Oil Sands Tailings: Reclamation Goals & the State of Technology

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ABSTRACT
Accumulation of fluid fine tailings presents a challenge to the oil sands industry for mine reclamation and closure. The origin and nature of the problem is presented along with the methods currently under active development by the industry.

RÉSUMÉ
L'accumulation de fluide des résidus fins représente un défi pour l'industrie des sables bitumineux pour la restauration des mines et de la fermeture. L'origine et la nature du problème est présentée ainsi que les méthodes actuellement en développement actif de l'industrie.

1 INTRODUCTION

Five decades of commercial oil sands mining operations have seen progress on many fronts in terms of both mining and extraction efficiencies. Significant progress has been made in streamlining mining and material handling, reducing process energy intensity, managing wear, improving bitumen recovery from lower grade oil sand ores and creating the ability to produce fungible, market-grade bitumen.

One issue continues to challenge the industry – finding practical methods to control the build-up of fluid fine tailings (FFT) – the muddy water that results when fine clays stay in suspension in the extraction process water. A large effort has been underway for decades to develop a fundamental scientific knowledge of, and engineering predictive tools for, the generation and behaviour of these clay suspensions. As of 2009, approximately 700 million cubic metres of mature fine tailings (or MFT) remain within retention dams at five operating mine sites and one completed mine undergoing reclamation (Reference 1 [1]).

Generation of FFT is a phenomenon shared with many other types of mining worldwide. However, the scale of oil sands mining, and the fact that conditions for significant evaporative drying are present for at most five months of the year, present significant additional challenges for the industry. In addition, un-recovered bitumen in the FFT further complicates its behaviour compared to similar clays encountered elsewhere in the world.

Research and development since the 1980s have yielded several FFT treatment methods that have been or are now being scaled up for commercial implementation. These include:

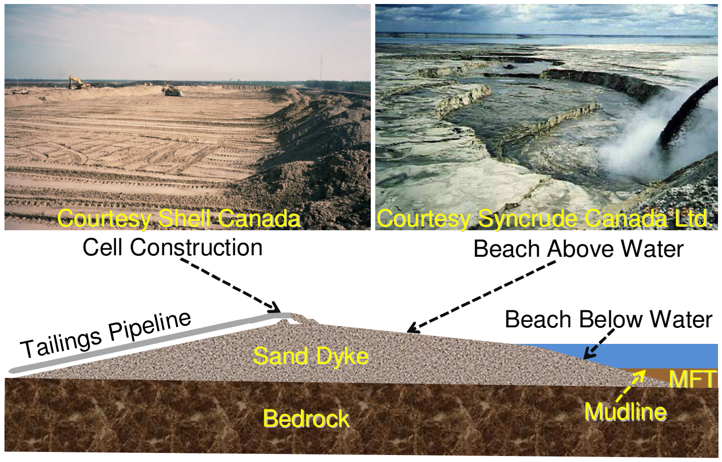
- Sand-MFT mixture (CT) technology has been operated for some years. Some challenges have been encountered with production of a consistent CT product, which have mostly been overcome, but operation with minimal segregation still needs to be improved.
- Commercial-scale, water-capped, in-pit lake disposal is currently being constructed and will undergo assessment over the next few years.
- Sand-capping and surface reclamation of fine tailings deposits has yet to be completed, but is well underway at the Suncor and Syncrude Mildred Lake sites.

It is clear that beyond the above techniques, additional fines de-watering methods are needed to provide operators with a suite of proven tools to complete mine reclamation and closure plans. Methods under development that de-water fines on their own, rather than when blended with sand, include MFT centrifuging, MFT in-line flocculation followed by thin-lift field deposition, in-pit accelerated dewatering of MFT and extraction fines thickening. These and other methods are described in Sobkowicz & Morgenstern, 2009[2].

The clay-dominated products of these FFT treatment methods produce what are referred to as cohesive deposits. It is clear that these methods will need some environmental assistance for additional de-watering following the initial process and deposition, in order for the deposits to achieve sufficient geotechnical strength.

While some of the methods are well advanced in the development path, none can currently be considered fully developed and proven through to having an engineering plan for a commercial-scale deposit fully implemented complete with an environmental assessment incorporating a follow-up monitoring program. Challenges remain respecting scale-up, attaining consistent operational performance, and developing performance metrics that allow mine planners to incorporate the methods into the site-specific conditions of each mine.

This paper will describe the methods under consideration, their state of development, and the particular obstacles and constraints challenging implementation of each method. While much work remains before performance and cost parameters are fully understood, it is evident that a number of methods can be made to work at some level. The challenge for the industry will be to refine and deploy a suite of methods that achieve reclamation objectives at a reasonable cost, so that the oil sands resource value is not seriously eroded.



Sand Cell & Beaching Construction

Figure 1

Oil Sands Tailings Acronyms

CT - Composite Tailings or Consolidated Tailings. A blend of MFT and sand used to dispose of fine tailings.

DDA – Dedicated disposal area. An area for disposal of fines to be reclaimed.

FFT - Fluid fine tailings. The clay-dominated fine mineral solids contained in the water run-off from the (mainly sand) tailings discharged from the oil sands bitumen extraction process.

FTT - Froth treatment tailings. The tailings stream resulting from removal of water and fine solids from bitumen froth recovered in primary extraction.

MFT- Mature fine tailings. Fluid fine tailings that have settled to the bottom of a tailings-water recycle pond - generally to a concentration of over 30% solids.

NST - Similar to CT except that TT is used in place of MFT in the sand blend.

TT - Thickened tailings. Fines withdrawn from the bitumen extraction process and chemically thickened for recovery of warm water and disposal of fines.

2 THE ISSUE - CAUSES & CONSEQUENCES OF FLUID FINE TAILINGS

After oil sand has been processed through the extraction plant, past practice has been for the remaining tailings (composed of sand, water, fines) and a small amount of un-recovered bitumen to be discharged to a tailings pond, so that the water can be recovered and recycled back to the extraction operation. Typically, the tailings have been used to construct the pond perimeter dykes through a combination of cell construction and beach discharge to raise the containment dam (Figure1).

During this deposition process, **segregation** of the tailings products occurs:

- Some of the fines are captured within the cell and beach sand, i.e., the fines remain within the interstitial space between the sand grains.
- The rest of the fines run off with the excess water into the settling pond (which is initially referred to as "Thin Fine Tailings" or TFT). The fines slowly settle and concentrate in the bottom of the pond (eventually forming "Mature Fine Tailings" or MFT), while the upper part of the water clarifies and is re-cycled for use in the extraction plant.

