Abstract

Bitumen extraction from surface-mined oil sands results in the production of large volumes of Fluid Fine Tailings (FFT). Through Directive 085, the Province of Alberta has signaled that oil sands operators must improve and accelerate the methods by which they deal with FFT production, storage and treatment.

This thesis aims to develop an enhanced method to forecast FFT production based on specific ore characteristics. A mass relationship and mathematical model to modify the Forecasting Tailings Model (FTM) by using fines and clay boundaries, as the two main indicators in FFT accumulation, has been developed. The modified FTM has been applied on representative block model data from an operating oil sands mining venture. An attempt has been made to identify order-of-magnitude associated tailings treatment costs, and to improve financial performance by not processing materials that have ultimate ore processing and tailings storage and treatment costs in excess of the value of bitumen they produce.

The results on the real case study show that there is a 53% reduction in total tailings accumulations over the mine life by selectively processing only lower tailings generating materials through eliminating 15% of total mined ore materials with higher potential of fluid fines inventory.

This significant result will assess the impact of Directive 082 on mining project economic and environmental performance towards the sustainable development of mining projects.
Acknowledgements

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I will always remember the endless love and influence of my mother. Mom you are my HEROINE. Thank you for the advice and discipline you instilled in me. I cannot imagine how my life would have been without your support and care.

Finally, I wish to thank my lovely son “Borna”. I dedicated this work to him for bringing lots of joy and noise to my life. I feel very much indebted to you for every moment that I did not spend with you. “Mom loves you forever”.

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<thead>
<tr>
<th><strong>Parameters</strong></th>
<th><strong>Definition</strong></th>
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<tbody>
<tr>
<td>Gbbl</td>
<td>Giga billion barrels</td>
</tr>
<tr>
<td>GDP</td>
<td>Gross Domestic Product</td>
</tr>
<tr>
<td>CHWE</td>
<td>Clark Hot Water Extraction</td>
</tr>
<tr>
<td>FFT</td>
<td>Fluid Fine Tailings</td>
</tr>
<tr>
<td>CT</td>
<td>Composite Tailings</td>
</tr>
<tr>
<td>AFD</td>
<td>Atmospheric Fine Drying</td>
</tr>
<tr>
<td>TRO</td>
<td>Tailings Reduction Operations</td>
</tr>
<tr>
<td>SFT</td>
<td>Solidified Fine Tailings</td>
</tr>
<tr>
<td>NST</td>
<td>Non-Segregating Tailings</td>
</tr>
<tr>
<td>MBI</td>
<td>Methylene Blue Index</td>
</tr>
<tr>
<td>EBV</td>
<td>Economic Block Valuation</td>
</tr>
<tr>
<td>AER</td>
<td>Alberta Energy Regulator</td>
</tr>
<tr>
<td>SCO</td>
<td>Synthetic Crude Oil</td>
</tr>
<tr>
<td>SAGD</td>
<td>Steam Assisted Gravity Drainage</td>
</tr>
<tr>
<td>PSV</td>
<td>Primary Separation Vessel</td>
</tr>
<tr>
<td>SSV</td>
<td>Secondary Separation Vessel</td>
</tr>
<tr>
<td>PSD</td>
<td>Particle Size Distribution</td>
</tr>
<tr>
<td>CEC</td>
<td>Cation Exchange Capacity</td>
</tr>
<tr>
<td>SA</td>
<td>Surface Area</td>
</tr>
<tr>
<td>CEAA</td>
<td>Canadian Environmental Assessment Agency</td>
</tr>
<tr>
<td>DDA</td>
<td>Dedicated Disposal Areas</td>
</tr>
<tr>
<td>Acronym</td>
<td>Description</td>
</tr>
<tr>
<td>---------</td>
<td>-------------</td>
</tr>
<tr>
<td>COSIA</td>
<td>Canada’s Oil Sands Innovation Alliance</td>
</tr>
<tr>
<td>k</td>
<td>Hydraulic Conductivity</td>
</tr>
<tr>
<td>e</td>
<td>Void Ratio</td>
</tr>
<tr>
<td>(V_v)</td>
<td>Volume of Voids</td>
</tr>
<tr>
<td>(V_s)</td>
<td>Volume of Solids</td>
</tr>
<tr>
<td>(V)</td>
<td>Volume of Sample</td>
</tr>
<tr>
<td>(M_s)</td>
<td>Sample Weight</td>
</tr>
<tr>
<td>(G_s)</td>
<td>Specific Gravity</td>
</tr>
<tr>
<td>(\rho_w)</td>
<td>Water Density</td>
</tr>
<tr>
<td>FTM</td>
<td>Forecasting Tailings Model</td>
</tr>
<tr>
<td>MT</td>
<td>Million Tonnes</td>
</tr>
<tr>
<td>NPV</td>
<td>Net Present Value</td>
</tr>
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</table>
Chapter 1

Introduction

1.1. Introduction to Alberta’s Oil Sands

Canada’s oil sands in northern Alberta are the largest proven reserves of oil sands deposits in the world and represent the third largest proven crude oil reserves after Venezuela (296 Gbbl) and Saudi Arabia (263 Gbbl) (Natural Resources Canada, 2015). Similar deposits of oil sands to those in Canada also have been found to date in Venezuela, the United States, Russia and the Congo (Oil Sands Tailings Dam Committee, 2014).

Alberta’s oil sands contain 167.2 billion barrels of recoverable bitumen. Three quarters of Alberta’s oil sands reserves are located in the Athabasca region, which are mostly recovered by open-pit mining (Natural Resources Canada, 2015).

In surface mining, the mined ore materials are crushed and mixed with hot water, and sometimes chemical additives such as sodium hydroxide, to extract the bitumen from sands. This method is called the Clark Hot Water Extraction Process (CHWE) and produces large volumes of tailings slurry (Kasperski & Mikula, 2011). The tailings are composed of sand, fines (silt and clay), water and residual bitumen and are stored temporarily in safe containment areas, known as settling or tailings ponds.

