Fluid Fine Tailings Processes:

Disposal, Capping, and Closure Alternatives

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Abbreviations

3D	three-dimensional
ADW	accelerated dewatering
AFD	atmospheric fines drying
BAW	beach above water
BBFFT	beach below fluid fine tailings
BBW	beach below water
CADD	computer-aided design and drafting
CEMA	Cumulative Effects Management Association
COSIA	Canada’s Oil Sands Innovation Alliance
CPT	cone penetration test
CT	composite tailings
CWZ	clear water zone
DDA	dedicated disposal area
ERCB	Energy Resources Conservation Board
FFT	fluid fine tailings
FT	fluid tailings
FTT	froth treatment tailings
FOFW	fines over (fines + water) ratio (see definitions)
GCPT	gamma cone penetration test
GHG	greenhouse gases
LFH	luvic, fulvic, and humic
LiDAR	light detection and ranging
MBI	methylene blue index
MFT	mature fine tailings
NST	non-segregating tailings
off-spec	off-specification
OSPM	oil sands process-affected material
OSPW	oil sands process-affected tailings water
OSTC	Oil Sands Tailings Consortium
OWS	oil-water-solids
PMDS	production management data system
PSD	particle size distribution
RCW	recycle water
SFR	sand-to-fines ratio
TLD	thin-lift drying
TRO	tailings reduction operations
TSS	total suspended solids
TT	thickened tailings
VST	vane shear test

Note to reader

This document was created to support a keynote presentation of the same name at the International Oil Sands Tailings Conference in Edmonton in December 2018. The intent of the presentation and this report is to provide candid advice to the oil sands industry, its suppliers, regulators, and local communities, regarding the current state of oil sands tailings development and commercialization, to indicate the need for a major course correction. Specifically, the authors call for all to embrace the use of pit lakes for tailings disposal and to quickly move away from creating deep deposits of soft tailings destined for terrestrial cover that are difficult or impossible to cap. Even if capped, the deposits have too much post-reclamation settlement. Deposits for upland landforms need to achieve bearing strength and complete settlement in a reasonable time to support sustainable mine closure. While sand-dominated Composite Tailings and dried fines deposits can attain these properties, both have spatial limitations for mine planning. Thus, there is a need to continue the search for a game-changing technology that could include all or most fluid tailings-forming fine solids and support terrestrial landforms at reasonable cost.

The authors have endeavoured to present a state of the industry and the needed onward path - free of influence from the oil sands operating companies. The authors are very supportive of continued successful operations and support existing practices that have appropriately weighed closure risks. However, the authors wish to identify changes in practice where needed to benefit the environment and sustainable mine closure.

The presentation generated a lot of response, almost all positive and inquisitive. This report better explains the authors' position and sets the tone for further discussions. The authors invite readers to make contact for more information, to offer alternative thoughts, and to generate relevant debate.

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Definitions

Adaptive management	Adaptive management is a decision process that promotes flexible decision making that can be adjusted in the face of uncertainties as outcomes from management actions and other events become better understood. Careful monitoring of these outcomes both advances scientific understanding and helps adjust policies or operations as part of an iterative learning process. Adaptive management also recognizes the importance of natural variability in contributing to ecological resilience and productivity. It is not a 'trial and error' process, but rather emphasizes learning while doing. For oil sands, it involves having well defined contingency measures for all potential outcomes with a monitoring program supporting the decision on whether to change course. (Adapted form Adaptive management does not represent an end in itself, but rather a means to more effective decisions and enhanced benefits. Its true measure is in how well it helps meet environmental, social, and economic goals, increases scientific knowledge, and reduces tensions among stakeholders. Adapted from AMWG (2009).
Bitumen content	Mass of bitumen divided by mass of (solids + bitumen + water) x 100%.
Coagulation	The agglomeration of fine particles in a tailings slurry, usually by the addition of a chemical agent that alters the electrical charge on those particles, thereby reducing inter-particle repulsive forces.
Fines, fine solids	Mineral solids with particle size ≤ 44 μm, (does not include bitumen).
Fines content	Mass of fines divided by mass of (solids + bitumen + water) x 100%.
Fines/(fines + water) ratio (FOFW)	Mass of fines divided by mass of (fines + water) x 100%.
Flocculation	The "clustering" of fine particles in a tailings slurry into groups or "flocs," usually by the addition of a chemical agent that binds to those particles, thereby tying them together.
Fluid fine tailings (FFT)	A liquid suspension of oil sands fines in water with a solids content greater than 2% but less than the solids content corresponding to the liquid limit.
Geotechnical fines content	Mass of fines divided by mass of solids x 100%.
Geotechnical water content	Mass of water divided by mass of solids x 100%.
Interburden	Bitumen-lean (or free) layers within the orebody of sufficient thickness to be mined selectively and rejected for disposal with overburden or used for construction material.
Liquid limit (LL)	The geotechnical water content defining the boundary between a liquid and a solid in soil mechanics, with an equivalent remolded shear strength of 1 to 2 kPa. This state is defined by a standard laboratory test (ASTM D4318-10; modified for use in oil sands tailings containing bitumen).
Mature fine tails (MFT)	FFT with a low SFR (< 0.3) and a nominal solids content greater than 25% (note revised from 30% stated in the COSIA Guides)
Mud farming	The process of mechanically spreading a thin fine tailings deposit and discing the deposit to expose underlying material to atmospheric drying.
Meromictic	A meromictic lake has layers of water that do not intermix.
Overburden	The soil overlying the mined and processed oil sands ore, which may be used for various construction purposes or placed in overburden disposal deposits.

Plastic limit (PL)	The geotechnical water content defining the boundary between a plastic (i.e., remoldable) solid and a brittle solid in soil mechanics, with an equivalent remolded shear strength of about 100 kPa. This state is defined by a standard laboratory test (ASTM D4318-10; modified for use in oil sands tailings containing bitumen). It can also be described in terms of an equivalent FOFW.
Pore water	The water occupying the void spaces between solid particles in a soil or tailings.
Sand	Mineral solids with a particle size greater than 44 µm (does not include bitumen).
Sand to fines ratio (SFR)	The mass ratio of sand to fines, – i.e., the mass of mineral solids with a particle size > 44 µm divided by the mass of mineral solids with a particle size ≤ 44µm.
Shrinkage limit (SL)	The geotechnical water content defining the point at which a soil, upon loss of moisture, will experience no further volume reduction. This state is defined by a standard laboratory test (ASTM D4943-08; modified for use in oil sands tailings containing bitumen).
Solids	Sand, clay, and other solid particles contained in oil sands tailings (does not include bitumen).
Solids content	Mass of solids divided by mass of (solids + bitumen + water) x 100%.
Subaerial deposition	Deposited above water with exposure to the atmosphere.
Thin fine tails (TFT)	FFT with a low SFR (< 0.3) and a solids content between 2% and 25% . (Note: Modified from 15% to 30% stated in the COSIA Guides)
$t/m^{2/}yr$	Tonnes (typically of dry solids) per square metre per year as a loading rate
tremie diffuser	A device used to dissipate energy at the discharge of a slurry into water to avoid segregation.
Water content	Mass of water divided by mass of (solids + bitumen + water) x 100%.
Whole tailings	Tailings as produced directly from the primary separation cells in the extraction plant, containing water and most of the sand and fines from the oil sands ore.
µm	microns or micrometres; one-millionth of 1 m

Note: The definitions of MFT and TFT have been altered from those in the COSIA Guides for the following reasons:

- MFT was changed from a lower limit of 30% solids content to 25% because observations suggest that at 25% solids content clay concentrations have reached a stable level and at 30% solids content MFT has already accumulated significant amounts of silt and sand.
- The lower limit of 15% solids content for TFT was changed to 2% to avoid a gap from 2% to 15% in the FFT definition.

Note that the he Government of Alberta *Tailings Management Framework* defines fluid tailings as:

> *Any fluid discard from bitumen extraction facilities containing more than 5 mass per cent suspended solids and having less than an undrained shear strength of 5 kPa. The term 'fluid tailings' is used synonymously with 'fluid fine tailings'.* AER Directive 85 also uses this definition. In practical terms there is little difference between using 2% or 5% solids content in a settling pond as the vertical transition from less than 2% to over 5% solids content is very sharp. Whether 5kPa or the measured liquid limit is used as the upper bound of FFT is also of little consequence for a fines-dominant deposit. In both cases, such a strength is very weak and a deep deposit (e.g., 50 to 100 metres) will undergo settlement for centuries.

1 Executive summary

Oil sands tailings have been produced for more than 50 years. The tailings slurry resulting from the extraction process is about half mineral solids content with the balance composed of water and a small amount of unrecovered bitumen. Oil sand mineral solids are predominantly silica sand and silt. However, a fraction of the mineral, generally less than 10%, consists of clay particles. As the slurry is deposited and forms settled sand beach, a portion of the clays remains suspended in the water runoff to the recycle water pond. There, the particles settle to form a thin slurry and remain in suspension indefinitely. More than two dozen fluid tailings ponds now exist, with fluid areas covering more than 90 square kilometres, holding over 1.3 billion cubic metres of fluid tailings.

Reclamation of a number of tailings containment areas has been undertaken.

- One settling pond (Suncor Wapisiw Lookout, formerly known as Pond 1), an area of 2.2 square kilometers, was substantially reclaimed by displacing most of the fluid tailings volume with sand, transferring the FFT to other containment ponds and reclaiming the surface. Tar Island Dyke, the dam which contained Pond 1, is also substantially reclaimed but not delicensed.
- Syncrude's Sandhill Fen (formerly part of Northeast In-Pit) is a sand-capped, composite tailings deposit (i.e., CT – sand tailings blended with fluid fine tailings) that has been reclaimed as a 0.5-square kilometer research wetland watershed.
- Substantial areas of Syncrude's Mildred Lake Settling Basin dyke, toe berm, and firm sand and coke beaches have been reclaimed to forest or wood bison pasture and the mature fine tailings (MFT) are being both displaced and capped with coke.
- CNRL's Muskeg River External Tailings Facility and South Expansion Area have landform designs that are being hydraulically capped with tailings sand.

All are technological and operational achievements, but none has been put forth for reclamation certification, the ultimate goal of most operators. The above deposits are predominantly tailings sand and therefore none serve as models to achieve timely final disposal of the large accumulation of fluid tailings which need to be incorporated into mine closure landscapes.

Most of the ponds are still in operational mode. The wet areas filled with fluid tailings present a daunting challenge: improve the tailings (generally through reprocessing), then stabilize, cap, and reclaim the boreal forest. Elsewhere in the world, where land-use standards are less onerous than those for the oil sands region and where climate and scale are less challenging (but where chemistry may be similar but in many cases is more problematic), such reclamation projects can cost $100 million per square kilometre.

The fundamental technical problem is that the clay slurries in oil sands tailings have low permeability and high compressibility. They are slow to dewater, have low densities and strengths, and are generally too weak to support a solid cap. Even if capped, deposits would exhibit tens of metres of settlement over hundreds of years – behaviour unsuited to sustainable terrestrial landforms.

About $1.5 billion[1] have been spent on research and development of various methods of reprocessing oil sands fluid tailings with even greater sums expended for their commercialization. Some technologies have proven difficult and costly to implement commercially (CT, dried MFT) or have resulted in tailings suitable only for water capping in pit lakes (MFT, centrifuged MFT, thickened tailings). Despite large efforts and a full-scale prototype (Syncrude Base Mine Lake), regulatory and local community support for large fluid tailings deposits underlying water-capped lakes remains lacking. All proposed 26 pit lakes have provisional approval, subject to proving the technology at commercial scale.

Research on oil sands tailings and process-affected water continues, generating well over 100 technical papers and theses each year. Much of this effort is based on incremental improvements to the dewatering of clay slurry and behaviour of the resulting deposits. Even after dewatering, such clay-dominated deposits are prone to excessive settlements over long time frames – posing a challenge to sustainable terrestrial surface reclamation. A paradigm shift is needed.

Pit-lake technology should be embraced by industry, regulators, and local communities, with a pledge to work together to improve the technology and reduce its risks. Clear goals, objectives, and design criteria should be developed and adopted on an industry-wide basis and fine-tuned for individual mine sites and lakes. Approvals

[1] www.cosia.ca

for the lakes should be granted subject to meeting their design basis. An alternative to placing untreated fluid tailings under a pit-lake water cap, as in the Base Mine Lake, is to treat the material for dewatering before placement, building upon chemical treatment used for decades in municipal water treatment technology. This treatment approximately doubles the amount of fluid tailings solids contained in a given in-pit volume, and provides the capability to create a stronger "mudline" interface with the overlying water cap. Two methods now in commercial operation using this technology are:

- Centrifugation of chemically treated fluid tailings to produce a "cake" consisting of about 55% solids content.
- Similarly treating the fluid tailings in the transfer line to an in-pit deposit and allowing gravitational settlement of the "flocs" to dewater the deposit.

After operating a commercial centrifuge demonstration plant with thin-lift drying deposits until 2015, Syncrude then commenced operating a large-scale centrifuge plant with placement of the centrifuge cake to a deep in-pit deposit area of the North Mine at Mildred Lake. In 2018, Suncor commenced deposition of in-line treated fluid tailings to a deep in-pit deposit referred to as DDA 3.

As their density increases, clay-dominant deposits have extremely low permeability. As a result, irrespective of whether the treatment employs centrifugation or simply in-line treatment, deep in-pit deposits of 50 to 100 metres are anticipated to have settlement times of many centuries, or in the extreme more than a millennium. Hence, water-capped surfaces are preferred for such deposits to avoid impacts that would occur with a terrestrial cover including: disruption of surface drainage pathways, disturbance to established vegetation, unanticipated development of large wetlands and unsustainable (saline) lakes, and upward flux of tailings porewater that could salinize surface reclamation soils and contaminate surface drainage courses. The interface between the deposit and cap water could be enhanced by desiccation of the deposit surface before water placement and/or by placing a layer of coke, sand or soil over parts of the deposit.

While pit lakes occupy a small proportion of overall closure landform areas, their role is critical to successful design of site drainage. An important design constraint for pit lakes is the need to limit the relative area of open water surface as a percentage of its contributing drainage basin area – nominally 10% or less to prevent the lake from becoming saline through evapoconcentration.

For terrestrial reclamation of tailings, deposits need to be in the order of 80% solids content versus the 45% to 60% solids content typical of current clay-dominant deposits (that have not been exposed to drying). The resulting one or two orders of magnitude higher strength can support a terrestrial surface cap that will undergo minimal post-reclamation settlement.

CT, if delivered on spec, meet these criteria, as do sufficiently dewatered dried MFT and perhaps filtered tailings. Further treatment of tailings from existing all-fines processes involves initial chemical dewatering, then drying them (perhaps with thermal heating) until they become unsaturated and form a soil that can be conveyed, and/or trucked, and then spread and compacted with dozers.

While CT deposits can support terrestrial reclamation, the use of current CT processes is limited on many sites due to its high demand for sand and containment space. Filtration and drying methods have high cost or require substantial land area or both.

For all deposits, the combination of release water volume and quality must be suitable to be managed in the surface drainage design for the closure landscape.

Given the site constraints of the CT and deep-deposit/pit-lake methods and the high cost and/or excessive land requirements for drying methods, the industry needs new cost-effective methods that will support sustainable mine closure. The quest for a silver bullet, a game-changing technology, remains. Such a technology would create deposits that would:

- Allow all fluid fine tailings to be deposited in non-fluid landforms.
- Have high enough permeability to allow consolidation to be completed within a generation – ideally, about a decade or less - to support track-packing and stackable deposits.
- Be non-segregating and release clear, low-toxicity water to be incorporated into surface drainage without adverse consequences to the downstream environment.
- Be easy to cap and reclaim to terrestrial landforms, allowing for timely decommissioning and delicensing of any containment dams.

Such a method(s) would give greater flexibility to ongoing mine operations, mine and closure planning and would expedite the process of reclaimed land certification.

In the absence of such a game-changing method, current proven methods and planning constraints require large fines-dominant deposits that should be below grade, capped with water and positioned appropriately in the overall site drainage.

2 Introduction

This paper assesses the current state of oil sands tailings management and criteria for low-risk, sustainable mine closures with minimal long-term maintenance needs. It reviews the performance of current tailings processes and depositional concepts that will lead to desired sustainable outcomes and those that will not.

With several careers worth of collective experience in the oil sands, the authors wish to see the industry continue to generate economic benefits for Canadians while building robust pathways to sustainable closure.

Operators, regulators, First Nations, and stakeholders must come to a consensus on how to manage oil sands tailings and support mine closure objectives based on what is now known about the performance of existing processes, the resulting deposit behaviour, and the fate of organic and inorganic components of process water in the context of diverse depositional environments.

This paper does not negate ongoing efforts to improve existing process performance nor does it abandon the quest for game-changing solutions. However, closure plans should be based upon today's established process performance and the behaviour of clay-dominant fines deposits that constitute a significant portion of tailings management operations.

Following this introduction, the document is arranged in four further sections. The current state of production and processing is described in Section 3. It looks at historical practices, explains tailings processes, deposition and capping, and the ongoing tailings research and development and the quest for a game-changer technology. The lead author of Section 3 was Al Hyndman.

Section 4 goes into detail on tailings stabilization, capping and reclamation, and the expected post-closure performance for technologies listed in Section 3. It highlights the need for tailings technologies that are easy to cap and reclaim and involve limited long-term settlement where terrestrial land uses are targeted. The lead author of Section 4 was Gord McKenna.

Water issues are the central focus of Section 5. The need for pit lakes is highlighted and methods to manage the closure landscape are discussed. The lead authors of Section 5 were Les Sawatsky and Jerry Vandenberg.

The report ends with conclusions, recommendations, and a reference list.

2.1 The current situation

In the 50 years since large-scale development of the oil sands began, numerous technology changes have been introduced to keep the industry economically viable and to improve environmental performance. As the industry has expanded, so too have society's demands and expectations for sustainable mine closure.

By the end of 2016, nearly 1,000 square kilometres of land had been disturbed by oil sands mining (Alberta Energy 2019; AEP 2019). This included open pit areas, mine waste (overburden and inter-burden) disposal sites, and tailings deposits. About 90 square kilometres were water-covered, mostly underlain by soft tailings. About 100 square kilometres of land (10%) had been reclaimed (including extensive areas of tailings dykes and toe berms).

Between 2009 and 2018, an average of about 115 square kilometers were newly disturbed annually as new mines opened and others expanded, while 13 square kilometers were reclaimed each year. A one-square-kilometre overburden disposal area has received reclamation certification.

Figure 2-1 Fluid fine tailings have a muddy water consistency

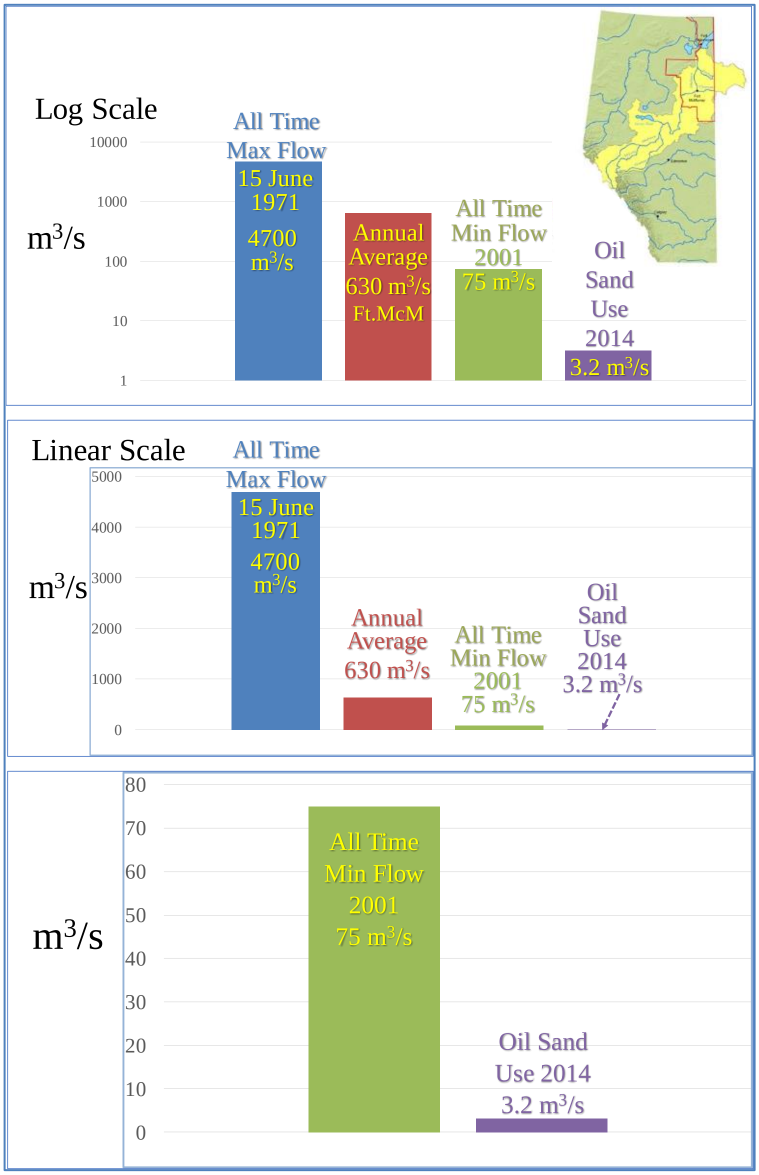
According to the Alberta Energy Regulator (AER 2019a), at the end of 2017 there were 1240 million cubic metres of fluid tailings (see Figure 2-1) and 385 million cubic metres of ponded water stored in 35 oil sands tailings facilities. The rate of accumulation of fluid tailings is about 40 million cubic metres per year; the ponded water volumes have been static over the past four years.

Several tailings technologies have been implemented over the past 20 years at commercial scale, with mixed technical success. Some face high capital and operating costs and others have seen less-than-optimal results. These are reviewed in the following section.

Current regulatory directions are not aligned with achievable outcomes that will provide sustainable closure landscapes. Deep deposits of clay-dominant fines dewatered to 45% to 60% solids will take many centuries to settle, retaining the consistency of very soft mud (McKenna et al 2016c). They are not suited to above-grade upland features that could require centuries-long observation and maintenance of drainage systems to preclude the emergence of an elevated lake on fill (i.e., a dam). Near-grade wetland features over such deposits will revert to open water through subsidence and consequently should be planned as such.

Oil sands ore contains about 3% to 5% water, referred to as connate water, surrounding the sand grains. The depositional environment (fluvial, marine, tidal, etc.) during the geologic time of the oil sand deposits influences both the mineral solids character and the salinity of the connate water. For example, different areas of the mineable oil sands have chloride contents varying from less than 50 ppm to more than 500 ppm of the oil sand mass. The chloride salts remain in solution and concentrate in the recycle water (RCW) system, reaching equilibrium once the amount of salt removed by remaining in the tailings pore space equals the incoming amount in the ore being processed. With zero discharge of process water during active mining, as has been the practice to date, depending upon the oil sand processed, chloride levels in the RCW can reach levels (> 1000 mg/L) that begin to affect the extraction process recovery. High levels could also prolong stabilization of the closure drainage water system, including the pit lake. For these reasons, the quality parameters for discharge of process water are now under review. Standards for release of site water analogous to those set for other industries are presently a regulatory gap; in Section 5.4 this paper proposes a set of criteria to address this gap. Oil sands mining remains an outlier among Canadian industries in not having established criteria for discharge of water.

The following highlights several myths and misconceptions that persist among some members of the public and stakeholders:



Misconception 1: The Athabasca River flow is over-stressed due to industrial and human-use demands.

Fact: About 5% of the Athabasca River's water is allocated for human use. Oil sands mining utilizes about 0.5% of the Athabasca average annual flow and 4% of the all-time minimum daily flow recorded in 2001 (see Figure 1-2). By comparison, over 50% of the Bow River is allocated for human use, with about 30% used.

Fact: For the Athabasca River, any projected significant impacts due to oil sands withdrawals or controlled discharge during extreme low flows could be mitigated by reducing withdrawals and discharge and during such periods, using off-stream storage on sites where that storage is available.

Figure 2-2 Athabasca River Recorded Flows

Misconception 2: Terrestrial surface cover on deep, soft-soil deposits offers lower risks than open-water (pit lake) covers for those deposits.

Fact: The reality is that geotechnical risk is best managed by keeping weak, slowly consolidating deposits below grade in secure containment. Safe disposal of tailings and other mine waste in pit lakes, rather than above grade, is considered a best practice in many jurisdictions in Canada and worldwide (Verburg et al 2009, Vandenberg and McCullough 2018, McCullough et al 2018). Surface water will best attenuate the slow rate of upward drainage from the underlying deposit as well as the drainage from surrounding sand-dominant deposits.

Misconception 3: When process water fails a fish bio-assay toxicity test, the water must be loaded with persistent toxins.

Fact: Naphthenic acids, related compounds, and their associated toxicity naturally biodegrade over time before planned release to the Athabasca River. Other constituents of process water such as metals are present at lower levels than in the Athabasca River and within discharge criteria for other industries.

Misconception 4: Zero discharge of water for the full period of active mining would provide the least environmental impact to the Athabasca watershed.

Fact: Control of chlorides and other salts is the primary concern for managing site water quality and discharge timing. Controlled discharge of water during active mining can limit concentration buildup and may provide the least impact and optimal closure timing for some sites (Beddoes et al 2014).

Misconception 5: Pit lakes with submerged mine waste are unlikely to ever host sustainable aquatic ecosystems and are too risky for the Alberta Government to approve as a closure strategy.

Fact: Of the more than 20 existing pit lakes in Alberta, some contain submerged mine waste, and all have been reclaimed to a beneficial end use.

Plans and operations that embrace out-of-pit, deep deposits or segregated clay-rich components of out-of-pit landforms will not lead to desired closure outcomes. Meanwhile, some development efforts pursue high-intensity solutions that are incompatible with current economics. Full-cycle MFT-centrifuge costs, in the range of $30/tonne of MFT solids, should represent the upper limit of process costs. In-line thickened fines directed to in-pit deposits may represent about half that unit cost. Research and development efforts should be directed to low-intensity processes while considering ancillary benefits, such as reduction in total mine footprint and energy consumption.

While the industry continues to pursue solutions that could lead to more flexibility and options for closure landforms within realistic economic parameters, regulators should support plans and operations based on what has been successfully demonstrated.

Oil sands tailings management is an internationally recognized issue affecting the sustainability of the industry (e.g., VanderKlippe 2013). Pressure from owners, investors, regulators, and local communities to solve the oil sands tailings management problem continues to increase.

An experienced community of technical and operational employees, consultants, and academics is equipped with the knowledge to foster a shared understanding among regulators and local communities and support practical solutions. With several large tailings deposits approaching the capping and reclamation phases in coming years, and new deposits being explored, it is a good time to examine the real impacts of current tailings management technologies and focus tailings management technologies on achieving sustainable mine closure landscapes that encompass terrestrial uplands, wetlands, and open-water components. Change is needed: the industry, its regulators, and local communities need to work together to agree on clear, realistic goals and objectives, and to select and deploy practical and reliable technologies for processing, discharging and depositing; stabilizing and capping; and ultimately reclaiming and decommissioning tailings deposits. Such an approach will deal with both existing and new deposits in a way that produces acceptable reclaimed tailings landforms and landscapes.

2.2 Closure performance criteria for oil sands tailings landforms

Fluid fine tailings management objectives to support the over-arching goals of sustainable mine closure and progressive reclamation have been set out in a tailings management guide published by COSIA (2014) (2):

1. *To eliminate fluid containment dams in the closure landscape.*
2. *To establish a stable closure landscape, with sustainable and diverse ecosystems, within a reasonable time after cessation of mining.*
3. *To develop sustainable surface drainage, including a functional lake system.*
4. *To facilitate progressive reclamation (i.e., the reclamation of mine areas, to the extent practical during mine life, to reduce post-closure liability).*
5. *To optimize full life-cycle costs and minimize life-cycle environmental impacts without compromising reclamation and closure objectives.*
6. *To understand technical uncertainties and appropriately manage their associated residual risks.*

Operational and closure goals to achieve the above objectives include:

- **Operational Goal** – Maintain a safe and efficient tailings operation consistent with managing costs and dam safety protocols (minimizing the risk of a catastrophic breach), while creating deposits that meet long-term landscape performance requirements and respect progressive FFT volume management commitments.