Once the solids concentration of the MFT increases to the point where the repelling forces between the clay particles dominate the behaviour, further densification is resisted. After 3 years, the MFT solids content will typically reach about 30%m - 35%m (i.e., 35% solids content by total mass) and further densification is extremely slow. Increased densities may result through other mechanisms such as in-migration of fine sand and silts or microbial action.

In addition to the primary capture of fines in the sand voids, additional capture will be influenced by the nature of the sand beaching. Fine silts settling at the beach toe (and MFT if its level intersects the beach toe), will be "sanded over" by the sand beaching, trapping additional fines. Thus, pond design and beaching operations are important variables in the overall site fines balance and the proportion converted into MFT.

For example, recent drilling and analysis by Syncrude on the tailings settling basin at the Aurora North Mine has shown nearly double fines content in beach below water deposits compared to the content in beach above water deposits. (Figure 2)

In a conventional sand beaching / pond operation, the split between fines capture in the sand and the generation of MFT will be determined by several variables: the whole tailings density (%solids), the fines concentration in the slurry (e.g., whether fines have been cycloned out of the sand slurry or added in from other sources), and the nature of the beaching operation. Typically, over 50% of the fines will remain with the sand, but lower or higher fractions may result depending upon the above factors.

Aurora Settling Basin Grain Size				
Relationship between 44 micron and other grain sizes for ASB Tailings				
		BAW	BBW	MFT (>70% fines)
Average <44 micron fines content		11.9	21.5	87
Ratio of split to <44 micron	<22	0.68	0.68	0.90
	<11	0.50	0.48	0.73
	<5.5	0.36	0.33	0.52
	<2	0.19	0.17	0.24

Figure 2

Fines capture within sand cells and beaches is the lowest cost fines disposal method. Geotechnical and surface reclamation factors are very favourable for this method of fines sequestration in reclamation landforms. It would therefore be useful if the fines capture parameters associated with slurry density, fines concentration and beaching practices were better understood, and quantified in a beaching model.

In addition to the primary extraction tailings, a small stream of froth treatment tailings (FTT) is also produced by removal of solids and water from the recovered bitumen froth in the extraction plant. This stream includes the following components:

- A small portion of the fines trapped with the froth water, comprising about 2% of the oil sand solids processed.
- A small amount of un-recovered bitumen and trace amounts of process diluent.
- Titanium and zirconium, minerals with potential economic value, enriched in the froth fines through the bitumen flotation mechanism.
- Where the paraffinic froth treatment process is used, the tailings will also contain rejected asphaltene – the very high molecular weight component of the bitumen.

The asphaltenes fraction may have negligible to negative value to a downstream refiner, so that project value will be relatively insensitive to rejection rate. However, a means of segregating the asphaltenes from the rest of the froth treatment tailings would be useful in order to provide the option of their future use as an energy source. Unless the froth treatment tailings are managed separately, they will contribute to the generation of MFT.

Even with optimized capture of fines within sand structures, the issue remains as to how to sequester the segregated fines (i.e., the MFT) into a reclaimed landscape. Growth in the volume of MFT on a mine site can incur significant costs for the construction, technical monitoring and maintenance of containment dams. World-class performance monitoring and risk management systems have been adopted to prevent dyke failures, which if allowed could result in catastrophic consequences. Beyond these costs and liabilities is the concern that the growing volume of MFT may exceed the amount that can be incorporated into a reclaimed landscape with the current mine closure plans, which are based upon proven methods of reclamation. This could require ongoing monitoring and maintenance well beyond the productive life of the mine – an undesirable prospect for all concerned.

2.1 Reclaimed Mine Sites

A fundamental public-interest goal is to avoid abandonment of mine sites with substantial ongoing liabilities. It is therefore important to ensure that research and development, mine closure planning and regulations are focused on this outcome. What do we mean by reclaimed landscape? The following essentials are required to return mine site lands to the public without ongoing liabilities.

- Avoid tailings ponds and dams in the reclaimed landscape that require ongoing maintenance for decades following active mining.
- Attain landforms with geotechnical stability, which are resistant to natural processes and are self-healing after natural erosion, with self-sustaining, native vegetation cover.
- Design productive, self-sustaining land and water features that are integrated into the natural ecosystem without adverse consequences to downstream water courses.

2.2 Goals for the Operating Period of the Mine

Goals for the operating period of the mine preceding mine closure include to the greatest extent practical:

- Reclaim tailings as mining proceeds, avoiding excessive accumulations of contained fluid fines that must be remediated at or near the end of mine life.
- Limit the required containment volumes of MFT - in particular, in out-of-pit dam structures, to that required for effective tailings management.

Without compromising the essential elements of a closure landform design, a further overarching objective is to conduct as much remediation as is practical during the active mine life, when there is operating revenue to cover the costs and while the mine organization and operating infrastructure are in place to efficiently conduct the activity.

2.3 In-Pit versus Out-of-Pit Deposits

While landscape design, aesthetics and timely re-vegetation are important elements of mine reclamation, an *a priori* condition is the attainment of geotechnical stability for all deposits of mined materials to avoid catastrophic failures.* Failure could be triggered by a seismic event or by extreme surface erosion. For this reason, diligence is required in the geotechnical design of disposal structures.

With the goal of achieving a reclaimed site meeting the above-described criteria for reclamation certification and return of public lands to the province, it is important to distinguish between out-of-pit and in-pit deposits. Where weak, clay-dominated materials are involved, disposal below grade within the excavated mine pit is preferable to out-of-pit structures. However, it will be necessary to permanently place some of the soft material in out-of-pit disposal areas, with the proportion governed by site conditions. In this situation, geotechnical design and improving the strength of these deposits (on a predictable trajectory) will be critical factors.

Design of out-of-pit deposits must consider and avoid the potential for large-scale (i.e., mass) failures. Geotechnical integrity considerations include the following:

- Provision of acceptable margins of safety against gross failure through weak or liquefiable materials under anticipated maximum loads (including earthquake), or against erosion caused by anticipated maximum hydrologic events, for reasonable return periods (e.g., 100 years).

- Over very long time frames and more extreme loading or hydrologic conditions, soil movements typical of the surrounding landscape should be expected and tolerated. Design of dumps or "dedicated disposal areas" (as defined by the ERCB Tailings Directive 074, for fine tailings) should be sufficiently robust to achieve this condition.