In a pond, the consolidation rate of fluid tailings decreases, and the fine particles become suspended within the water column to form Fluid Fine Tailings (FFT) (Kasperski & Mikula, 2011). The consolidation rate of FFT in this stage may take decades or longer to become Solidified Fine Tailings (SFT) with a solid content of about 70%, and this has created major environmental challenges (BGC Engineering Inc., 2010).
1.2. Statement of the Problem

Fluid tailings cannot be discharged to the environment. The regulatory requirements for mine site reclamation mean that, at some point, fluid tailings must be treated and reclaimed.

Through Directive 085, the Province of Alberta has signaled that oil sands operators must improve and accelerate the methods by which they deal with fluid tailings production, storage and treatment (Alberta Energy Regulator, 2016b).

As of 2013, 176 km$^2$ of land in northern Alberta had been occupied by tailings ponds, this being approximately 21% of the total mined area (Natural Resources Canada, 2015), which contain over one billion cubic meters of FFT, and are growing at 75Mm$^3$ per year (Alberta Innovates Energy and Environment Solution, 2014).

To date, no company has been able to meet government guidelines or either its own internally-set tailings treatment targets aiming to reduce the FFT accumulations.

Many studies have focused on tailings treatment, mainly through accelerating the dewatering rate in order to transform fluid tailings into a dry or solid landscape. Less attention has been paid to date to the linkage between different ore characteristics and the resultant tailings inventory. If different ore characteristics result in the production of different volumes of tailings (for a fixed mass of ore) there may exist the possibility to:

1) reduce the volume of fluid tailings produced by selectively processing only lower tailings generating materials

2) improve financial performance by not processing materials that have ultimate ore processing and tailings storage and treatment costs in excess of the value of bitumen they produce
The above considerations may require changes to how material to be processed is defined in oil sands mining. Under Alberta Directive 082, bitumen grade, continuity, and a stripping ratio proxy are used to discriminate ore and waste, not economic criteria (Alberta Energy Regulator, 2016a)

1.3. Objectives of the Study
Mining cannot be scheduled regardless of potential tailings generation due to the capacity of tailings storage facilities and the limitations of leased areas. In the case of oil sands mining, tailings production also has a mutual relationship with water use. The two parameters of water and land use have a direct impact on economic aspects of mining projects and are subject to environmental limitations and regulations.

The objective of this thesis is to develop, based on literature review, a method to predict how an ore will process based on properties contained in the mining block model and to prepare a mass relationship and mathematical model for predicting tailings accumulation as a function of different ore properties.

In order to predict how an ore will process, to set appropriate operational strategies, and to assess the linkage between different ore facies and tailings inventory, the main components of an ore and its associated tailings, as well as their characteristics, behavior and reaction with other minerals and process chemical(s) on FFT inventory, need to be identified. These data can be applied as the main indicators to develop the theoretical Forecasting Tailings Model (FTM).

Therefore, this study will be divided into three areas in order to achieve the thesis objectives:
(i) A review of oil sands ore properties and their characterization, including literature review

(ii) Determination of tailings properties and their influence on FFT inventory

(iii) Identification of indicator ranges to use in the FTM for different tailings streams

The potential impact of the theoretical model will be assessed using an industrially-supplied block model that is representative of a typical oil sands deposit. A corresponding tailings model will be evaluated economically using an Economic Block Valuation (EBV) process. Then the associated costs of tailings treatments and remediation using the FTM approach versus the criteria of Directive 082 can be assessed.

1.4. Research Methodology

In order to achieve the thesis objectives, a research methodology has been designed to group each block of ore into high, medium and low tailings streams based on percent fines (materials sized at <44µm), clay content, host reservoir environments of deposition and ore facies descriptions.

A comprehensive literature study on the use of fines and clay boundaries as the two main indicators in FFT accumulation has been conducted to develop the Forecasting Tailings Model (FTM).

The clay content of an ore has been obtained using the Methylene Blue Index (MBI) technique which was made available from block model data (Omotoso et al., 2007).

These studies, in combination, have been used to estimate the amount of tailings produced with specific sets of ore properties resulting from certain amounts of ore of a specific composition.
Then, blocks of ore with similar bitumen contents and different FFT streams have been compared volumetrically and financially.

In this research the EBV has been used only to provide an indication of the specific tailings cost associated with each block in the model. A full block valuation would require additional data on mining and processing costs, material-specific recoveries, etc.

The uniqueness of this study is that the ore blocks, used to meet the required criteria to classify them as ore and to assess revenue generation potential, might be omitted with respect to fluid tailings generation and bitumen value using the FTM approach.

1.5. **Structure of the Thesis**

This thesis is presented in five chapter sections.

Chapter 1 presents the introduction of this study, statement of the problem, the objectives of the study and the research methodology.

Chapter 2 introduces oil sands mining procedures, ore properties, processes used and current tailings challenges in the first part. In the second part, the characteristics of different ores and clays as main components of oil sands tailings are briefly explained.

The theoretical framework to initiate the methodology for the forecasting tailings model is provided in Chapter 3. The important and general factors affecting the consolidation rate of tailings are discussed in the first part of this chapter. In the second part, based on available data, a quantified model is presented in order to achieve the objectives of this research.

Chapter 4 is concerned with the verification of the FTM using the most profitable blocks of ore, with the primary objective being for minimizing fluid tailings inventory in the earliest stage of planning throughout the mine life. The main aim of providing this simulation model is to specify
the associated tailings treatment and storage costs for different ore properties. This cost can be a factor to define the actual profitable ore in open pit optimization practice. Then, the sensitivity analysis will be done on the basis of FFT production for different variable inputs in this chapter. Finally, Chapter 5 provides a summary of research, contributions of the research, conclusions and recommendations for future work.
Chapter 2

Literature Review

This chapter summarizes a literature review of oil sands ore properties, mining procedures, processing operations, tailings properties and management. The main aim of this study is to discover primary characteristics of oil sands that influence extraction and tailings volumes.

2.1. Oil Sands Ore Properties and Classification

Oil sands are composed of 55-80 wt. % solid contents (sand, silt and clays), 0-16 wt. % bitumen and 0-7 wt. % water. The water contains dissolved ions such as sodium, calcium, magnesium, chloride, potassium, sulphate and bicarbonate. The bitumen, as an unconventional fossil fuel, is an extra heavy oil with high viscosity, density and heavy metal concentrations, and a low hydrogen to carbon ratio, which makes the oil extraction process more costly, compared to that for conventional oil recovery (Masliyah et al., 2013).