- **Closure Goals** – Some legacy situations preclude ideal closure scenarios. The long-term care and maintenance required for these areas should induce managers to strive to attain the ultimate goals of a sustainable landscape. Care and custody of these legacy deposits will continue for centuries if corrective measures are not taken. The following goals will help create safe, stable, self-sustaining landform features compatible with the local boreal forest and the Athabasca drainage basin to attain sustainable mine closures:

a. Open-water areas in the closure landscape must be planned correctly when establishing minimum ratios of drainage area to open-water area. Such a criterion is required to avoid salination of lakes due to inadequate flow to overcome evapoconcentration of salts resulting from drainage of surficial soils and flux from consolidating fine tailings deposits that occur in the drainage area. While saline lakes and wetlands are naturally common in the world, including in Western Canada (Purdy et al 2005), in general, oil sands pit lakes should be designed for fresh water, supported with adequate upland and wetland inflow areas (CTMC 2012).

b. Upland features must be free of excessive residual settlement (McKenna et al 2016). Any above-grade landforms with post-closure settlement greater than 1 to 2 metres should be analysed on a site-specific basis to ensure that:

   - The drainage system can accommodate the settlement without being negatively disrupted
   - Open-water areas will not expand to the extent that water bodies become hydrologically unsustainable with evapoconcentration
   - Settlement will not cause discontinuities resulting in accelerated erosion in upland areas
   - Upward flux of tailings porewater resulting from settlement of a fine tailings deposit will not contaminate reclamation soils and surface drainages
   - An emergent open-water body will not occur and fall under the definition of a dam (OSTDC 2014).

c. Closure design should minimize the active care period following closure activities (McKenna 2002; Govt of Western Australia 2015). Ideally, major landform adjustments and terrestrial and aquatic surfaces would be completed within a decade of cessation of mining. Passive observation and any low-impact maintenance requirements could continue for several decades.

d. Controlled release of site water to manage the overall salt load should be initiated during active mining. This would be continued at closure until surface water quality is consistent with near-field objectives (AEP 1995) and regional limits (Alberta Government 2012; 2015), at which point controls can be removed and natural unregulated inflow/outflow can begin. Reducing the accumulated salt load by the time of mine closure will reduce:

- The concentrations in closure waterbodies
- The time required to return the landscape to baseline conditions
- The cumulative load to the Athabasca River during concurrent mine closures (Beddoes et al 2014).

e. To the extent practical, lands should be reclaimed and certified progressively through the active mining period and closure activities (Government of Alberta 2012).

Developing a lease-wide and deposit-specific design basis including setting goals, objectives, and design criteria for tailings is described in in Section 4.2.

3 Oil sands tailings production and processing

This section sets out some of the history of oil sands tailings since production began 50 years ago. It goes on to look at management of oil sands process water (OSPW), the tailings processes (and reprocessing) and tailings deposition. It goes on to talk about the state of oil sands tailings R&D and the need for a game-changing technology. Partly by way of summary, lessons learned are appended to the section.

3.1 The history and behaviour of oil sands fluid fine tailings

At the commencement of large-scale commercial development of the oil sands by Great Canadian Oil Sands Ltd. in 1967, the phenomenon of fluid fine tailings generation was unforeseen. No one anticipated that clay-dominated fines would run off from sand tailings beaches (resulting from tailings slurry discharge) instead of settling or being incorporated into the sand. A deep watery mud layer accumulated below the recycle water. To contain the growing volume, a planned 10-metre berm at the toe of the sand beaching operation had to be raised and converted to a dam approximately 100 metres tall using sand cell and beach construction (Morgenstern 2012). Thus, the Tar Island Dyke and (now Suncor) Pond 1 were created. By 1975, it was understood that accumulating fine tailings would pose challenges for oil sands mine reclamation (FTFC 1995).

How evident this phenomenon of accumulation and resistance to particle settlement of clay-dominated thin slurry was during the Mildred Lake "Lower Camp" pilot operations undertaken by the original Syncrude joint venture (operated by Cities Service Athabasca Inc. from 1959 to 1963) is unknown. In any event, the Syncrude Mildred Lake Project, completed for start-up in 1978, incorporated planning criteria to accommodate projected volumes of MFT[2] below the clarified recycle water zone:

- The Mildred Lake Settling Basin (MLSB) was designed to settle fines from process recycle water and contain the FFT generated throughout operations with transfer of MFT to in-pit disposal. Starter dykes were constructed across

[2] The non-settling, clay-dominated fluid that segregates on sand beaching operations has over time been referred to as slimes, sludge, mature fine tailings (MFT) or fluid fine tailings (FFT). In this paper FFT refers to all fines-containing liquids from the thin slurry running off the sand beach, generally ≤ 10% solids to the pond-settled slurry ≈ ≥ 25% solids, whereas MFT refers specifically to the latter denser material.

the northwest end of Mildred Lake and across the Beaver Creek valley. Sand beaching and upstream cell construction were used to raise one of the world's most massive dams (Fair 1987; Morgenstern et al 1988).

- Sufficient mined-out pit volume was to be retained to contain all MFT volume generated throughout the active mining period so that the MFT could be transferred to in-pit, below-grade deposits, allowing for decommissioning of the MLSB dam for mine closure.

Similar tailings dam practices are routinely employed in other mining operations, but the scale in the oil sands was unprecedented for the time. The practice of maintaining below-grade, geotechnically secure disposal of weak or fluid materials remains a key criterion for dam decommissioning and oil sands mine closure (OSTDC 2014).

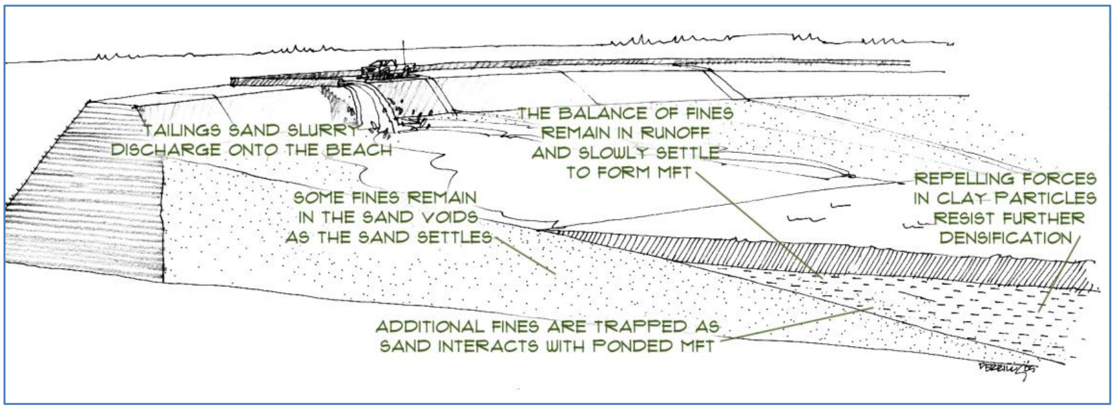


Figure 3-1 Sand beaching and MFT formation

In an active tailings settling pond, once the fine clay particles have settled to their maximum concentration, further densification is resisted by the water layer attracted to the clay surfaces and the repelling of clay surfaces to each other (FTFC 1995). Further densification of total mineral solids in an active settling pond results only from migration of fine sand and silts into the clay-dominant fluid zone (Figure 3-1); clay densities do not increase. The MFT in a static pond will remain in a fluid state indefinitely. This behaviour and plans for in-pit MFT disposal to end-pit lakes led to more than four decades of research (Lawrence et al 1991, 2016; MacKinnon 1991; MacKay and Verbeek 1993; Verbeek et al 1993; Dompierre and Barbour 2016, 2017; Dompierre et al 2016; Hurley 2017; and White and Liber 2018 being a few key studies). This research culminated in Syncrude's 800 ha Base Mine Lake demonstration project, where filling of a pit with MFT and process water was completed in 2012. It is now the subject of intensive ongoing evaluation as mandated by regulatory approvals.

Since the Base Mine Lake was approved as a full-scale demonstration project in 1994 (ERCB 1994), much effort has gone into developing processes to incorporate the clay fines into a solid soil matrix or, alternatively, to dewater and densify FFT. The direction is now for future pit-lake MFT disposal to be based upon densified material.

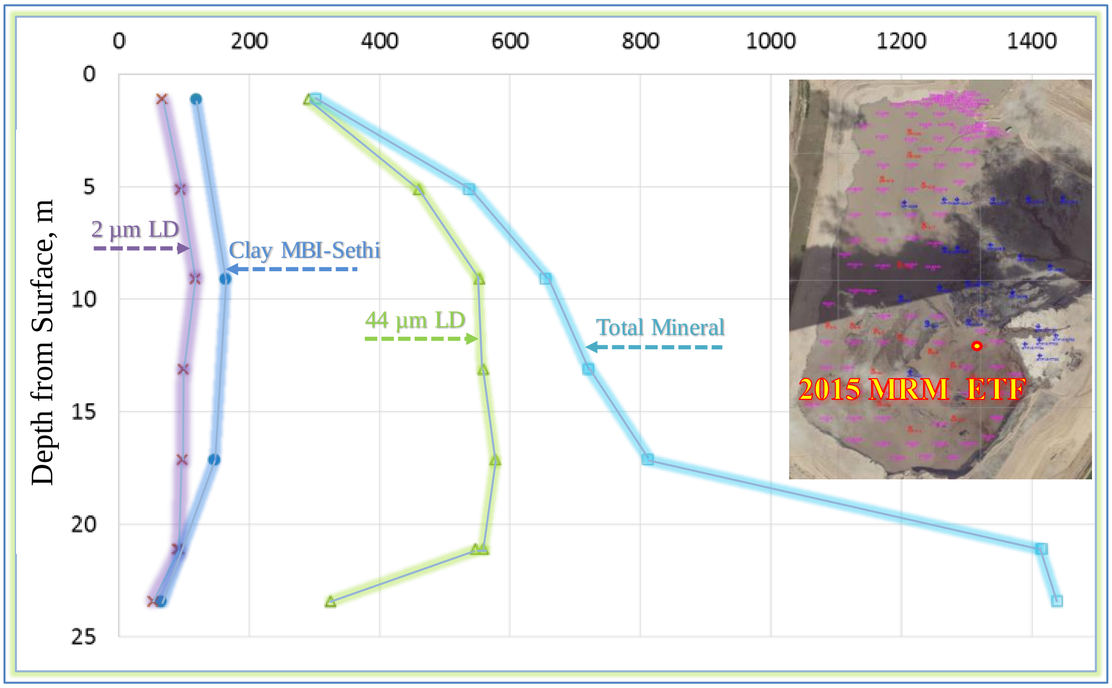


Figure 3-2 Typical settling pond solids concentration profiles, kg/m³
The MBI-Sethi (1995)[3] correlation and Laser Diffraction (LD) particle-size mass percentages are as determined by Shell Canada for the 2015 pond surveys.

3.2 Managing process water quantity and quality

Mines require a supply of fresh water; in the oil sands region, water is supplied by the Athabasca River. While water to operate the extraction process is recycled from the tailings settling pond (RCW), some water uses are supplied from the fresh water

[3] Sethi-correlation values are not true mass percentages. The correlation was derived from analyzing a set of cores from the Suncor mine in the early 1980s and correlating the MBI values with clay mass percent. However, each oil sand sample has a unique mix of clay types with different surface areas and will not have an exact match from Sethi% to true mass%. Moreover, in a settling pond, the upper zone of settled solids tends to have a greater proportion of small, high-surface-area clay types — typically with values greater than 100%. The correlation is therefore an index that approximates mass% for oil sand samples. Consistency in performing the analysis and applying the correlation would make it more useful in comparing results from different operators.

supply. River water is clarified and demineralized for steam generation or treated for potable water use. RCW with a sufficiently low level of suspended solids (typically < 1%) will not impede the extraction process.

During early operations, fresh water is added to the recycle water system to maintain an RCW layer — typically a minimum depth of 3 m — over the FFT mudline (OSTC & COSIA 2012) in the tailings pond to operate the recycle system. As the site development footprint expands, and mine pit dewatering and surface drainage from out-of-pit deposit areas are directed into the RCW system, the RCW depth may grow to be much greater than the 3 m minimum. To minimize excess water, efforts are made to minimize fresh water demand, use RCW in place of fresh water, and direct clean surface drainage to the river rather than into the RCW circuit.

Over the life of a surface mine, measures taken to increase recycling of water will not change the net water removed from the Athabasca drainage basin. The phreatic surface lies within a few metres of surface pre-development and will return to a natural level post-development. The end mine pit not backfilled with tailings (or other solids) will be filled with water from the river or drainage that would otherwise go to the river. Consequently, the largest factors impacting net withdrawal are:

- Bulking of tailings and overburden versus their *in situ* density and the water contained within the voids of these in-pit and out-of-pit deposits (true for all mines)
- The proportion of pit backfill composed of solids versus water.
- The amount of evaporation, as influenced by site activities such as large water surfaces, cooling tower evaporation, particularly where there are on-site upgraders.

Managing the timing of river withdrawals can mitigate any impacts during low-flow periods. Some projects have implemented off-stream storage to reduce or eliminate withdrawals for such events.

Because process water is recycled, intercepted, and not discharged to the receiving environment, there is no requirement to manage process water quality to environmental standards during operations. Depending on the rate of accumulation of salts within a closed process-water system, high rates of water recycling will increase the concentration of salts in the recycle water upon mine closure and result in high concentrations of salt to the receiving water courses.

For mines with relatively saline connate or groundwater, salinity buildup in the recycle water is the most significant factor for water management. This includes both its potential impact on extraction processing, as well as the salt concentrations that will be present in the water at closure, in both the site's free-water inventory and in the pore water of tailings deposits. Salt concentrations in the drainage from these deposits will decline over time as the pore water is displaced by precipitation and will vary significantly in relation to precipitation events. Drainage through a pit lake will moderate concentrations of salts and organic constituents present in the pore water as well as provide natural aerobic degradation of organic constituents such as naphthenic acids (CEMA 2012).

Chloride salt concentrations in the RCW and in tailings pore water are predominantly a function of their concentrations in the processed oil sand. This can vary from < 50 ppm to several hundred ppm of chloride. In the COSIA (2018) study – *Fluid Fine Tailings Management Methods*, cases were examined of ore chloride levels of 50 and 300 ppm for several tailings treatment methods. With water discharge held at zero prior to closure, tailings pore water varied from a low of 200 mg/L to a high of 3000 mg/L (with implications for ore processing), the dominant influence being the chloride content of the oil sand ore processed. Chloride management should therefore be addressed in site-specific planning. Release of chloride via water discharge through the active mining period could mitigate chloride levels for closure (Beddoes et al 2014).

3.3 Tailings processes

This section describes various tailings processes. Descriptions are based on work previously published by CTMC (2012).

3.3.1 Fundamental options

The clay particles that form MFT can be placed in a limited number of settings in the closure landscape:

- In a fluid or semi-fluid state within a geotechnically secure in-pit deposit.
- As a solid soil
  - dewatered to a solid of 75% – 80% solids content
  - mixed into either sand or overburden.

The deposits may be in pit or, with suitable strength, out of pit.

The following section describes the processes used to create these deposits and their development status.

3.3.2 Conventional tailings management

Conventional tailings management is based on constructing an out-of-pit containment dam structure for settlement of solids and clarification and retention of water from the tailings slurry (Figure 3-1). The recovered water is recycled to the extraction process.

Typically, starter dykes (Figure 3-3) are constructed prior to start of operations using material from pre-stripping of overburden (e.g., List et al 1997). The balance of the dam is constructed from tailings using a compacted cell-and-beach method. Alternatively, all or part of the compacted shell may be constructed of overburden and inter-burden.

The constructed out-of-pit tailings pond may be used for the life of mine or the pond operation may be transferred in pit during active mining when space is available.

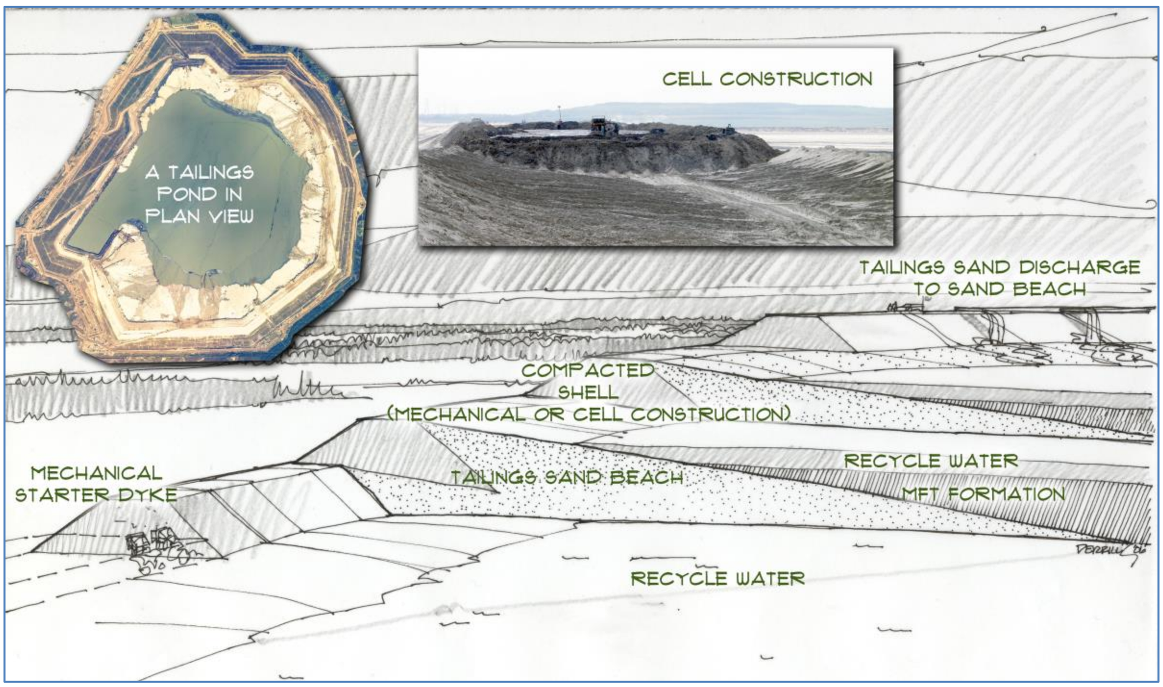


Figure 3-3 Upstream cell and beach construction of a tailings dam

3.3.3 Composite tailings (CT)

CT[4] (see Figure 3-4) is generated by a process that produces fines-enriched sand by mechanically combining discrete streams of fines and coarse-grained tailings, with gypsum added as a coagulant (Caughill et al 1996; Matthews et al 2002; Pollock et al 2000). To produce CT, tailings are pumped from the extraction plant to the CT plant, where they are cycloned to produce a densified coarse tailings stream, which is blended with gypsum and MFT recovered from a tailings pond. The resulting slurry is then pumped and discharged by tremie below water, preferably into the MFT zone.

Alternatively, the slurry may be discharged to a beach and the fluid removed. The process is currently operated by Syncrude at both the Mildred Lake and Aurora Mine sites.[5] A subaerially beached deposit in the area known as the East Pit at the Mildred Lake site was capped and a fen surface constructed (Wytrykush et al 2012; Pollard et al 2012). Subaqueous deposition using a tremie diffuser below the MFT mudline is now used for deposits in the Syncrude Base Mine (West Pit) and is planned for the Aurora North Mine following CT beaching. Variations of the process using thickener underflow in place of MFT and with different coagulants have been tested by Shell at the Muskeg River Mine and operated by CNRL at the Horizon Mine.

[4] The term “composite tailings” describes the process of combining sand and fines. “Consolidated tailings” and “non-segregating tailings” (NST; for the variant of thickener underflow added to sand), describe desired outcomes. See Tables 2-1 and 3-4.

[5] Suncor operated CT for nearly a decade but it was discontinued due to the large containment volume required, along with the associated demand for construction sand. The assumption at the time was that in-line treatment followed by drying operations, under the heading TRO (Tailings Reduction Operations) would meet MFT reduction targets. As noted in the following section, this was not to be. Shell/CNRU has also operated a CT plant periodically at the Muskeg River Mine.

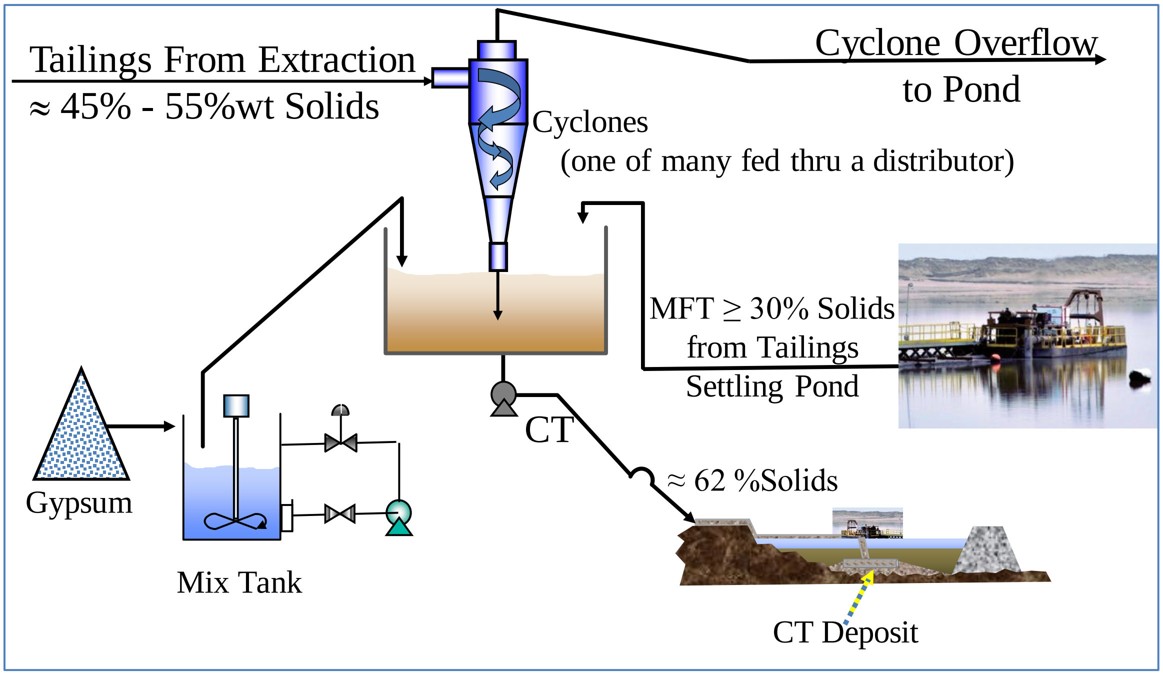


Figure 3-4 Composite tailings process

Because of shear in the transport pipeline system, CT slurries undergo segregation in the deposit, releasing a portion of the composite-slurry fines to the release water. A shortcoming of the historical reliance on "fines balancing," using 44 µm as the cut-off between sand and fines, is that primarily the clay fines component (certainly not all fines) generate the structure and volume of MFT. Operators use different procedures for determining clay content of their tailings and oil sands deposits. The methylene blue index (MBI) of particle surface area combined with the Sethi (1995) correlation conversion to clay percentage has not been applied consistently among operators. Testing results can be inconsistent, depending upon sample preparation and operation of the analytical procedure. Some operators use laser diffraction (LD) to measure particle size. As is evident in Figure 3-2, using the geotechnical definition of 2 µm for clay understates the clay percentage compared with the MBI-Sethi method. While LD does not replace a measure of clay surface area, assessing CT effectiveness by mass-balancing a smaller particle size, such as 2 µm or 5 µm, would be better than relying on the 44 µm standard, which may overstate the capture of MFT-generating particles.

With a recipe of 4:1 SFR, the main limitations of CT are its demand for sand in competition for its use for construction material and its requirement for large pit-void volumes for containment. On high fines sites, CT could not absorb all the FFT produced, while on lower fines sites, which tend to be more spatially constrained, re-handling costs can make it less attractive than other solutions (COSIA 2018). However, CT does offer the ability to reclaim the deposit with a terrestrial surface and therefore can play a role in the percentage of open water in the closure landscape. Sand-fines composite solutions that could absorb more clays into the sand matrix while improving deposit drainage would make the method more attractive. This is discussed in the section on "game-changers."

3.3.4 Thickeners (TT)

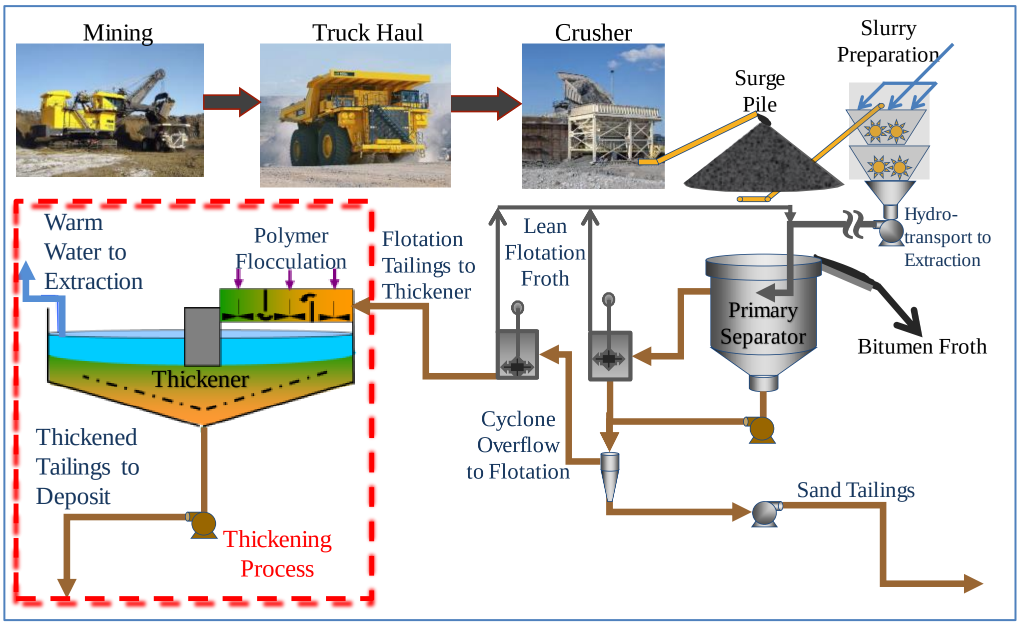


Figure 3-5 Thickener integrated with an extraction process

Thickeners (Figure 3-5) employing polyacrylamide co-polymer flocculants to dewater fines directly from the extraction plant (Jeeravipoolvarn 2010) were tested extensively by industry and government partners at the Syncrude Aurora Mine in the early 2000s. Several successful test deposits were produced. At the same time, Shell installed thickeners at the Muskeg River Mine and later at the Jackpine Mine, based on energy recovery from the warm water available for the extraction process.

Unfortunately, dewatered thickener underflow segregates due to shear in the transport pump and pipeline. To date, thickeners have not provided the desired reduction in MFT volume nor generated reclaimable deposits, despite ongoing efforts by several operators to achieve these outcomes.

3.3.5 MFT centrifuge (cMFT)

MFT centrifugation (Nik et al 2016) uses thickening chemistry but replaces the large gravity mechanical thickener with a solid-bowl scroll centrifuge (Figure 3-6). It immediately produces a partially dewatered solids stream referred to in the industry as "cake," although at 55% solids, the consistency is more akin to cake batter that flows across a surface at a shallow slope (≈ 1%). MFT, dosed with the chemical additives, is fed into the spinning solid bowl of the centrifuge. A helical scroll conveyor with a small differential to the bowl speed conveys the solids stream up the sloped-beach section of the bowl, where it is discharged onto a conveyor. The process sometimes uses gypsum as a coagulant followed by a polyacrylamide flocculant or flocculant alone. Syncrude conducted trials at increasing scales from 2004 through 2009 and then committed to a large commercial installation with a nominal capacity of about 10 million tonnes per year of MFT solids.

There are two deposit options for cake disposal:

- In shallow cells constructed of tailings sand or overburden. A layer (≈ 2 m) of the deposit undergoes a year or two of freeze-thaw and drying before a second layer is placed. After drying, the deposit, now about 2 m of consolidated depth, is covered with a layer of sand or overburden and is immediately ready for surface reclamation.
- Area requirements for the above type of deposits led to the preference for contained, deep in-pit deposits, which are now the basis for Syncrude's commercial operations. The trade-off for the much-reduced footprint is that such deep, low-strength deposits will undergo settlement for centuries and possibly more than a millennium, as described in Section 4.3.3.

The cake can be transported by three different methods:

- Truck haul
- Slurry pump and pipeline
- Stacking conveyor

Truck haulage is the most expensive form of transport but provides the greatest flexibility for delivery points. The slurry pump-and-pipeline method provides low-cost transport but can limit the solids content of the cake. A stacking conveyor could be effective if the centrifuge plant can be located near to the deposit. It would fit well with a modular plant that could be relocated after each deposit fill.