- Consolidation of the deposit must have advanced to the point where further surface subsidence is manageable and there will not be large-scale differential settlement which could lead to disruption of the closure landscape (to the point where it does not function as intended). Final topography and surface drainage design can anticipate moderate subsidence and design to preclude a large accumulation of surface water.

In-pit deposits that are below the original topography present fewer design constraints if the following factors are present:

- Weak deposits are contained within a large, stable landmass, including a substantial undisturbed segment adjacent to any natural water bodies.

- The surface of the deposit cap is at or below the original surrounding topography.

- If only the surface cap of the in-pit deposit is above grade, consideration of future subsidence to avoid a perched lake is similar to an out-of-pit deposit except that any contained tailings would not be exposed to the risk of an uncontrolled release.

Maximizing in-pit sequestration of weak materials conflicts with the goal of implementing fines-dominated remediation methods early in the mining cycle. This trade-off requires reasonable judgments in determining the appropriate deferral period to allow for adequate working room to be developed in the active mine pit.

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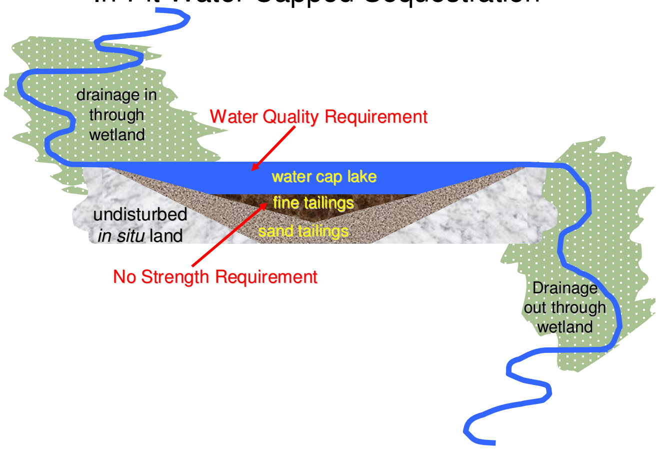
*One of the most famous failures attributed to lack of diligence is the *Aberfan Disaster* of Wales in October, 1966 which killed 144 people, including 116 children when waste mine rock and slag disposed on a hillside liquefied and inundated a school at the base of the hillside.

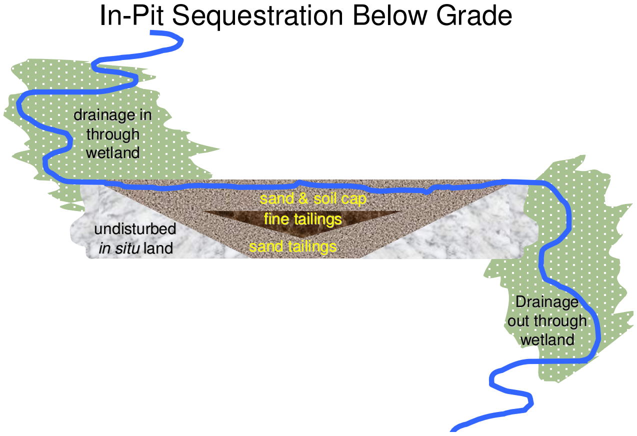
Depositional Environments

Figure 3

In-Pit Water Capped Sequestration

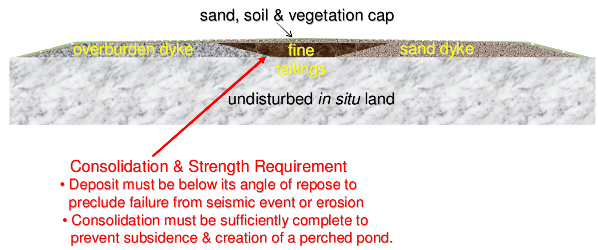


In-Pit Sequestration Below Grade

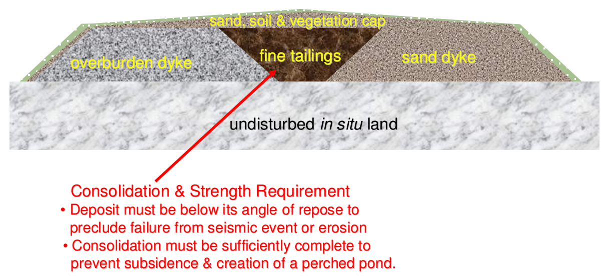


In-Pit Sequestration – Capped Above Grade

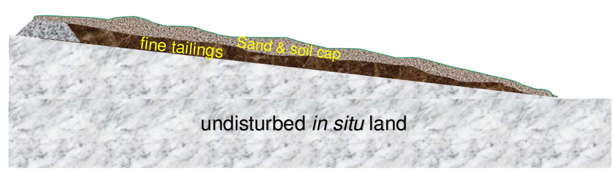
Out-of-Pit Contained Sequestration



Out-of-Pit Contained Sequestration



Out-of-Pit Un-contained Sequestration



3 SCIENCE AND ENGINEERING

3.1 De-Watering of Tailings

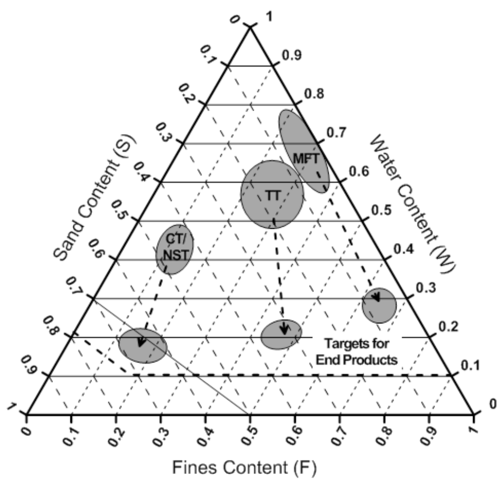
After placement in a pond or in-pit, tailings should, with time, meet several objectives important for reclamation:

- It should develop strength at a rate sufficient to allow timely capping, in order to meet reclamation and closure requirements.

- It should develop a low compressibility so as to minimize post-closure settlement and not disrupt the closure landscape.

Both of these mechanisms require dewatering of the tailings, which increases solids content, effective stress, and strength. This can be accomplished by a variety of processes, including settlement, consolidation, drying, etc.