Takamura (1982) presented a description of the generic microscopic structure of Athabasca’s oil sands. As shown in Figure 1, the bitumen particles are surrounded by sand particles. A thin layer of water separates bitumen from sand particles, and, as the water content of an ore increases, the bitumen content decreases (Takamura, 1982). Also, the bitumen and water contents vary and depend on the ore variation and the clay mineralogy (Kasperski, 2001).
Figure 1: Microscopic structure of Athabasca oil sands (Takamura, 1982)

Of the solid component, 92% of the sand component is composed of quartz. Some other trace minerals, such as mica, rutile, zircon, tourmaline, vanadium, and pyrite, are also found in the sand composition (OSDC, 2014).

Fines in the solid component mostly consist of silt and clay. Kaolinite (40-70 wt %) and illite (28-45 wt %) are the dominant clay minerals in Athabasca’s oil sands (Chalarturnyk et al., 2002). The other common clay minerals are montmorillonite (1-5 wt %), chlorite (~1%), smectite (~0.3%), and mixed layer clays (~1.7%) such as kaolinite-smectite and illite-smectite (Masliyah et al., 2013).

There are several ore classification schemes for oil sands based on the bitumen content, fines content and the processibility of ore as indicated in Table 1 (Kaminsky, 2008; Kasongo et al.,
The Alberta oil sands industry has traditionally used the 44µm size as the boundary between fines and sand solids. The material which passes a 325 mesh sieve (<44µm) is classified as fines in the industry (Boratynec, 2003).

Table 1: Oil sands ore classification

<table>
<thead>
<tr>
<th>Methods of Classification</th>
<th>Content</th>
<th>Ore Classification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bitumen %</td>
<td>&gt; 10</td>
<td>High</td>
</tr>
<tr>
<td></td>
<td>between 8-10</td>
<td>Medium</td>
</tr>
<tr>
<td></td>
<td>&lt; 8</td>
<td>Low</td>
</tr>
<tr>
<td>Fines Content %</td>
<td>&gt; 18</td>
<td>High Fines Ore</td>
</tr>
<tr>
<td></td>
<td>&lt; 6</td>
<td>Low Fines Ore</td>
</tr>
<tr>
<td>Processability</td>
<td>bitumen &gt; 10</td>
<td>Good Processing Ores</td>
</tr>
<tr>
<td></td>
<td>Fines &lt; 6</td>
<td></td>
</tr>
<tr>
<td></td>
<td>bitumen &lt; 8</td>
<td>Poor Processing Ores</td>
</tr>
<tr>
<td></td>
<td>Fines &gt; 18</td>
<td></td>
</tr>
</tbody>
</table>

(Kaminsky, 2008; Kasongo et al., 2000)

A cutoff in the bitumen grade has been considered at 7% and a minimum ore thickness of 3 meters in Athabasca oil sands mining operations has been regulated based on Directive 082 (Alberta Energy Regulator, 2016a).

Another ore classification by Masliyah et al. (2013) has classified ore into the three different groups based on bitumen content as low, medium and high grade ores with bitumen contents between 7 to 8%, 8 to 10.5% and greater than 11% respectively (Masliyah et al., 2013).

The Alberta Energy Regulator (AER) has also classified ore into rich (>12% bitumen) and poor (<7% bitumen) based on the bitumen content.

In oil sands mining, the bitumen grade greater than 7% is considered as ore due to the criteria of Directive 082 (Alberta Energy Regulator, 2016a).
2.2. Oil Sands Mining and Processing

To date, two methods are used to extract the oil sands in Athabasca and convert it to synthetic crude oil (SCO): by surface mining and in-situ methods.

Surface mining is used for shallow deposits with 75 meters or less thickness of overburden (Energy Resources Conservation Board, 2008), by excavating through benches or steps and using off-highway haul trucks and mining shovels to extract and move the ore. Vegetation and overburden consisting of muskeg, glacial tills, sandstone and shale are removed first to expose the oil sands formation. At the end of the mine life, mined out areas are backfilled with overburden and tailings, and backfill is subsequently compacted by driving 400 tonne trucks over it (Natural Resources Canada, 2015).

In-situ methods are mostly used when the oil sands are located hundreds of meters below the surface, and are not economically feasible to be mined by surface mining.

Six large projects in Alberta use surface mining, and are mostly located in the Athabasca region of the Fort McMurray Formation. These are the Syncrude Mining Project, Suncor Base Mine, CNRL Horizon Mine, Athabasca Oil Sands Project (Shell Canada) in Muskeg River, Jackpine Mine and Imperial’s Kearl Mine (Natural Resources Canada, 2015).

The schematic process of bitumen extraction using the surface mining method is shown in Figure 2. This process is called the Clark Hot water Extraction (CHWE) process and has been used commercially in the oil sands industry since 1967 (Kaminsky, 2008).
As is indicated in Figure 3, the excavated and crushed oil sands are transferred to a processing facility, where hot water and sometimes process chemicals like sodium hydroxide (NaOH) or calcium citrate are added to produce a slurry. These process aids are added to improve the bitumen recovery by raising the slurry pH, and repelling the bitumen from sand which has been surrounded by a water film (Masliyah et al., 2013).

The slurry is hydraulically transported to a primary separation vessel (PSV) and is separated into three different layers by a gravity settling process. Sand settles on the bottom as a coarse stream.
(> 44 µm), a middlings stream (< 44µm) which sits in the middle (consisting of sand, clay, water, residual bitumen, process aids, and minor impurities), and a thin layer of bitumen that floats on the surface and is pumped for further processing in the froth treatment plant. The process separates bitumen via froth flotation, and produces a tailings stream that is composed of water, residual bitumen, sand, silt and fines. Tailings streams are impounded in surface tailings ponds for separation through time.