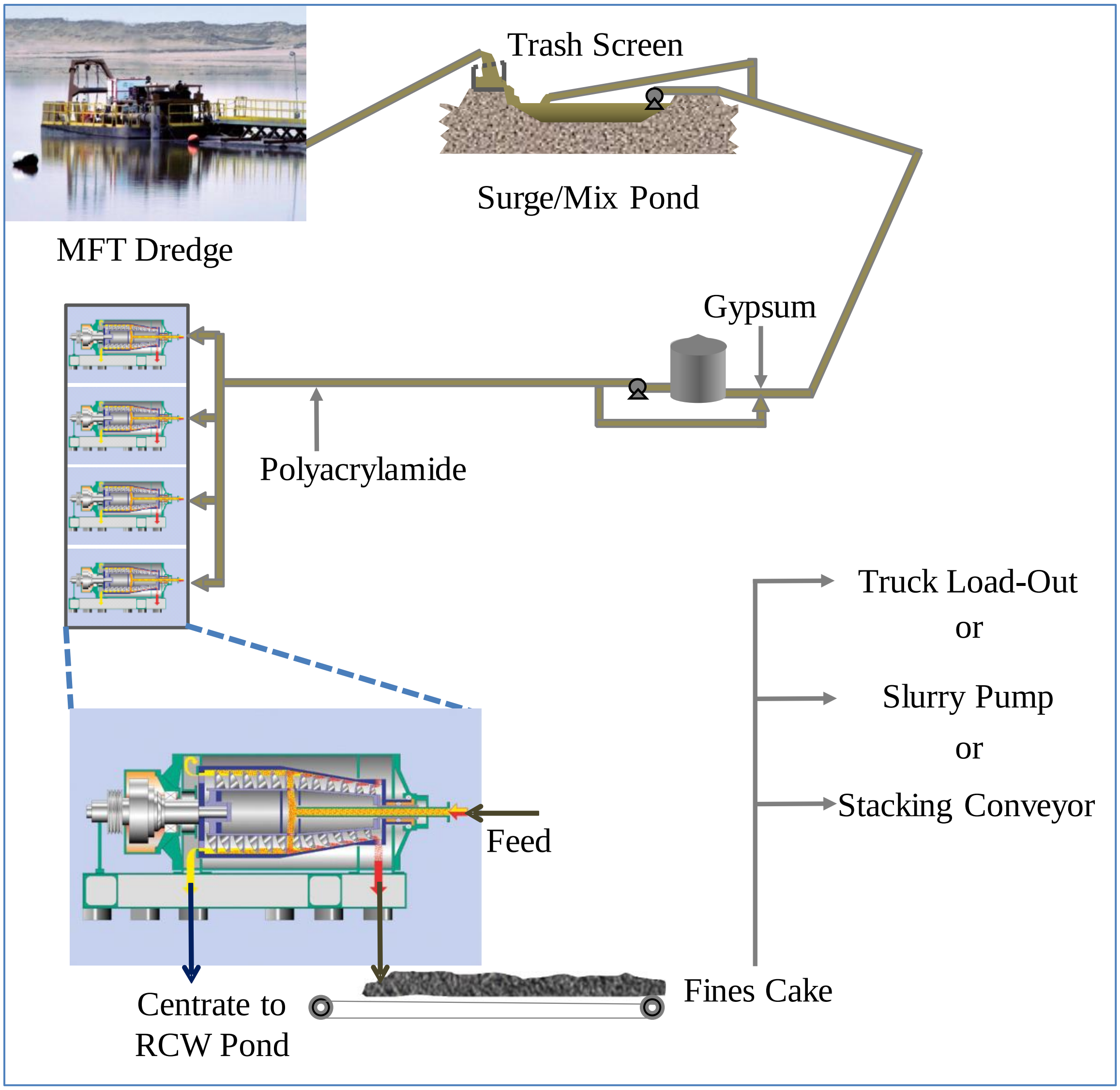
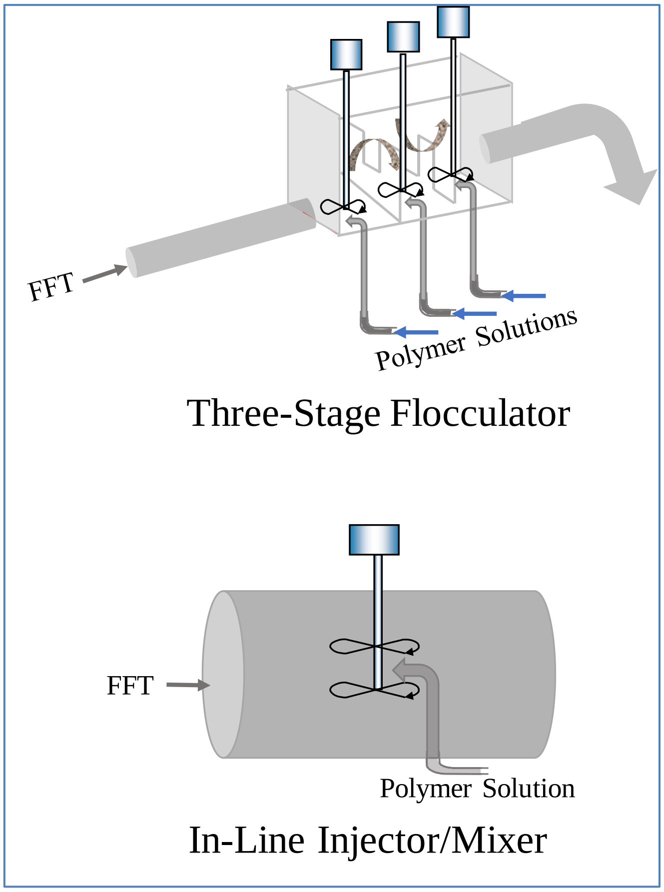


Figure 3-6 MFT Centrifuge Process

Given improvements with in-line flocculation (see the following section) with deep deposit densities approaching that of centrifuge cake within a short time, it is doubtful that any new large-scale centrifuge plants will be constructed to produce cake for deep deposits.

3.3.6 In-Line Flocculation

In-line flocculation of fluid tailings (Figures 3-7 & 3-8) began with the concept of thickening without a thickener (Jeeravipoolvarn 2010; Webster et al 2016) – that is, using treatments like those applied to extraction fines with a mechanical thickener. But ILTT allows the dewatering to occur in the deposit, which can be either a thin-lift area for atmospheric drying or a deep basin to undergo self-weight consolidation.



Following tests of conventional thickener conducted at the Aurora Mine, several successful trials were undertaken in the early 2000s at the Aurora and Mildred Lake sites, building on the treatment protocols tested for the thickener trials using polyacrylamide flocculants and organic coagulants.

Efforts then shifted to in-line treatment of MFT recovered from tailings ponds. Flocculant injection and mixing in the more viscous and thixotropic MFT is more complicated than in the comparatively watery slurry drawn directly from extraction. However, recovered MFT is not directly connected to the extraction process and therefore presents an opportunity to have a more uniform rate and composition of fines feed to the treatment process.

Figure 3-7 Example flocculant injector/mixers

This treatment technology took two different pathways to deposit creation:

- Thin-lift dewatering, in which the treated MFT is discharged to a shallow sloped cell, generally with water released to open drainage into a tailings settling pond. The deposit may then be exposed to atmospheric drying or freeze-thaw to increase solids content.
- Accelerated dewatering, in which the treated MFT is discharged to a deep deposit, generally anticipated to be used for in-pit deposits (Lahaie et al 2010).

The process of in-line flocculation consists of injecting the treatment chemical solutions into the FFT flow, either in the pipe or in a mixing system at discharge. There may be one or more points of addition, one or more stages of mixing, and one or more chemicals employed. Generally, a polyacrylamide flocculant is used, possibly in conjunction with an organic or inorganic coagulant. Both static and dynamic mixers have been employed, but dynamic mixers are preferred as they can adjust to changes in rates of flow or rheology of the slurry being treated. Figure 3-7 illustrates two mixer types that have been used in thickener or in-line flocculation processes.

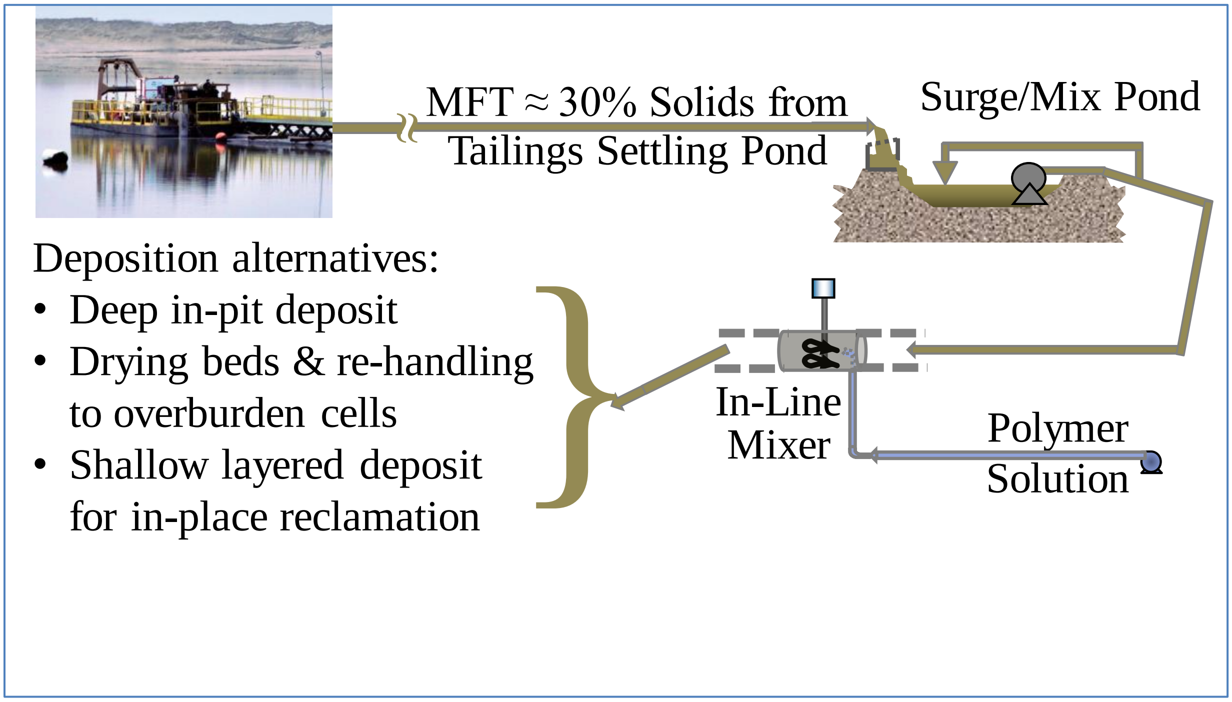


Figure 3-8 Typical in-line flocculation process with disposal options

3.4 Tailings deposition

3.4.1 Planning for tailings in the closure landscape

The products of each of the processes described in the preceding section must be placed in closure landforms. Planning parameters, including composition from originating source materials, geotechnical properties, and volume parameters, are necessary for site planning. Deposit behaviour over the long term is critical to achieving acceptable closure outcomes. The following sections describe depositional practices in use by the industry.

3.4.2 Deep deposition

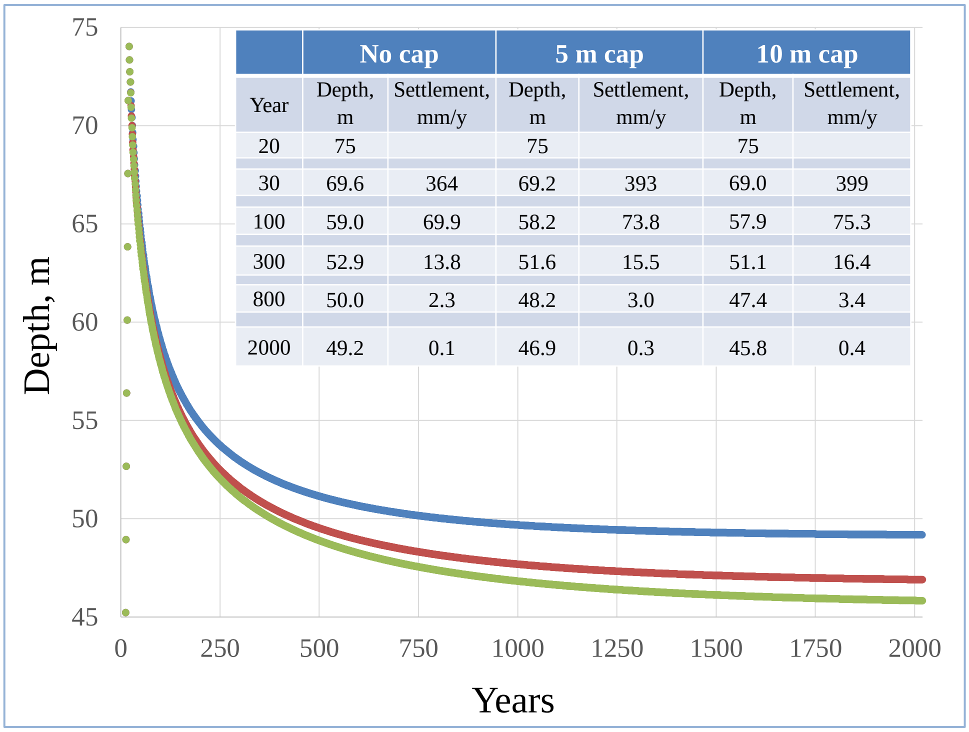
As noted in the previous sections, the advantages of deep-fines deposits are their relatively small footprint compared with large area requirements for thin-lift drying operations and their smaller volume compared to 4:1 SFR CT deposits containing the same quantity of fines.

Deep deposits of high-clay-content fines will have extremely long settlement times. Figure 3-9 models the consolidation and related settlement trajectory of a deposit filled to a depth of 75 metres with treated MFT at 45% solids content. The deposit attains an average solids content of 58% at fill completion. At year 30, 10 years after deposit completion, annual settlement (and corresponding release of OSPW) is at 364 mm, 393 mm and 399 mm for the uncapped, 5 m cap and 10 m capped deposits respectively. At year 100, with or without a surcharge cap, approximately 10 metres or more settlement remains, and after 300 years 3 m to 5 m remain. The slow settlement resulting from decreasing permeability as the deposit densifies, generates a correspondingly low release of OSPW.

As shown in the chart, sand-capped deposits release more total water (corresponding to their greater settlement) and at a somewhat greater rate over longer time. Thus, an in-pit deposit, without a substantial cap surcharge (i.e., deposition beneath a water cap in the end-pit lake) would retain more OSPW and its salt content for geologic time compared with a heavily capped deposit destined for terrestrial reclamation.

Due to their long-term settlement, and related issues of water quality management discussed in Section 5.4.3, such deposits are best placed in a pit, below grade, and covered with open water (a pit lake) to avoid the need for extended care.

The nature of the high-clay-content fines material, and the compounding effect of deposit depth create centuries-long settlement times. As noted earlier, centrifuging of MFT provides marginally greater initial density compared with a deep deposit with similar depth produced by in-line flocculation, but with a substantial increase in cost. Lower cost and lower energy requirements will therefore favour in-line flocculation for future deep fines deposits.



	No cap		5 m cap		10 m cap	
Year	Depth, m	Settlement, mm/y	Depth, m	Settlement, mm/y	Depth, m	Settlement, mm/y
20	75		75		75	
30	69.6	364	69.2	393	69.0	399
100	59.0	69.9	58.2	73.8	57.9	75.3
300	52.9	13.8	51.6	15.5	51.1	16.4
800	50.0	2.3	48.2	3.0	47.4	3.4
2000	49.2	0.1	46.9	0.3	45.8	0.4

Figure 3-9 Settlement over time for a model deep fines deposit
Modeling by William Shaw, P.Eng. of WHS Engineering
Model per Silawat Jeeravipoolvarn, https://www.fscasoftware.com
Consolidation Model Parameters (derived from many observed lab and field deposits)

<table>
<tr><td>A kPa: 2.492</td><td>B: -0.229</td><td>C m/day: .000053</td><td>D: 5.43</td></tr>
<tr><td colspan="2">Material SG: 2.46</td><td colspan="2">Initial total Solids Content: 45%</td></tr>
<tr><td colspan="2">Bitumen Geotechnical B/(B+S) 4.23</td><td colspan="2">Clay Content 75%</td></tr>
<tr><td colspan="2">Pond Area m^2 vertical Walls: 3420000</td><td colspan="2">Base Elevation: 0 m</td></tr>
<tr><td colspan="2">Loading Rate t/yr dry tonnes: 11372133.0</td><td colspan="2">t/m2: 3.325</td></tr>
<tr><td colspan="2">Filling Period 20 years</td><td colspan="2">Deposit height 75m</td></tr>
<tr><td colspan="2">Rate of Rise 3.75m/yr</td><td colspan="2"></td></tr>
<tr><td colspan="2">Sand Cap “5 m Cap
First load 5 years after filling completed and five one metre loads for five years.
I metre load at
Load (kPa) — Load date (days)
10.9872 — 1825
10.9872 — 2190
10.9872 — 2555
10.9872 — 2920
10.9872 — 3285</td><td colspan="2">Sand Cap “10 m Cap”
First load 5 years after filling completed and five 2m loads for five years
2 metre load at
Load (kPa) — Load date (days)
21.9744 — 1825
21.9744 — 2190
21.9744 — 2555
21.9744 — 2920
21.9744 — 3285</td></tr>
</table>

In-line flocculation of MFT with deposition to a deep deposit was first tested by Syncrude at Mildred Lake. The Accelerated Dewatering trial was accompanied by rim ditching the deposit, as widely practiced by the Florida phosphate industry (Carrier 2001). This procedure removes surface water from the deposit, allowing for development of a crust to surcharge the underlying deposit.

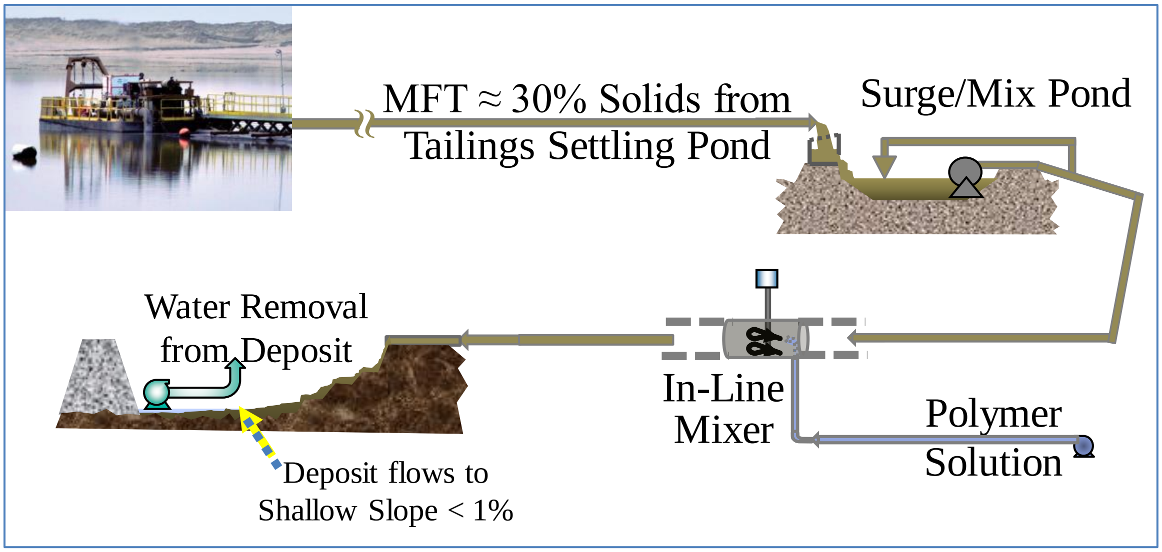
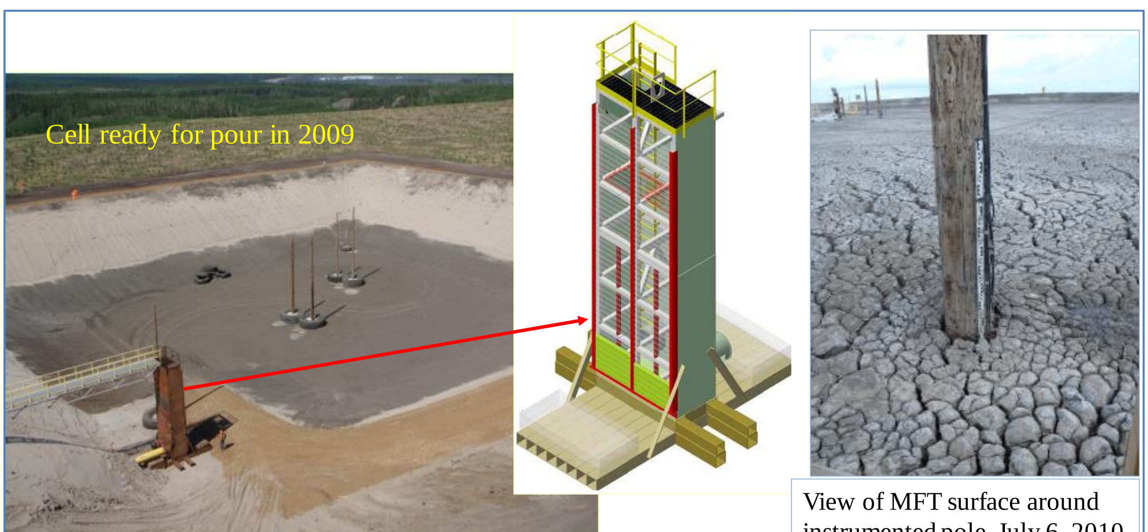


Figure 3-10 In-line flocculation with disposal to a deep deposit

Since the accelerated dewatering test deposit was produced (Figure 3-11), understanding of the process of flocculating MFT has improved — in particular, the process of mixing polymer solution into MFT.



View of MFT surface around instrumented pole, July 6, 2010 (ten months after pit filling).

Sources: *Technical Guide for Fluid Fine Tailings Management;* COSIA, 30 August 2012. *Development of Accelerated Dewatering Technology for Managing Oil Sands Fine Fluid Tailings;* Rick Lahaie, *et al.*

Figure 3-11 Accelerated dewatering test deposit at Mildred Lake

3.4.3 Thin-lift deposition (dried MFT)

Thin-lift development was primarily pursued by Suncor (Wells & Riley 2007) and branded as TRO (Figure 3-12), although trials were conducted at other sites, and commercial operations continue at both the Suncor and Shell MRM (now operated by CNRL) sites.

Figure 3-12 Thin-Lift Dewatering and Drying Cell

Drying operations suffer from large area and time requirements to reduce water contents enough to allow for out-of-pit, above-grade, free-standing, stacked-deposit landforms. Consequently, drying operations are now operated largely by re-handling the material from drying beds using co-disposal with overburden in cells. The result is a costly method.

3.4.4 Co-disposal of soft tailings with overburden

MFT or MFT centrifuge cake can be co-disposed with overburden to absorb water and provide a mixed soil with enough strength to support mobile equipment and surface reclamation activity within a short period. The Clearwater formation, which is composed of clay shale, overlies the oil sands on many surface-minable leases. It can absorb significant water and retain strength (Syncrude 2015).

Figure 3-13 shows the shear strength of a range of Clearwater clay (Kc) mixtures with MFT. The mixtures may be produced by spraying the MFT over the overburden on a conveyor belt prior to loading trucks, or by layering the two materials with mobile equipment. Within a few weeks the MFT water has migrated into the clay and the deposit is trafficable. Mixtures with centrifuge cake in place of (un-densified) MFT allow for a much higher proportion of MFT solids in the blended soil.

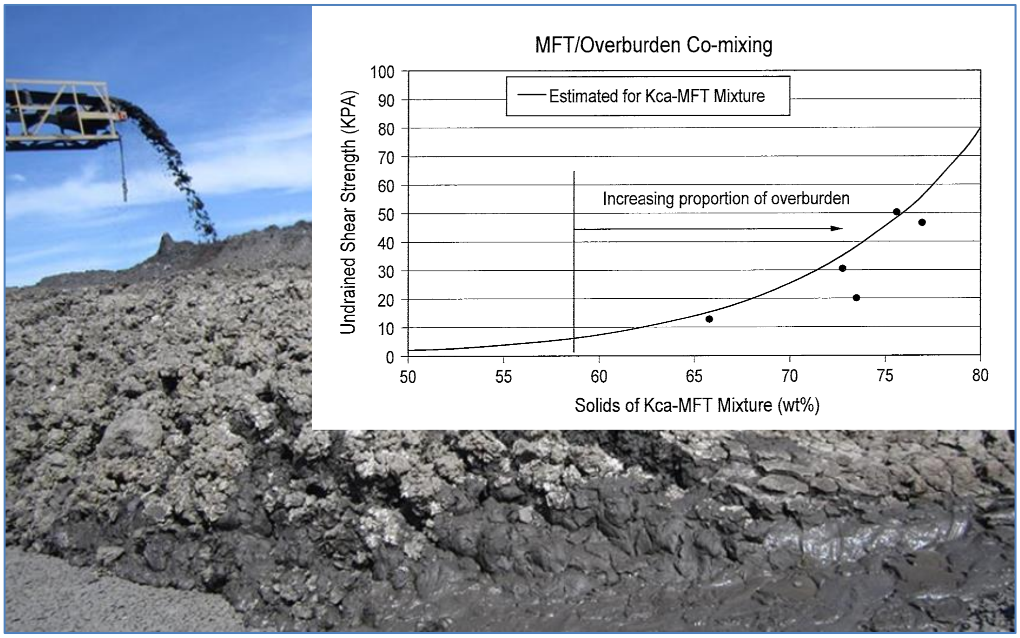


Figure 3-13 Strength of clearwater clay – MFT mixtures
Source: Syncrude and Patent Application # US20140119833A1

3.4.5 Coke capping

Coke (either crushed, delayed coke or "shot coke" from a fluid coker) is a light-weight, permeable aggregate that can be placed over a weak deposit to provide a base for an additional surcharge layer of sand or overburden (Abusaid et al 2011).

In an extreme example, Suncor placed coke over a geotextile covering FFT (resulting from segregation of fines during CT deposition) in Pond 5, creating a "floating cap" to provide access for placement of wick drains into the deposit (Figure 3-14).

Figure 3-14 Constructing Coke Cap Over Suncor Pond 5

3.4.6 Wick drains

Wick drains can be inserted into weak deposits to accelerate drainage and consolidation. Due to the extremely low permeability of dewatered MFT, spacing must be tight and dewatering is extremely slow (Liu and McKenna 1999; Abusaid et al 2011; Brown & Greenaway 1999). Wicks accelerate consolidation, they do not change the ultimate magnitude of settlement.

3.4.7 Summary of current commercial methods

Table 3-1 summarizes the attributes of FFT treatment methods currently in commercial operation.

Table 3-1 Summary of current commercial methods

Treatment & deposition	Other names	Advantages	Limitations	Current performance
Composite tailings (CT)	Consolidated tailings, non-segregating tailings (NST)	Low cost Suited for terrestrial surface or open water	Uses large in-pit volume High demand for sand	4:1 SFR recipe Segregation loses some fines from sand dominant deposit ≈ 80 to 90% 44 µm fines captured to sand, but clay balance needed to better quantify net capture
Centrifuge/ co-disposal in shallow overburden cells (cMFT)	Centrifuge cake, centrifuge fine tailings, centrifuge product, cake	Reclaimable with terrestrial cover	High capital investment Large area required	Some smaller deposits created
Centrifuge / deep deposit (cMFT)		Predictable deposit, observable if water removed from surface	Very long-term settlement suited for in-pit water cover	MFT densified from ≈ 30% to 55% solids, forms shallow (≈ 1%) slope
In-line thickening / thin-lift drying (dMFT)	ILTT, Tailings reduction operations (TRO), atmospheric fines dried (AFD), polymer-assisted thin lift drying, dried mature fine tailings		High cost and land-area intensive	Stackable deposits very limited due to time/area required Primarily a re-handling method for co-disposal with overburden
In-line MFT dewatering /deep deposit	Accelerated dewatering	Lowest cost of all-fines methods Small area required	Very long-term settlement suited for in-pit water cover	Improvements in flocculation produce deposits with densities approaching MFT centrifuge
Thickened tailings (with a thickener)	(TT)	Recovery of warm water can save energy	Variation in incoming extraction fines make control difficult	Segregation at deposition Neither reclaimable deposits nor MFT reductions achieved
In-line thickening (w/o a thickener)	ILTT	Avoids cost of a thickener. Floc near discharge to limit shear	No heat recovery; water removal at deposit	Successful field trial but no commercial application

3.4.8 Froth treatment tailings – characteristics and options

Bitumen froth, produced in the extraction process of surface mining, contains approximately 60% bitumen, 30% water, and 10% solids (Canmet 2009; Oil Sand Magazine 2016). Froth treatment tailings (FTT) result from the solids and water removed from froth by diluting the froth bitumen with a light hydrocarbon (referred to as diluent or solvent) to reduce its density and viscosity and facilitate the separation process in gravity and/or centrifugal separators. The light hydrocarbon used is either naphtha produced in the on-site upgrader (a naphthenic froth treatment process is used at Suncor, Mildred Lake and Horizon) or a paraffinic solvent such as pentane or pentane/hexane (a paraffinic froth treatment process is used at Muskeg River, Kearl, and Fort Hills). In the case of the paraffinic process, about half of the C_5 asphaltenes (high-molecular-weight molecules, with low hydrogen content and relatively high concentrations of sulphur, nitrogen, and porphyrins of nickel and vanadium) are rejected and become part of the FTT.

The prevailing practice for disposal of FTT has been to discharge the high-temperature slurry into an area of the external tailings pond constructed for, and with the tailings from, the extraction process. Several adverse consequences result:

- The light hydrocarbon (naphtha or paraffinic solvent) mixed with bitumen is less dense than water and prolongs floating oil on the recycle pond. It also provides food for anaerobic bacteria, resulting in methanogenesis in the pond MFT. The resulting bubbling prolongs the presence of an oil sheen on the pond surface.
- Residual naphtha or solvent and methane complicate processing when MFT is being recovered and treated in a disposal process.
- Small amounts of pyrite in the oil sand are concentrated through flotation in the extraction process. In some cases, if the deposit is not completely submerged, deposit concentrations may be enough to generate acid rock drainage from the area (Siddique et al 2014a, 2014b; Kuznetsov et al 2015, 2016).
- Similarly, concentrations of naturally occurring radioactive materials may approach occupational health limits.