To illustrate the amount of dewatering that may be required, consider several common tailings products as shown in the following figure (Tailings End Products). The as-placed condition of CT, NST, TT and MFT are shown on a tailings ternary diagram (Figure 4), which plots sand, fines and water content (by total mass; the ternary diagram is described in Scott[5] [2005] and Sobkowicz & Morgenstern, 2009)



Tailings End Products

Figure 4

- CT and NST are sand-dominated materials with a solids content of about 50% to 60%. To achieve sufficient drained strength and sufficient density to avoid liquefaction, the solids content must be increased to about 80%.

- TT is a fines-dominated material with a solids content of about 40% to 50%. To get sufficient undrained strength to allow capping and sufficient stiffness to avoid excessive settlements, the solids content must be increased to about 75% to 80%.

- MFT has a solids content of about 30% (SFR=0.05 material) to 35% (or more; SFR=1 material). To develop sufficient strength and stiffness (as in the previous bullet), the solids content must be increased to about 70% to 75%.

For all of these materials, the required amount of de-watering is large, and will not be achieved in one step. Multiple steps will be required. In most cases, the final de-watering stage will need to be assisted by environmental processes such as drying or freeze/thaw. This is discussed in detail in Sobkowicz & Morgenstern, 2009.

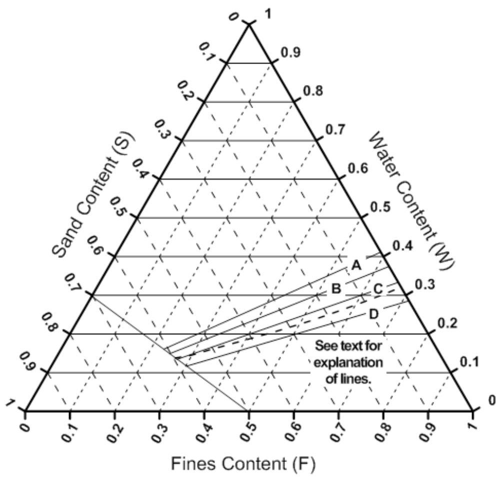
3.2 Sufficient Strength

The development of “sufficient strength” for capping, initial reclamation, and creation of closure landscapes depends on several factors. In both coarse and fine tailings, the most important factor is to increase the effective stress in the soil.

For sand-dominated material (such as CT), which has a relatively high permeability, this is achieved by direct loading of the deposit surface. For example, assuming a water table at the top of a CT deposit, placement of a 1 m cap increases the vertical effective stress by 20 kPa, which is sufficient to develop an un-drained (very short term) strength of 5 kPa. This same cap provides an even higher resistance (> 10 kPa) to drained loading conditions.

For fines-dominated materials (such as TT or MFT), loading and subsequent consolidation can be a very slow process. Other de-watering mechanisms (such as those discussed in the previous section) are required to develop un-drained strength. In essence, the solids content of this type of material must be increased until the material behaves as a solid, which is usually defined as the point where its un-drained strength is more than 1 kPa to 2 kPa. The geotechnical water content at which this occurs is called the “liquid limit” of the soil. The location of the solid-liquid boundary on a ternary diagram is shown on the figure “Solid-Liquid Boundary” (Figure 5). Several possible boundary locations are shown on this figure, depending on the value of the liquid limit of the fines portion of the tailings – Line A corresponds to a fines liquid limit of 70%, Line B of 60%, Line C of 50% and Line D of 40%.

The approximate location of the “Tailings End Products” solids content (previous figure) was based on the dashed line.

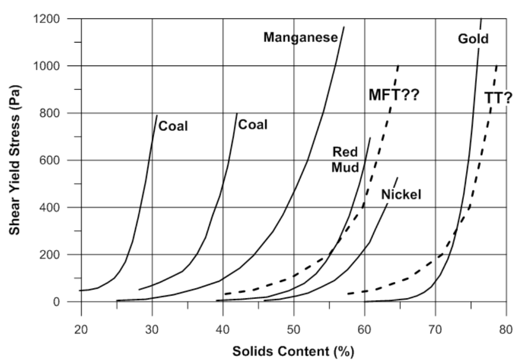


Solid / Liquid Boundary - Variation with Liquid Limit

Figure 5

Relevant to the development of strength at higher solids contents (i.e., below the liquid-solid boundary on the ternary diagram) is the deposit's "plastic limit". This term has a specific geotechnical meaning, but in general terms represents the point at which a soil has an un-drained strength of about 100 kPa to 200 kPa.

Knowing the plastic and liquid limits of a particular tailings material, and using established (approximate) relationships between liquidity index and un-drained strength, it is possible to predict the variation of un-drained strength with solids content as shown in the following figure (Figure 6).



Variation of Yield Stress with Solids Content

Figure 6

It is important to note that the effective stress in clayey soils is not just a function of total stress and pore pressure, but also depends on physio-chemical effects between the clay particles. Thus, factors such as pore water chemistry, migration of ions through (and precipitation from) the pore fluid, the presence of bitumen, and the presence of flocculants and coagulants in the tailings material, all play a role in the development of un-drained strength, particularly when the soil is near its liquid limit. The observed impact of these factors include the development of a "gel strength" at water contents above the liquid limit and the time-dependent development of strength in material that is otherwise "quiescent" (e.g., not consolidating). Ignoring physio-chemical effects can lead one to be overly conservative in estimating the un-drained strength of some tailings materials.

3.3 Time for De-watering

The time to achieve sufficient de-watering is a critical parameter in designing tailings treatment systems and developing tailings strength in a dedicated disposal area (DDA). As noted above, the normal consolidation process is slow for fines-dominated soils, and often the operator will want to invoke other de-watering processes that act in a timelier manner.

In other cases, it may be possible to argue that deposition of a tailings material in a DDA, followed by consolidation, is a reasonable approach to meet reclamation objectives. For example, this approach is currently under consideration for deposition of TT in a DDA.

The analysis of this type of problem is complex, and poses several challenges to the design engineer, as discussed in the following paragraphs.

To start, if the solids content of the TT is too low, the material as placed in a DDA may be in a "hindered settling" rather than a "consolidating" mode. The time to transition from hindered settling to consolidation may be long and practically unpredictable, and thus design approaches that assume consolidation right after deposition could be wrong. This may particularly be a problem in tailings materials that segregate to some extent during deposition. Clearly, it would be prudent to monitor such deposits carefully to determine not only their state but also their mode of de-watering.

In the case of a consolidating deposit, a large strain consolidation model must be used, and soil parameters selected that are representative of the likely soil behaviour. This is not a simple matter, as there are only a limited number of pilot scale tests of TT consolidation, making it necessary to extrapolate (during modeling) to much higher placement rates and deposit thicknesses than have been experienced to date.