2.3. Oil Sands Tailings Properties

Typical oil sands tailings properties in tailings ponds are shown in Table 2. A tailings slurry stream has about 55 % solids where the solids consist of 82 % sands, 17 % fines, which mostly consist of clay, 1-3 % residual bitumen and some organic chemicals such as naphtha (0-1%). The solid content in FFT may take few years to reach about 30% to 35% which is mostly composed of fines and clay (> 95%) (Beier et al., 2013; Chalaturnyk et al., 2002).

Table 2: Oil sands tailings properties

<table>
<thead>
<tr>
<th>Tailings Slurry (typical values)</th>
<th>Fluid Fine Tailings (typical values)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solids Content (55%)</td>
<td>Sand Content 82%</td>
</tr>
<tr>
<td>Fines Content 17%</td>
<td></td>
</tr>
<tr>
<td>Fluid Content (45%)</td>
<td>Fines Content &gt;95% (30%-35% clays)</td>
</tr>
<tr>
<td>Fluid Content (60%-70%)</td>
<td></td>
</tr>
</tbody>
</table>

(Beier et al., 2013)
In Table 2, non-captured bitumen in FFT can be assumed to exist as a solid phase due to very low mobility and high viscosity of the bitumen. Typical schematics of tailings pond is shown in Figure 3 (Imperial, 2015).

![Figure 3: Schematic view of tailings pond (Imperial, 2015)](image)

In a pond, tailings slurry solids are settled through gravity separation. Sand particles are settled rapidly from the slurry at the edge of the tailing ponds to form beaches and dykes, and are easy to reclaim. The top 1 to 3 meters of the pond is referred to as recycled water which is sent back to the extraction plant (Devenny, 2010). The second layer in the middle of a pond is referred to as fluid tailings, and it settles to about 30% to 35% solids content after a few years of placement (Beier et al., 2010).

The segregation behavior of FFT has been studied extensively, and shows that solids settling is dependent on the mineralogy of the clay content, fines particle size distribution and solids content (Azam & Scott, 2005).

### 2.4. Linkage Between Oil Sands Ore Mineralogy and Bitumen Recovery

The physical and chemical properties of oil sands ore play an important role in the processibility of ores and operational conditions. The high grade ore typically contains less fines, and therefore
has a good recovery (Liu et al., 2004). Low grade ore produces large volumes of FFT and uses more water which will not be feasible for mining (Devenny, 2010).

The physical properties of oil sands are divided into the bulk properties and interfacial properties (Masliyah et al., 2013).

The density and viscosity of bitumen, particle size distribution of fines (PSD), the pH of the formation water and its Na, Ca, K, Mg, Cl and bicarbonate concentrations, are all included in bulk property characteristics. The interfacial properties, which deal with the interactions between coarse and fine solids, bitumen droplets, and air bubbles, are influenced by surface characterization of fine solids, clay content and their mineralogy. For example, the attachment of bitumen droplets either into the sand grains or clay particles is impacted by surface characteristics such as wettability and surface charge of the clays, bitumen and sand grains (Masliyah et al., 2013).

Studies by Takamura & Wallace (1988), Kasongo et al. (2000) and Wallace et al. (2004) have been done to investigate the impact of the process water chemistry and oil sand characteristics on processibility.

An investigation by Takamura and Wallace (1988) indicated that, in slurry at a certain pH and in the presence of sodium ions, the clays are coagulated and increase in viscosity, and therefore inhibit bitumen floatation.

Kasongo et al. (2000) did an empirical test procedure to emphasize the impact of the presence of calcium ions and clays in reducing the bitumen recovery for high grade ore (Sanford & Seyer, 1979; Sanford, 1983; Smith & Schramm, 1992).

This study observed that the bitumen recovery decreased due to the strong affinity of calcium ions on montmorillonite clays to bitumen droplets. When attached calcium ions and
montmorillonite clays interacted with bitumen droplets, calcium carboxylate is coagulated. This process hindered bitumen floatation by air, while kaolinite and illite clays did not have similar impacts on bitumen recovery (Kasongo et al., 2000). In 2004, Wallace et al. indicated that soluble potassium ions, which could be associated with the presence of degraded illitic clay, decreased bitumen recovery. This degraded illite expresses the swelling character of montmorillonite which is caused to coagulate solids and to increase the viscosity in the middlings (Wallace et al., 2004). Also Tu et al. (2005) demonstrated that ultra-fine clays (<0.3µm) are responsible for the gel structure of FFT and lower the rate of densification of fines which will impact the processability of bitumen in separation vessels and for froth treatment as well (Tu et al., 2005). Although many efforts have been made to demonstrate the impact of bulk properties of oil sands ore on bitumen recovery, it is equally important to understand the clay characteristics and mineralogy of these materials in the oil sands. Their characteristics play a very important role in forming the gel structure of FFT streams for providing further densification, and therefore impact bitumen recovery.

2.5. Oil Sands Clay Mineralogy and Characteristics on FFT Generation

The term clay is generally applied to very tiny sized particles, smaller than 2 micrometers that have plastic properties. Scientifically, clays are described as hydrous aluminum phyllosilicates with layers of tetrahedral and octahedral sheets (Pauling, 1930). These layers are able to exchange cations on the interlayer surfaces. Through this exchange process the shape of the molecular structure changes and results in totally different characteristics and structure (Kaminsky et al., 2009).
In highly ionic environments, in which residual bitumen is present, the physical behavior of clay minerals is changed by increasing the plasticity index and the yield strength of the clay content, which causes less densification and bitumen floatation.

Information concerning 27 clays assessed, by Skempton (1953) indicated that this change may be due to the relationship between the activity, mineralogy and geological history of a clay. The clay activity is measured by dividing the Plasticity Index (PI) over the clay-sized particles present.

Based on Skempton’s study, three classes of clay were recognized with each having different clay activity characteristics, these being inactive, normal and active clay. Normally the activity of clay is between 0.75 and 1.25 (without unit), and in this range clay is called normal. Clay with activity less than 0.75 is called inactive and greater than 1.25 is considered as active clay.