There are at least three potential ways to manage FTT:

- Continue current practice and deal with final disposition as part of mine closure. This would be costly if excavation and transportation of the material to below the phreatic surface of the closure landscape is required. Moreover, deferring final disposition to the end of mine life is not in accord with progressive reclamation.

- Alternative #1: Inject the FTT into a large extraction tailings discharge stream. This can effectively disperse the metallic components to concentrations commensurate with those in the natural state. However, it does not resolve the matter of methanogenesis in the MFT. It could be the most effective method if the upstream naphtha/solvent recovery component of the froth treatment plant was modified to leave negligible concentrations of light hydrocarbons in the FTT.
- Alternative #2: Densify the solids (for example, using scroll centrifuges[6]) for segregated disposal or co-disposal with overburden. Co-disposal with overburden in the mine pit (i.e., below the closure phreatic surface) may be the best practice.

The Titanium Corporation has proposed removing valuable concentrations of titanium (TiO_2 is the brilliant-white pigment base used in paints, plastics, paper, cosmetics, etc.) and zirconium (ceramics, refractories, and other uses) minerals prior to segregated disposal (Moran et al 2016). The minerals recovery follows an oil recovery step. The process could be an add-on to either of the above two alternatives options.

The negatives associated with current practice suggest that operators consider adopting one of the above two alternatives or another effective method.

3.4.9 Filtration

Filtration of oil sands fine tailings is still in the development stage (CTMC 2012). Various filtration methods have been tested since the late 1970s with a view to producing a stackable deposit:

- **Vacuum filtration** of whole tailings or sand tailings with treated MFT added. Water content suitable for stackable deposits has not been achieved within reasonable filter-area requirements.
- **Filter press** technology has a long history in the clay-china and wastewater treatment industries and is used in some mining applications, sometimes producing high solids content filter cake. The disadvantage is the cost associated with the filter area, which is required for the low permeability of MFT, and the potential for bitumen fouling of the filter. Development work continues for oil sands applications.

[6] It is notable that the original naphthenic froth treatment process uses scroll centrifuges to remove the heavy mineral upstream of solid-bowl disc centrifuges that remove the froth water content and finer solids.

- **Geobags**: Geotextile dewatering bags have been used to dewater sludge from wastewater treatment and for other dewatering applications. The scale required in the oil sands suggests this might be useful in niche applications.
- **Cross-flow filtration** uses a weeping pipe to dewater whole tailings while in transport to attain density at disposal to prevent segregation (Ifill et al 2010). The unique aspect is that the sand layer formed at the pipe wall is continuously scoured by the flow, creating a constantly refreshed sand filter media surface. Scale up to commercial tailings line capacities has yet to be undertaken.

CTMC (2012) provides a description of these technologies and of the ones that follow in Section 3.4.10.

3.4.10 Other processes and deposit management

The industry has tested or operated many other methods that could be applied in some situations. Among these are:

- **Electro-kinetic dewatering** (see Raats et al 2002; Guo 2012) of MFT has been demonstrated by ElectroKinetic Solutions Inc. at a range of scales including a swimming-pool-sized deposit at a C-FER Technologies facility in Edmonton. As an *in situ* treatment technology, it represents the only alternative to wick drains tested at a reasonable scale. An order of magnitude reduction in dewatering timing is projected compared with wick drains. Electrode spacing is a critical cost and performance element for large-scale deployment. A scaled-up version of this technology awaits further validation.
- **Particlear** is the Dupont brand name for its sodium silicate formulation (Moffett 2015). The treatment turns water into a rigid material. Applied to MFT over a soft deposit, it could provide surface access and serve as an alternative to coke capping.
- **Sand raining** consists of spraying a sand slurry from a barge onto the water layer over a weak deposit. The intent is to slowly build up a permeable surcharge layer over the deposit (Bailey and Palermo 2005). Due to the fluid nature of MFT, failure of the surface sand layer into the fluid zone during deposition is probable (unlike natural and dredge sediments, untreated MFT does not consolidate / strengthen with capping).

3.5 Tailings R&D and commercialization: the quest for a game-changer

Many of the processes described previously seek to dewater FFT to form discrete deposits with a variety of thicknesses, allowing further post-placement densification through natural processes, including atmospheric drying, freeze-thaw cycles, and self-weight consolidation. Much effort has been devoted to improving those processes, understanding their consolidation behaviour, and planning for their place in various closure landforms. What has become clear through laboratory testing and field trials is that thin-lift drying takes a combination of a large area and extended time to produce trafficable deposits, whereas deep deposits can take centuries to settle.

A longstanding industry tailings management goal has been the ability to avoid the accumulation of large volumes of FFT and incorporate all fines into a solid soil matrix using low-cost methods that do not introduce additional material-handling complexity. CT and earlier efforts to treat whole tailings to prevent segregation of FFT were attempts to achieve this end. As previously noted, limitations of containment space for CT formulations (with deposits that liquefy upon initial placement) and segregation behaviour have limited the adoption or extent of use of these methods.

An ideal process would avoid:

- The need for excessive material handling and large drying areas
- The creation of deposits with centuries-long settlement times associated with deep fines deposits
- The limitations of current CT/NST formulations with their high demands for sand and in-pit space.

The following describes a sand-fines tailings composite that, if developed, would constitute a game-changer for the industry, obviating the need to accumulate large FFT volumes, or to produce deposits with centuries-long settlement times. Game-changing success arises with meeting these characteristics, not with fine-tuning existing technologies.

The current options — CT and MFT treatment with in-line flocculation or centrifuging to produce thin-lift drying or deep deposits — result in tailings management processes that drive the mine development footprint and the required area for open water in-pit deposits. Success with all the game-changer outcomes described in Table 3-2 would give developers greater control over the development footprint and design of the closure landscape.

Table 3-2 Impacts of a game-changer process

Characteristic	Description	Outcome
1. Fines (clay) content of sand-fines composite.	Sand matrix can contain all FFT-producing fines within the oil sand site ore body. A composite blend of ≈ 2:1 SFR with a corresponding clay content, would allow all FFT fines to be incorporated into sand-dominated deposits. The resulting deposit must achieve settlement within a reasonable time.	All FFT is incorporated into deposits that can be reclaimed to a terrestrial surface, a wetland, or open water (a lake), depending on site-specific conditions and the operator's mine closure design.
2. Deposit permeability	Deposit has high permeability. Drainage rate is high enough to support cell and contained-beach construction.	Out-of-pit deposits and in-pit deposits well above original grade can be constructed, facilitating upland components in the closure landscape. Some sites could see reduced out-of-pit overburden and tailings footprints, with attendant savings in development and reclamation costs.
3. Non-segregating behaviour upon deposition	Deposit release water has low suspended solids (< 1%).	The deposit is not releasing fines to the runoff. Release water is immediately re-usable in the process.
4. Clarified release water	Deposit release water is free of suspended solids and hydrocarbon components. Salt concentrations (TDS) are a function of the ore salinity.	Water is suitable for industrial discharge criteria. This would assist in "blowdown" of the salt in the site recycle water system, avoiding a build-up to excessive salinity.

In the game-changer process, each characteristic in Table 3-2 provides added flexibility to the site design and fosters early closure. Development of a low-cost method of realizing such performance would enhance industry sustainability.

The quest continues for a process with some or all the above attributes. In the meantime, deep, in-pit deposits of treated FFT with extended settlement times will be a necessity at most sites. Until such a process is developed, successful application of such deposits must include:

- A secure geotechnical setting (ideally geologic containment, but lacking that, meeting the dam de-licencing criteria set out by OSTDC (2014). Section 4.6 provides a discussion.
- Rigorous hydrogeological and surface drainage design for the in-pit deposit and its surrounding terrain with a surface water cover having an adequate drainage area to yield a sustainable lake (see Section 5).

- A regulatory pathway from final deposit placement and water capping, through controlled and monitored discharge under science-based industrial criteria (AEP 1995), to a state where surface water quality and natural inflow/outflow provide for sustainable mine closure.

3.6 Processing and deposition lessons learned

This section provides some hard-won lessons learned from the past 50 years that crystalized during the writing of this section.

- Permeability of clay-rich fines deposits (MFT solids) decreases as water is removed. Settlement times for these deep deposits can exceed a millennium, making terrestrial reclamation of such deposits challenging. However, such deposits, placed securely in pit, can be reclaimed with an open-water surface — a pit lake.
- The proportion of open-water surface area within a closure landscape needs to be planned to criteria that will maintain long-term freshwater quality. A survey of natural lakes in the boreal suggests 15% open water for a maximum proportion of the contributing drainage basin. For pit lakes with a declining but prolonged salinity input, a maximum of 10% represents a reasonable guideline, subject to site-specific projections of salinity decline.
- As presently operated, MFT centrifuges provide marginal benefits (≈ 55% solids) over in-line flocculation deposits, which can generate ≥ 50% solids in a relatively short period. In the absence of significant improvement in cake density, future deep fines-dominant deposits will rely mostly on in-line flocculation.
- Deep deposits of in-line flocculated MFT make more efficient use of pit void volume than do untreated MFT. With the use of surface ditching and drainage, establishment of a surface crust can be used to provide a robust mudline for the overlying water in a pit lake. Capping, say with coke and/or sand, would further stabilize the mudline.
- It is time to adopt and implement a strategy for managing froth treatment tailings. Methods are available to treat and dispose of this material to mitigate risks.
- CT deposits provide an opportunity for terrestrial reclamation — including to a wetland — as has been successfully demonstrated where the segregated fluid runoff was removed (Wytrykush et al 2012). Containment volume

limitations, competing demands for sand, and footprint impacts will limit its use on some sites. Reliance on 44 µm fines balancing in the absence of determining the clay content of these deposits leaves the clay-capture benefit (MFT reduction) of the process inadequately quantified.

- Processes such as thin-lift dewatering/atmospheric drying and co-disposal with overburden can contribute to the total MFT volume management. Area requirements and costs will limit their contribution to the total management. Stabilization of such deposits can occur even after mine closure using a large tailings sand beach or overburden plateau.
- Site specifics may favour one process over another on one site but the opposite on a different site.
- Currently, site footprint requirements, closure drainage, and planned pit-lake areas are reactive to MFT accumulation. A game-changing technology that incorporates all fines within a free-draining sand matrix would provide greater freedom when designing closure landscapes and a reduction in the development footprint area of disturbance.

The following sections describe the consolidation predictions of deposit materials and options for their capping and position in mine closure.

4 Landform design for oil sands tailings deposits

This section provides an overview of soft tailings deposits — how they are formed, how they are stabilized and capped, how they are reclaimed, and what to expect from post-reclamation performance. It builds on the processes described in Section 3 and sets the stage for evaluation of the water and topography changes described in Section 5. These changes will profoundly affect the water balance and sustainability of the mine closure landscapes – each which will occupy hundreds of square kilometres, and which will include hundreds of kilometres of water courses, innumerable wetlands, and one or two pit lakes. These city-sized landscape designs are featured in conceptual mine closure plans, which are too often based on incomplete understandings and optimistic assumptions that can lead to fatal flaws, typically related to soft tailings (McKenna et al 2016a).

Figure 4-1 Members of the landform design team

Landform design is an iterative process of building mining landforms and landscapes with flair (McKenna 2002). Inclusive and multidisciplinary (Figure 4-1), it meets the goals of a mine and society to create safe and useful land. With the right design, planning, and operations, regrading volumes are minimized, surface water and groundwater are directed and managed, placement of covers is expedited, and strategic revegetation anticipates the inevitable physical and chemical evolution and ecological changes. This section provides a framework for design and focuses on creating tailings deposits that can be easily and reliably capped to meet an agreed-upon design basis supported by a formal adaptive management process (CEMA 2012).

Soft tailings are defined (Jakubick et al 2003) as residual wastes from milling that, owing to the low density and shear strength, are un-trafficable to normal mining equipment Figure 4-2 shows the impact of spiking sand tailings with MFT to increase fines content.

Figure 4-2 Mired in soft tailings

As described in detail in the following sections, the major issues for disposal of oil sands fluid and soft tailings include:

- Difficulty (in some cases impossibility) in physically capping the fluid or soft tailings due to their inherent low density and extremely low shear strengths.
- Excessive post-reclamation settlement, which can lead to large areas of ponded water flooding even larger areas, trigger dyke failure, become highly salinized, and starve downstream ecosystems of suitable water.
- Expression of oil sands process-affected water (OSPW) into the reclaimed landscape.

4.1 Landform design framework for tailings deposits

Landform design operates at landform, landscape, and regional scales (McGreevy et al 2013). Design teams include planners, engineers, geologists, hydrologists, geochemists, keepers of traditional knowledge, ecologists, and operations and reclamation specialists (Figure 4-1). A design-basis document provides agreed-upon goals, objectives, and design criteria. This living contract evolves over the decades between the initial vision and final signoff. Table 4-1 describes the stages of landform design for tailings deposits; additional detail is provided in the sections that follow.

Table 4-1 Stages of landform design for tailings deposits

Stage/activity	Description
Stages	
Setting out a design basis	A design basis document sets out clear goals, objectives, and design criteria agreed upon by regulators and local communities (Ansah-Sam et al 2016). It includes an adaptive management program based on Peck's (1969) geotechnical observational method, with full monitoring and contingency measures.
Choosing tailings technologies	A formal planning/decision-making process to select tailings process, transport, discharge and deposition, stabilization, capping, reclamation, and post-closure case (McKenna et al 2011).
Designing the containment	Design the geologic and any dyke containment for any potentially mobile tailings with a focus on long-term containment (and dam delicensing) and controlling seepage of OSPW (OSTDC 2014).
Designing the deposition	Focus on keeping the as-deposited tailings to the design specification to meet the design basis, removal of off-spec materials.
Designing the capping	Design the capping blanket and the ridge and swale topography to safely cap the tailings, accommodate modest settlement, control water, and provide targeted land uses (McKenna and Cullen 2008).
Designing reclamation and decommissioning	Design efficient reclamation cover placement and revegetation (CEMA 2012, CEMA 2006; CEMA 2015) and decommissioning of infrastructure and operational elements in preparation for delicensing of dams (OSTDC 2014) and writing the application for reclamation certification (AENV 1991a) and organizing transfer of custodial care (McKenna et al 2015a, 2016b).
Activities	
Constructing as per design	Containment, deposition, stabilization, capping, and reclamation all need to be constructed to spec, using methods akin to those in oil sands tailings dam construction and dam safety programs.
Monitoring and maintaining	From before deposition through to post-closure, the landform is monitored and maintained to guide operations, protect the investment, allow contingencies to be implemented if needed, and demonstrate the landform meets the design basis for certification (Fair et al 2014).
Enacting pre-designed contingencies as needed	An effective adaptive management program includes an approved contingency plan and designs that can be applied in a timely manner if needed (CEMA 2012).
Achieving reclamation certification	The focus of much of the work in landform design in oil sands tailings is the reclamation certificate, although this is expected to be challenging and may not be realistic (Morgenstern 2012).
Containing care	While a matter of some disagreement (even among the authors), it is generally agreed that some tailings landforms and elements of the closure landscapes will require some level of continuing care (monitoring and maintenance) to meet the goals and objectives in the design basis and manage long-term liability (e.g., Morgenstern 2012)

4.2 Setting the design basis

The design basis is often referred to in the oil sands industry as a design basis memorandum, or simply a DBM (Ansah Sam et al 2016). It is a 10- to 20-page document that covers the basis of the plan, the tools that will be used, and, crucially, the design goals, the design objectives, and supporting design criteria. These criteria are measurable and detailed enough to allow stakeholders to verify whether they have been met. Such an approach is on the way to becoming standard practice at some international mines, and at some oil sands operations. Table 4-2 provides a few examples of elements of such an approach. CEMA (2015) provides a checklist for landform design.

Table 4-2 Examples of goals, objectives and design criteria for tailings landforms

Design item	Example
Operational goals	Safe and efficient tailings operations Manage cost, dam safety Meet closure requirements Meet MFT volume requirements
Land goals	Achieve useful, self-sustaining, locally common, beautiful boreal forest Build landforms that can receive reclamation certification Design pit lakes with adequate watersheds
Aquatic goals	Provide attenuation of peak flow, TSS, organics and other constituent concentrations Retain water until it is non-deleterious for release Create a beneficial end use, such as fish habitat or recreational waterbody
Design objectives	Tailings deposits support their intended cap Sustainable long-term settlement Supports wetlands and upland forests Acceptable water quality for wetlands Minimize salinization
Supporting design criteria for solid landforms	Soft tailings operational strength greater than 25 kPa Minimum 2 m sand cap with an average thickness of 4 m to 8 m. Cap to be pervious to reduce required topographic relief; hence composition of cap should be sand. Supports loaded 100 tonne trucks on ridges Post-reclamation settlement < 1 m Upland water table 2 m below ground surface (at least 1 m below the reclamation soil) Withstand a 1/1000-year earthquake Variable topography to concentrate ground water discharges flowing into defined swales that facilitate ground water table control at adjacent areas. Variable relief should be at least 5 m so that the ground water table has sufficient gradient to flush out residual salts from the pores of sand cap. Total dissolved solids in water downstream less than 1000 ppm; no acute toxicity; other proposed criteria listed in Section 4.

4.3 Choosing technologies

One of the most critical steps in constructing an oil sands lease is the choice of tailings technologies (CTMC 2012). Too often, operators take a narrow view that focuses on process technology alone (Section 3.3). For successful reclamation, it is the entire suite of technologies chosen — process(es), transport, discharge and deposition, stabilization, capping, reclamation, and post-closure care — that will achieve sustainable closure.

The task is to evaluate all the technologies that can reliably satisfy the goals and objectives set out in the design basis. All oil sands operators have teams that evaluate and test new technologies. Careful evaluation and structured decision-making notwithstanding, many technologies are optimistically chosen and end up being difficult to cap and reclaim. This is a central theme of this report; a more thorough process using a formal and robust design basis is needed.

4.4 Options to build a suite of complementary technologies

Many options are potentially available in a plethora of combinations, although many are not compatible. Table 4-3 provides a listing of technologies adapted and enlarged from CTMC (2012) and BGC (2010a, 2010b).

Table 4-3 Available choices in holistic tailings technology selection

Unprocessed tailings streams	Processed tailings streams	Tailings transport	Tailings discharge	Tailings deposition	Tailings stabilization	Tailings capping	Tailings reclamation
BAW tailings sand BBW / BBMFT tailings sand *Overflow (cyclone or thickener overflow, floatation tailings)* Cycloned sand (CS) Coke (delayed or fluid) Fluid fine tailings (FFT) Froth treatment tailings (FTT) Primary extraction tailings Oil sands process water (OSPW) *Raw water import* *Plant & refinery wastes*	Centrifuged FFT (DMFT) Composite tailings (CT) Dried fluid fine tailings (evap) (DMFT) Dried fluid fine tailings (thermal) (TFT) Filtered tailings (FT) Overburden Kc-FFT codisposal Spiked tailings Thickened tailings (TT)	Conveyor *Ditch* Slurry pipeline *Tramming* Trucking	*Amendment at discharge* *Barge dumping* Codisposal *Chute channel – launder* Conveyor – self-dumping Conveyor – stacker Cyclostacking *Energy dissipator* Floating pipeline discharge Leaky pipe Open pipe discharge Raining in Scraper dumping Slurry distributor Spigotting Spray discharge – rainbowing Spray freezing Spreader - flinger Tremmie – sub tailings Truck dumping	Central discharge Co-deposition of streams Compacted cell Contained beaching Geotube containment Landfill Mechanical spreading Perimeter beaching Pond settling Poldering / slop cells Riverine deposition Sand & fines layering Sand farming Subaerial deposition Subaqueous deposition Sub-FFT deposition Sub-lake and submarine deposition Thin-lift evaporative drying Thin-lift freeze-thaw Thin-lift freeing	Amendments – crust enhancement Amendments – deep mixing Consolidation – granular surcharge Consolidation – self weight Consolidation – wick drain Crust management – evaporative drying, land farming Dewatering – underdrain or pumping Dredge rehandle – reprocessing Freeze-thaw Freezing Rim ditching Ripping and mixing with a dozer Shock densification Soil cap to stabilize Vegetation for dewatering or stabilization	Floating cap Granular blanket capping Granular hydraulic beaching Granular ridge and swale topography Granular thin-lift raining-in Low k blanket capping Low k ridge and swale topography Reclamation material capping on tailings Soft-ground techniques Standard earthworks techniques Water capping	Fertilization Flooding / irrigation Reveg – direct seeding tailings Reveg – hydroseeding Reveg – natural invasion Reveg – planting Reveg – seeding Riparian reclamation Riprap channels and outlets RM amended tailings RM placement – hydraulic reclamation RM placement – spreader-flinger RM placement – dump & spread Stream reclamation Upland reclamation Water treatment Wetland reclamation Wildlife enhancement elements

Unprocessed tailings streams	**Processed tailings streams**	**Tailings transport**	**Tailings discharge**	**Tailings deposition**	**Tailings stabilization**	**Tailings capping**	**Tailings reclamation**
UNPROCESSED TAILINGS STREAMS	**PROCESSED TAILINGS STREAMS**	**TAILINGS TRANSPORT**	**TAILINGS DISCHARGE**	**TAILINGS DEPOSITION**	**TAILINGS STABILIZATION**	**TAILINGS CAPPING**	**TAILINGS RECLAMATION**
Streams that are going to tailings facilities with little beneficiation of product	Tailings that have seen significant processing to make an engineered product	Moving tailings from the plant to the deposit	Initial release from transport at deposit	Flow, accumulation, sedimentation of tailings at deposit – planned and relied upon	Treatment of tailings after deposition largely complete	Placing materials on top of tailings surface	Placement of reclamation material and revegetation
BAW tailings sand BBW / BBMFT tailings sand *Overflow (cyclone or thickener overflow, floatation tailings)* Cycloned sand (CS) Coke (delayed or fluid) Fluid fine tailings (FFT) Froth treatment tailings (FTT) Primary extraction tailings *Raw water import* *Plant & refinery wastes*	Centrifuged FFT (DMFT) Composite tailings (CT) Dried fluid fine tailings (evap) (DMFT) Dried fluid fine tailings (thermal) (TFT) Filtered tailings (FT) Overburden Kc-FFT codisposal Spiked tailings Thickened tailings (TT)	Conveyor *Ditch* Slurry pipeline *Tramming* Trucking	*Amendment at discharge* *Barge dumping* Codisposal *Chute channel – launder* Conveyor – self-dumping Conveyor – stacker Cyclostacking *Energy dissipator* Floating pipeline discharge Leaky pipe Open pipe discharge Raining in Scraper dumping Slurry distributor Spigotting Spray discharge – rainbowing Spray freezing Spreader - flinger Tremmie – sub tailings Truck dumping	Central discharge Co-deposition of streams Compacted cell Contained beaching Geotube containment Landfill Mechanical spreading Perimeter beaching Pond settling Poldering / slop cells Riverine deposition Sand & fines layering Sand farming Subaerial deposition Subaqueous deposition Sub-FFT deposition Sub-lake and submarine deposition Thin-lift evaporative drying Thin-lift freeze-thaw Thin-lift freeing	Amendments – crust enhancement Amendments – deep mixing Consolidation – granular surcharge Consolidation – self weight Consolidation – wick drain Crust management – evaporative drying, land farming Dewatering – underdrain or pumping Dredge rehandle – reprocessing Freeze-thaw Freezing Rim ditching Ripping and mixing with a dozer Shock densification Soil cap to stabilize Vegetation for dewatering or stabilization	Floating cap Granular blanket capping Granular hydraulic beaching Granular ridge and swale topography Granular thin-lift raining-in Low k blanket capping Low k ridge and swale topography Reclamation material capping on tailings Soft-ground techniques Standard earthworks techniques Water capping	Fertilization Flooding / irrigation Reveg – direct seeding tailings Reveg – hydroseeding Reveg – natural invasion Reveg – planting Reveg – seeding Riparian reclamation Riprap channels and outlets RM amended tailings RM placement – hydraulic reclamation RM placement – spreader-flinger RM placement – dump & spread Stream reclamation Upland reclamation Water treatment Wetland reclamation Wildlife enhancement elements

4.5 Geotechnical and geoenvironmental properties of tailings deposits

Table 4-4 builds on Table 3-1 to provide a summary of properties and issues related to capping and closing tailings deposits.

Table 4-4 Typical properties and issues regarding various oil sands tailings deposits

Name	Description	Density, fines content, and strength	Typical wet density and peak undrained strength relating to capping	Issues and demonstrated opportunities for capping and closure
Unamended FFT (uFFT)	Settled fines segregated from whole tailings	30–40% solids content >80% fines content Fluid consistency.	1250 kg/m^3 < 1 kPa	1, 2, 3, 4, 5, 7 A
Centrifuge MFT (cMFT)	Flocculated/coagulated FFT that has been centrifuged	45–60% solids > 80% fines Fluid to very soft consistency.	1400 kg/m^3 < 1 kPa	1, 3, 4, 5 A, B
Thickened Tailings (TT)	Flocculated (and maybe also coagulated) FFT from a thickener or in-line treatment (ILTT)	35–50% solids 50–80% fines Fluid to very soft consistency.	1650 kg/m^3 < 5 kPa	1, 3, 4*, 5* A, B, C*
Dried FFT (dMFT)	Flocculated FFT deposited in thin-lifts for drying	60–85% solids > 80% fines Very soft to firm consistency.	1750 kg/m^3 5–20 kPa	1, 3, 4* A, B, C
Composite tailings (CT)	Mixture of cycloned sand, FFT, amended to form non-segregating slurry	75–84% solids 20% fines Very soft to soft.	2000 kg/m^3	1, 2, 3 A, B, C
Beach below FFT tailings (BB-FFT)	A mixture of sand tailings and FFT that forms in conventional tailings ponds	Highly variable < 10% to 80% fines. Soft to firm consistency.	2000 kg/m^3 5–20 kPa	1, 3, 4* A, B, C
Froth treatment tailings (FTT)	Naphtha or paraffinic froth tailings	Highly variable. Fluid to firm consistency.	Variable	1*, 3, 4*, 5*, 6 A, B, C*
Tailings sand (TS)	Fine quartz sand that segregates during tailings deposition	> 80% solids 5–10% fines. Forms beaches and caps and dykes.	2000 kg/m^3	7

Hazards / issues

1. Potentially mobile material if saturated (dam delicensing risk)
2. Low fines density for disposal.
3. Poor trafficability to reclamation equipment
4. Difficult to establish capping topography
5. Large post-reclamation settlements predicted to occur over long timeframes.
6. Poor pore-water quality
7. Highly erodible

Capping opportunities

A. Can be capped with water
B. Can be capped with floating coke
C. Can be capped with sand

* indicates favourable properties required.

Adapted from CTMC (2012) and McKenna et al (2016).

Several conclusions can be drawn from Table 4-4:

- Most tailings deposits are suitable for water capping. The low fines density and potential for resuspension make water capping of uFFT more challenging than denser tailings.
- Owing to their low density and low permeability, uFFT, dMFT, and most TT likely cannot be capped reclaimed terrestrially except under special circumstances.
- Froth treatment tailings are highly variable and have geo-environmental issues requiring special attention (see Section 3.4.8).
- BB-MFT and CT have similar properties.
- Some materials have the potential for superior performance (sandy TT, dMFT, BB-FFT) where properties are at the high end of the range of those experienced in lab and field.
- Most soft tailings are potentially mobile and need special attention for dam delicensing. High fines soft tailings are unlikely to liquefy, but given their sensitivity (the rapid loss of strength from peak to remoulded states) they may be potentially mobile with respect to dam delicensing (see Boulanger& Idriss (2006) regarding liquefaction of silts and clays). Desaturating these materials greatly reduces mobility risks.
- Game-changing technologies focus on reducing or eliminating hazards and issues of concern. They would offer non-mobile tailings and high fines density, allow capping and establishment of reclamation topography, and experience little settlement but acceptable pore-water release.
- Oil sands fine tailings have low hydraulic conductivity, requiring the need for numerical modelling to predict the densification of tailings due to consolidation as discussed in Section 4.7. The modelling indicates that fine-tailings deposits will undergo many metres of post-reclamation settlement releasing large quantities of OSPW.

Geo-environmental properties of oil sands tailings relate to the OSPW quality that has received increasing scrutiny over time. It is increasingly recognized that the geochemical processes are important. Table 4-5 provides a summary of the main constituents of various waters in the region. In addition to these constituents, OSPW contains a complex mixture of organic acids, polycyclic aromatic hydrocarbons, nutrients, and metals (CEMA 2012, Mahaffy and Dube 2017, Li et al 2017) that need to be accounted for in the drainage of any closure option.

Table 4-5 Oil sands process-affected water quality

Variable (mg/L)	Syncrude MLSB tailings pond	Syncrude demonstration ponds	Suncor tailings pond water	Suncor NST /CT release water	Suncor NST/CT Pond seepage	Athabasca River water	Regional lakes
Total dissolved solids (TDS)	2221	400–1792	1887	1551	1164	170	80–190
Conductivity (us/cm)	2400	486–2283	1113–1160	1700	1130	280	70–226
pH	8.2	8.25–8.8	8.4	8.1	7.7	8.2	7–8.6
Sodium	659	99–608	520	363	254	16	< 1–10
Calcium	17	15–41	25	72	36	30	2–25
Magnesium	8	9–22	12	15	15	8.5	1–8
Chloride	540	40–258	80	52	18	6	< 1–2
Bicarbonate	775	219–667	950	470	780	115	9–133
Sulphate	218	70–513	290	564	50	22	1–6
Ammonia	14	0.03–0.16	14	0.35	3.4	0.06	< 0.05– 0.57

Adapted from Allen 2008a and CEMA 2012.