Often, modellers rely on "average" or "best estimate" curves relating void ratio to effective stress and to permeability. The results obtained thereby can be very misleading, as small changes in assumed permeability or compressibility can result in widely varying conclusions about the ability of the deposit to consolidate in a timely manner.

Given a particular TT filling rate, finite strain models will predict deposit thickness with time, and at any particular time, predict profiles of effective stress, void ratio, and solids content with depth in the deposit. What they do not predict is deposit strength. As discussed in the previous section, relating un-drained strength to effective stress in not a simple matter. Some modellers have elected to apply a constant ratio of un-drained strength to vertical effective stress (Su/p'), based on critical state soil mechanics considerations. However, this ignores physio-chemical effects, which as discussed in the previous section, can be very conservative.

The only prudent approach for finite strain modeling at present is to a) select permeability and compressibility curves that are "self-consistent", that is, derived from observations of one specific deposit, and b) use strength versus effective stress or solids content relationships that are derived from that same deposit, recognizing that such relationships may be time-dependent. As a lower-bound check on the predicted results, an Su/p' ratio in the range of 0.25 to 0.35 may be used.

4 TECHNOLOGY – THE METHODS IN PLAY

There are three fundamental approaches to remediate fine tailings:

- One approach is to enrich sand with fines, while maintaining the combined blend such that a granular or sand-dominated deposit is maintained. Methods described below in this category include CT, NST and sand-fines filtration.
- A second approach is to separately treat segregated fines (MFT) or "thickened tailings" (TT), to attain sufficient dewatering (with release only of clear water) so that strength is developed within a reasonable time frame and on a trajectory consistent with adequate geotechnical stability for the resulting deposit. These deposits will be fines-dominated or cohesive in nature. Example treatment processes include centrifugation of MFT, in-line flocculation and thin-lift deposition of MFT or TT, direct deposition of TT, and accelerated dewatering.
- The third method is to sequester the fines under water, below original grade, within a geotechnically-secure area in a mined out pit.

These methods are described and mapped in Sobkowicz & Morgenstern, 2009, and discussed in more detail, along with advantages and disadvantages, in the following sections.

4.1 Granular or Sand-Dominated Deposits

4.1.1 CT

CT is an acronym for "composite tailings" or "consolidated tailings". It is created from a sand-fines-water slurry which is made non-segregating through the addition of a coagulant such as lime or gypsum. Consolidation to a sand-dominated matrix releases fines-free water.

CT was originally conceived as a method of making whole tailings non-segregating through the addition of lime so that the fines would remain trapped in the sand matrix and accumulation of MFT would be avoided.

As further developed and implemented by Syncrude and Suncor, the sand tailings were enriched with fines by blending cycloned sand with MFT (accumulated from prior years of operation), and gypsum was added as a coagulant. Maintaining a ratio of sand (>44 µm) to fines (<44 µm), referred to as SFR, of ideally around 4, but no less than 3, allows the non-segregating slurry to settle and consolidate to a sand-dominated matrix with grain-to grain contact (Sobkowizc and Morgenstern, 2009). Surface "capping" of the completed CT deposit with lower fines-content sand is necessary to achieve final consolidation and to provide a surface for placement of reclamation soil and vegetation.

Other coagulants or pH modifiers are possible, e.g., lime, CO_2 (planned for use at CNRL), and H_2SO_4.

4.1.2 CT Challenges and Limitations

Experience with CT has shown a number of design and operational areas where attention is critical:

- The SFR must be maintained above 3 to ensure a granular behaviour, where strength can be readily attained upon load addition from subsequent layers or surface capping.
- An average SFR of about 4 is targeted to provide capture efficiency significantly above that attainable with sand beaching and produce a robust CT "recipe".
- Consistent control of CT slurry density and/or the use of appropriate (i.e., low shear) depositional methods are needed to minimize segregation and generation of excessive amounts of sandy MFT in the deposit, which can be costly to remediate.

Above-water beaching of the slurry, or deposition of slurry directly into water or MFT, is prone to segregation if density is too low or too much shear occurs at deposition. An alternative deposition strategy is to deposit the slurry into itself and/or using a tremie diffuser at the deposit surface to dissipate the energy. While this method has been successfully employed to maintain discharge integrity in sediment dredging operations, it has only been successfully demonstrated at pilot scale in oil sands CT operations.

Another precaution for CT operations using gypsum as the coagulant is the effect upon water chemistry. Build-up of calcium or sulphate ions can adversely impact the extraction process. Concentrations within the water table must be considered in the design of the reclamation landscape. For this reason, and to consistently attain adequate sand-fines slurry densities, some operators may prefer to use extraction fines thickened with Polyacrylamide flocculants (i.e., TT, in place of MFT and gypsum) in the formulation, combined with sand from a cyclone underflow. This variation is referred to as NST (non-segregating tailings). Another way to deal with the water chemistry issue is to use alternate coagulants in the CT formulation, as described earlier.

Apart from operational challenges, CT and NST face an additional limitation - until they have been fully consolidated through surface sand loading and time, the deposit is potentially liquefiable and must be contained. As CT consumes large amounts of sand, it competes for the very material that provides the most economic containment dyke construction material. For this reason, it may be most useful on some sites as an in-pit disposal solution to be applied after a large pit void has been established.

4.1.3 NST

As noted above, NST is produced by blending thickened fine tailings with cycloned sand. In its proposed application, the thickened fines are produced by sending an extraction middlings stream or cyclone overflow to a mechanical thickener, after the fines stream has passed through a secondary, bitumen-recovery flotation stage. The thickened fine tailings product is then blended with cycloned sand.

This could be accomplished using a high rate thickener, as has been planned at Shell's Jackpine mine. If a paste thickener is used, the result is a higher-density blend which is even less prone to segregation upon deposition but will be more difficult to pump.

NST has the advantage of not changing the water chemistry as occurs with the use of gypsum. Use of carbon dioxide to assist in coagulation has also been proposed for NST (e.g., at the CNRL mine) but has not yet been demonstrated on a large scale.

4.1.4 Tailings Filtration

Previous small-scale tests have shown that vacuum-assisted filtration could be technically feasible for a range of dense tailings slurries. Depending on the amount of dewatering, the filtration objective could be:

- Removing sufficient water and increasing density to reduce the mixture's segregation potential, thereby incorporating all or most of the fines within the sand matrix.
- Removing more water, to the point that the sand-fines mixture would be stackable and would only require compaction to form a stable land form.