Skempton (1953) presented the activity values for various clay minerals as shown in Table 3. Based on Table 3, various clay mineralogies and geological histories of clay resulted in different ranges of clay activity (Skempton, 1953). The activity of clay is the Plasticity Index (PI) divided by the percent of clay-sized particles present. Due to the different specific surface areas of the various types of clays, different amount of wetting is required to move a soil from one phase to another such as across the liquid limit or the plastic limit. Therefore, various clay types contain different clay activity. A complete explanation of clay activity will be provided in Chapter 3.
Table 3: Values of activity for some clay minerals

<table>
<thead>
<tr>
<th>Minerals</th>
<th>Activity</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>0</td>
<td>Van Moss (1938)</td>
</tr>
<tr>
<td>Calcite</td>
<td>0.18</td>
<td>Van Moss (1938)</td>
</tr>
<tr>
<td>Mica</td>
<td>0.23</td>
<td>Van Moss (1938)</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>0.33</td>
<td>Van Moss (1938)</td>
</tr>
<tr>
<td></td>
<td>0.46</td>
<td></td>
</tr>
<tr>
<td>Illite</td>
<td>0.90</td>
<td>Northey (1950)</td>
</tr>
<tr>
<td>Ca-montmorillonite</td>
<td>1.5</td>
<td>Samuels (1950)</td>
</tr>
<tr>
<td>Na-montmorillonite</td>
<td>7.2</td>
<td>Samuels (1950)</td>
</tr>
</tbody>
</table>

(Skempton, 1953)

Kaminsky (2008) summarized the literature on the clay mineralogy of Athabasca’s oil sands deposits. This study indicated that the dominant clay minerals in this region are typically kaolinite (50 to 60%) and illite (30-50%). In addition, montmorillonite, minor amounts of chlorite, vermiculite and mixed layer clays such as kaolinite-smectite or illite-smectite have been identified (Chalaturnyk et al., 2002; Kaminsky, 2008).

It is observed in all studies that the major clay minerals in oil sands, these being kaolinite and illite, have fairly low clay activities in comparison with the smectite group clays (such as montmorillonite) resulting in lower cation exchange capacity (CEC), surface area (SA) and yield strength characteristics. Therefore these clays are less responsible for the gel structure of the FFT.
Furthermore, other clay minerals such as montmorillonite are not widely distributed in oil sands and may have less impact on gel-structure tailings behavior.

The question that arises is why is there a discrepancy in tailings properties observed?

In seeking an answer, other components of oil sands, such as amorphous iron, silica fine solids and interlayered clay minerals with higher CEC and SA, have been investigated.

Kotlyar et al. (1990) indicated that amorphous iron and silica fine solids can be a main reason for the lower densification rate (Kotlyar et al., 1990). However this theory was denied by Zhou et al. (1999) and Omotoso et al. (2002) since silica, in the presence of calcium, is absorbed onto the bitumen, thereby affecting bitumen recovery in a froth treatment plant and producing less impact on the middlings fraction (Omotoso et al., 2002; Zhou et al.).

A study of a low grade oil sands samples from the Suncor lease, with 8.5% bitumen that was done by Kaminsky (2008), indicated that kaolinite is more likely an issue in froth treatment but that illite-smectite will likely be more of an issue in tailings disposal. The influence of these interlayered clay minerals has not been well defined. However it seems that the mixed layer clays, such as illite-smectite or kaolinite-smectite are more likely to create poor settling of fines in oil sands tailings (Kaminsky, 2008).

Furthermore, the electro-chemical activity of the clay and non-clay minerals, which affects the permeability and compressibility of the system, will impact settling and consolidation rates in fluid tailings and can be used to define clay type(s) (Kasperski & Mirkula, 2011).

Low hydraulic conductivity and high compressibility will hinder rapid dewatering, consolidation and any ion exchange mechanism which is caused by negative surface charges of clay particles (Azam & Scott, 2005). The hydraulic conductivity can be calculated using knowledge of the void
ratio and the degree of saturation of fines content which is not commonly measured in the oil sands industry.

2.6. Fine Tailings Management

The large volume of fluid tailings created needs to be densified to Solid Fine Tailings (SFT) having a density of 70% solids by weight to become a self-supporting solid for reclamation purposes (Kasperski, 2001).

Kasperski and Mikula (2011) summarized a study on fine tailings management procedures for FFT which required the following handling steps:

- “Wet-landscape reclamation by storing the FFT in end-pit lakes under the water capping
- Composite Tailings (CT) by mixing FFT and sand in the correct ratio to produce non-segregating tailings (NST) for rapid settling and then pump the released water for recycling.
- Rim-ditching by digging a ditch around the rim to increase dewatering
- Thin-lift dewatering by spreading FFT in shallow slope in order to drain the water away
- Centrifugation by spinning FFT to create a solidified material”

Although some of the mentioned tailings treatment technologies such as CT and rim-ditching are commercially used in the oil sands industry, only one tailings pond (Suncor-pond 1) has been reclaimed to date and one billion cubic meters of FFT have been stored in tailings ponds (Chalaturynyk et al., 2002). The characteristics and behavior of clays control the segregation rate of fluid tailings and have not been considered in the current tailings treatment methods.
Thus, the Province of Alberta has signaled that oil sands operators and stakeholders must commit to improve and accelerate the methods by which they deal with fluid fine tailings production, storage and treatment through Directive 085 (Alberta Government, 2015). This framework has been approved by the Alberta Energy Regulator (AER), and has identified several requirements for managing and reducing fluid tailings volumes on the landscape during and after mine operation as follow:

- “to minimize and eventually eliminate long-term storage of fluid tailings in the reclamation landscape;
- to create a trafficable landscape at the earliest opportunity to facilitate progressive reclamation;
- to eliminate or reduce containment of fluid tailings in an external tailings disposal area during operations;
- to reduce stored process-affected waste water volumes on site;
- to maximize intermediate process water recycling to increase energy efficiency and reduce fresh water import;
- to minimize resource sterilization associated with tailings ponds; and
- to ensure that the liability for tailings is managed through reclamation of tailings ponds”

The oil sands operators are required to meet the requirements of Directive 085, by using suitable tailings management techniques and must report on annual fluid tailings volume and quantity of fines in the processed ore and FFT.
The Alberta Energy Regulator (AER) will conduct annual supervision over all mining operations’ performance and plans to eliminate the growth of tailings ponds.
Chapter 3

Examination of the Causes of Fluid Fine Tailings Generation

This chapter focuses on developing a linkage between ore properties and fluid fines tailings generation. The general theoretical frameworks and mathematical formulations are developed to initiate the algorithm for the forecasting tailing model by constructing the mass balance relationship between the ore facies and fluid fine tailings generations as a function of fines content and clay indicators.