Tailings sand has a porosity of approximately 35% (McKenna 2002) and is mostly saturated. This means that some 35% of tailings sand volume is water, almost all of which will eventually drain or flush from the dykes, beaches, and deposits. As explained in Section 5, this OSPW reports to groundwater or surface water and is directed to the pit lake before being discharged to the environment, where it flows to the Athabasca River and ultimately the Arctic Ocean. For most sites, this means approximately a billion cubic metres of process water will flush from the sand deposits over the next few hundred years (the inventory is far in access of that of ponded OSPW). The base flow in the tens to hundreds of kilometres of permanently flowing constructed creeks will have a strong OSPW signature — for much of the year it may be almost entirely OSPW. Each pit lake is designed to dilute this volume with other waters from the natural and reclaimed landscape, allowing natural aerobic degradation of naphthenic acids and dilution of salts (CEMA 2012). The significant impacts of OSPW to the environment are explained in Section 5.

Tailings sand is prone to wind erosion, causing on-site and offsite dusting (CCA 2015; Shotyk et al 2017), affecting adjacent reclamation and vegetation and contributing to poor air quality during windy periods. Controlling blowing sand (and the fines entrained in the air column) is an operational requirement and likely to become more important as large tailings plateaus are hydraulically sand-capped. The main method used for controlling blowing sand is reclamation capping; occasionally dust suppressants are employed (CTMC 2012).

Being a fine, cohesionless material, tailings sand is also highly erodible by water, requiring a contiguous vegetated cover on slopes and maintenance to repair gullies, particularly until the vegetation is well established. Provision for long-term erosion of sand dyke slopes and protection of toe creeks is indicated (McKenna 2002).

A number of trace metals and other constituents in oil sands tailings may marginally exceed guidelines, need to be assessed as part of landform design, and may complicate reclamation certification. Agreeing to an evaluation framework in the design basis is critical to success.

4.6 Designing and constructing tailings containment

Most oil sands fines-rich tailings require at least short-term containment unless they are self-supporting (as in track-packable tailings). In most cases, long-term containment will also be required if the tailings remain potentially mobile. Tailings can be considered potentially mobile if they are liquefiable (such as loose saturated tailings and CT), sensitive clay (losing more than 75% of shear strength when strained), or fluid or become a fluid when strained (nominally < 2 kPa shear strength).

Four types of containment are recognized:

- Full geologic containment – the tailings are positioned below original ground in an area where the pit walls are stable (i.e., resistant to river erosion). This is the ideal situation.
- Low perimeter dyke – a low dyke surrounding some or all of the deposit to increase containment above the full geologic containment level. Potentially mobile materials should not be positioned above the original ground unless sufficiently set back from the dyke crest and future settlement should not create a volume of contained water that would cause the perimeter dyke to be a dam.
- ETF ring dyke – an above-ground high dyke (often 30 to 90 m in height). Most external tailings facilities in the oil sands are constructed in this manner. The volume and disposition of potentially mobile materials often needs to be determined through site investigation (drilling the deposit). To decommission these dams, fluid is removed either through breaching the dyke or displacing the fluid with sand and/or overburden.

- In-pit dykes – typically used to allow mining in the pit to continue. These dykes are typically overtopped or breached prior to closure.

The OSTDC (2014) provides guidance on delicensing structures involving potentially mobile materials, using a risk-based approach if required. If the containment is designed and constructed well, the risk of potentially mobile materials breaching and flowing post-closure will be minimal. Applying the OSTDC to deposits that have not been designed with delicensing in mind will be challenging and may not be feasible.

Containing water post-closure is one of the greatest challenges, as water can cause dyke failure due to a number of mechanisms (e.g., overtopping, wave erosion, saturation of fills, piping, reducing strengths in the downstream face, or gully erosion). It is a significant “follower force” that can turn a minor breach of small volumes of potentially mobile materials into a major dam failure, as famously demonstrated by the Mount Polley tailings dam failure (Morgenstern et al 2015) that had a large operational water cap. Some water will inevitably collect on reclaimed tailings plateaus, but this volume needs to be limited in areal extent and depth to allow delicensing. Settlement of soft tailings (see the next section) can create unacceptably large flooded areas.

The containment must also provide long-term protection against leakage of excessive quantities of OSPW into surface waters, groundwater aquifers (CEMA 2013), or even aquitards (Abolfazlzadehdoshanbehbazari et al 2013).

4.7 Consolidation settlement

Consolidation is defined in the Glossary of Geology (AGI 2011) as “the gradual reduction in volume and increase in density of a soil mass in response to increased load or effective compressive stress; e.g., the squeezing of fluids from pore spaces.” Industry and academia have devoted considerable resources to understanding the densification of untreated fluid tailings within this consolidation (and other) frameworks (e.g., Pollock 1988, Suthaker 1995, Jeeravipoolvarn 2005, Jeeravipoolvarn et al 2009; Abazari Torghabeh 2013). Unfortunately, repeated attempts to demonstrate the formation of effective stresses in untreated oil sands fluid tailings have failed (except in the zone immediately adjacent to the pond bottom where sand and silt contents have increased). After 50 years, the mechanics of fluid tailings densification is still poorly understood, or inadequately explained.

In contrast, recent unpublished work, both in the lab and the field, shows that oil sands fine tailings dewatered with a flocculant or coagulant do show measurable reductions in pore-water pressure with time (and thus increasing effective stress) throughout the column (e.g., Pollock et al 2000). Materials shown to exhibit this behaviour include dMFT, cMFT, TT, and CT. The large vertical deformations in these materials preclude the use of traditional consolidation theory (Terzaghi and Peck 1967), but commercially available software based on large-strain consolidation theory (Gibson et al 1967) can be used for useful predictions when scaling up hydraulic conductivity from the lab to the field (e.g., Schulze-Mauch et al 1999; McKenna 2002).

Examples of such predictions, based on work by McKenna et al (2016), are shown in Figures 4-3 and 4-4. These simple model runs indicate extremely large post-filling settlements over 20 to 1000+ years. Each 1 m drop in the deposit height indicates 1000 mm (1 m^3/1 m^2) of OSPW release to the capping material (and hence to wetlands and into pit lakes). The tailings landform and downstream ecosystems need to be designed to manage the flux of OSPW. Over time, many of these materials lose more than 30% of their original thickness, and this difference will be expressed as consolidation water.

This slow consolidation means that the tailings are weak, often fluid-like, at the mudline. Where they are too weak, the deposit cannot be easily capped with solid materials (see Section 4.9).

If somehow capped, the impact of such large settlements is daunting. As discussed below, there is currently no scheme to manage settlements of such scale, except in the case of water capping, which is restricted to deposits with geologic containment and adequately sized watersheds (see Section 5.4.2). Figure 4-5 illustrates the impact of such settlements. For almost all tailings landforms (except pit lakes with geologic containment), these settlements are a fatal flaw for the design.

The water balance around natural and reclaimed wetlands in the oil sands is an area of intensive study (e.g., Devito et al 2012; Wytrykush et al 2012). The climate in the Fort McMurray area has a net water deficit most years. Although potential evaporation from open water exceeds precipitation, wetlands with a water table below the surface (fens) and some very shallow marshes are net producers of water, feeding downstream wetlands and pit lakes.

As post-reclamation settlement progresses, standing water deepens, and the water floods larger and larger areas (in addition to the areas that will be flooded by beavers (Eaton et al 2013). The potential impacts include:

- Upland forest areas drown, affecting trees and shrubs and transforming these areas to wetlands. The riparian zone also shifts. This is common in natural areas, but such a shift in land use or ecosystems is not always desirable in reclaimed areas.

- Water encroaches on areas closer to dyke crests, increasing the risk of a dyke breach (due to overtopping, piping, wave erosion, or slope stability). This risk can preclude delicensing or cause the dam to be relicensed (OSTDC 2014).
- Larger areas of open water signal a shift in water balance — the watershed becomes more evaporative (Section 5.4.2). Less water is available downstream for wetlands, creeks, and pit lakes, and if the watershed-to-open-water ratio shifts too much, outflow will diminish dramatically, and evapoconcentration will cause the remaining shrinking water body to become saline, affecting the ecosystem.

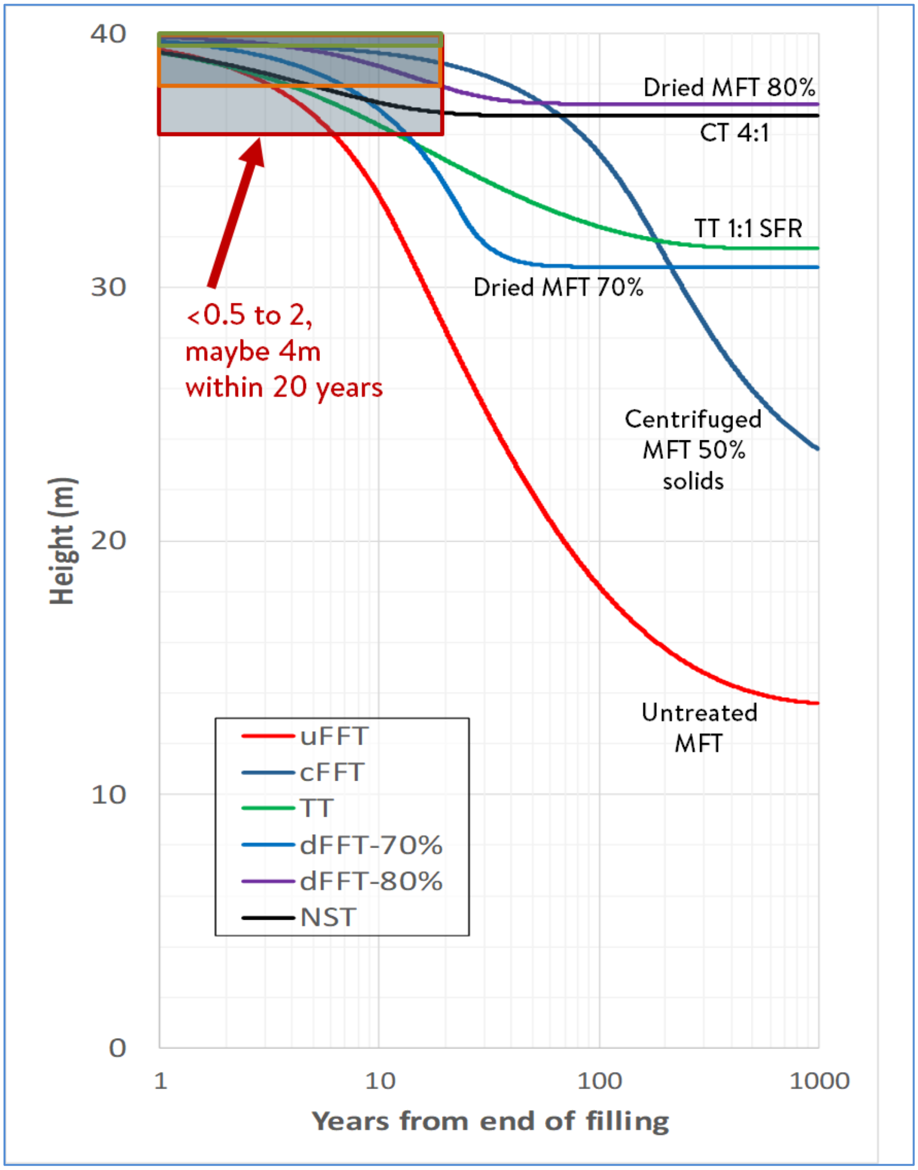


Figure 4-3 Consolidation modelling indicating settlement with time for various tailings types (after McKenna et al 2016a)

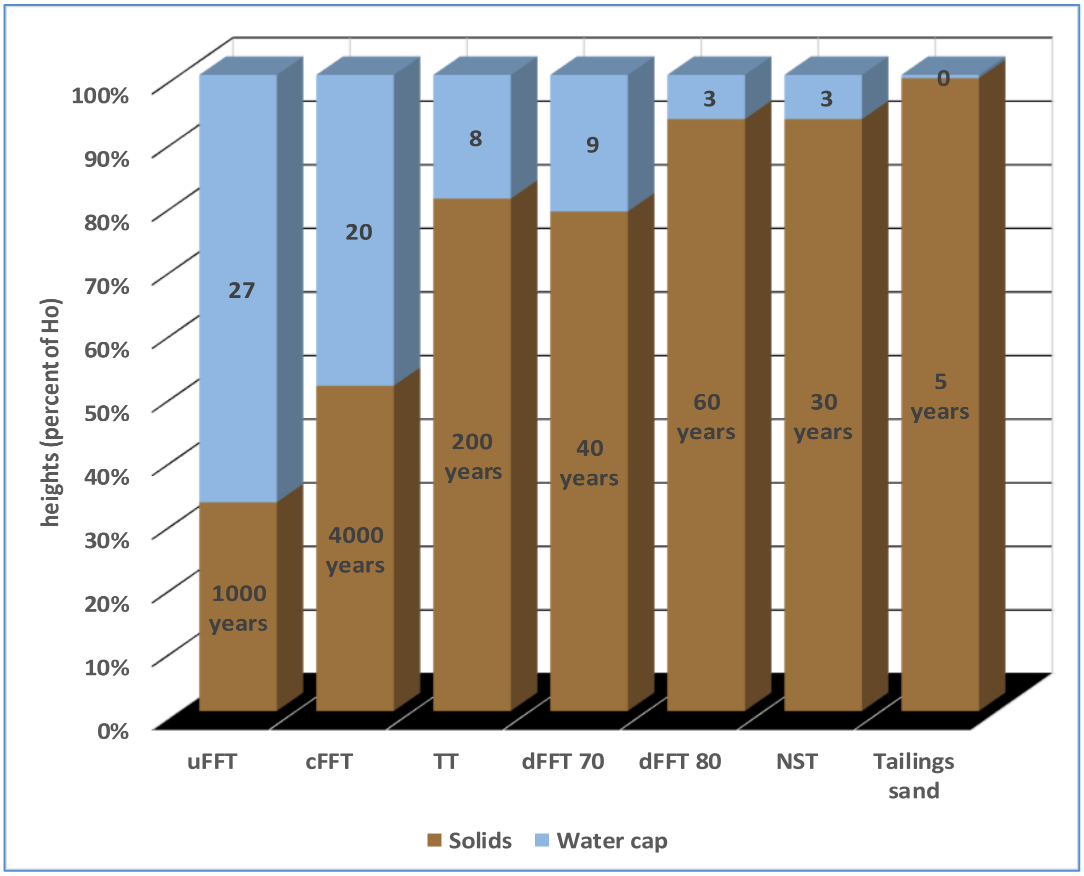


Figure 4-4 Ultimate settlement for various types of tailings

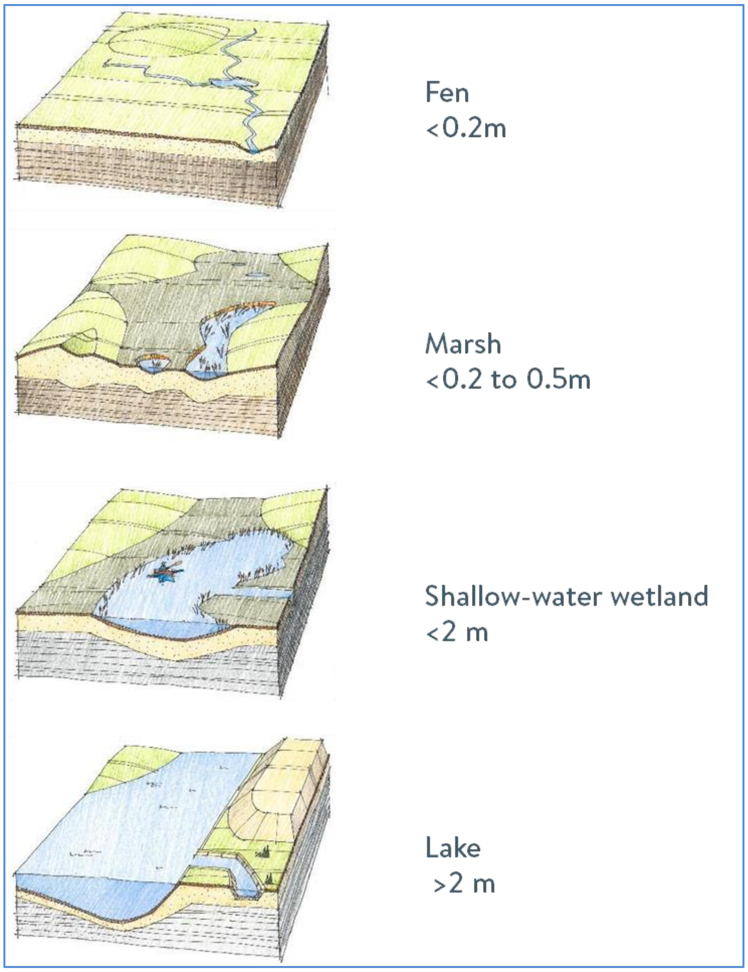


Figure 4-5 Impact of settlement on reclaimed wetlands (after CEMA 2014)

How much settlement is too much? It comes back to the design basis and the goal for the landform.

For deposits with full geologic containment, the size of a pit lake is typically limited to a fraction of the contributing watershed (See Section 5.4.2) and must include a minimum littoral zone size relative to the lake surface (CEMA 2012). Some enlargement can be accommodated but it is particularly difficult to design a littoral zone to survive more than a few metres of settlement and still be large enough to support a productive lake. Where there are shallow beach slopes of ~ 0.5%, each 1 m of settlement results in enlargement of the lake by 200 m, or by 400 m if there are beaches on both sides of a lake. Fetch and shoreline erosion become a design issue.

For deposits with perimeter dykes or ring dykes, the water must be kept out of geotechnical critical and buffer zones near the dyke crest (see CEMA 2014) if the dyke is to remain eligible for delicensing (OSTDC 2014) — a central goal of landform design for tailings deposits. This can be accomplished by building a narrow central swale with steep sloped ridges, as was done at Suncor Wapisiw Lookout/Pond 1 (Russell et al 2010). While the key is to have suitably high ridges, tailings likely to settle many metres are not strong enough to support high ridges (described below). As such, settlements of 2 to 4 m would seem to be a practical maximum for containing open water and keeping it outside of the geotechnical buffer zone. Suncor Wapisiw Lookout benefitted from a generous supply of hydraulically placed sand, fair foundation conditions in most areas, settlements largely limited to a few metres in small pockets, and a skilled and dedicated operations crew. Even with these advantages, the project was still challenging.

Geotechnical engineers recognize the inherent risk of perching open water high in the landscape behind a former dam that is scheduled to forego monitoring and maintenance at some time in the near future. The OSTDC (2014) document warns that ponded water must be minimized if a dam is to be delicensed. Even modest settlement is difficult to accommodate; excessive settlement precludes delicensing.

Excessive settlement is also a potential fatal flaw for fines-dominated deep deposits, not only for those contained by dykes but even for deposits with full geologic containment as ponding of open water affects the water balance as described in Section 5.

Adding to the risk is the uncertainty in prediction of settlements. A large-strain consolidation model, updated annually with the latest data, does a reasonable job of guiding short-range tailings planning in most cases. It is used successfully for long-range tailings planning, with only occasional surprises. The total amount of ultimate settlement should be simple to predict in theory, but the time for this settlement can only be estimated to within half an order of magnitude.

Uncertainty in predicting the ultimate settlement relates to some parametric uncertainty, variability in fines content, and density in the deposit (horizontal layering and zonation both have important impacts), the potential for lateral movement of solids (partial self-levelling) due to differential consolidation, changes to boundary conditions, and even in who does the modelling and what assumptions (explicit and implicit) are used. Predictions are enhanced with detailed characterization of the deposit, and close monitoring of post-depositional pore-water pressures and surface settlements. But these measurements can only be made once the deposit is at least partially in place. It may become necessary to design containment volume for almost no settlement, then design the cap and outlet to permit a few metres of settlement.

Even compacted in-pit dykes and waste dumps are expected to settle a few percent of their initial height (settlements of 1 m to 2 m are often predicted).

Beyond carefully designed terrace-and-finger ridges and narrow central wetlands, a variety of methods have been proposed to accommodate settlement. Table 4-6 summarizes these schemes and notes some of the risks and potential fatal flaws. In some cases, the concern will be for very high costs. Simple calculations expose fatal flaws for these schemes in most cases.

Deposits that are out of pit or in pit above original grade should be designed to have post-closure settlement of no more than two metres.

Table 4-6 Theoretical options proposed for managing long-term settlements

Scheme to accommodate soft tailings settlement	Risks, impacts, and fatal flaws
Accelerate consolidation with wick drains	Wick drains may blind off in fine grained deposits and become ineffective; costs are high (See Section 2.4.6)
Doming the deposit – placing a cap equal to the expected amount of settlement	Deposits with excessive settlement are weak, typically much too weak to support a thick cap. In addition, over-pressured tailings may fracture the cap and report to the surface or flow over the dyke crest.) Volumes to dome the deposit are large and can only be practically moved during active mining.
Building high ridges	Foundation conditions are unlikely to support high ridges. Operational shear strengths of more than 25 kPa are needed even to support modest ridges.
Waiting for consolidation and topping up the deposit (or the cap) over time	Large settlements typically take centuries to manifest, making timelines impractical. Reclamation needs to be stripped and replaced prior to topping up, disrupting ecosystems. The volumes to top up are large, necessitating mining a reclaimed dump nearly as large as the pond being topped up. Topping up would need to occur beyond the period of active mining, greatly increasing costs.
Managed drainage outlets – construct the outlets from tailings facilities to be lowered with time	For deposits with geologic containment, the amount the outlet can be lowered is a function of downstream water elevations (for instance, in the pit lake). The outlet channel would need to be deep and therefore costly unless achieved by mining oil sand. For deposits with containment dykes, an upstream cofferdam would need to be constructed (difficult unless there is solid ground previously constructed upstream of the outlet), and the cost to lower the outlet would be tens of millions of dollars and perhaps be required several times as consolidation progressed. Initial sketches suggest this alternative is impractical for most cases. There may be a reasonable way to reduce the outlet elevation once with planned-in-advance innovated engineering.
Allow erosion from the reclaimed landscape to top up settlement	Would require unacceptable amounts of erosion even if this were a remotely possible scheme.
Peat accumulation will make up for settlement	Likely only effective at the end of consolidation near the perimeter of wetlands. Typical peat accumulation rates in the boreal peatlands (where the water table is near the surface) are 30 to 100 mm per century (Bauer et al 2003; Korhola et al 1995).
Ensure large watershed to open water ratio	May be practical for small lakes and wetlands.
Manage dykes and water supply (pump in fresh water) actively	Practical and cost-effective but would require high levels of ongoing monitoring and maintenance (actually operation).
Select tailings technologies with very low settlement for terrestrial areas and wetlands; select water capping for high settlement deposits	A focus of this report.

Methods to avoid excessive settlement:

- Ensure that settlement of the deposit is complete within a decade or two (this requires tailings with enhanced permeability).
- Deposit at the final solids content (create track-packable tailings).
- Keep soft tailings deposits thinner than a few metres to allow rapid consolidation.

None of these options is compatible with present tailings technologies, apart from on-spec CT (which has high permeability) or poldered soft tailings (although more efficient drainage than is currently offered by low-permeability dump containment may be required).

Figure 4-6 provides some insight into densities, strengths, and hydraulic conductivities required for tailings to avoid excessive settlement.

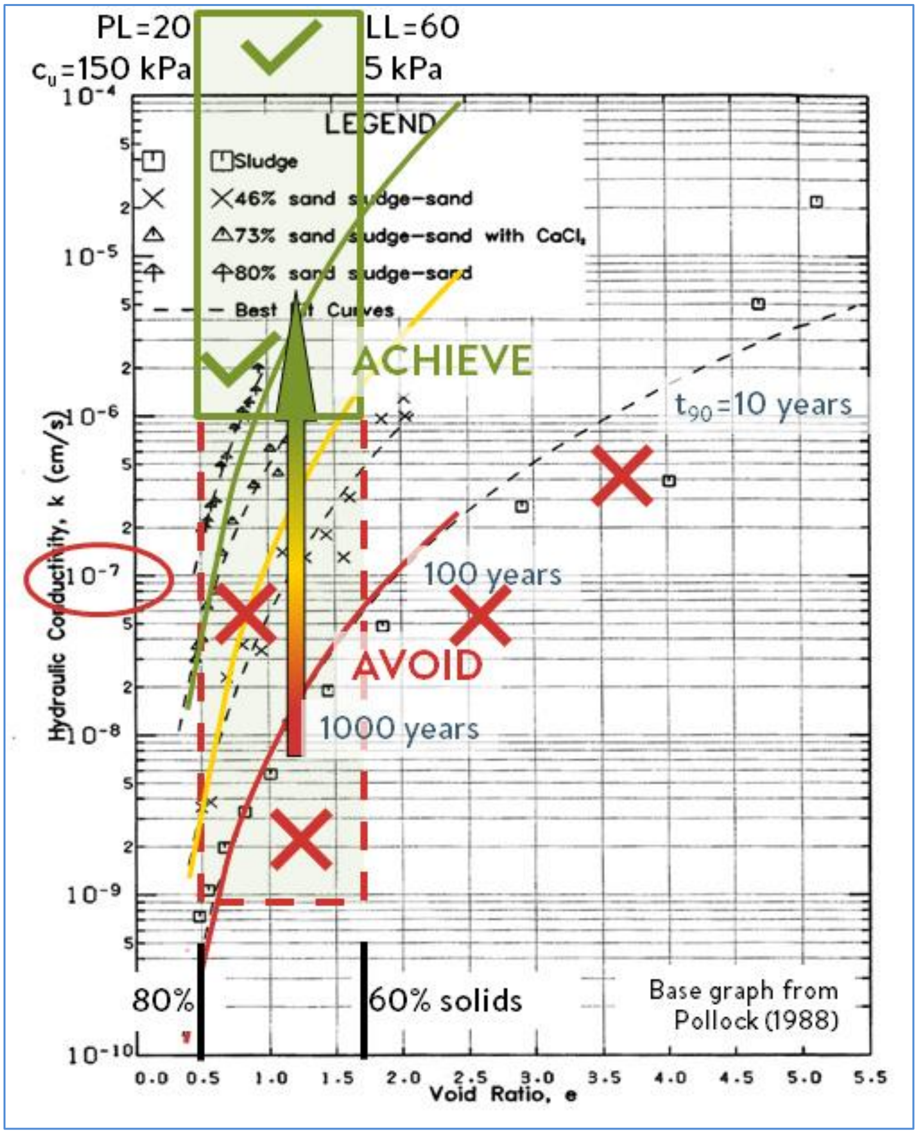


Figure 4-6 Target for tailings consolidation properties

Most of the current work in oil sands tailings is focussed on materials in the zones with the red Xs. As discussed above, these slurries are weak and prone to excessive settlements over extended time frames. A move from the red zone into the green zone might be accomplished by changing the chemistry and behaviour of the clays. As a point of reference, landfill liners are typically designed to have hydraulic conductivities of less than 10^{-7} cm/s (USEPA 1993) – this is the criterion used to *impede* the movement of water. Dewatered MFT deposits may have hydraulic conductivities of 2 orders of magnitude *less* than this criterion. Oil sands tailings designed to dewater should have at least two orders of magnitude higher permeability to meet useful consolidation and strength-gain timeframes.

4.8 Discharging and depositing tailings

There are numerous ways to discharge and deposit tailings (see Table 4-3). Part of the design process is to select the best combination. Most oil sands tailings are discharged subaerially from open pipes and form a subaerial beach that flows into a pond to form a subaqueous (and sub-MFT beach). Subaerial deposition of soft tailings, by allowing for removal of off-spec segregated fines, typically results in better deposits than subaqueous ones, but makes access for drilling more difficult. Additional information on deposition is presented in Section 3.4.

Tailings types prone to segregation (such as CT and TT) or shear straining (such as TT or ILTT) often require specialized discharge and deposition techniques to ensure low-energy deposition to avoid excessive off-spec tailings.

Some off-spec tailings will be generated by any process, requiring a dredging system at the distal end of the deposit to remove fluid including off-spec materials for re-deposition and/or reprocessing. Close monitoring of the process (minute by minute), discharge (hourly), deposition (daily), and the performance of the deposit (monthly to annually) are essential components of an adaptive management program. Thin-lift deposition requires nearly constant visual control.

4.9 Stabilizing and capping of tailings deposits

4.9.1 Tailings stabilization

Deposits require stabilization prior to capping. Table 4-3 provides a list of options. In some cases, only the top surface needs to be stabilized, for which there are several options. Increasing the strength of the top surface can help reduce erosion during hydraulic capping and may improve soft-ground capping techniques (see the following section) but does little to provide geotechnical stability for thick caps or ridges. Deep tailings stabilization is often costly and needs to be balanced against the cost of simply dredging, reprocessing, and redepositing the tailings. All aspects of tailings (containment, discharge, deposition, stabilization, capping, reclamation, and decommissioning) need to be planned in advance of deposition with reasonable complementary technologies selected, and with contingencies for when deposits differ from design.