Two methods have been considered:

- Filtration of whole tailings on a belt filter or using in-line filtration (the latter is currently under study at OSTRF).
- Filtration of a mixture of sand and TT using a belt filter.

For methods using belt filters, there are three requirements needed for filtration to provide a useful contribution to fine tailings management:

- The filter-cake must be sufficiently dewatered to permit mobile equipment to distribute, spread and compact each layer of the deposit.
- Fines incorporated in the sand matrix must show a significant increase over that achievable with conventional hydraulic sand cell construction and beaching.
- Filtration rates (tonnes/m^2/hour) must be at a practical level, while attaining the previous two requirements.

Achieving all three of the above criteria has been elusive and most operators have determined that even if technical feasibility could be demonstrated, costs would be prohibitive for commercial-scale operations. There is therefore low industry support for continued research on belt filters, based on outcomes of past demonstrations and economic evaluations.

Research work continues on in-line filtration, which holds some promise of being a cost-effective method.

4.2 Fines-Dominated Cohesive Deposits

While the basis of CT, NST and filtration processes is to produce granular or sand-dominated material, other methods rely on de-watering MFT or other FFT on their own. The resulting fines-dominated deposits will behave in a cohesive rather than granular manner. The rationale for developing these methods is that there is a large volume of existing MFT to be treated, and the direct treatment of FFT may be less complex or costly than CT, NST and the other sand-dominated deposits described previously. Unlike the sand-dominated deposits, where strength is attained through grain-to-grain sand contact, cohesive deposits rely on sufficient initial de-watering so that they pass through the liquid limit, towards the plastic limit, and are on a consolidation trajectory of increasing solids content and shear strength, to the extent necessary for geotechnical stability.

4.2.1 Centrifugation of MFT

The most positive of the fines-dominated methods demonstrated at field pilot scale to date is the use of centrifuges to process MFT from settling ponds. In its simplest form, the method uses solid-bowl scroll centrifuges in the following configuration:

- MFT is dredged from the tailings settling pond.
- The MFT is diluted to a constant solids composition of about 20%m to provide positive control over the centrifuge process variables and to make polymer/MFT dispersion and mixing easier.
- Polyacrylamide flocculant is added to the centrifuge feed to control turbidity of the centrate water.
- The flocculated MFT is run through the centrifuge.

Solid contents of over 55%m have been demonstrated for the centrifuged MFT using this method (Lahaie, 2008[3]).

A variant of this method is to centrifuge the MFT without polymer addition, removing the coarser fraction (constituting about half of the total mass). The remaining centrate from this first stage is then flocculated and centrifuged in a second stage, and the two cake products are then mixed for disposal. The savings in chemical for this alternate method are offset by some increase in process complexity and the cost of some additional centrifuging capacity.

Centrifugation to a >55%m solids cake appears to be consistently attainable, and scale-up is expected to be relatively routine. Work remains to be done with respect to the material transportation and deposit methods and their incorporation into reclaimed landforms. Three transport methods are available to deliver the cake to the disposal sites:

- Trucking.
- Conveyor-stacker.
- Positive displacement pump and pipeline.

The following disposal sites can be considered:

- Seasonally layered deposits of cake either in-pit or out-of-pit.
- Large cells (e.g., 250,000 m^2 to 1,000,000 m^2 several metres deep) retained by sand and covered with additional sand to promote weighted consolidation.
- Co-disposal with overburden in dumps.
- Placed at the base of what will later become in-pit lakes.

All the above methods can likely be made to work. Total costs will determine which methods are most practical within each site-specific mining and reclamation plan.

While centrifugation is, at present, considered by oil sand operators to be the most positive and best-developed of the cohesive deposit methods, efforts are underway to develop other methods that avoid the high capital and operating costs.

4.2.2 In-Line Flocculation/Thin Lift Deposition

In-line flocculation followed by thin-lift deposition is a method to process MFT and create free-standing cohesive deposits. Initial trials conceived and conducted by SNF Canada Limited (supplier of polymer flocculants) at the Suncor site showed promise. In this process:

- MFT is removed from the settling pond with a dredge.
- The MFT may be stored in a tank or small pond to dampen out sudden changes in both dredge flow rate and MFT composition.
- Flocculation of the MFT is accomplished by injecting polymer solution into the MFT as it is transported through a pipeline, (dilution for constant density control similar to the centrifuge method is an option, but is not required).
- The flocculated mixture is discharged to a beach area, generally with a base slope of over 2% to facilitate flow layering of about 100 mm – 200 mm, initial de-watering and shedding of precipitation.
- The thin layers undergo an initial de-watering phase due to shear and settlement of the MFT flocs on the beach, followed by downward drainage and environmental de-watering (evaporation or freeze/thaw) during the following days and weeks.
- The deposit may also be worked with mobile equipment to control slope and promote de-watering as is practiced with “red mud” in the bauxite-alumina industry.

The challenges with this method are:

- To achieve timely and effective mixing and contact of the polymer with the clay particles. This is a challenge because the MFT is denser and more viscous than is normal for polymer mixing in conventional mechanical thickeners.
- To transport and discharge the material on the beach at just the right stage of flocculation, (neither under-flocculated nor over-sheared) to avoid a “gel condition” and achieve optimal de-watering.

Polymer addition to thick slurry is not a well-established art. It will require considerable refinement to achieve optimum conditions. As illustrated in the batch polymer-MFT mixing test shown below (Figure 7)[*], the optimum time for maximum dewatering potential has a relatively narrow window.

To develop a continuous injection and control system for large-scale continuous field operations with variable MFT input properties will undoubtedly require a number of iterations of improvement following field experience. Effective in-line flocculation and polymer optimization will benefit not only In-Line Flocculation - Thin-lift Deposition, but also other MFT processing methods such as centrifugation and accelerated dewatering.

The spatial and time metrics (average layer thickness, area coverage, time between layers, net fines loading achievable per unit area) for a full summer season of operation are yet to be demonstrated. These parameters will determine the extent to which this method is applicable in a specific operation and the unit costs. Clearly, more area will be required with this method than for centrifuged deposits.

Deposition of a few layers in winter, to go through the freeze-thaw cycle, is a companion method that deserves evaluation. The depth for this method will be limited by the time requirement for thawing in the spring, and the area will not be available for placement of an additional layer during the thaw period.

