large scale.

### 1.2 The solution: dewatering to meet reclamation and closure objectives

With the issuance of Directive 074 (Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes) on 3 February 2009, the Alberta Energy Resources Conservation Board (ERCB) took the first step in regulating tailings management, in an effort to press industry to speed up the process of reclaiming fluid tailings deposits. Some of the history and thinking behind Directive 074 is given in Houlihan et al. (2010).

Directive 074 requires the industry to:

1. Reduce the amount of fluid tailings by depositing fines in dedicated disposal areas, in a manner such that these deposits meet specified tailings performance criteria (e.g. achieving 5 kPa undrained strength within one year of deposition and at least 10 kPa strength within 5 years of cessation of deposition) and can be reclaimed in a short time. The amount of fines to be captured in dedicated disposal areas is also specified in the regulation.
2. Submit plans to the ERCB indicating how they will achieve this fines capture and operate their dedicated disposal areas.
3. Submit annual fluid tailings pond status reports, providing information on the volume and properties of the fluid tailings on the mine lease.
4. Measure the performance of the material in each dedicated disposal area.
5. Submit an annual compliance report for each dedicated disposal area that compares tailings performance to plan.
6. Mitigate any deposits in dedicated disposal areas that do not meet approved plans.

These requirements are focussed towards achieving the reclamation and closure objectives that are given in Directive 074. A more recent set of reclamation and closure objectives for oil sand tailings was developed as part of the Tailings Roadmap Project, reported elsewhere in this seminar (Sobkowicz et al., 2013).

### 1.3 The challenge: developing technically effective and cost effective dewatering technologies

The oil sands industry is challenged to meet the requirements of Directive 074, both in terms of technical effectiveness and cost. There are a number of reasons for this, as discussed in the following sub-sections.

#### *1.3.1 Dewatering of fluid tailings is technically difficult*

Either because of segregation from whole tailings streams or because of production in the extraction plant, fines end up in a highly dispersed state in tailings ponds, typically with initial solids contents of 15 to 20% (mass of solids / total mass) and sand to fines ratios (mass/mass) of less than 1. In the oils sand industry, this material is referred to as thin fine tails. The clay, silt and fine sand particles settle out with time resulting, after several years, in a mature fine tails with a solids content of about 30 to 35% and a sand to fines ratio of 0.1. This material, composed mostly of clay and finer silt particles (<44 µm), remains remarkably stable for tens of years, showing little propensity to settle further or to start consolidating.

The highly dispersed nature of the fines is due, in part, to dispersing agents that are added during the extraction process to maximise the recovery of bitumen from the ore.

To progress from a fluid to a solid, and furthermore to meet Directive 074 reclamation criteria, fluid tailings must be significantly dewatered. Mature fine tails, for example, must see an increase in solids content from 35% to about 75%, to achieve a remoulded undrained strength of 5 to 10 kPa. This represents a loss of about 80% of its original water volume and 70% of its original total volume.

Currently there is no tailings treatment technology that can produce this amount of dewatering in one step. Available technologies, incorporating one or two stages of dewatering, can dewater mature fine tails to a paste with a solids content of 60 to 65% and a remoulded undrained strength of 500 to 1,000 Pa. Additional dewatering to meet minimum reclamation requirements involves environmental assistance (typically drying; Boswell and Sobkowicz, 2010), which in the northern Alberta climate is both fickle and short-lived. Technologies that rely on drying as a final dewatering step achieve only modest dewatering efficiencies (0.7 to 1 tonne of solid fines per $m^2$ per year), require very large deposit areas, and result in very high

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dewatering costs. Alternatively, technologies that rely on consolidation to achieve the last stage of dewatering are too slow to meet Directive 074 reclamation timelines.

### *1.3.2 Long research and development cycles*

Progressing a new technology from concept through the various research and development steps to a mature commercial implementation can be a daunting task in the oil sands industry. The typical timeframe required is from two to three years for the research stage, from two to five years for the development stage, and another one to five years (or more) during commercial implementation to bring the technology to a mature state. Timelines from concept to full, mature commercial implementation are thus in the order of five to more than 10 years, under ideal conditions.

The long timeframe of the research and development cycle, and the size of the operations at full scale, both have a large impact on cost. It is not uncommon for pilot scale trials to cost several million dollars, for prototype scale trials to cost tens of millions of dollars, and for initial commercial implementations of a tailings treatment technology to cost tens to hundreds of millions of dollars. Even then, further development may be required to bring the technology to a mature commercial state, delivering all of the desired performance.

The complexities of the technology development process are described in Gidley and Boswell (2013). Many attempts have been made over the past 30 years to test different tailings dewatering technologies, most without success (Sobkowicz, 2010). Often this was caused by the need for a quick solution and a focus on short-term development, and/or by discouragement with poor performance in early trials and failing to recycle back through the research and development cycle to fully investigate and prove out the technology.

As also pointed out in the Tailings Roadmap Project (Sobkowicz et al., 2013), it has been difficult for new tailings technology proponents and vendors to engage oil sand operators sufficiently to result in serious research and development effort. There are a number of reasons for this, but the result is that testing and development of new technologies can be slow. Those without deep pockets or robust business organisations often languish by the wayside.