3.1. Ore and FFT Mass Balance Relation

The oil sands deposits contain different mixtures of ore grades. Such variations are encountered for ores from different mines and from one location to another within the same mine. In order to develop the mass balance relation between oil sands ore and fluid fine tailings, the main components of oil sands ore, such as bitumen grade, mineral solids which are mostly composed of fines content and clay content, and their impacts on FFT accumulation, should be recognized and quantified. Also, the amount of FFT components such as fines, clays and water need to be measured and tracked.

3.2. Bitumen Grade

The range of bitumen grades in Athabasca’s oil sands varies from 0 % to 16 % by weight. The oil sands bitumen content ranges in four commercial oil sands open pit mines in this region is from about 9 % to 13 % with a minimum cutoff grade of 7 % bitumen (Masliyah et al., 2013).
Bitumen grade impacts the hot water extraction process, and therefore fluid fine tailings inventory. Lower bitumen grade ore produces higher amounts of FFT due to the higher amounts of fines present.

However, in this study, the bitumen grade variation has not been considered and bitumen content greater than 7% has been selected to develop the forecasting tailings model based on Directive 082 (Alberta Energy Regulator, 2016a)

3.3. Mineral Solids

A typical mineral solids component analysis by x-ray diffraction analysis in coarse and fine solids fractions of oil sands ore is given in Table 4 (Hepler & Smith, 1994). Heavy minerals, such as titanium, also have been found in smaller sized fractions of mineral solids.

Table 4: Mineral components in a typical oil sands deposit

<table>
<thead>
<tr>
<th>Mineral</th>
<th>Weight Percent</th>
<th>Mineral</th>
<th>Weight Percent</th>
</tr>
</thead>
<tbody>
<tr>
<td>Quartz</td>
<td>82</td>
<td>Kaolinite</td>
<td>4</td>
</tr>
<tr>
<td>K-feldspar</td>
<td>5</td>
<td>Illite</td>
<td>7</td>
</tr>
<tr>
<td>Calcite</td>
<td>Trace</td>
<td>Chlorite</td>
<td>1</td>
</tr>
<tr>
<td>Dolomite</td>
<td>Nil</td>
<td>Smectite</td>
<td>Trace</td>
</tr>
<tr>
<td>Siderite</td>
<td>Trace</td>
<td>Mixed layer clays</td>
<td>1</td>
</tr>
<tr>
<td>Pyrite</td>
<td>Nil</td>
<td>Anhydrite</td>
<td>Trace</td>
</tr>
</tbody>
</table>

(Hepler & Smith, 1994)
The particle size distribution (PSD) of mineral solids is from sub-micron (fines sized particles < 44µm) to over 1 mm (coarse size particles >44µm) and is not constant across the Athabasca region.

The PSD of mineral solids has a significant impact on designing tailings disposal sites and pipelines due to the minimum required velocity to move the slurry. In addition, this factor plays an important role in oil sands tailings accumulations. Low grade ores contain finer-sized mineral solids, whereas coarse solids are present in high grade ores (Masliyah et al., 2013). To some extent, the bitumen grade is correlated to the percent fines content. A high fines content ore leads to a lower bitumen recovery, accompanied by a high FFT inventory (Kasperski & Mikula, 2011). Masliyah et al. (2013) presented the relationship between percent fines and bitumen grade, as shown in Figure 4. Despite the high degree of scatter in this plot, which is expected from a natural formation, the clear trend shows that the high grade ores are associated with lower percentages of fines and thereby lower FFT generation.

Figure 4: Relationship between bitumen grade and percent fines (Masliyah et al., 2013)
The same degree of correlation between bitumen grade and percent fines has been recently presented by Cuddy (2004) for mines operated by Syncrude, Suncor, and Imperial Oil (Masliyah et al., 2013).

The visual correlation shown in Figure 4 demonstrates that, in order to develop the forecasting tailings model, apart from bitumen grade, ores need to be classified on the basis of different fines and clay contents, as a dominant component of fines.

3.3.1. Fines Content of Mineral Solids

Many studies have focused to date on determining the fines boundaries in low, medium and high grade oil sands ore.

Sanford (1983), classified that high fines content ores contain more than 20% fines. Masliyah and Murray (1999) expressed that high grade ores (greater than 10% bitumen) are also known as low fines ores, and contain less than 17% fines; low grade ores (less than 8% bitumen) contain greater than 25% fines; and medium grade ores (between 8% to 10% bitumen) contain between 17% and 25% fines (Figure 5).
Another ore classification by Kasperski (2001) categorized oil sands ores into the high fines content ores with more than 18% fines and low fines content ores with less than 6% fines. In addition, Liu et al. (2004) demonstrated that ores with less than 10% fines content are classified as a low fines ore, and ores containing more than 35% fines content are classified as high fines ores.

One study on bitumen extraction of high and medium grade ores for four samples, with similar bitumen, water and solids contents but different percent fines, expressed a reduction on bitumen recovery for high fines content ores with more than 20% fines (Srinivasa, 2010).

A summary of the previous studies is provided in Table 5.
Table 5: Summary of different studies on ore classification based on fines contents

<table>
<thead>
<tr>
<th>Author</th>
<th>High Fines Ores (%)</th>
<th>Medium Fines Ores (%)</th>
<th>Low fines Ores (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sanford (1983)</td>
<td>&gt;20%</td>
<td>&lt;20%</td>
<td></td>
</tr>
<tr>
<td>Masliyah &amp; Murray (1999)</td>
<td>&gt;25%</td>
<td>18% to 25%</td>
<td>&lt;18%</td>
</tr>
<tr>
<td>Kasperski (2001)</td>
<td>&gt;18%</td>
<td>&lt;6%</td>
<td></td>
</tr>
<tr>
<td>Liu et al. (2004)</td>
<td>&gt;35%</td>
<td>&lt;10%</td>
<td></td>
</tr>
<tr>
<td>Srinivasa (2010)</td>
<td>&gt;20%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Based on the literature review, the different tailings streams have been classified based on the percent fines, using the results of Masliyah and Murray (1999) (Table 6).