Another concept put forward by some operators (Shell, Suncor) is to layer the flocculated material on overburden (or otherwise mix the flocculated material with overburden) and then excavate and haul the blended material to an overburden dump. The cost of this double handling, and the impact on mine plans from potentially rendering the overburden into a weakened material unsuitable for dyke construction, must be evaluated for the specific site conditions.

[*] Polymer Mixing Test and CST Results per CANMET, courtesy of Syncrude Canada Ltd. and Total E&P Canada Ltd.

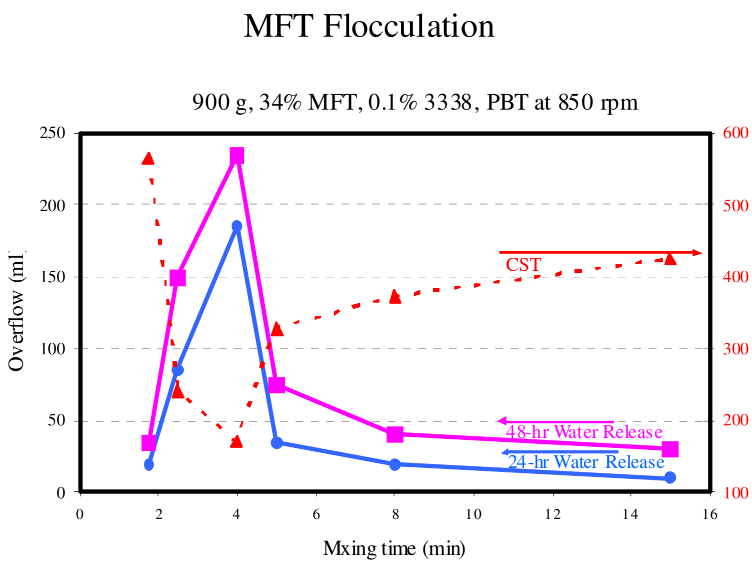


Figure 7

4.2.3 Accelerated De-watering

Syncrude is testing accelerated de-watering of in-line flocculated MFT (Lahaie, 2008). This method, also called rim-ditching, is employed in the Florida phosphate industry (Wayne A. Ericson, Carrier, et al.[4])

- Unlike with thin lift deposition, the flocculated mixture is discharged into a contained area at much greater thicknesses – for example 10 metres or more.
- A decant structure with removable boards is pre-installed in the containment area so that the level is reduced by board removal as water is released on the surface.
- Downward drainage may also be promoted by installing under-drains or placing the material on sand. While the rate of under-drainage may be lower than upward drainage, it has the advantage of not being interrupted by winter freezing.
- Once the surface is sufficiently strong, channelling of the surface to promote water flow to the decant structure, and perimeter ditching for additional water removal, are added.

Because of the containment requirement, this method is most useful for in-pit applications but it could also be used out-of-pit – for example within large sand-cells.
While the de-watering time for a 10-metre deposit may be greater than for a similar centrifuge deposit, the capital and operating costs are lower. Scaling this method to full operational deposit size has yet to be completed.

4.2.4 In-Pit Lake - Water Capping of MFT

Sequestration of MFT under a water cap in a completed mine pit is a method that has been under development and assessment for more than 20 years.

The principal features of this method are as follows:

- MFT is transferred into a mine pit generally below original topographical elevation in a geotechnically secure setting.
- Fresh water and/or tailings pond water is added to the surface.
- Lake contour design is important including lake depth profile and provision for development of a littoral zone with plant growth.
- Any further consolidation of the MFT will transfer naphthenic acids and related compounds into the active water layer where they bio-degrade over a 1 – 2 year period.
- Once the surface water has equilibrated to an acceptable quality, inflow and outflow are re-established to natural water courses.

Lakes in the temperate and subarctic zones typically exhibit dimictic behaviour – with the potential for wind-induced turnovers during near-isothermal conditions which can occur in both spring and fall. Water capping of MFT relies on the higher density MFT zone exhibiting merimictic behaviour (no turnovers) to avoid excessive uplifting of mud during the dimictic turnover of the upper layer. Lake water quality also depends upon aerobic biodegradation of naphthenic acids released from the MFT into the upper water layer.
This method has been successfully demonstrated in a 4-hectare pond at Syncrude and observed for over 15 years. What remains is to scale up and assess the results at a commercial scale as per the requirements in Syncrude's 1994 regulatory approval. The 800 hectare Base Mine Lake is scheduled to be water capped by 2012.

4.2.5 Thickened Tailings

As applied in the oil sands, thickened tailings generally refers to thickening a sand-depleted tailings stream. Typically, secondary recovery flotation cells are fed a middlings stream from the primary separator where the sand is withdrawn from the bottom. Alternatively, the primary tailings are cycloned and the cyclone overflow stream is fed to secondary flotation. In either case, secondary flotation tailings provide the feed source for thickening.
The thickening operation may be a high rate thickener or a paste thickener and the feed stream could have a sand:fines ratio (SFR) of 1 or as low as 0.1. A paste thickener with feed SFR of 1 can produce a thickened product of over 60% solids. A high rate thickener with feed SFR of 0.1 may produce underflow solids concentrations of less than 40%.
There are three potential disposal options for the thickener product (TT):

- The TT may be blended with cyclone sand to produce a variation of CT called NST as described previously.

- The TT may be discharged to a beach above water drainage surface and layered in thin lifts for further de-watering by under-drainage and surface drying.

- The TT may be discharged onto an underwater deposit using a tremie-diffuser to dissipate energy and avoid segregation and re-suspension into water. This method would be most useful in pit.

The main advantage of a TT process at ≈ 1:1 SFR over MFT treatment processes is that the coarser grain components make the TT deposit more permeable than an MFT deposit at the same solids content, resulting in a faster de-watering trajectory.
The disadvantages of this method are:

- The mass of material to be deposited is approximately doubled compared to an MFT process due to the inclusion of the coarse fraction in the thickener feed. (See following section on containment efficiency.) The increase in TT mass will be much further increased if fines are depleted from the beached sand through the cyclone preparation of the thickener feed.

- Unlike MFT treatment processes, the TT operation is directly connected to the bitumen recovery operation and exposed to the real time variation in oil sands feed characteristics and fines content. Recycle water quality targets must be met simultaneously with TT density targets. Extraction recovery objectives will often take precedence over thickener product goals, which could result in mal-operation of the thickener and segregation upon deposition of the TT.