### *1.3.3 Late breaking issues*

Even when conscientiously following a proper research and development process, it is possible to encounter late breaking issues that threaten the success of a new technology. The technology may have been run in a prototype setting, integrated into one tailings stream from the extraction plant. However, further scale-up, continuous commercial operation, exposure to all the vagaries of a northern Alberta winter, and integration into tailings and closure plans, often expose new technology weaknesses.

A good example of this issue is the development of consolidated tailings (CT). This technology involves running the whole tailings stream through a cyclone to separate the sand and some water from the fines and most of the water, and the addition of mature fine tailings and a coagulant into the cyclone underflow. This produces a tailings stream with a sand to fines ratio of about 4 and a solids content of between 55% and 60%. This material has a slightly higher density than whole tailings from the extraction plant and is less susceptible to segregation.

The laboratory, pilot and prototype testing of CT carried out in the early to mid-1990s, showed a viable technology for increasing fines capture. The industry thus adopted CT in commercial operations in 1996 at Suncor, and in 2000 at Syncrude. Performance issues were still encountered. The first was in producing a CT that met a prescribed, robust recipe – a variable whole tailings feed density, the bitumen and rock content, and an unreliable supply of chemical additive all posed challenges. It took operators several years to identify and implement process changes and controls so that they could reliably produce a CT that met specifications.

The second challenge was to provide a sufficiently low energy environment when CT is discharged to a disposal area, so that it does not segregate under high shear stresses. Partial segregation of CT has

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occurred in existing CT ponds. The issue is understood but does not have a simple solution, due to challenges associated with winter weather and optimal tremie operation from a floating platform. Fifteen years after initial commercial implementation, oil sand operators are still actively researching and developing discharge techniques to solve this problem.

### *1.3.4 Industry collaboration*

While a significant amount of research and development effort has been expended over the past 40 years to address the fluid tailings issues, the work by individual operators has proceeded on essentially independent paths. Some information was shared via normal technical channels, such as conferences, student thesis, etc. However, the lack of full and active collaboration between operators on tailings issues, the complex nature of those issues, and a focus on quick fixes (the latter two described earlier), generally led to slow progress on fluid tailings solutions.

With the release of Directive 074 by the ERCB, the pressure to develop effective tailings treatment technologies increased significantly. This provided an increased incentive for collaboration, as discussed in Section 2.2.

### *1.3.5 Unexpected environmental implications*

When the ERCB was formulating Directive 074, they released several drafts of the regulation, seeking input from industry and public stakeholders. The early drafts seemed to favour CT as a tailings technology of choice, but the focus in the final regulation shifted to in-line flocculation of mature fine tails combined with thin-lift dewatering and drying (not explicitly, but implied in the tailings criteria). Suncor was the early champion of that technology, implementing it at commercial scale over a very short (2 year) period. As such, the technology was immature and there were numerous lessons learned while continuing to operate a commercial facility.

The first hard lesson was the difficulty of achieving reliable drying in the last stage of dewatering of the mature fine tails, given the northern Alberta climate, and thus the large drying area required. The following points are germane to this discussion:

- Overall dewatering/drying efficiencies are in the range of 0.7 to 1 tonne of fines/m$^2$/year.
- A thin-lift dewatering system handling nominally 700 m$^3$/hour of 30% solids content mature fine tails equates to processing about 235 dry tonnes of fines per hour.
- Operating in about a 180-day spring/summer/fall window, with no allowance for down time, the maximum amount of fines that could be handled in this manner from one mature fine tails stream is in the order of 1 M tonnes.
- At the above noted dewatering efficiency, this would require a dedicated disposal area with an area of 100 to 150 ha. With allowance for containment berms, drainage ditches, and access roads, the area requirements are even higher – as much as 150 to 200 ha for every 1 M tonnes of fines captured in this manner.
- With Directive 074 fines capture requirements increasing to 5 M tonnes or more annually for some mines, using this dewatering/drying method exclusively, 5 or more mature fine tails streams and up 800 to 1,000 ha of land area would be needed.

The lesson from this experience is that fluid tailings treatment by in-line flocculation and thin-lift dewatering is very expensive, requires large (not necessarily available) tracts of land, and has a high environmental impact (in terms of additional land cleared and later needing reclamation). This is one example, but the issue is common to any tailings technology that produces a paste as an intermediate product and relies on environmental assists for the final stage of dewatering. The lesson is, of course, specific to the geographical location and climate.

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### 1.3.6 Evolving regulations

All of the existing oil sand mining companies have in place social license policies that state, in effect, that they will comply fully with all government laws and regulations. In living up to these policies, they are all struggling to modify existing tailings plans to meet Directive 074 criteria and their fines capture commitments to the ERCB. The ERCB anticipated some difficulty in making these changes and phased in some aspects of Directive 074, such as scaling up of the required amount of fines capture over several years. However, neither they nor the oil sand companies at first fully appreciated the time required to develop new tailings technologies, and thus the phasing-in aspects of Directive 074 are insufficient for an orderly progression to new fluid tailings treatment technologies. As discussed previously, this has resulted in some operators attempting to short circuit the normal research and development cycle to bring a new tailings technology to a commercial level, and in so doing accruing unnecessarily high costs, as well as, in some cases, less than optimal performance.