4.9.2 Capping technologies

Due to their low densities and correspondingly low strengths, most oil sands soft tailings are uncappable (except with water or coke), failing one of the major goals for such deposits. Figure 4-7 illustrates the six methods used to cap soft tailings (from McKenna et al 2016). Figure 4-8 shows available public data relating the shear strength and density of oil sands tailings (the dashed lines indicate the general envelope, the mauve colored lines are based on sensitive natural clays with Atterberg limits similar to MFT (Houston & Mitchell 1969) suggesting that MFT is perhaps not that special with respect to strength behavior at low density. Figure 4-9 shows the minimum required densities and strengths required for each capping technology (though the lines continue to move with each new capping experience).

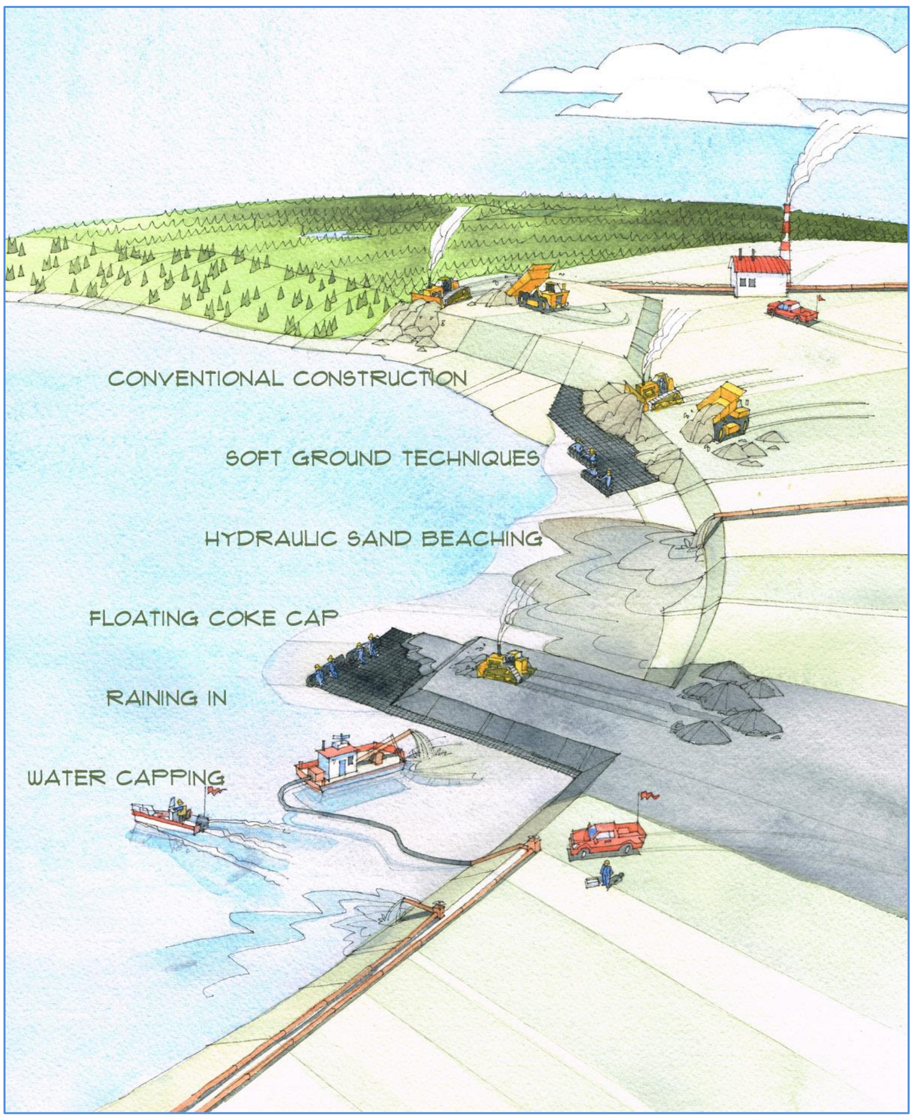


Figure 4-7 Six-pack of tailings capping techniques

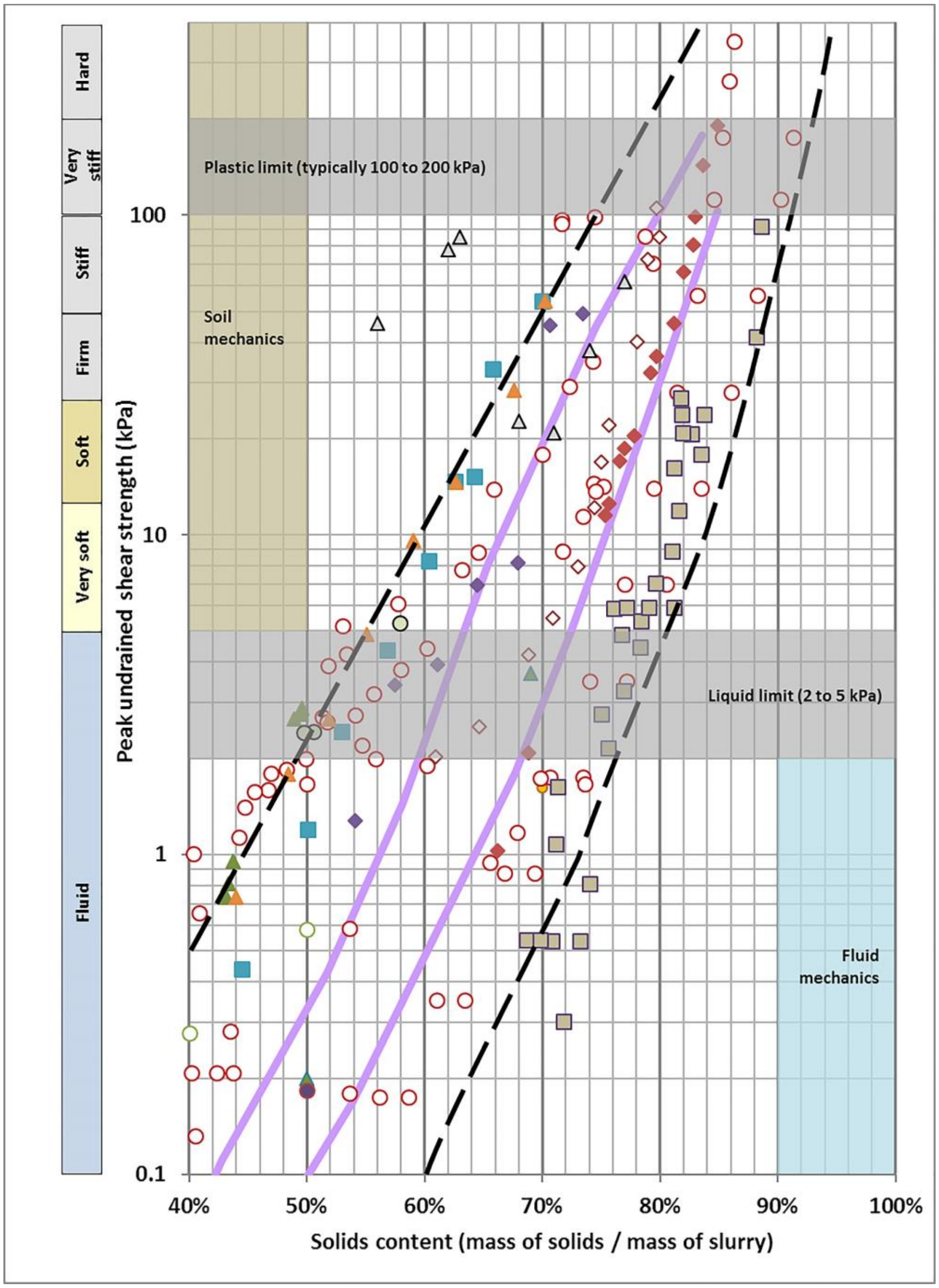


Figure 4-8 Oil sands tailings strength / density relationships (see McKenna et al 2016 for details and the legend for lines and data symbols)

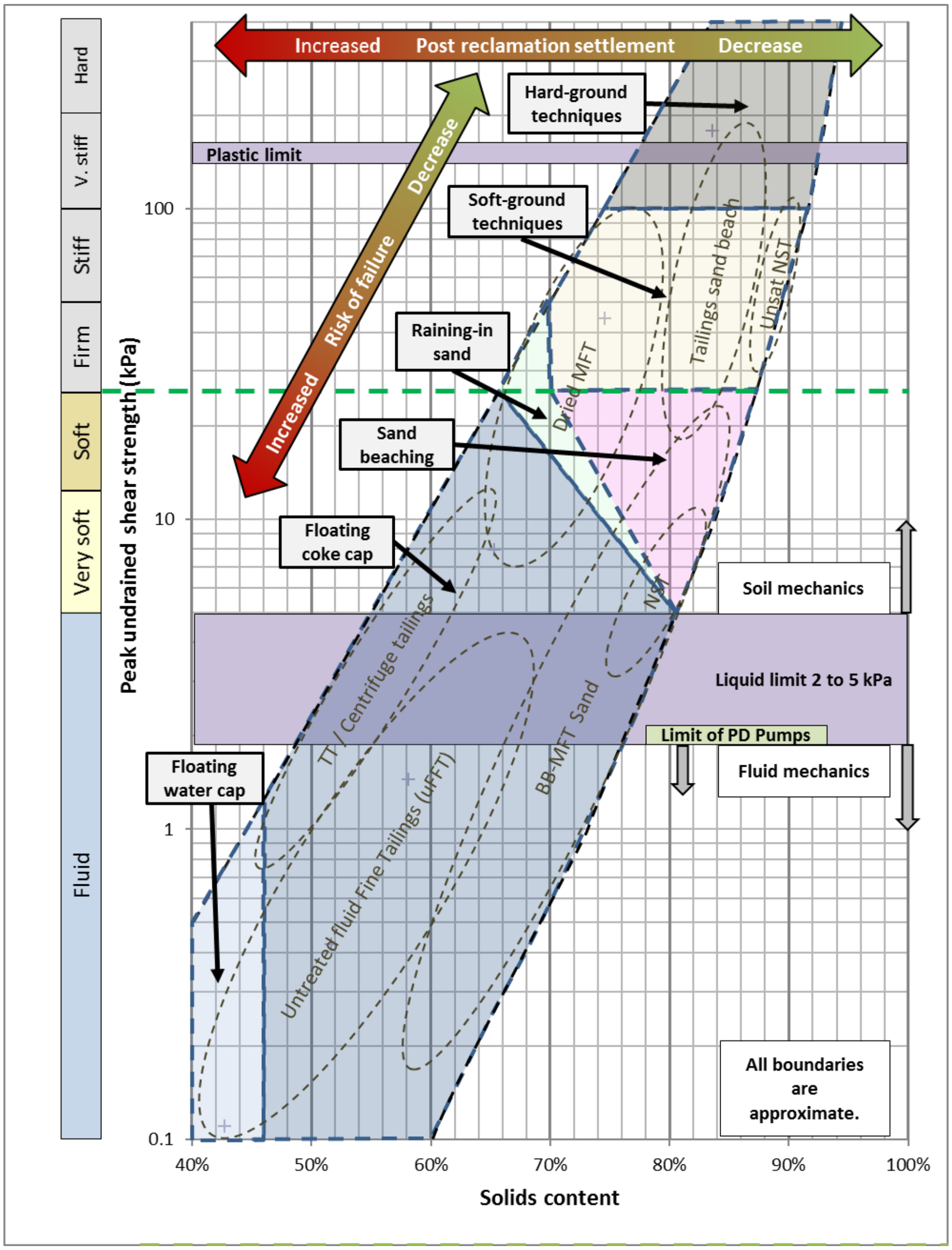


Figure 4-9 Estimated requirements for various types of capping for oil sands tailings

Several lessons can be learned from Figures 4-8 and 4-9:

- Shear strength is a function of the tailings density, albeit with considerable scatter, partly due to variations in chemistry and suctions in the tailings and partly due to inherent measurement errors.
- The strength at a given density can be increased with additives. In extreme cases, a cement additive can push the tailings strength off the top of the chart.

- Water capping and coke capping work because the cap floats on the soft tailings.
- Empirically and analytically, a combination of enough strength and enough density is required to reliably cap soft tailings.
- The sensitivity of oil sands tailings is often overlooked — peak strengths in excess of 25 kPa may be required just to manage deformations and avoid strains that can cause the tailings to lose most of their strength, as is often seen in the field. The magnitude of post-reclamation settlement also decreases with increased initial density.

Figure 4-10 provides another snapshot of various tailings, assessing various capping methods included in the final columns. Green shading indicates that the tailings generally meet the criteria, red indicates that it does not, and yellow indicates an intermediate condition that may be solvable with technical effort and investment or that different deposits show different behaviour.

Issues & hazards	Ease of operation	Potentially mobile material	Fines density storage	Trafficability	Support topo relief	Settlement	Pore-water quality	Erodibility	Water cap?	Coke cap?	Sand cap?
Untreated MFT				X	X					X	X
Centrifuge MFT											
Thickened tailings											
Dried MFT						?					
Composite tailings											
Beach below MFT						?					
Froth treatment tailings		?		?	?	?		?	?		?
Tailings sand		?								X	X

Figure 4-10 Tentative scoring of issues and hazards related to various tailings technologies

4.9.3 Depositing the tailings cap

Leaving a roughly planar cap over low-permeability tailings invites water logging and salinization of the soil cap yet to be placed. It also allows ponded water to accumulate near the dyke crest in large shallow ponds (violating the geotechnical-critical and buffer zones important to dyke stability and delicensing). The water needs to be deflected away from the crest, toward wetlands, and separation must be created between the water table and the rooting zone of upland forest communities. To this end, ridge-and-swale topography is needed above the tailings blanket cap.

A cover composed of granular tailings (sand cap) is typically required on soft tailings deposits to provide improved safety and trafficability, and to allow unimpeded drainage of upwardly mobile consolidation waters. This cover is usually deposited using hydraulic sand capping, but a floating coke cap or soft ground techniques over large areas can be used, albeit at greater cost. The cover should provide enough relief to prevent the phreatic surface of the ground water from contaminating surface reclamation soils, forcing groundwater to discharge over a relatively small area in swales that serve as surface drainage courses. Modelling has shown the need for variable topography (5 m relief from top of ridges to bottom of swales) with cover material thicknesses varying from 2 m to 7 m.

These ridges are typically at least 4 m high. Simple limit equilibrium slope stability analysis (Taylor 1937) suggests that about 25 kPa of operational strength is needed to support even these low ridges (Figure 4-11), or else the ridges simply sink. Ridge slope failures during construction on soft tailings are common. These strengths are more than an order of magnitude greater than the peak strengths provided by many tailings technologies.

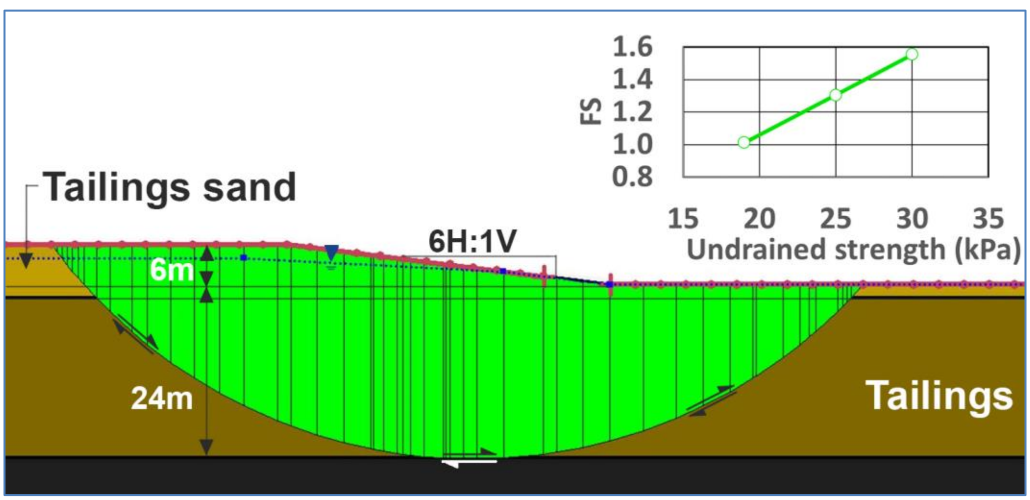


Figure 4-11 Required shear strength to support modest ridges on soft tailings

4.9.4 Adopting track-packable tailings

Fluid and soft tailings don't have the strength to support caps, and even if they did, they cannot support swales and will settle too much. Track-packable tailings (or unsaturated tailings with a firm to stiff consistency sometimes referred to as drystack tailings) have several benefits:

- The fines density (mass of fines per cubic metre of tailings) for track-packable tailings is relatively high, minimizing tailings sprawl (e.g., CCA 2015).
- Track-packable tailings do not require licensed dykes for containment. Using shell specifications (or building overburden shells akin to normal waste dumps in the region) would create a stable and easy-to-reclaim structure. The dump would still be subject to the "abandonment" regulatory process (AER 2019b), which is often less onerous than dam delicensing.
- Track-packable tailings are strong enough to support efficient capping and reclamation. They should be possible to cap using methods associated with overburden dumps and frost to support medium-sized mining trucks and dozers. Or they can be encapsulated in a shell atop overburden, as noted above.
- There is little seepage from the deposit; it has little impact on water quality.
- Settlements will likely be slightly higher than dykes and dumps, but this is easily managed with surface topography, using "horseshoe" berms common in overburden dumps to control surface water, even with expected minor surface settlement.
- Track-packable tailings are also suitable for water capping. An overburden cover could be placed, further isolating the tailings from the water column.

Track-packable tailings produced by fines-drying methods are costly to produce and transport and are likely to generate considerable greenhouse gases. However, the net energy budget may be lower, given the ease of reclamation. To address such questions, a full mine and tailings plan and would need to be developed and assessed. The comparison base case would also need to meet the design basis. The use of track-packable tailings has already been demonstrated commercially as part of dried MFT with landfarming. Filter technology, perhaps with some additional drying, would also likely produce acceptable track-packable tailings. Trucking or conveyors would be used to transport tailings to the disposal site. A road network would be needed for the trucks using procedures already developed for weak zones in overburden dumps.

Track-packable tailings (Figure 3-12) can be created using various technologies including thermal drying, cement-amended tailings, thin-lift drying with landfarming, filtered tailings, and co-mixing and co-disposal with overburden. It seems likely that a staged process will be needed and that for some suites of technologies, thermal drying may be required to desaturate the materials before placement.

The cost and energy intensity to produce track-packable tailings by these methods may be higher than other methods but will be required to meet the goals and objectives in the design basis for all tailings deposits destined for terrestrial reclamation. Research and development efforts should focus on suitable technologies and strategies to reduce cost and energy while attaining the performance properties.

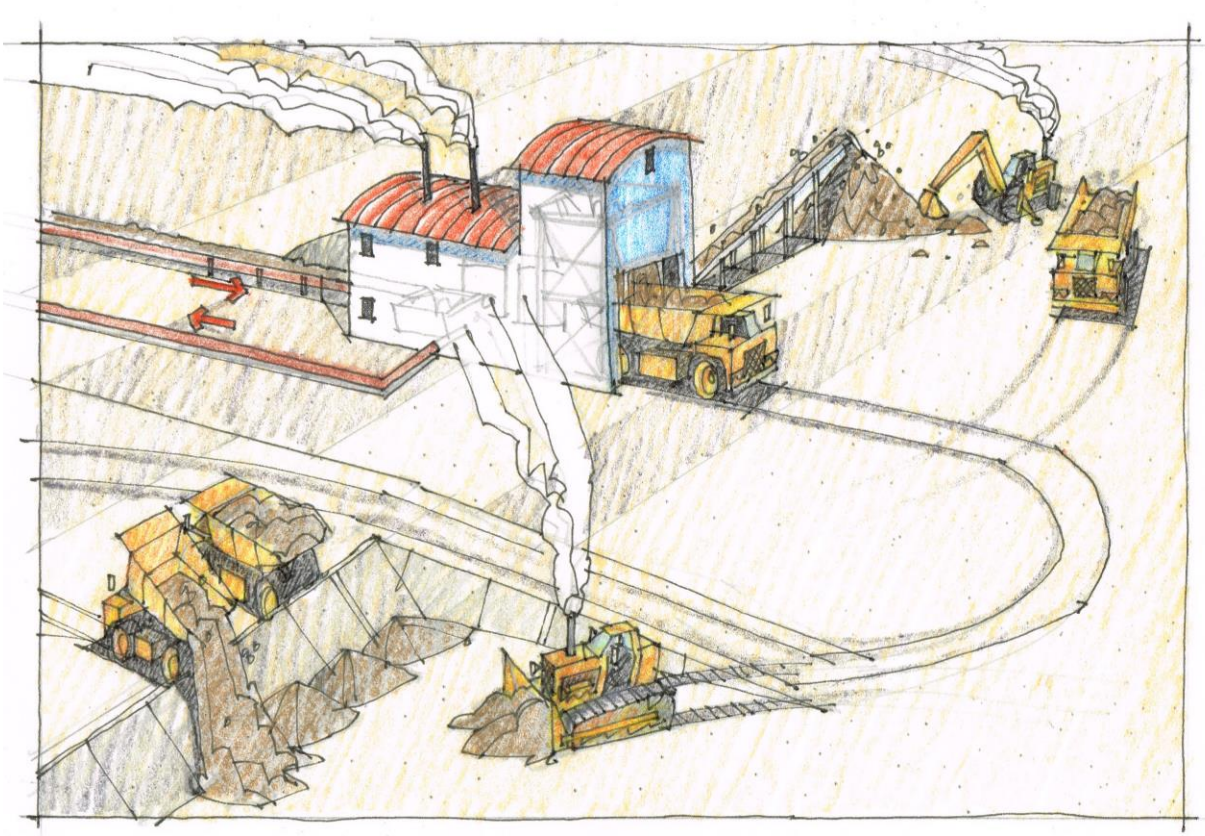


Figure 4-12 Track-packable tailings

4.9.5 Reclaiming the tailings landform

Reclamation of a capped tailings deposit (such as CT) with ridge-and-swale topography has been demonstrated by Syncrude and Suncor and has proven to be reasonably straightforward to implement. Upland reclamation (on the ridges) is a mature technology (RSC 2010; CEMA 2006) but continued commercialization efforts are needed for fen-and-marsh construction in the swales (BGC 2010; CEMA 2014; Kessel 2016), including adherence to limits for minimal post-closure settlement.

4.10 The importance of adaptive management

It has long been recognized tailings do not necessarily perform the same in the field as in the lab. The scale-up process is often fraught with failure (McKenna et al 2011; CTMC 2012) and the performance of a complex tailings management system is never entirely predictable. The traditional adaptive management process is often offered as a method to ensure that the deposits meet their design bases. Too often in practice, this approach has more in common with conventional trial-and-error (CEMA 2014; Walters 2007).

An effective adaptive management program begins with establishing the design team and governance, a familiar task at most mines. Creating a design basis that spells out what will be achieved, designing the deposit, assessing risks, and — crucially — developing real and detailed contingencies to manage all these risks, are the more challenging steps. The overall goal is to construct, cap and reclaim the landform while monitoring performance and implementing contingencies as needed in a timely manner.

This is the approach used for the design and construction of oil sands tailings dams. Often referred to as Peck's (1969) geotechnical observational method, it needs to be extended from containment dams to entire deposits. The required work is formidable, but tens of billions of dollars have been allocated for tailings management in the coming decades, and many billions more will be needed if rework is required. To be successful, industry, regulators and local communities must work together within a framework of effective adaptive management.

4.11 Landform design lessons learned

Following are lessons learned from landform design for tailings deposits over the past 20 years (some would say 50 years). There have been few pleasant surprises:

- Oil sands tailings technology has advanced in many ways over the past 50 years, with a focus on predicting consolidation and the strength gain of hydraulically deposited tailings slurries. Many new technologies have been developed and commercialized, but only a few have been successful.
- Life-of-mine plans, environmental impact assessments, and closure plans have been used to look ahead to a reclaimed landscape comprising numerous large tailings deposits, but they often have missed fatal flaws to achieving those end states. Most were too optimistic, and all suffered from an insufficiently detailed design basis. The geotechnical community needs to be clear on the tailings properties needed for landforms and landscapes to meet the goals of

mining companies and society. Every deposit will be different, but they all need a good design, good construction, and good monitoring.

- What is needed?
  - Hydraulic conductivity > 10^{-6} cm/s; full settlement in 20 years
  - Easy to cap and reclaim deposit
    - Track-packable
    - Operational undrained shear strength > 25kPa
    - Able to be capped with hydraulic sand placement
    - Support for ridges
  - Easy to delicense dykes
  - Post-reclamation settlement < 0.5 to 4 m (depending)
  - Open-water < 10% of watershed
  - Acceptable drainage water quality.
- Water capping of dense treated tailings can meet the goals (the topic of the next section).
- For terrestrial land uses, the clay-dominant tailings need to be deposited at close to their final density and unsaturated. They need to be track-packable with mining dozers, supplied by conveyors or mid-sized mining trucks. Mines appear to be moving to such dry-stack tailings internationally, mainly to reduce the risks of dam breach and reclamation liability more generally.
- A staged process to create track-packable clay-dominant tailings is likely required — centrifuging or thickening followed by filtration or to increase the density, followed by atmospheric drying or thermal heating to reduce the water content to the point of desaturation so the tailings can be handled like overburden.
- CT provides a reasonable alternative that still allows a slurry delivery system. What is needed is a more robust product made of higher fines and higher densities, one that captures more fines, more reliably and more robustly (super-CT (CTMC 2012)).

Use of processes that deliver material properties required for the target landforms, combined with a sound closure plan, an effective management program, and a dedicated team, will create truly sustainable landscapes.

5 Water issues in the mine closure landscape

This section builds on the tailings technologies described in Section 3 and the geotechnical performance of soft and dry-stack tailings discussed in Section 4. The purpose of this section is to describe and compare the hydrologic and water quality impacts of several types of tailings management technologies on future lease closure environments. This section discusses the very serious impacts of deep deposits of fine tailings unless they are sequestered below grade beneath a water cap.

The hydrologic processes of natural and reclaimed mine disturbed areas are comparable and are illustrated on Figure 5-1. A unique condition that distinguishes the hydrology of mine disturbed areas from that of natural terrain is the occurrence and conveyance of tailings pore water (oil sands process affected water; OSPW) from deposited tailings. OSPW is conveyed to the surrounding environment beyond lease boundaries both by surface water flows and ground water seepage.

This section begins with a discussion of the significant effects of water in the mine closure environment with explanation of how these effects are strongly related to tailings treatment, disposal and reclamation technologies. This section explains the main sources of OSPW in the mine closure area and how OSPW is conveyed within the mine disturbed area to off-lease areas. Based on an understanding of the occurrence and conveyance of OSPW in the mine closure environment, this section goes on to discuss the sustainability of pit lakes and the benefit of disposal of treated fine tailings in a pit with a water cap. This section also describes the serious impacts of treated or untreated fluid fine tailings contained in areas designated for terrestrial reclamation. There are serious risks of fluid fine tailings contained above original ground level behind dams or below ground level beneath an elevated area designated for terrestrial reclamation. The serious impacts of deep deposits of FFT beneath a terrestrial environment include large differential settlement, unstable drainage courses, upward flux of OSPW, OSPW discharges to surface drainage courses, surface erosion resulting from differential settlement, and increasing depths and areas of wetlands and lakes that will likely become saline. This section ends with a discussion of water releases to the environment (that sooner is better than later), management of the closure landscape and lessons learned over the past 50 years during which operators, regulators and stakeholders did not account for full life-cycle implications of some proposals and approvals.