This approach can be extended to ores with different characteristics across the entire Athabasca oil sands region.

Table 6: Relationship between fines content of mineral solids and FFT generation.

<table>
<thead>
<tr>
<th>Fines Content (%)</th>
<th>FFT generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 18%</td>
<td>Low FFT</td>
</tr>
<tr>
<td>18-25%</td>
<td>Medium FFT</td>
</tr>
<tr>
<td>&gt;25%</td>
<td>High FFT</td>
</tr>
</tbody>
</table>

(Masliyah & Murray, 1999)
3.3.2. Clay Content of Mineral Solids

Sanford (1983) indicated a positive correlation between percent fines and smaller sized minerals (sized particles < 1.9 µm and sized particles < 5µm) (Figure 6). This reasonable correlation led to use of 44 µm as a cutoff size marker for fines solids in the oil sands industry. Clays refer to particles that are smaller than 2 µm by this industry, which only appear in the fines fraction of solids, and need to be taken into account in developing a forecasting tailings model.

Figure 6: Relationship between fines particles and smaller sized minerals (<5 µm and <1.9 µm) (Sanford, 1983)

The clay content and types of minerals, a major component of fines content, affect bitumen recovery, the froth treatment plant, tailings management and process-affected water recycling capabilities, as listed: (Masliyah et al., 2013)

a) in bitumen recovery, clays cause slime coating on bitumen droplets, make a gelation
s

lurry form, and hinder bitumen floatation to the surface of the primary separation vessels.

b) in the bitumen froth treatment plant, clays stabilize the emulsion of water in diluted bitumen and create challenges in downstream upgrading.

c) in tailings management ponds, slow settling and consolidation rate of fine particles is mainly attributed to clays due to the high specific area and cation exchange capacity.

In order to investigate the impact of clay minerals in FFT accumulations, a better understanding of clay types, amounts and physical properties as a continuing problem in oil sands tailings segregation should be taken into account. Additionally, the commercial practice for specifying and quantifying clay types and content on bitumen recovery or FFT accumulations based on the current available data needs to be applied.

Kasongo (2006) investigated the impact of different clay types and water chemistry on bitumen recovery depletion, even for high grade bitumen ores which resulted in tailings volume growth as well.

In this regard, the effect of 20 bulk raw ore samples, using poor and good processing ores containing 6.05%-14.88% bitumen grade from the Syncrude Mildred Lake Mine, Aurora Mine and Albian Sands Energy Inc. Muskeg River Mine, on bitumen recovery was tested. In laboratory tests, lower primary bitumen recovery for some higher grade ore samples containing 12.8%-13.6% bitumen was observed, in contrast to higher bitumen recovery for lower grade ore samples containing 10.3-10.74% bitumen (Kasongo, 2006).

These results identified two major factors in bitumen recovery and tailings accumulations:

1) the effect of additional montmorillonite clay content in ores which was not observed with
kaolinite and illite clays

2) and the presence of calcium ions in water

The same result, this being the poor recovery of higher grade ores, was demonstrated earlier by Crickmore et al., (1989).

However, these results were in contradiction to the expected behavior of oil sands ore shown by Kasperski (2001), who demonstrated that higher grade ores (having less fines content) featured a higher bitumen recovery. In this work, clay types and contents were neglected in assessing processibility of ore and FFT produced.

Therefore, in order to develop the forecasting tailings model based on clay types and contents for each block of ore, the clay mineralogy and the physical properties of clay, such as cation exchange capacity, charge distribution and clay activity, need to be well known which will be explained in the following study.

**3.3.2.1. Clay Type Mineralogy**

Clay minerals are composed of two basic layers: a silicon-oxygen tetrahedron sheet (SiO$_2$) (T) and an aluminum-oxygen-hydroxyl octahedron (AlO$_6$) (O). Different clay minerals are defined based on the arrangement of these two basic layers, where kaolinite is made of two-layers (1:1 or -TO-TO-) and illite and montmorillonite groups are made of three-layers (2:1 or -TOT-TOT-) (Figure 7) (Konan et al., 2007). These three-layers are held together by sharing oxygen and hydroxyl groups between them and are electrically neutral (Kasongo, 2006).
Illite differs from montmorillonite by the absence of interlayer water and belongs to a different class of three-layer structural clay. Montmorillonite belongs to the smectite group of clay. The smectite group clays are easily delaminated and water or electrolyte solution can be placed between layers, thereby increasing the layer thickness (Masliyah et al., 2013).

Additionally, weathered illite is known to behave similar to smectite-montmorillonite in ion exchange capacity.

The structures and characteristics of four common clay minerals in oil sands are given in Table 7 (Mitchell, 1976).
Table 7: Characteristics of four common clay minerals in oil sands

<table>
<thead>
<tr>
<th></th>
<th>Kaolinite</th>
<th>Illite</th>
<th>Montmorillonite</th>
<th>Chlorite</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Composition</strong></td>
<td>Al₂Si₂O₅(OH)₄</td>
<td>K(Al,Fe,Mg)₅(Al,Si)₈O₂₀(OH)₄</td>
<td>(Na,Ca,H₃O)x[Al₄₋ₓ(Fe,Mg)ₓSi₈O₂₀(OH)₄]</td>
<td>(Mg,Fe,Al)₆(Al,Si)₄O₁₀(OH)₈</td>
</tr>
<tr>
<td><strong>Type of structure</strong></td>
<td>Two-Layer (TO)</td>
<td></td>
<td>Three-Layer (TOT)</td>
<td></td>
</tr>
<tr>
<td><strong>Specific surface area (m²/g)</strong></td>
<td>10-20</td>
<td>65-100</td>
<td>50-120 (external)</td>
<td>42</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>700-840 (total)</td>
<td></td>
</tr>
<tr>
<td><strong>Cation exchange capacity (meq/100 g)</strong></td>
<td>3-5</td>
<td>10-40</td>
<td>80-150</td>
<td>10-40</td>
</tr>
</tbody>
</table>

(Mitchell, 1976)

Based on Table 7, the specific surface area and cation exchange capacity of montmorillonite is higher than for kaolinite and illite clays which can cause higher swelling characteristics of these clay minerals. The swelling characteristic of clay is an important factor in determining dewatering ability and the gelation form of middlings (Kessick, 1978; Olphen, 1963).