Both parties have also learned some of the unanticipated consequences of the regulations as written, but there does not appear to be a clear path forward to improve the regulations. At one point, another government department (Alberta Environment and Sustainable Resource Development) was preparing a more broad policy document for oil sand tailings, referred to as the Tailings Management Framework. This document has gone through numerous drafts and rounds of discussion between regulators, the industry and other stakeholders. However, it now appears to be stalled, for the reason discussed below.

In December 2012, the Alberta government passed the Responsible Energy Development Act, which creates a single regulator for oil, gas, oil sands and coal projects in the province, with responsibilities from project application to final reclamation. In particular, the new Alberta Energy Regulator will bring together the regulatory functions of the ERCB and Alberta Environment and Sustainable Resource Development. However, the exact structure and function of this regulator has not been announced; in fact, the Alberta government has just now finished public consultations, seeking input on how to structure the new regulator.

Some time may be required before the new Alberta Energy Regulator is in place and fully functional and improvements to oil sand tailings regulations can be addressed. In the meantime, the oil sand mining companies remain in limbo, continuing to expend large amounts of money and resources to meet Directive 074 in its current form.

## 1.4 Current tailings practice

While this paper is focussed mostly on future tailings technology development and solutions, it is useful to consider the methods currently in use for dewatering fluid tailings at oil sand mines. Methods that have been commercially implemented are discussed briefly below. Some of these are still under active development and so are also covered in the following section. For the interested reader, a detailed discussion of current tailings technology suites, including their strengths and weaknesses, is found in the reports of the Tailings Roadmap project (Sobkowicz et al., 2013).

- The earliest and still common method of tailings treatment is discharge of whole tailings into a pond, forming sand beaches and accumulating fluid fine tails. The tailings are conveyed to the discharge site by pipeline, using centrifugal pumps, as a 50% solids content slurry, with a sand to fines ratio typically of 4 to 6 (depends on ore characteristics). From 40 to 60% of the fines in the pipeline are captured in the sand beaches. This method is inexpensive and, as long as an operator has a secondary technology for dewatering the mature fine tails, an acceptable approach.
- On one mine, the underflow from a conventional tank thickener with highly variable solids content is co-disposed in one area of their tailings pond, along with whole tailings and cyclone underflow tailings.
- CT has been produced at both Suncor and Shell, and will soon be implemented (at least for a short time) at Shell's Muskeg River Mine. As discussed in Section 1.3.3, even after commercial

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implementation, challenges have been encountered with this technology, the solutions for some of which have been found and for others are still under development (Section 2.3.9).

- The most recent commercially implemented technology is in-line flocculation of mature fine tails with thin-lift dewatering. Mature fine tails with a nominal solids content of 30% and a sand to fines ratio of 0.1 are recovered from tailings ponds, injected with a polyacrylamide polymer, and discharged on shallow beaches in thin lifts (100 to 300 mm) in dedicated disposal areas. After initial water release (within about 24 hours) solids contents increase to 50% or so. Additional dewatering occurs by drying. In some cases, the material is spread further in the cell by mechanical means and/or worked mechanically to promote drying. End targets for drying are in the range of 65 to 70% solids content, reaching peak undrained strengths of 5 to 20 kPa and remoulded undrained strengths of 1 to 5 kPa. The material is then either windrowed or removed to make room for the next lift, and eventually trucked to waste dumps. No multi-lift deposits have yet been formed due to the long time required to reach higher strengths, but these are under consideration for the future.

One other tailings technology is in a commercial scale demonstration (in-line flocculation and centrifuging of mature fine tails); this is discussed in Section 2.3.4.

# 2 Research and development efforts

## 2.1 Historical research and development work

Historical research and development work on fluid tailings treatment technologies have been ongoing for 40 years, since the early 1970s. Highlights of this work are presented in Sobkowicz (2010), and some of the difficulties and problems encountered along the way are discussed in the previous sections. Valuable research was carried out in industry and university settings, the latter demonstrated by a long line of practical and useful MSc and PhD theses.

The state of practice regarding tailings technologies was provided in a technology roadmap for reclaiming oil sands tailings (Sobkowicz and Morgenstern, 2009), and further defined in the Tailings Roadmap Project (Sobkowicz et al., 2013). The latter also established priorities for future research and development on promising new technologies.

## 2.2 Incentives for a more coordinated and focussed effort

With the release of Directive 074 by the ERCB, the pressure to develop effective tailings treatment technologies increased significantly. Given that the research and development gestation period is long, industry recognised the value of a complete sharing of, and collaboration on, tailings research. This led to the formation of the Oil Sands Tailings Consortium in December 2010, when "…seven of Canada's largest oil sand mining companies agreed to share tailings research and technology in a unified effort to advance tailings management…" (Canadian Association of Petroleum Producers' Website). This consortium became a forum for complete sharing of tailings information and for coordinating future research and development efforts (Fair and Beier, 2012). It also collaborated with various Alberta government agencies, under the aegis of Alberta Innovates – Energy and Environment Solutions, in sponsoring the Tailings Roadmap Project (Nelson and Fair, 2012). The Oil Sands Tailings Consortium recently became part of Canada's Oil Sands Innovation Alliance (Tailings Environmental Priority Area), but carries on its mandate of inter-industry collaboration, and collaboration with Alberta government departments and agencies, to follow up on the recommendations of the Tailings Roadmap Project and to pursue tailings technology solutions of importance to individual oil sand mining companies.