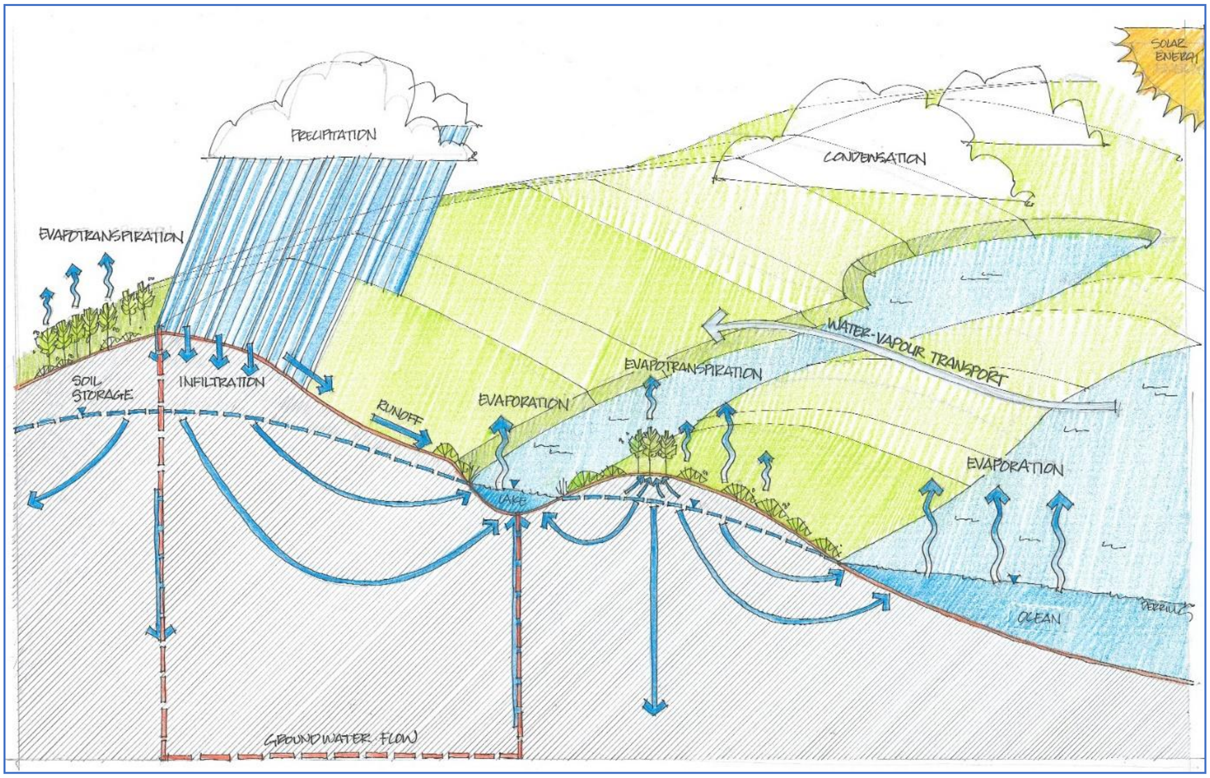


Figure 5-1 Water in the landscape (from CEMA 2012)

5.1 Hydrologic and water quality effects of tailings technologies

The occurrence, quantity, and quality of water are fundamental to understanding the sustainability of planned terrestrial and aquatic mine closure environments resulting from current tailings technologies recently proposed by industry and approved by government (AER). Water is a principal medium through which tailings treatment technologies and deposition methods affect the environment. The significant effects of the occurrence, quantity and quality of surface water and ground water on the mine closure environment are governed by tailings technologies that include fluid fine tailings treatment, deposition methods and reclamation systems.

Details of the quality of OSPW and discharges from tailings deposits are readily available (see Verbeek et al 1993; Allen 2008a, 2008b; Miskimmin et al 2010; Mahaffey and Dubé 2017; Li et al 2017; Holden et al 2011a, 2011b). Table 4-5 provides some typical water quality values. Without treatment (typically by residence time in the pit lake or active water treatment), OSPW is toxic to aquatic life and may have sublethal effects on wildlife and waterfowl (Beck et al 2015) mainly because of organic compounds such as naphthenic acids. In addition to organic acids that are responsible for most of the OSPW toxicity, tailings process water contains elevated levels of ions that would require dilution before direct discharge to the environment.

5.2 Sources of OSPW in the closure landscape

Natural boreal surface hydrology depicted in Figure 5-1 is dominated by precipitation (rain and snow), infiltration, recharge of the groundwater table, deep seepage, interflow, surface runoff, streamflow and various forms of water storage in surface soils, floodplains, wetlands and lakes (see Devito et al 2012). These hydrologic processes result in typical landscape in the oil sands region as shown in Figure 5-2.

Figure 5-2 The water-dominated landscape of the boreal forest in the oil sands region

Unlike natural terrain, surface hydrology of mine-closure landforms will be affected by elevated levels of salinity and organic compounds derived from OSPW. Process-affected water occurs in all areas where tailings sand, treated fluid tailings and untreated fluid tailings are deposited because these materials are conveyed to deposition sites in pipelines with OSPW used as the medium for slurry transport.

Volumes of OSPW in the closure environment are large, in the order of 1 billion cubic metres at each mine upon closure. Initially, the rate of OSPW discharge to the environment will be significant (as much as 50% may drain in the first millennium after mine closure) as a result of gravity drainage of above-ground sand tailings deposits and consolidation of treated FFT deposits. Eventually, in the extremely long term, all tailings OSPW from tailings sand and treated FFT will discharge to the environment although pore water from in-pit deposits of tailings sand and consolidated FFT will be released to the environment over geologic time frames.

The quantity of OSPW discharging to surface water courses varies depending on the selected suite of tailings technologies. The impact of the various types of tailings technologies must be assessed based on an understanding of the principal sources of OSPW in the mine closure environment that are itemized below:

- **Ponded tailings transport water that has not been recycled for processing during mine operation.** This includes small ponds containing tailings process-affected water as well as pit lakes where tailings process-affected water collects at the terminus of the mine closure drainage system.
- **Porewater of treated fluid fine tailings (FFT).** The voids of treated FFT are composed mainly of OSPW because process water was used to transport these materials. A portion of this porewater discharges from treated FFT during the consolidation. Most of the excess porewater during the initial stages of consolidation seeps upward. Following releases to surface from consolidation (over many decades, centuries, possibly more than a millennium), seepage will eventually follow a lateral and downward flow path, discharging directly to the environment very slowly over geologic time frames (Ferguson et al 2009). This source of OSPW can be significantly reduced by selecting technologies that densify the FFT and sequester the densified FFT beneath a water cap in a pit lake.
- **Porewater of sand tailings deposits.** This is the largest quantity of OSPW that exists on each mine site upon mine closure, because of the large volume of tailings sand derived from processing the oil sand ore. The voids of the resulting tailings sand deposits are initially filled with process water because tailings from the bitumen extraction process is transported and deposited at tailings disposal areas by a slurry pipeline comprising tailings sand and OSPW. The amount of OSPW in voids of deposited sand tailings is about three times greater than the quantity of pore water associated with treated FFT. Initially, the rate of discharge to the environment is relatively rapid as a result of gravity drainage at above-ground tailings sands deposits. The rate of discharge to the environment is significantly reduced after above-ground deposits of tailings sand have drained. The release rate of OSPW is much lower for sand tailings that are deposited in-pit below original ground.
- **Residual process water in voids of unsaturated tailings sand.** After partial drain-down of saturated tailings sand, the voids of unsaturated tailings

material contain residual process water that is flushed out by repeated cycles of wetting from precipitation and infiltration. Cycles of wetting by such meteoric water result in flushing and dilution of process water in the voids of unsaturated tailings sand. Tailings sand deposits will continue contributing OSPW to the environment by this process long after initial drain-down.

The composition of OSPW is the product of choices made by operators and regulators in terms of which areas of the orebody are mined (different areas have different chemistries – particularly salinity), the amount of recycling versus fresh water import, the choices of process aids for extraction of bitumen, the choices of tailings amendments and the choices of tailings treatment and deposition techniques. For new operations, there are more choices. For existing tailings deposits, the OSPW chemistry of the day is largely locked into the porewater.

The composition of OSPW is the product of many factors related to the ore body and processing systems. However, the foremost consideration is the salinity of the OSPW at mine closure – predominantly a function of the oil sand salinity in the ore body, the amount of recycling versus fresh-water import, and the quantity of OSPW discharge to the environment during mine operation.

5.3 Conveyance pathways of OSPW

The effects of tailings treatment technologies and deposition methods need to be assessed based on an understanding of the transport mechanisms and pathways by which OSPW is released to the environment. Transport mechanisms and pathways are highly complex and have been investigated extensively by discipline specialists (Ferguson et al 2009; Holden et al 2011, 2013; Abolfazlzadehdoshanbehbazari et al 2013; Kessel 2016; Roy et al 2016; Vessey et al 2019). The following key findings can be gleaned from these studies:

- Water flow through tailings deposits is highly complex, owing to the heterogeneous nature of the tailings deposit created by variable deposition and consolidation patterns over time (Ferguson et al 2009).
- Most of the OSPW resulting from consolidation of treated fluid tailings seeps upward to the surface.
- The dominant pathway for OSPW in the initial mine closure landscape involves flow to a pit lake. This includes OSPW transferred from residual ponds at the end of mining, drain-down of saturated tailings sand deposits, flushing of unsaturated tailings sand deposits, and consolidation of fine tailings and treated FFT deposits. This observation may be surprising to

non-specialists but there is little doubt among specialists in hydrogeology and geotechnical engineering that, upon mine closure, most OSPW (mainly tailings pore water) flows to a pit lake. Direct seepage and surface flow to the environment (without passage through a pit lake) represents a very small portion of the total OSPW in the mine-closure landscape.

- Non-uniform terrain (topography composed of ridges/hummocks and swales) is needed in the mine closure landform to concentrate ground water discharges that contain OSPW and to channel the resulting surface water runoff to the pit lake. The technique for concentrating OSPW discharges to the surface is discussed later in this paper.

Several conclusions can be drawn from these findings. First, the quality of surface flows at terrestrial reclaimed areas upstream of a pit lake must be assessed to determine if the predicted water quality is harmful to aquatic organisms, other wildlife, and aquatic vegetation. Like most mine reclamation projects, oil sands mines will likely require a period of active management until the on-site waters are non-toxic. Second, OSPW flowing in small drainage courses and major streams in terrestrial reclaimed areas will need to be treated (either actively or passively) before discharge to the environment. Third, OSPW flowing to a pit lake is an essential feature of closure plans because the pit lake is known to provide aerobic degradation of naphthenic acids contained in OSPW (Han et al 2009; CEMA 2012; Scott et al 2005).

5.4 Sustainability of pit lakes

5.4.1 The need for pit lakes in closure landscapes to treat OSPW inflows

Pit lakes are integral to oil sands mine closure plans, as they are to open-pit mines. They are present in the closure landscape for several reasons.

First, the last mined-out pit becomes an end-pit lake, either by natural infilling from groundwater and surface water (an extremely long process) or by intentional filling to form a productive aquatic habitat. A pit lake at the end of mining can only be avoided if the end pit is filled with mined out material. However, such an operation at the close of mining would ravage the area, undoing much prior progressive reclamation. The cost would be enormous, and the process would have large adverse environmental effects.

Second, a pit lake is required in the closure landscape to intercept OSPW emanating from deposits of tailings sand and treated FFT, so that the OSPW will have the required residence time to be passively treated by aerobic degradation of organic compounds. The residence times provided in a pit lake for process water treatment typically exceed 10 years (for a 10 m deep lake whose drainage area is 10 times the lake area). The minimum residence time required to treat the organic compounds in a typical mine closure plan is believed to be approximately one year to remove acute toxicity and 10 years to remove residual chronic toxicity (CEMA 2012). The required time frame is site-specific and must be determined for each lake. Accordingly, a predictive water quality model has been developed that incorporates all relevant tailings processes as described in Prakash et al (2015) and Vandenberg et al (2015).

Third, pit lakes are used to settle out suspended solids and associated particulate metals and nutrients that will be produced by the reclaimed landscape if not mitigated. Such beneficial interception and trapping of sediment in other mine pit lakes is well documented in the literature (Vandenberg and Litke 2018).

Fourth, runoff from a newly reclaimed mine during spring freshet and after high precipitation events is likely to be prone to sudden peaks in both discharge rate and concentrations of contaminants compared to natural areas. Until mature vegetation has been established, a large water body such as a pit lake is required to moderate such peaks and avoid adverse environmental effects to downstream water courses.

Three key issues pertaining to pit lakes must be addressed in any closure plan: hydrologic sustainability, the water quality of lake outflows (and the long-term water quality of the pit lake itself), and the presence of fluid tailings beneath a water cap of the pit lake. These issues are addressed below.

5.4.2 Hydrologic sustainability of pit lakes

The key question regarding hydrologic sustainability is: will inflows from rainfall and runoff from the drainage area be sufficient to maintain the lake as a productive aquatic system with sustained annual discharges to an outlet channel, without excessive lake level drawdown and with suitable flushing to prevent salinization? To answer this question, industry research teams have modelled lake water balances over long periods of the climate record. They have also investigated analogue drainage areas of natural lakes in Northern Alberta to determine common characteristics of sustainable lakes. The modelling approach has merit where models can be calibrated by recorded precipitation, evaporation, and catchment runoff. The analogue drainage approach suffers from an absence of drainage areas in northern Alberta that provide an accurate replication of mine disturbed oil sands mine areas (where the drainage area is composed of mature, reclaimed, mine-disturbed areas, including oil sands tailings deposits).

The authors encourage the use of natural analogues of non-mine areas, not to serve as a firm criterion, but to provide guidance. The guidance based on natural analogues is based on lakes in Northern Alberta with a small ratio of drainage area to lake area. Of the many non-saline lakes in the oil sands region, all have ratios of drainage-to-lake area exceeding 6.7. The minimum ratio occurs at McClelland Lake, which is located within the oil sands mine region. Historical air photos show that McClelland Lake was half full (under significant stress) during the early 1950s, following a prolonged period of dry years in Northern Alberta. It seems that a drainage-to-lake area ratio of 6.7 as in the case of McClelland Lake may present a lower limit for natural lakes and drainage areas. This ratio does not apply to the oil sands industry because the mine closure landscape conveys OSPW to the end-pit lake. Unless the disturbed area can be shown to provide higher water yields than the drainage area of McClelland Lake (which is composed of sand hills and wetlands) this ratio serves as a lower limit, depending on the amount of OSPW entering the pit lake. Considering the potential effects of climate change and the saline inflows of OSPW from reclaimed mine areas, the authors recommend a minimum ratio of 10 for planning purposes. Modelling of climate change and inflows of saline water resulting from drainage of reclaimed mine tailings deposition areas may show the need for a higher ratio of drainage area to lake area for some sites (see Figure 5-3).

Some mine plans recently submitted to the AER propose large lake areas with relatively small drainage areas with a drainage area to lake area ratio that is less than 10. These may prove to be unsustainable as fresh-water lakes, due to high salinity in the end pit lake. Taking account of future enlargement of lakes caused by differential settlement, as discussed earlier in Section 4, inflows of salts from OSPW and possible future dryer climate cycles, hydrologic sustainability may be unachievable for some currently planned pit lakes that have been recently submitted to AER.

It is not too late to change this outcome but mine closure planners will need to alter their mine closure plans.

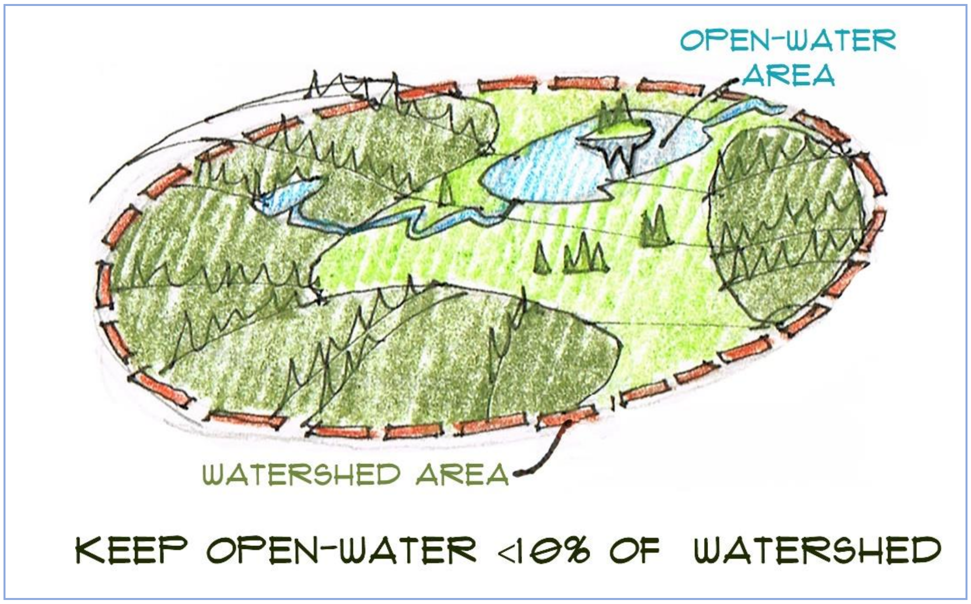


Figure 5-3 Open water to watershed ratio for sustainability in the oil sands region

5.4.3 Initial pit lake outflow water quality

Pit lake water quality has been investigated extensively as part of pilot-scale experimentation, supporting studies of Base Mine Lake sustainability, modelling studies for mine closure planning, and for Environmental Impact Assessments. The conclusion is that pit lake water and pit lake discharges of properly designed pit lakes will not be toxic to aquatic species, wildlife, or waterfowl after an initial period of natural detoxification (CEMA 2012). This positive outcome results from degradation of organic compounds by residence time in the pit lake. The studies also show that without site-specific planning and design, prediction and adaptive management (involving dilution), levels of organic acids and salinity could exceed aquatic life and drinking water guidelines.

Some operators propose to dilute pit lake outflows until organic acids and salinity meet regulatory criteria. Accordingly, water quality of pit lakes and pit-lake discharges are expected to meet targets that may be set by government regulation, depending on management of pit lake discharges and importing water from the Athabasca River and other sources. Water quality criteria have not yet been developed or adopted by regulators, although a set of criteria have been proposed for their consideration (Vandenberg, submitted to Mine Water and the Environment December 2018). Pit-lake water quality criteria have been proposed for the following constituents: dissolved oxygen; total suspended solids; pH; total molybdenum, nickel and vanadium; acute and chronic toxicity; and oil and grease.

In addition to water treatment, tailings management strategies can be used to reduce rates of OSPW inflows and/or concentrations of process water in a pit lake as follows:

- Producing fully consolidated treated fluid tailings material for deposition at terrestrial areas to avoid excessive settlement after mine closure.
- Delaying commissioning of a pit lake until the initial rapid rate of consolidation of treated fluid tailings material, is over.
- Covering deposited sand tailings with sufficient reclamation soil to enable lush vegetation that increases evaporation and reduces deep percolation, thereby reducing flushing of underlying sand tailings deposits.
- Configuring a mine closure drainage system that increases catchment runoff to the pit lake.
- Placing relatively dense treated fine tailings beneath a water cap in the pit lake so that self-weight consolidation is extremely slow following placement of the water cap.

The latter measure for improving the water quality of the pit lake is superior to other measures because it has the potential to offer minimum flows of OSPW into the pit lake while reducing deposition of treated FFT at terrestrial landforms.

5.4.4 Long-term pit lake water quality

While the goals of the initial stage of pit lake development are to provide attenuation and detoxification of OSPW and OSPM, the long-term goal should be to create beneficial end use of any pit lake. Nearly all pit lakes have been planned to become fish habitat because oil sands pit lakes have been designed and assessed individually rather than regionally. Base Mine Lake is a notable exception.

With 23 pit lakes conditionally approved for the oil sands region, regional planning provides an opportunity to balance the needs of timely mine reclamation with realistic outcomes and end uses. Since many pit lakes are planned to drain in succession, one approach might be to contain tailings in upstream pit lakes, leaving the downstream pit lakes with a higher likelihood of water and sediment quality suitable for fish and other aquatic species. Other beneficial end uses would apply to the upstream pit lakes, such as providing habitat for forage fish, attenuating mine drainage quantity and quality, and providing cleaner inflows to the downstream pit lake. An additional benefit that could be provided by upstream pit lakes is to moderate seasonal flow variation, increasing winter low-flow and the low dissolved oxygen content presently limiting to fish habitat in many small streams throughout the mineable oil sands region.

Continued planning of pit lakes on an individual basis is likely to result in additional commitments to create fish habitat in all pit lakes, which would preclude trade-off considerations that might otherwise lead to a holistically planned pit lake region.

5.4.5 Fluid tailings in pit lakes

A recent review of 180 pit lakes worldwide (Vandenberg & McCullough 2018; McCullough et al 2018) evaluated the root causes of successes and failures in case studies involving subaqueous mine waste disposal. The review concluded that:

> *"Holistic planning views the pit lake as one part of a larger closure landscape – successful pit lake closures were typically well-planned in advance and in consideration of other post-mining landform elements across the closure landscape. Holistic planning may improve overall mine closure outcomes (reduced risk and liability) at the expense of reduced pit lake success."*

Rather than simply asking "Should this pit lake contain tailings?" a more appropriate question would be "Given the land disturbance & waste materials generated by a mine, along with the local water balance, climate, economics, desired end-land uses and other factors, which closure strategy achieves the desired closure outcomes and yields the lowest overall environmental risk?" This paper strongly recommends that treating FFT and sequestering the resulting material in a pit lake beneath a properly designed water cap, results in the lowest environmental risk for deposits of such high-clay-content, fines-dominant tailings.

There are significant benefits from sequestration of FFT (treated or untreated FFT) in pit lakes rather than in terrestrial landforms:

- Reducing or eliminating FFT deposits beneath terrestrial landforms would enable far superior reclamation of terrestrial landforms. Terrestrial landforms containing deep fines-dominant deposits with substantial long-term settlement would result in serious geotechnical impacts (settlement and changes in surface slope), altered terrain from upland to wetlands and lakes, deepened wetlands and lakes, deformation and alteration of surface drainage courses, upward flux of OSPW to surface soils and higher porewater concentrations in surface drainage courses. FFT placed below pit lakes would reduce such undesirable impacts. Disposal of all FFT in pit lakes would eliminate such undesirable impacts.
- Placing FFT in pit lakes would avoid the large energy consumption, cost and large land disturbance associated with treating FFT in a manner that might avoid the significant negative impacts of depositing FFT beneath terrestrial

landforms. To attain terrestrial landforms that are free of long-term settlement would require the FFT to be dewatered to close to the shrinkage limit. This would require substantial energy and/or the disturbance of a large land surface area much larger than currently envisioned in the approved tailings management plans that were recently submitted to AER. FFT sequestered in pit lakes would reduce such land disturbance.

- The distribution of tailings porewater releases to the end pit lake containing FFT is superior to tailings porewater releases from FFT disposal beneath a reclaimed terrestrial landform. Tailings pore water expressed from a consolidating FFT deposit in a pit lake is spread over the surface of the deposit and is diluted in the water cap over a large area where it is exposed to natural aerobic degradation of organic constituents, including naphthenic acids. In contrast, porewater expressed from a consolidating FFT deposit beneath a terrestrial landform enters the pit lake at a point source resulting in relatively high concentrations of OSPW, much higher than the concentrations associated with FFT deposited in a pit lake.
- A deep in-pit deposit of FFT designated for terrestrial reclamation would need to be capped and its surface raised significantly above grade to maintain a terrestrial surface after settlement. The resulting rate of pore water expression would be greater than for a similar deposit in a pit lake, due to the greater surcharge load on the deposit, particularly in the early years after cap placement. The increased rate of settlement and associated tailings porewater discharge is illustrated on Figure 3-9 for three scenarios: no surcharge for the case of FFT deposition beneath a pit lake, 5 m of sand cap which is close to the minimum average sand cap thickness to enable terrestrial reclamation, and 10 m of average sand cap thickness. Comparing placement of FFT beneath a pit lake (no surcharge) and placement of FFT beneath a terrestrial reclamation area requiring a minimum 5 m surcharge, Figure 3-9 shows 2.8 m additional settlement at the terrestrial reclamation area. Assuming a 5 km^2 FFT deposit area, this additional settlement is associated with 14 million m^3 of additional tailings porewater discharging to the pit lake and ultimately to the Athabasca River. Figure 3-9 shows that discharge of saline porewater to the pit lake and to the Athabasca River can be reduced by permanently sequestering tailings porewater in a FFT deposit beneath a water cap in a pit lake.

FFT disposal in a pit lake can be significantly improved by treating the FFT to an optimal density. Designed appropriately, treated FFT material is superior to untreated FFT contained in a pit lake beneath a water cap because:

- Treated FFT is more volume-efficient than untreated FFT in a pit lake. Treated FFT at 50% solids content occupies about half the volume of the same FFT untreated at 30% solids content and contains nearly 60% less OSPW. Accordingly, if the solids content is increased from 30% to 50%, a given pit volume can contain about twice the quantity of FFT solids. This benefits the environment because doubling the quantity (weight of solids) of fine tailings in the pit lake reduces the amount of fine tailings material that might otherwise be placed beneath a terrestrial reclamation area, requiring alternative treatment with related environmental impacts.
- Treating FFT to increase its solids content will reduce the potential risk of fines re-suspension. Any FFT deposit needs to be designed to avoid the risk of fines re-suspension. Regional lakes are generally dimictic – exposed to vertical mixing from overturning in the spring and fall, when the lake is isothermal. Untreated FFT in a pit lake, with suspended solids at its surface, is exposed to turbidity events during such turnovers. Denser treated FFT makes it easier to create a robust interface between the FFT deposit and the overlying water zone. Development of a robust interface may be enhanced by (a) desiccating the surface before water cover placement by ditching and draining to expose the surface to freeze-thaw processes and evaporation; by (b) placing a granular layer of coke and/or thin sand layer over the surface; by (c) chemical treatment; or by (d) some combination of these methods that can be achieved with a treated FFT surface but not easily on an untreated FFT surface.

Greater water depth might also be used to avoid re-suspension from treated or untreated FFT deposits in a pit lake. The optimal water depth for a pit lake containing treated or untreated FFT is site-specific (depending on lake area and geometry and wind conditions) but can be predicted by analytical techniques (Lawrence et al 1991) or by numerical modelling (Prakash et al 2015). However, too great depth combined with basal salinity could result in a meromictic lake. Treated FFT with a robust interface has less risk of contaminating the surface water. Release water rates can be observed following placement and are predicable by settlement modelling. Settlement rates decline after initial consolidation as deposit density increases and permeability decreases as illustrated in Figure 3-9. Therefore, water quality can be managed with observational and predictive tools.

As noted in Section 3.4.8, avoiding naphtha content in the FFT by precluding froth treatment tailings from the tailings settling pond would be a benefit whether the FFT in the pit lake is treated or untreated.

FFT treatment to achieve the greatest attainable deposit solids content and selection of an appropriate deposit surface amendments followed by observation and controlled outflow through the period of initial consolidation, will enhance the significant benefits resulting from placement of treated FFT beneath a water cap in a pit lake.

5.4.6 Pit lake shoreline stability

All oil sands mine closure plans involve pit lakes and therefore lake shoreline stability is an issue that is common to all oil sands mines irrespective of the adopted tailing management technology. Various techniques for controlling shoreline stability have been proposed (Sawatsky et al 2011) including riprap protection, placement of select course material, cobbles/boulders in overburden dumps that may be used to line the lake, off-shore groins that encourage littoral vegetation in protected areas along the shore, and shallow-sloped shorelines that cause waves to break further from the shoreline.

Some areas of the lake may be susceptible to considerable shoreline erosion, as is the case in any new reservoir or lake. Such erosion is anticipated and built into the design basis (CEMA 2012).

5.4.7 Achieving long-term pit lake stability

The most important requirement for achieving long-term pit lake sustainability is sufficient drainage area to assure hydrologic sustainability. This can be achieved by appropriate mine planning and mine closure planning, whereby the ratio of drainage area to lake area is large enough to sustain annual through-flows and avoid excessive salinity. Drainage from outside the project development area can also contribute to inflow and long-term hydrologic sustainability, as is the case with Syncrude’s Beaver Creek diversion into Base Mine Lake.

Another requirement is minimization of process water inflows. This can best be achieved by depositing non-consolidating or very slowly consolidating fine tailings in the lake beneath a water cap. A time period for stabilization of the water cap quality will normally be required so that input of OSPW from residual consolidation is low enough and that aerobic degradation of organics and flow-through volumes maintain acceptably low concentrations in the surface water. This period can be modeled with consolidation projections and confirmed by observation.

Sequestering non-consolidating tailings or slowly consolidating fine tailings in a pit lake enhances long term pit lake sustainability as follows:

- Reduced quantities of OSPW entering the pit lake, depending on the density, depth and rate of settlement of the in-pit fine tailings deposit.
- Tailings porewater entering the water cap of a pit lake is immediately diluted by the water cap over a wide area (the area of the pit lake). In contrast, OSPW (tailings porewater) from terrestrial areas containing tailings deposits, enters the pit lake at discrete locations where the concentrations of OSPW can be expected to be relatively high, possibly toxic to aquatic habitat.
- Avoidance of out-of-pit deposits of compressible FFT with long-term settlement that could negatively affect reclamation soils, vegetation cover, hydrologic sustainability of wetlands and lakes, and quality of water in surface drainage courses.

5.4.8 Risks associated with treated FFT in pit lakes

This paper presents a sound rationale for positioning treated FFT beneath a water cap of a pit lake. Risks of this approach have already been mentioned. A more complete list, with a qualitative discussion of the severity of each risk, follows. However, before discussing the risks of treated FFT in pit lakes, it is vital to consider the risks associated with *not* depositing treated FFT in pit lakes — that is, placing them in a terrestrial environment. Several potential impacts have already been discussed and others are covered in subsequent sections. The following adverse impacts are associated with deep deposits of treated FFT in the terrestrial environment:

- Settlement causing upland erosion, failure of erosion protection systems on major streams, and relocation (avulsion) of wetland and lake outlet channels
- Settlement causing enlarged lake and wetland areas, unplanned (opportunistic) wetlands and lakes, increased salinity in lakes and wetlands, and deteriorated aquatic habitat due to elevated salinity
- Settlement resulting in dams emerging in the closure landscape as water bodies develop due to differential settlement
- Upward flux of OSPW from deep deposits of treated FFT, resulting in contamination of wetlands and upland drainage courses, inundation of surface reclamation soils and discharge of OSPW to the pit lake
- Changes to oxidation state within tailings, leading to geochemical changes of drainages waters that can affect downstream environments.