4.3 Containment Efficiency

Excessive containment volumes can be costly and impede efficient mine development. Therefore, an important metric is the relative volume storage efficiency of fines, for various tailings products that require containment within dam structures. The Fine Tailings Volume plot illustrates the relative storage volume of fines, for various tailings materials with a range of sand-to-fines ratios (Figure 8). MFT generally has a sand-to-fines ratio of less than 0.1. Clearly, if limited in-pit volume is to be used for processed fine tailings products, dewatered MFT requires the least volume. As can be seen, CT and NST require very high volumes to store a comparable amount of fines, which may limit their use on some mine sites – particularly during early years of operation where no open pit is available. The advantages of MFT densification are also evident.

4.4 Other Research

Other novel dewatering methods have been proposed and are being researched. For example, work at the OSTRF (Oil Sands Tailings Research Facility) has tested slotted and porous-walled pipe on a small scale, for filtering tailings. In this method, whole tailings are dewatered sufficiently to produce non-segregating sand-fines slurry that would contain all of the feed fines in the sand discharge – thus avoiding generation of fluid fine tailings when this material is discharged onto a beach.
Monitoring progress of novel methods is important so that industry will be ready to support larger-scale testing of any worthy methods that show promise for practical application.

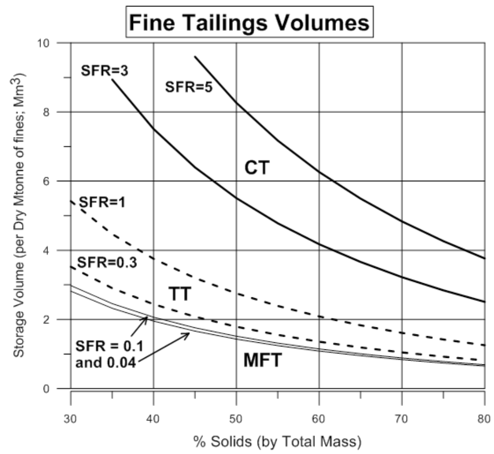


Figure 8

4.4.1 Processes Without Water Tailings

Waterless processing methods have been tested and proposed in the past to avoid fine tailings generation. Processes involving solvent recovery or direct retorting come with their own set of economic and environmental management challenges (e.g., solvent loss associated with exposure of the entire oil sand mass to solvent, fine particulates in SO_X-bearing combustion gas). Proponents of such processes do not often appreciate the remarkable efficiency of current water-processing methods. Based on currently available technology, the largest systems can process up to 10,000 tonnes per hour of oil sand (over 6000 lbs per second) through a simple, single processing sequence composed of crushers, vessels, slurry pumps & pipelines.
Sequestration of fines into oil sands reclaimed mine sites at reasonable cost is a challenge – but not an insurmountable one. While we cannot exclude the possibility of future R&D solutions, thus far, non-water processes have been found unattractive compared to the very efficient material handling and relatively simple processing based upon water.
To put the R&D cost challenge in perspective:

- Assume an ore body of 3 billion tonnes of processed oil sand yields 2 billion barrels of bitumen.

- If 5% of the solids fraction of the oil sand must be processed as 30% solids MFT, this amounts to 150 million tonnes (dry basis) of fines in MFT to be processed or just over 400 million cubic metres at 30% solids.

- If an aggressive method such as centrifugation is used at a net additional cost of $5/m^3, the undiscounted cost will be about $1 per barrel.

A cost of $1 per barrel will not render the industry uneconomic. However, it presents a significant R&D opportunity for economic improvement.

5 CONCLUSIONS

Given the current state of tailings management methods currently under active development the following conclusions can be made:

- A portfolio of fine tailings reclamation methods will be needed to achieve the mine reclamation and closure plans for the surface mines of the Athabasca oil sands. For most mines, several methods will be deployed with the site-specific conditions determining the proportion of use.
- There are no clear winners or losers among the methods being actively developed. Until full-scale design and operating performance parameters are known, the relative technical and economic assessments will be imprecise.
- Any of the fines-dominated, cohesive methods will require area for dewatering and may also benefit from being placed upon a low-sloped sand surface. Overall site plans need to recognize that sufficient area and large sand surfaces will be needed to effectively incorporate these methods into a site plan.
- In-pit deposits should be favoured over out-of-pit deposits for slow consolidating or weak materials.
- Progress on tailings management knowledge and technology could benefit from open cooperation. There is now a vast amount of industry data available with more coming as testing underway is completed. Technical knowledge would be advanced if industry data were to be openly available and work on solutions were fully shared.

6 REFERENCES

[1] Source: Submissions of Approved Oil Sands Mines under ERCB Directive 074.

The Approved Mine sites include:

Operator	Mine Site	MFT Volume Mm^3 (2010)
Canadian Natural Resources Ltd.	Horizon Mine (Ops. Started 2009)	Start-up volume only
Fort Hills Limited Partnership:	Fort Hills Mine (Ops. Not Started)	0
Imperial Oil Limited:	Kearl Mine (Ops. Not Started)	0
Shell Canada Limited:	Jackpine Mine (Ops. Not Started)	0
	Muskeg River Mine	67.6
Suncor Energy Inc.	Tar Island Mine (No longer producing) (Ponds 2,3,5,6,7)	250 (estimated)
	Steepbank & Millennium Mines (Ponds, 8A, STP1)	
Syncrude Canada Ltd.	Mildred Lake base Mine and North Mine	437.4
	Aurora North Mine	73.9
	Aurora South Mine (Ops. Not Started)	0
Total MFT Volume*		829*

*The ERCB number for the end of 2008 was 740 million m^3

[2] Sobkowicz & Morgenstern, “Oil Sands Tailings Reclamation – Technology Road Map”, 2009

[3] Rick Lahaie, “Syncrude Canada Ltd., “New Tailings Concepts”, International Oil Sands Tailings Conference, Edmonton, Alberta December 9, 2008

[4] Wayne A. Ericson, W. David Carrier, III, Luiz G. De Mello, and R.X. Gonzalez; Bromwell & Carrier, Inc. Lakeland, Florida 3380, “Stabilization and Design Planning for Reclamation of an Abandoned Phosphatic Clay Settling Pond”, Symposium on Surface Mining, Hydrology, Sedimentology, and Reclamation (University of Kentucky, Lexington, Kentucky 40506 – 0046 - December 2 – 7 1984)

[5] Scott, J.D. (2005) “Revisiting the Ternary Diagram for Tailings Characterization and Management”. *Geotechnical News*, December 2005, pp. 43-46.