The heightened sharing of information and focussed research and development effort that has come about over the past 2 years is a tribute to both industry and government on what can be accomplished when a fully collaborative spirit prevails.

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## 2.3 Research and development initiatives – where is the industry headed?

### 2.3.1 Preliminary comments

The legacy of past research and development work on fluid tailings provides oil sand mining companies with a rich field from which to develop improved technologies. In addition, new concepts or concepts adopted from other industries are also a fertile source of information. With the heightened need to develop effective solutions and the increased focus of the industry (driven partly by new regulation), there are multiple research efforts underway on a variety of promising tailings technologies. Some of these were identified in the Tailings Roadmap Project; others have come forward more recently.

The following sub-sections discuss some of the technologies that, in the author's opinion, have a moderate to high probability of success. Because of the varied conditions on different oil sand leases, the different challenges in each operator's mining, tailings and reclamation plans and the issues associated with retrofitting existing plants, there will be no 'one size fits all' fluid tailings solution. One or a combination of the following technologies will prove effective for a particular operator; an entirely different combination may be the right match for another.

### 2.3.2 Tank thickeners

Geotechnical engineers working in the oil sands industry have for years, perhaps naively, hoped that tank thickeners would be a solution to their tailings problems. The hope was that either thickened tailings alone (i.e. the thickener underflow), or thickened tailings combined with a high solids content coarse tailings stream, would be sufficiently robust to not segregate upon deposition and to consolidate quickly enough to meet progressive reclamation goals.

This hope has not materialised in practice. There is only one oil sand mining company using thickeners at present. These conventional thickeners have not performed well since start up, at least in terms of producing a robust underflow. Their underflow density has varied widely, often having very low solids contents. There are several reasons including:

- The priority for their operation has been as a clarifier, with clean water and heat recovery seen as their main benefits.
- The extraction plant has for most of the time since start up suffered from a surfeit of water. The only way to return this water to the tailings/recycle pond was by adding it to the thickener underflow.

More recently, due to water conservation efforts, the extraction plant is now a net importer of water and these conventional thickeners have for a short time produced an underflow with a relatively consistent solids content of 45% (density of about 1.39). While the owner has not yet been able to take advantage of this performance, it bodes well for future application of the technology.

Two other oil sand mine companies have tank thickeners under construction with improved designs and the objective of producing a consistent and relatively high-density underflow. In one case (Chu et al., 2008), the underflow will be combined with a coarse sand stream (cyclone underflow) and a coagulant to produce what is referred to as non-segregating tailings. This product is similar to CT, but may prove more robust on deposition due to having a more consistent, higher density that is less susceptible to segregation.

Some of the thickener improvements include:

- Keeping water out of the thickener underflow.
- Operating the thickener to optimise underflow density.
- Rakes that can handle a higher torque than in previous oil sand tailings thickeners, with a rake lift mechanism.

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- A shear thinning loop to reduce the yield stress of the underflow at the higher density and allow easier pumping.
- Multi-stage cycloning to produce a higher density, more consistent sand stream that will be combined with the thickener underflow.

In another case, the thickener underflow may be deposited directly into a dedicated disposal area to produce a material that will consolidate and gain strength. Estimated to take tens of years; the potential for consolidation behaviour of thickened tailings is discussed in Shaw et al., 2010.

Research has also been undertaken by Shell in 2007 to 2009 on the use of high rate and paste thickeners, to make very high-density slurries and pastes that can be combined with coarse tailings, resulting in super-CT, a very robust product with almost no segregation potential on deposition. The main issue with this product is the need for alternate pumping or transportation methods to convey the super-CT to a disposal area and to deposit it in cost-effective manner.

### *2.3.3 In-line thickening*

In-line thickening has been tested for a variety of oil sand tailings products, as listed below. While holding some promise for interim solutions, it is unlikely that in-line thickening of fluid fine tailings will be able to produce a solids content greater than about 50 to 55% on initial discharge (in some cases less), with a yield stress in the range of 100 to 200 Pa (i.e. a very high density slurry).