Processes such as settlement and upward flux of OSPW in a terrestrial environment containing treated FFT, are best characterized, not as risks but known consequences of deep deposits of treated FFT in terrestrial areas. There is no uncertainty regarding their occurrence, but there is some uncertainty surrounding the severity of impacts that depend on the depth of the deposit and the density of the initial deposit. The known impacts of deep deposits of treated FFT (as proposed by operators) violate critical closure criteria and regulatory requirements. Therefore, these impacts cannot be fairly compared with the risks associated with treated FFT (at higher density) in pit lakes beneath a water cap because the impacts of the latter are much less likely, as discussed below. None of the impacts listed above for terrestrial landforms containing treated FFT, will occur as a result of treated FFT deposited at higher density in pit lakes beneath a water cap.

The major risks of treated FFT contained in pit lakes have been discussed in various submissions to government regulators, conference presentations and technical literature as follows:

- **Meromixis** is the process of long-term stratification in lakes, resulting in higher-salinity water at the lake bottom that does not fully mix with surface water during seasonal turnover events. Meromixis is often associated with deep lakes that have significant inflows of saline water. The main issue with meromictic pit lakes is that oxygen does not penetrate to the lower layer, leading to anoxia and reduced-gas generation (Vandenberg et al 2015). Although meromixis may be a risk in pit lakes containing treated FFT (at higher density) beneath a water cap, the risk of meromixis is greater in pit lakes that contain no solids. The magnitude of the risk is related to water depth, lake geometry, and the amount of saline inflows. As discussed above, both the depth of the lake and the amount of saline inflows are reduced for mine closure plans that contain densified FFT in pit lakes.
- **Pit lake discharges** will have higher salinity if FFT is deposited beneath areas designated for terrestrial reclamation. Treated FFT in a pit lake beneath a water cap reduces the risk of saline outflows from the end-pit lake because this system permanently sequesters a significant amount of the OSPW in the tailings deposit beneath a water cap in a pit lake. In contrast, deep deposits of treated FFT contained beneath a sand cap required to develop a terrestrial environment result in higher releases of OSPW. In tailings management plans with no pit lake whatsoever (although no such plan has been presented), the release of OSPW would be expected to be highly variable in terms of both quantity and quality, resulting in frequent regulatory exceedances.
- **Re-suspension of lake bottom sediment** risks can be managed by designing a water cap with adequate depth over the tailings, and by treating or amending

the tailings surface by desiccation, chemical treatment or covering with sand (sand raining) or with coke followed by sand.

- **Buoyant bitumen separating from the submerged deposit** of treated FFT (beneath the water cap of a pit lake) and accumulating on the surface of the pit lake, is a risk pertaining to the effectiveness of the treatment process in permanently sequestering these materials. A major cause of buoyant bitumen is the inclusion of froth treatment tailings in untreated FFT. The naphtha-containing bitumen has density lower than water and methanogenesis of the naphtha creates bubbles which can transport the diluted bitumen out of untreated FFT to the lake surface. Mine operators report that permanent sequestration of bitumen is proven. However, mitigation of this risk needs to be demonstrated. A demonstration pit lake has been constructed and is being operated to prove this claim. To mitigate this risk, the outflow point of the pit lake has been modified to skim the floating sheen during the initial years of development.

Perhaps the most convincing argument for pit lake sequestration of treated FFT is the success (or successful elements) of Syncrude's Base Mine Lake, which contains both transferred MFT and segregated whole tailings; and Suncor's Demonstration Pit Lake, which contains treated (partially densified) MFT. Base Mine Lake was partially filled with whole tailings that segregated during end-of-pipe deposition, resulting in accumulation of ultra-fines at the surface of the deposit - similar to behaviour in tailings pond beach construction. The composition of segregated whole tailings makes this type of tailings deposit more vulnerable to resuspension of fines and floating bitumen. It is widely recognized that depositing treated FFT at higher density in a manner that prevents segregation will result in superior performance. Accordingly, Base Mine Lake represents a "bookend" and its observed water quality trajectory to date is evidence that treated FFT placed beneath a water cap, at an optimal solids content (e.g., 50% solids versus 30% for MFT), without segregation, will be successful.

5.5 Sustainability of terrestrial landforms

5.5.1 Avoiding dams in the mine closure landscape

It is commonly accepted that dams are not permitted in the mine closure plan because they present long-term liability in terms of never-ending monitoring and maintenance (perpetual care). Dams in Alberta are defined as fluid-containment structures greater than 2.5 m high that contain more than 30,000 cubic metres of fluid (AENV 1999b) –

a definition that is under review by Alberta regulator. There is a broad consensus by government regulators and stakeholders that all dams as currently defined must eventually be decommissioned.

A document prepared by dam specialists from industry, stakeholders and regulators proposes a process for dam decommissioning (OSTDC 2014). Key elements of the process include reducing or eliminating fluid containments (water, fluid tailings, and materials that are vulnerable to liquefaction), avoiding terrestrial deposits subject to excessive settlement over time that could result in large ponds, and providing an outlet for surface water drainage that is not vulnerable to failure or excessive erosion.

Some tailings management strategies can result in a proliferation of dams in the closure environment with little chance of dam decommissioning, depending on the effectiveness of fluid tailings treatment and tailings deposition configurations. Depositing relatively low-density treated fluid tailings above the original ground level behind dams would require long-term monitoring, maintenance, and regulation with little or no chance of dam decommissioning or de-licensing. Continued settlement of such tailings deposits can be expected for hundreds if not thousands of years, as discussed in Sections 3 and 4. Settlement could result in unplanned wetlands, deepening of wetlands to form lakes and deepening of lakes with enlarged fluid containments behind dams that require perpetual maintenance.

There is a simple and cost-effective alternative to treated fluid tailings positioned in elevated terrestrial environments behind dams that require long-term monitoring, maintenance, and regulation. The alternative is to place these materials in a pit, below original ground with no man-made containment structure (see Section 3.6).

5.5.2 Providing sustainable drainage courses

Designing sustainable drainage courses on stable landforms is a mature science (e.g., USDA 2007). Stable channels can be designed by structural methods that provide a rigid configuration to handle specified conditions. Better still, stable channels can also be designed based on the geomorphic approach that attempts to replicate the physical processes whereby natural channels are free to evolve over geomorphic timeframes (Golder 2008). The resulting channels designed by the geomorphic approach are better suited to accommodate unanticipated conditions and extreme events. The geomorphic design facilitates channel evolution, like natural systems. In either case (structural or geomorphic) the science is advanced, even mature.

However, industry has little experience with designing long-term drainage courses on landforms that are subject to long-term settlement, such as those landforms composed mainly of compressible tailings. Designing drainage courses on landforms whose deformation trajectory is uncertain, and poses several risks:

- Reduced stream gradients resulting in development and growth of wetlands (sometimes called opportunistic wetlands), water bodies, sediment deposition, reduced channel depth and ultimately avulsion of streams (sudden relocation of the drainage pathway)
- Steepened channel gradients at the upstream end of a settlement area, resulting in higher flow velocities, possible channel erosion, and possible failure of erosion protection systems
- Gullying and failure of erosion protection systems as a result of abrupt differential settlement.

The consequence of such occurrences is failure of the drainage systems leading to serious erosion and/or sediment deposition, unplanned water bodies that may be hydrologically unsustainable (resulting in saline wetlands and lakes) ultimately leading to degradation of the reclaimed landscape.

In addition to known risks associated with drainage of landforms that are subject to long-term settlement and deformation, there are unknown risks associated with designs for terrain that has not been tested and for which there is no long record of successful performance. A good example of such unknown risks is mid-winter piping at a drainage channel situated on a saturated sand structure, as occurred several years ago in the oil sands region. A channel invert became buoyant in the dead of winter (-30°C temperatures), resulting in a large flood and delivery of large amounts of sediment to downslope areas. This type of flood and failure of a drainage channel in winter was a surprise to the designers who were unable to anticipate such an occurrence because of the limited precedent and experience with designing drainage systems on saturated sand structures.

Fortunately, there is a cost-effective option to building drainage facilities on terrain that is subject to long term settlement and deformation. Instead of placing compressible tailings (fine tailings and treated FFT) material beneath a terrestrial landform, compressible tailings materials may be disposed to a mine pit below original ground and beneath an appropriately sized water cap.

5.5.3 Controlling upward flux of tailings porewater

5.5.3.1 Upward flux at terrestrial deposits of treated FFT

Geotechnical engineers and hydrogeologists understand that most of the tailings pore water in deep deposits of compressible tailings (fine tailings including treated FFT), flows upward (upward flux) as the deposit consolidates and settles (e.g., Jeeravipoolvarn 2010). Upward flux is the dominant seepage path when the deposit is consolidating. In comparison, downward and lateral tailings porewater seepage through the base and sides of a treated tailings deposit result in relatively small quantities of seepage compared with upward flux that occurs during consolidation. The dominant seepage pathway during consolidation is upward due to higher hydraulic conductivities of tailings in the upper part of the deposit, and the relatively short flow path length of upward seepage. A veneer of fine tailings material located at the bottom and sides of a deposit is composed of relatively high density fine tailings material with correspondingly low permeability.

Upward flux of tailings pore water presents a high risk that reclamation soils will become contaminated with OSPW resulting in deterioration of the vegetation cover (Price 2005; Daly et al 2010). Upward flux in deep deposits of compressible tailings material can be controlled by providing a thick sand cap configured with well-defined ridges and swales (Pollard and McKenna 2018). Seepage water (OSPW) will then discharge near the base of swales, avoiding contamination of large areas of terrestrial reclamation.

Tailings management plans that fail to provide sufficient topographic relief (ridges and swales) and sufficient depth of cover material (sand cap) over deep deposits of compressible tailings will result in salinization of reclamation cover soils and degradation of the vegetation. Some tailings management plans recently submitted by oil sands operators have had insufficient thicknesses of sand cover materials and lack sufficient topographic relief to control the local water table.

The above practices can mitigate soil contamination risks with deposits with relatively little settlement such as for CT. For deep clay-dominant deposits, there is a better alternative to prevent contamination of reclamation soils, namely avoiding placement of compressible tailings into terrestrial landforms. This can be accomplished by sequestering such materials beneath a water cap in a mine pit lake where upward flux cannot damage reclamation cover soils.

5.5.3.2 Upward flux at wetlands and surface drainages

OSPW discharges to surface drainage courses when upward flux of tailings pore water at deep deposits of compressible tailings reaches the surface. The resulting flow in surface drainage courses will contain OSPW that is diluted with water from precipitation. Concentrated groundwater discharges composed mainly of OSPW (tailings pore water) are likely to occur during extended droughts when there is little or no dilution with meteoric water. Undiluted tailings pore water flowing in surface water courses can threaten vegetation at water courses and wetlands, aquatic life, and wildlife/waterfowl that may encounter the surface water and wetlands.

Contamination of surface drainage courses and wetlands by upward flux of tailings pore water at terrestrial tailings deposition areas can be minimized by selecting tailings management technologies that produce a high-density tailings material. Ade et al (2011) and CEMA (2014) wetland manuals describe the use of ridge-and-swale topography for accommodating consolidation water from soft tailings (Figure 5-4). Contamination of surface drainage courses and wetlands can be avoided by having fully consolidated fines within terrestrial landforms or as previously noted by sequestering deep fine tailings deposits beneath a water cap in a mine pit lake.

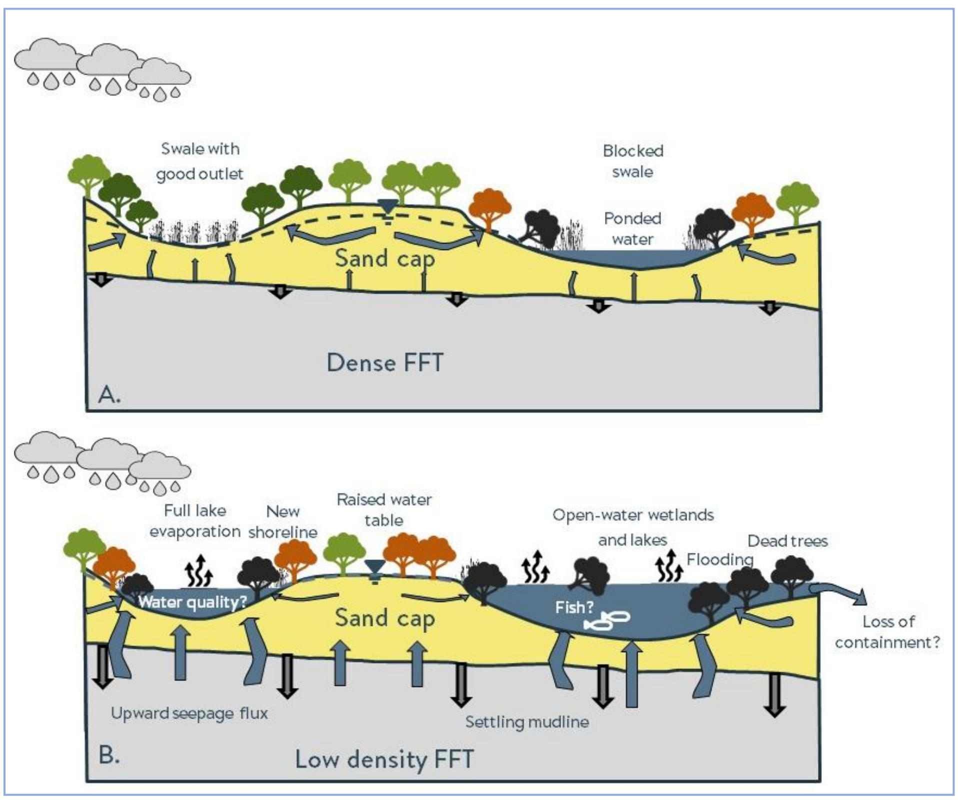


Figure 5-4 Ridge and swale topography. A: Dense FFT with low consolidation rate B: Low-density FFT with high consolidation rate and large settlements.

5.6 Erosion in upland areas

In addition to the risk of erosion at drainage courses situated at terrestrial areas as discussed above, terrestrial areas composed of compressible tailings materials are vulnerable to erosion when differential settlement creates sharp discontinuities of the ground surface. Differential settlement creates over-steepened slopes that are vulnerable to geotechnical instability, and scarps in the surface topography. Tailings sand or coke, used to cap soft tailings, are both highly erodible materials owing to their very fine grainsize and lack of cohesion (McKenna 2002). Coke suffers from having very low specific gravity, making it even more prone to erosion.

Landforms composed of non-compressible materials can be designed to minimize surface erosion by various well-understood methodologies, including the geomorphic approach and many other soil conservation guidelines in the literature. But it is far more difficult and at times impossible to prevent accelerated soil erosion of landforms containing deep deposits of compressible tailings material that are subject to future settlement of uncertain magnitudes.

5.7 Discharges to the environment

Oil sands mine operators have declared their intent to release water from their reclaimed mine areas to the environment following mine closure. Their intention to release water to the environment upon mine closure is reported in almost all EIAs that were submitted in support of mine development permit applications. Such declarations of future water releases have also been reported in updated mine closure plans. Water releases to the environment are necessary because increasing water accumulation after mine closure would require continued increases in the capacities of reservoirs held by large dams.

It is reasonable to release water that collects in the reclaimed mine after mine closure because the water, even OSPW, will eventually comply with regulatory targets as discussed above (based on degradation of organic compounds in the pit lake and dilution of salts). As noted in Section 1.1, it is imperative that regulatory processes be established to allow such releases to avoid accumulation of excess water, even OSPW, on the reclaimed mine site and avoid the need for dams in the reclaimed mine site upon mine closure.

A good case can be made for *early* release of excess water from operating mine areas. Early release, during mine life, would benefit some sites with high-chloride oil sand and would provide control over site water inventory. Discharges to the environment can be treated to comply with regulatory requirements but there is currently no regulatory provision for such discharges. The absence of such regulatory provision is detrimental because it delays releases, resulting in higher future saline discharges or extended periods of discharge and higher costs to operators and government. The costs are higher because of the larger fluid containment required to accommodate the delay in regulatory approval to release treated water to the environment.

5.8 Managing the closure landscape

5.8.1 Geomorphic approach

Design of the closure landscape by the geomorphic approach has been practiced in the oil sands region for more than 20 years. The basic premise is that mine-disturbed terrain should be patterned after natural analogues both in terms of function and configuration, and that natural processes of landscape evolution over geomorphic time frames should be replicated by mine closure landforms (Keys et al 1995). The key objective is that the closure landscape should perform much like the natural landscape and exhibit similar rates and types of evolution by geomorphic processes such as erosion and sedimentation. The geomorphic approach considers the unique characteristics of closure landforms and emphasizes similar geomorphic processes, not just similar appearance (Ade et al 2011; McKenna et al 2011).

Key drainage design features associated with the geomorphic approach include:

- Constructed lakes in the oil sands region should have a large drainage area that provides for hydrologic sustainability. For natural terrain, the drainage area to the lake should be at least 6.7 times the lake area as discussed earlier in this section. For mine-disturbed land involving inflows of OSPW, this ratio should be higher (Figure 5-3).
- The required density of drainage courses, allowable water course gradients, cross-sectional configuration and size of tributary drainage areas can be derived by investigating natural analogues (see Schumm 1956). Many drainage courses in the natural environment are vegetated water courses. Natural vegetated water courses can be replicated to reduce reliance on active channels that require armouring for erosion protection. Equally, active channels can be designed with reduced armouring if natural systems are replicated to enable slow rates of change. Detailed design guidelines can be found in a drainage study of natural analogues sponsored by a consortium of oil sands companies (Golder 2006).

- Natural analogues for channel drainage down the Athabasca River valley wall (escarpment) and other geotechnically unstable areas indicate a need for continuous re-supply of large rocks to the channel. Most sediment at high-sediment-yield streams in the oil sands region is derived from channel erosion at unstable landforms and over-steepened slopes such as the headwaters of many streams and rivers on the west side of the Athabasca River as well as the relatively steep and unstable slopes of the Athabasca River valley wall. Other terrestrial areas located on flat-lying stable terrain exhibit minimal erosion.

A great deal of guidance for future climax vegetation can be derived by examining the natural environment. Landforms with thick covers of sand (i.e., 12 to 15 m) and deep water tables enabled by relatively thick sand cap deposits over treated FFT, are more likely to produce a pine forest similar to the natural environment. Flat-lying mine closure landforms with thin covers of sand (1 to 3 m) and relatively shallow water tables, such as the thin layers of sand caps over treated FFT proposed in some tailings management plans, are more likely to become wetlands — or even saline wetlands — because of upward flux of tailings porewater.

5.8.2 Progressive reclamation and certification

Oil sands operators practice progressive reclamation. But the types of areas being reclaimed progressively are limited to downstream slopes of dams, overburden waste dump areas, and other stable landforms that do not contain appreciable quantities of compressible tailings materials. One such landform (Gateway Hills by Syncrude; an overburden dump) has been certified by the Alberta Government (AENV 2008).

In contrast to the current progressive reclamation practice of the oil sands industry at landforms that do not contain treated FFT, terrestrial landforms containing appreciable quantities of compressible tailings materials will not be reclaimed and certified for many years — perhaps never (Morgenstern 2012) — depending on the depth, density, and quantity of treated FFT in the composition of these landforms. The reason for this is the regulator’s reluctance to certify landforms that are evolving, and whose final configuration cannot be accurately predicted (Creasey 2012).

There is an obvious solution to the slow pace of reclamation and certification of such landforms: *such areas should not be built*. Compressible materials such as treated FFT should not be placed in terrestrial landforms, but in pit lakes well below the original ground, capped with an adequate depth of water. Locating compressible tailings material beneath the water cap of a pit lake would help accelerate the current pace of certification; eliminating compressible materials from terrestrial areas would reduce the timeframe for development of mature vegetation on a stable landform and would also reduce the uncertainty associated with the long-term performance.

Time to certification currently depends on development of a stable landform with vegetation exhibiting an observable trend towards long-term sustainability. Changes to the physical condition of a landform caused by ongoing consolidation will result in significant delays to certification because the performance of the reclaimed area is subject to change and the final state cannot be predicted with certainty.

Depending on the depth and clay content of a deep fines-dominant deposit, settlement time to attain a state of minimal residual settlement could range from many decades to over a millennium (Figure 3-9). Clearly, a terrestrial landform with such behaviour represents an obstacle to near-term sustainable closure and a dilemma for certification.

The industry and regulators need to establish suitable timelines for attaining acceptable residual settlement on terrestrial deposits to support reasonable certification timelines. The amount of residual settlement needs to be understood and agreed to be acceptable in the site-specific context.

5.8.3 Monitoring and maintenance

Regulators, mine owners, and stakeholders desire a mine closure landscape that is self-sustaining and doesn't require ongoing monitoring and maintenance far into the future. This concept is sometimes referred to as a "walk-away" solution and is applicable to reclaimed landforms that perform like natural systems with little risk of accelerated erosion or long-term deformation.

While such an ideal reclamation outcome should be targeted by all mine owners and closure designers, it cannot be applied to some legacy landforms that have been built in the oil sands region. It is unfortunately too late to apply such a target to existing landforms that will require ongoing monitoring and maintenance for hundreds of years to come or possibly longer.

Oil sands mine operators, regulators, and stakeholders can change the current trend of building reclaimed terrestrial landforms that are not self-sustaining. Terrestrial landforms containing appreciable quantities of highly compressible tailings material should not be built. Instead, highly compressible materials should be placed in pits, well below the original ground and below a water cap of adequate depth. Placement in a pit avoids the need for dams and placement below a water cap eliminates the problems of differential settlement on terrestrial landforms.

Why are some landforms destined for perpetual care instead of maintenance-free closure? Likely because closure and reclamation objectives were not well-defined decades earlier. Worldwide, other jurisdictions are recognizing the need for long-term care and funding for mine sites (e.g., McKenna 2002; Government of Saskatchewan 2019). With maintenance-free closure now a remote possibility for some existing landforms at oil sands mines, industry and regulators need to define objectives for new closure landforms. Regulators will also need to define a process for acceptance of legacy landforms that require centuries-long, or more, maintenance and monitoring. Such ongoing efforts will need to be backed by appropriate capital to fund such effort and to address unexpected deterioration and reclamation failures in the future.

5.8.4 Allowing users on the land

Based on stakeholder input at recent Enhanced Review Process sessions held for two tailings management plans in 2017 (see public domain documents from AER), stakeholders appear to favour a rapid return of mine-disturbed areas to traditional land use. This is feasible if the reclaimed land does not comprise large quantities of highly compressible treated FFT and if such usage is non-destructive. Activities that typically result in serious disturbance to surface soils and vegetation should be delayed until the resilience of the reclaimed landscape is proven, and a climax vegetation cover has been established with several cycles of growth and decay. Forestry operations should be delayed until the landscape proves to be resilient following a series of extreme hydrological and climate events. However, less-intensive land uses (especially traditional land use) are suitable for progressive return of the land to users. Such return of the land to users should be a central part of operations and closure planning where feasible (McKenna et al 2016).

5.9 Lessons learned

Many learnings pertaining to oil sands mine closure can be gleaned from the past 50 years of oil sands tailings management. A selection of learnings based on the authors' combined experience follows.

- **Environmental impacts of deep deposits of compressible tailings:** Long-term sustainability of terrestrial reclamation depends on the composition and geometry of a landform. Large amounts (deep deposits) of highly compressible tailings material in a mine-closure landform will result in significant settlement that could cause serious impacts to the environment (unplanned saline wetlands, enlarged open-water areas that are not hydrologically sustainable, failure of major drainage courses and upland erosion far greater than that of the natural environment). Eliminating compressible materials from a reclaimed landform bodes well for sustainable terrestrial reclamation, or even walk-away closure with minimal to no long-term liabilities. Even more significant, is the fact that large quantities of compressible tailings material in a mine closure landform will result in contamination of cover materials and surface drainage courses by OSPW expressed from consolidating tailings (fine tailings and treated FFT in particular). ***Deep deposits of fines-dominated treated tailings in the terrestrial environment should be avoided because of these serious negative environmental effects.***

- **Benefits of sequestering compressible tailings in pit lakes:** There are great environmental benefits incurred by sequestering densified treated FFT in a pit lake well below the original ground and beneath a suitable water cap (to prevent resuspension of fines and to avoid the negative impacts of deposit consolidation). Positioning soft tailings under a pit lake offers the best chance for optimal reclamation of terrestrial landforms. Positioning liquefiable materials below the original ground, fully contained in pit, avoids dams in the closure landscape. Locating densified treated FFT in a pit lake reduces OSPW discharge to drainage courses of terrestrial reclaimed areas and potentially limits the magnitude of OSPW contamination of the water cap. Perhaps the most consequential environmental benefit of positioning compressible tailings in a pit lake is that the rate of OSPW entering the water cap of the pit lake can be reduced by placing treated FFT in the pit, densified to the point of minimal rate of release of OSPW by future self-weight consolidation. With a slow rate of self-weight consolidation, the expression of tailings porewater into the water cap of a pit lake results in immediate dilution spread over the entire lake area as opposed to tributary channel inflows that can contaminate discreet entry areas of the pit lake. ***Sequestering densified treated fine tailings beneath a water cap in a pit lake located at or below the natural ground level is environmentally superior to placing such material in a terrestrial environment.***
- **Future liabilities:** Landscape performance at mine closure is strongly affected by tailings deposition methods and tailings treatment technologies. Some tailings management practices of the past 50 years, and some current plans for deep deposits of fines-dominated tailings that do not adhere to the criteria of below grade with a water cap supported by sufficient drainage area, will result in landforms that can never be permanently closed and that require

perpetual monitoring, maintenance, and possibly reconstruction of drainage outlet channels, regulation and associated funding into the far future. Accordingly, mine owners, regulators and stakeholders should recognize that ***many past and current tailings management decisions will result in significant future liabilities.***

- **Mine closure and material management should be viewed holistically:** Mine closure is the practice of planning and executing closure of the mining-disturbed landscape. This landscape includes the project area and may also entail consideration of the broader region. Leading mine closure practice seeks to holistically reduce the total project closure risk and maximize the total project closure benefit by considering landforms inter-dependently with each other. This holistic practice recognizes the implications of closure options for each landform on other landforms and how these options affect the primary aim of a successful complete-site closure (McCullough and Vandenberg 2018).

6 Conclusions and Recommendations

1. Landforms composed of out-of-pit tailings deposits or in-pit deposits taken above grade to form a terrestrial surface, should be composed of material that is near-fully consolidated so that the landforms will undergo minimal post-closure settlement which could disrupt surface drainage. Examples include tailings sand or fines material that has been dried to state approaching its shrinkage limit. Landforms composed of unconsolidated out-of-pit tailings deposits or in-pit deposits taken above grade to form a terrestrial surface, such as those proposed or recently requested by AER as alternatives to water capping, should not be built.
2. Deep fines-dominant deposits that will undergo long-term settlement, such as MFT that has been treated for dewatering (centrifuge cake, in-line flocculated MFT) need to be sequestered to geotechnically stable containment – in pit, below grade.

   Such deposits should be planned for open-water cover (pit lakes) so that landform settlement is avoided. Moreover, upward seepage into the pit lake surface will be reduced compared to equivalent ex-pit deposits and the pit lake will provide more effective control over declining salt concentration and natural aerobic degradation of organic acids.

3. Surface drainage design and water management at closure will be dominated by the need to manage salinity (chloride salts). Fundamental issues that need to be addressed for each site-specific design include:

   - Reduction of organic acids in the pit lake surface water and outflow. In most cases, natural degradation of organic compounds will be able to deal with these constituents. There is now an abundance of information on their behaviour.
   - An adequate in-flow area as a ratio to open water area in the closure landscape is essential to preclude lake salinization. Site-specific modeling of drainage and chloride salts is helpful to take account of site-specific saline water releases from consolidating tailings but a general guideline of 10% maximum open water in the closure watershed is recommended to provide for long-term sustainability of fresh water.
   - Drainage design for landforms containing tailings should direct flows through pit lakes to the Athabasca River.
   - Treatment and release of process water during active mining is beneficial to overall chloride management because it reduces the salt concentration in ground and surface water at mine closure.

4. Current systems for large-scale FFT treatment are not feasible (will not accomplish the adopted goals for mine closure) without the use of water-capped tailings deposits. A game-changer or super CT technology is urgently needed to provide operators with

greater control over closure landscape design, reduced land disturbance and reduced tailings containment liability. Such a process must contain more fines than current CT processes, avoid segregation upon deposition and exhibit high rates of drainage to avoid prolonged settlement.

5. Froth treatment tailings (FTT) represent a small fraction of mined material but contribute significant influence on tailings management. The current practice of discharging FTT into an area of the main tailings pond may accumulate substantial legacy liability. Two alternatives to the current practice are suggested as examples for consideration:
    - Treat the FTT with scroll centrifuges and co-dispose of the cake with overburden to in-pit deposits below the long-term phreatic surface.
    - Increase the naphtha (solvent) recovery in the tailings solvent recovery system significantly and disperse the FTT in sand tailings.
6. Measurement of clay content in oil sand ore and process streams through to tailings deposits is essential to assessment and prediction of deposit behaviour and for tailings planning and management. The industry is encouraged to adopt a common set of protocols for sample preparation and measurement of particle size and clay surface-area indices such as for laser diffraction and Methylene Blue Index.

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