- Trials were performed on whole tailings to test the ability of in-line flocculation to reduce the amount of segregation on deposition. While promising in pilot tests, this technology was not able to perform over the wide range of slurry density, sand to fines ratio and bitumen contents typical of oil sand whole tailings.
- In-line thickening of mature fine tails has been extensively researched and developed to commercial scale at both Suncor and Shell. To date, this has involved the use of polyacrylamide flocculants. The process has proven to be very sensitive to variations in solids content, type and amount of clay, yield stress, in pipe flow behaviour (turbulent or laminar), efficiency of mixing (of the polymer into the mature fine tails), mixing time, and the amount of shear of the flocculated product. Some of these issues are discussed in Wells et al. (2011). The current state of affairs on this issue is that better controls and improved polymers are needed to produce a more robust and reliable flocculation and initial dewatering process.
- In-line thickening of dilute fine tailings, such as cyclone overflow, was bench tested and piloted by Syncrude in 2005. The process used in that pilot involved three tailings treatment stages: 1) first, flocculation, 2) secondly, coagulation, and 3) finally agglomeration (using a flocculant). This work is reported by Hyndman and Shaw (2013). Similar work at the lab and bench scale was carried out by Jeeravipoolvarn (2010), who studied the fundamental properties and behaviours of this material, and also discussed its use as an alternate source of fines in the production of CT (Jeeravipoolvarn et al., 2010). The work by both sets of investigators demonstrated that fluid fine tailings can be effectively thickened without a tank thickener by in-line flocculation and beaching of the flocculated fines, i.e. to a solids content similar to a conventional thickener underflow. Such a deposit would still be subject to similar slow consolidation rates as conventionally thickened tailings.

### *2.3.4 Centrifuging*

An alternate method of producing a fine tailings paste, with perhaps a more consistent output, is in-line thickening followed by centrifuging. This technology has been piloted (Mikula and Dang-Va, 2009), prototyped, and is now in a commercial scale demonstration at one of the oil sands mines. Treatment of mature fine tails results in a paste with a solids content of about 55%, similar to what is produced after beaching and initial dewatering of in-line flocculated mature fine tails.

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At present, this material is trucked and end-dumped into disposal areas about 200 m long by 600 m wide, where it flows slowly across the cell, forming a layer nominally 1 to 2 m thick. The cycle of deposition is such that a season of both freeze/thaw and drying act to further reduce its water content. There are two challenges associated with the technology in this form:

- The disposal technique would be challenged in-pit, with larger disposal areas requiring a network of roads and berms to provide access for dumping (or spreading, if using conveyors).
- A similar fines dewatering efficiency would be achieved as with in-line thickening / thin-lift dewatering, and thus similarly large areas would be required to dry the centrifuged material to a reclaimable state (150 to 200 ha, including roads, berms, etc., per 1 M dry tonnes of solids).

Consideration has also been given to placing centrifuged mature fine tails in-pit, in cells up to 100 m deep. This approach is reasonable but has the same challenge as thick layers of in-line flocculated mature fine tails or in-line flocculated cyclone overflow, which is timely consolidation to a) allow capping and initial reclamation, and b) build a closure landscape with minimal remaining settlement.

Nik et al. (2010) discuss the use of centrifuged mature fine tails as a source of fines in the production of CT or super-CT, which would give a similar product to that produced in the Shell paste thickener pilot (Section 2.3.2). It would share a similar challenge of needing alternate pumping or transportation methods to convey the super-CT to a disposal area and to deposit it in cost-effective manner.

### *2.3.5 Treatment with silica technologies*

Silica technologies, with nanometre-sized particles, have been used both in water clarification and ground stabilisation. Laboratory and pilot tests have been performed with a commercial version of this technology (Particlear™) at one oil sands mine, to investigate its potential benefits for fluid tailings dewatering. Alternate sources of this technology might be available in the form of fly ash, a waste product in the cement industry, although there are issues with particle size, product consistency, and long term sourcing.

The concept behind this chemical additive is very different than either flocculants or coagulants (Moffett, 2010a, 2010b). The fluid tailings are dosed with Particlear™ based on the water content (not solids content or mineralogy), and the nano-sized silica particles form their own network within the water phase. In the process, any solid particles are trapped within the network but water can move through the solids as freely as it would otherwise do in the absence of the silica. In essence, the silica network forms a weak, synthetic soil structure, which develops its own strength and stiffness.

The perceived advantages of this technology include:

- Initially, the addition of Particlear™ to a fluid tailings reduces its yield stress, allowing it to flow long distances (500 m plus) with a relatively constant lift thickness. This is in contrast with polyacryamide treated fluid tailings, which rely on the development of significant yield stress (200 to 300 Pa) for optimal dewatering on discharge and thus experience only short runout distances (about 100 m or less, with current discharge schemes).
- The formation of the silica network and development of strength is delayed by shear, so that it initiates as the treated material slows down in the disposal area.
- For thin-lift deposits, a silica-treated mature fine tails dewaters and dries at a similar rate to polyacrylamide-treated mature fine tails, but it develops strength faster.
- For deep deposits, high strength at moderate solids contents allows early placement of intermediate drainage layers (to increase the rate of consolidation) or of a final cap and reclamation material.
- The Particlear™-treated mature fine tails has a similar hydraulic conductivity profile (with varying void ratio) as do untreated mature fine tails, but it is much stiffer and thus consolidates under a particular applied load faster.

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Under the effective stress profile expected for consolidated, deep deposits of fine tailings, Particlear™-treated mature fine tails will have a slightly lower average solids content than flocculated mature fine tails, which is the trade-off for obtaining higher early strength and faster consolidation.

This technology has advanced as far as pilot testing, but there are many technical issues yet to address as the process is scaled up through prototype testing to full commercial operation. One of these is determining the Particlear™ dose to obtain the right stiffness and strength at various levels in a deep deposit, and to develop sufficient erosion resistance to allow hydraulic placement of intermediate drainage layers or the final sand cap.

### *2.3.6 Novel chemical additives – ATA*

Another chemical additive that has been tested in the laboratory and at a large bench scale (flume testing) is a novel technology referred to as ATA, which is an acronym for Anchor-Tether-Activator. The technology is described in Soane et al. (2010a, 2010b). In this technology, the fluid tailings are split (via cyclone or similar) into a fines stream and a coarse stream. The process is described as follows:

- An activator polymer is added to the fines stream, causing an initial aggregation of the fines.
- At the same time, a tether polymer is added to the coarse stream, coating the individual sand particles in a mono-layer.
- When the two streams are recombined, the activated fines bind to the tether-anchor complex, creating solid clusters that quickly sediment out of the mix.

The perceived advantages of this technology include the quick release of low solids content (<0.1%) water, from which heat can be recovered, and a non-segregating tailings stream that settles quickly. The resulting product may also be suitable for filtration to increase its solids content further.

Because this technology is in an early research stage, there are still many questions about its application and scale-up that require answers. However, proof of concept has been demonstrated in a large flume test. The technology has application to a number of tailings streams and the potential to stabilise tailings at relatively low sand to fines ratios (less than that of CT).

### *2.3.7 Non-conventional filtering*

Several campaigns involving extensive testing of conventional technologies for filtering whole tailings were carried out in the late 1970s and the mid-1990s. The conclusion from these tests was that filtration was too slow to be practical for any fluid tailings with a fines content >12%, required too much filtration area, and was too costly (Hyndman and Sobkowicz, 2010). Additional testing in 2005 on separate coarse and fine tailings streams essentially repeated these findings.

Starting in 2008, the Oil Sand Tailings Research Facility (located near Edmonton, Alberta) started research on a non-conventional filtering technology referred to as cross-flow filtration (Beier and Sego, 2008; Zhang et al., 2009; Zhang, 2010). The concept behind this technology is that fluid tailings can be filtered while flowing through a section of porous pipe. Proof of concept for oil sand tailings was provided in several large bench scale (pipe loop) tests; work will shortly commence on pilot testing.

The perceived benefits of this technology are application to a wide range of tailings types, recovery of warm water, a continuous filtration operation, relatively low cost, and implementation at any location on a slurry line (depending on needs).

Because this technology is in an early research stage, there are still many questions about its application and scale-up that need to be addressed.

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### 2.3.8 Water-capped end-pit lakes

The idea of storing fluid tailings under a water cap in an end-pit lake has been discussed since the late 1970s. Small-scale (several hectares) pilots have been running from 1989 to the present, to investigate the science of end-pit lakes. Syncrude applied for and obtained approval for a full-scale trial of this technology in 1993/94. Transfer of mature fine tails from Syncrude's base mine tailings pond into their west mine pit started the following year and continued until 2012, in preparation for the commercial demonstration. This trial has now just started and likely will continue for 10 years or more to validate the early scientific findings. The west in-pit lake, referred to as the Base Mine Lake, covers an area of about 700 ha and contains a 45 m thick layer of mature fine tails at its base (with a total volume of 200 M $m^3$), capped by 10 m of thin fine tails and 5 m of water (Zubot, 2010).

The concept is that any process water exuded slowly from the capped fluid tailings due to consolidation over decades will be bio-remediated in the water cap. The end-pit lake can then form a permanent feature in the closure landscape, connected to the closure drainage system.

The costs associated with this technology are perceived to be low, which makes it an attractive solution to most operators. While this technology has yet to be proven at full scale, water-capped end-pit lakes are already included in the long-term tailings plans of all oil sand mine operators, with the intent of storing some portion of their mature fine tails inventory. However, even if proven effective and accepted by various stakeholders, this technology cannot be a panacea for all fluid tailings problems. End-pit lakes will be limited in number and size on any particular lease by the final closure drainage plan and the runoff water available to keep them operating in a viable manner. However, it is likely that at least one end-pit lake could be accommodated on each lease.

The Cumulative Environmental Management Association, which studies cumulative environmental effects in the Wood Buffalo district of northern Alberta, released an End Pit Lakes Guidance Document (CEMA, 2012) to the Government of Alberta in October 2012. This comprehensive document was the result of several years' work by a committee of scientific and engineering experts, which provides guidance for all reclamation activities associated with end-pit lake design and construction. Alberta Environment and Sustainable Resource Development recently endorsed the contents of the guideline. However, both CEMA and Alberta Environment await validation of the end-pit lake concept (as discussed above), and the latter expects that oil sand mining companies will demonstrate their consideration of the guidance document when they submit mining plans for approval to the ERCB.

### 2.3.9 Conveyance and discharge alternatives

Conveyance of fluid tailings has been almost exclusively by centrifugal pumping / piping, with open pipe or spigot discharge into disposal areas. Technologies that produce very high density or paste slurries need an alternate conveyance method: positive displacement pumping, conveyors, or truck and dump. As discussed in Section 2.3.4, centrifuged mature fine tails has been conveyed to a disposal area using truck and dump. So far the volumes thus handled have been small and it has not yet been determined that truck and dump is the most cost effective conveyance method. While conveyors were used extensively for carrying ore from the mine face to the extraction plant in the early years of mining oil sand, they have not been used in any significant way for conveying waste, due partly to the difficulties encountered during the very cold northern Alberta winters. Positive displacement pumping has been considered for use in several new tailings technology suites but has not been tested at any significant scale or implemented commercially. While it remains an option for conveying very high-density slurries or pastes, there is mixed opinion and enthusiasm for its use in the oil sand industry.

Several discharge alternatives are under consideration for treated fluid tailings:

- Syncrude is now prototyping the use of a tremie diffuser for discharge of CT, based on technology developed for sub-sea disposal of fine sediments in the Netherlands (Costello et al., 2008). Industry hopes are high that this technology will solve the problem of CT segregation when discharged under high shear conditions, but its application under continuous operating and/or

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winter conditions has yet to be demonstrated. If successful, this technology will address the last (hopefully) lingering issue with the CT technology.

- For technologies involving placement of treated fluid tailings in multiple thin lifts (with drying between lifts), serious consideration has been given to central discharge systems and to jacking header systems. At present, these are just ideas under consideration, as there has been no piloting of these technologies with oil sand tailings.

#### *2.3.10 Removing bitumen to improve dewatering*

Some of the challenges with consolidating, flocculating, drying, or otherwise treating oil sand fluid tailings have been the presence of residual bitumen. This component is encountered at levels up to 2% of the total fluid tailings mass, which sounds low until one calculates that it could occupy up to 20% of the volume of solid phase in a mature fine tails. Several investigators have postulated that the effectiveness of different fluid tailings treatment technologies could be increased by first removing the bitumen. Too little research has been carried out to confirm this idea, but given the impact of the bitumen on the fluid tailings properties, it makes sense.

Removal of bitumen from fluid tailings prior to further dewatering was recognised as an opportunity in the Tailings Roadmap project. Several technologies were identified that could be used for this purpose. The technology with the most testing (in the laboratory and in a pilot plant) is the oleophilic sieve, although other technologies also exist. This is an area of current research in the industry, and to the author’s knowledge, no effective technology has been demonstrated at a prototype or commercial scale, nor has the underlying thesis been demonstrated for any of the front-runner dewatering technologies.

#### *2.3.11 Other technologies*

There are numerous other technologies that have been proposed for dewatering fluid tailings, which are described in the Tailings Roadmap Project reports (see reference list Sobkowicz et al., 2013). Three technologies that some feel are worth pursuing, but which the author has elected not to describe herein, are accelerated dewatering, freeze/thaw, and electrokinetics. Information on the first two can be found in Beier et al. (2009), and in Fourie (2009).

#### *2.3.12 Level of research and development effort*

It should be clear from the previous discussion that there has been a very large and concentrated research and development effort ongoing in the oil sand mining industry, to identify new technologies and adapt existing technologies for use in treating fluid tailings. In the first few decades of oil sand mining, this effort was largely undertaken in an independent fashion by the various mining companies (Section 2.1), but in the past few years has involved a strong collaboration and intense focus (Section 2.2).

Costs for the early research and development work have not been published, but they were significant. In the five years preceding the formation of the Oil Sands Tailings Consortium (2006 to 2010 inclusive), the total tailings research and development expenditure (combined for all companies) was about C$400 M. In 2011 alone, the expenditure was C$73 M and in 2012 C$45 M (Fair, pers. comm., 2013), and these values do not represent the costs of additional development associated with technologies rushed to full scale, commercial implementation. The oil sand mining industry has invested heavily in efforts to progress fluid tailings dewatering technologies, and hopefully the returns on this investment will accelerate in the next few years.

## 3 Other considerations

### 3.1 Water balance

It may seem self-evident, but implementation of an effective fluid tailings dewatering technology, if taken to its logical conclusion in processing all of the legacy mature fine tails on the current oil sand mining

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leases, would result in the capture of 280 M dry tonnes of fines and require in the order of 140 M $m^3$ of storage space in the landscape. If the disposal areas had an average depth of 20 m, this would cover 700 ha of land area, which does not sound excessive given the total area of all open pit mining oil sand leases.

However, the much larger issue is that up to 710 M $m^3$ of process affected water could be liberated from the fines, and this water would either need to be stored or treated and released back to the environment. The challenge of storing fluid tailings then just transforms into the challenge of storing or treating and releasing a large volume of water.

While water treatment technologies are better understood than tailings treatment technologies, they are nevertheless both complex and costly. Oil sand mining companies are just beginning to examine the implications of this water issue.

### 3.2 Fully integrated mine, tailings, water, reclamation and closure plan

Oil sand operators employ mine and tailings plans that are not too different from other mining industries. The day-to-day operations are driven by a short term plan, of 6 months to a year in duration, and these are in turn governed by medium and long-term plans that tie into a 10-year business horizon. An oil sand company will also have a reclamation and closure plan for their lease; often times it contains much less granularity than the 10-year long term plan, particularly early in the mine life. Since mining on a single lease can continue for tens of years, there is in some cases a life-of-mine plan that attempts to bridge between the 10-year long-term plan and the reclamation / closure plan. However, this life-of-mine-plan may or may not exist, and if it does, it is not updated very frequently.

It is becoming increasingly apparent that there must be a much better and fuller integration of mining, tailings, water, reclamation and closure plans, and that all of these plans must be updated more frequently and in a manner that allows sensible business decisions to be made now about issues that may have an impact on or be impacted by tailings problems that will appear many years down the road. How can the industry expect their reclamation and closure plans to be credible if this integration does not exist?

## 4 Conclusions

The author draws the following conclusions from the preceding discussion of fluid tailings dewatering options:

There appear to be four main ways in which fluid tailings can be dewatered sufficiently to be stored in a dry closure landscape: 1) production of a paste and then further dewatering by drying and/or freeze / thaw (implies placement in thin lifts), 2) production of a paste, storage in a deep container, and consolidation, 3) production of a material that is sufficiently dry to be hauled and compacted in a waste dump, and 4) mixing with sand at a relatively high sand to fines ratio and density, with a non-segregating discharge, so that the fines are fully and reliably captured in the sand matrix. The effectiveness of technologies that employ these strategies is discussed below.

There are several tailings technologies that have demonstrated the ability, through one or two stages of dewatering, to produce a very high density slurry or a paste. There are still some issues related to reliable production, and to conveyance and discharge of this material in an oil sands mine.

Some technologies then rely on environmental assistance (drying or freeze / thaw) to increase the solids content of the paste and develop the strength necessary for reclamation in a dry landscape. Because of the poor dewatering efficiency associated with northern Alberta's climate, this requires a large land area for processing and disposal, which is not available on most leases, and results in additional environmental disturbance. The final conclusion on these technologies (e.g. in-line flocculation of mature fine tails followed by thin-lift discharge or by centrifuging and discharge in thin lifts) is that they have too high a land disturbance and too high a cost to be viable over the long term, or to be used for more than mop-up purposes.

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Many of the technologies that rely on consolidation of deep deposits to move from a paste to a solid (e.g. thickened tailings or centrifuged mature fine tailings) may not produce material in a dedicated disposal area that meets Directive 074 criteria. Irrespective of that requirement, the time to capping may be reasonable (within 5 years), but the time to reach substantial consolidation with less than 1 m of remaining settlement may be in the order of 30 to 50 years or more, depending on the nature of the fines (which varies significantly from lease to lease).

Consolidation of deep deposits of paste could be accelerated by the inclusion of intermediate drainage layers and/or by increasing the permeability of the material and/or by increasing the stiffness of the material. Some chemical additives (e.g. Particlear™) may be able to address the first and last items in this list.

The performance of deep deposits could also be enhanced by the use of chemical additives that increase strength at lower solids contents (e.g. Particlear™).

There are several groups of technologies that could directly produce a tailings with a sufficiently high solids content to be compacted in a dump. The first of these employ environmental drying and suffer from the issues of high land area and high cost discussed earlier. They also introduce high material rehandling costs. The second set involves some sort of tailings filtration. While conventional filtration techniques have proved ineffective and costly, the use of a non-conventional filtration method, e.g. cross-flow filtration, looks promising.

Tailings treatment techniques that produce a material more amenable to quick settlement and/or to filtration should also be considered. One possibility is the ATA technology described in Section 2.3.6.

Technologies that produce a consolidated tailings or non-segregating tailings have in the past suffered from insufficiently robust recipes and segregation under high shear. There are several solutions to this problem. One is to increase the density of the CT, which would be effective but might require positive displacement pumping rather than centrifugal pumping. Another is to decrease the energy and shear of normal CT at discharge, such as with an energy dissipating tremie. A third is to use a chemical which binds the fines to the sand particles in a more robust manner, changing the location of the segregation boundary (e.g. previous item). All of these technologies have been considered; the second is being more actively developed at present.

An alternative to storage in a dry closure landscape is storage of fluid tailings in the bottom of end-pit lakes. This is a promising but yet to be validated technology. If proven effective and accepted by various stakeholders, it cannot be a panacea for all fluid tailings problems. End-pit lakes will be limited in number and size on any particular lease by the final closure drainage plan and the runoff water available to keep them operating in a viable manner. Hence, the volume of fluid tailings that can be stored in this manner will also be limited.

If this were a horse race, it would be tempting to place a bet on which of the technologies discussed herein turns out to be the winner. However, to do so would be to misunderstand one of the constants of oil sand mining – that every lease is different – every ore body has its own peculiar amount and type of fines, its own water chemistry, and its own relative proportions of ore and waste. Also varying from lease to lease are the available areas for waste storage, plant retrofitting needs, and the amount of legacy fluid tailings. Solutions for each oil sand mine will need to be specifically designed and crafted to meet those unique conditions; there will be no 'silver bullet' or 'one size fits all' solution.

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