3.3.2.2. Clay Mineral Physical Properties

Clay minerals are very inactive because of their large surface area on which they can carry a charge. This charge causes them to exchange ions and therefore undergo swelling. The schematic structures and charges of four clay minerals in Athabasca’s oil sands are shown in Figure 8.
These clays react differently upon mining due to the various clay properties such as cation exchange capacity (CEC), surface charge and clay activity (Masliyah et al., 2013).

- **Cation Exchange Capacity (CEC)**

The electric surface properties of clay minerals are determined based on the isomorphic substitution and the location of compensation ions that can be exchanged by other available cations in solution (Figure 8). The capacity of a clay to exchange cations is quantified by the CEC value which is the millequivalents of exchangeable cations on the edges of and in the interlayered zones per 100 grams of clay (Masliyah et al., 2013).
Various clay minerals have typically different CEC values (Table 7). In general clay minerals with an accessible interlayer have much higher CEC values due to the higher ability to exchange ions.

As shown in Figure 8, in clays such as kaolinite and illite, cation exchange mostly occurs on the external basal plane and on the edge surfaces, and therefore the CEC value increases for clays with isomorphic substitution such as illite. The delocalized compensating ions resulting from a higher degree of isomorphic substitution in the octahedron layer increases this value (Mitchell, 1976).

The unique chemical structure of montmorillonite makes it more accessible for cation exchange, and thus produces higher swelling characteristics. As indicated in Table 7, the highest CEC value has been measured in montmorillonite (Mitchell, 1976).

The magnesium hydroxide of an octahedron sheet, which is called brucite in chlorite, decreases the CEC value. Since the divalent cations such as Mg$^{2+}$ have a higher affinity to clay surfaces than monovalent cations such as K$^+$, and they hinder exchanging ions (Stumm & Morgan, 1996).

- **Charge Distribution**

The structural layers, either tetrahedral or octahedral sheets of clay minerals, have a charge (Figure 8). This charge impacts the CEC value and adsorption of water and various polar organic molecules (Masliyah et al., 2013).

There are two types of charge: structural or permanent charge, which is related to ion substitution and surface, and pH dependent charge, which originates on the basal surfaces of the tetrahedral and octahedral sheets by adsorbing the surface ions (Stumm & Morgan, 1996).
The pH charge is highly dependent on the silicate structure, the pH and salinity of the solution. At low pH, the species would be able to exchange anions, and at high pH, would be able to exchange cations (Stumm & Morgan, 1996).

In clays such as kaolinite, with no ionic substitution and neutral electric charge, the major proportion of net charge is likely provided by pH dependent charge despite the presence of clays like smectite. In smectite clay groups less than 1% of the total net charge is derived from the pH dependent charge due to the higher isomorphic substitution of these clays groups (Ferris & Jepson, 1975).

- **Clay Activity**

In any particular clay stream, the clay activity is measured by dividing the Plasticity Index (PI) over the clay fraction (Skempton, 1953), as shown by Equation 1.

\[
\text{Activity} = \frac{\text{Plasticity Index (PI)}}{\text{Clay fraction}} \tag{1}
\]

In this equation, the plasticity properties of clays can be determined using the Atterberg limit chart which is shown in Figure 9. PI is calculated as the difference between liquid limit and plastic limit of the tested sample using the procedure for Atterberg limits determination. In this chart, the liquid limit is referred to as the amount of water contained in a soil which leads the soil to flow. The Plasticity Index specifies the minimum water content of the soil at which the soil can be rolled by hand into 3 mm thick columns without cracking and caving. This index indicates the maximum moisture content of the soil beyond which it will behave plastically and is expressed as a percentage by weight of the dried soil (Bain, 1971).
The clay fraction is the dry weight of the fines materials with equivalent spherical diameters less than 2µm (Kaminsky & Omotoso, 2011). Clay content can be calculated using the Methylene Blue Index (MBI) titration method which has been used commercially in the oil sands industry and will be explained in a following section in Chapter 4.

It is noted that the ‘A’ line in the chart of Figure 9 indicates the clay type to be illite. Other clay minerals may be found on either side of it.

\textit{Atterberg limits of clays}

Figure 9: Classic plasticity charts (Bain, 1971)

The Plasticity Index also provides an indication of cation exchange capacity, as clays with higher liquid limits and plasticity indices have higher activity, and higher cation exchange capacity.

Therefore, activity can also be calculated as the cation exchange capacity (CEC) divided by the clay content (Olson et al., 2000).
Boxill, (2011) suggested an alternative method to the Atterberg limits test to assess the cation exchange capacity (CEC) of clays which can be used to predict the properties of various clay minerals in tailings waste streams. In this regard, the use of MBI in CEC and surface area determination of the clay minerals present, which may lead to additional confirmation of the clay minerals and their associated physical behavior, should be taken into account (Boxill, 2011). Activities of dominant clay minerals in Athabasca’s oil sands have been provided in Table 3 (Skempton, 1953).

All the mentioned properties of clays can be used to determine the clay type(s) in oil sands ore. This has a significant impact on FFT accumulation due to the different reactions and characteristics of different clay types. Therefore, the determination of different clay characteristics, such as Plasticity Index, in oil sands ore samples should be taken into account in the current industry approach.

3.3.2.3 Clay Content Calculation Using Methylene Blue Index (MBI)

Apart from clay types, another important parameter in the forecasting tailings model is the clay content of oil sands ore. The clay content can be calculated from the Methylene Blue Index (MBI) method which has been patented by Yong and Sethi (1984) on the basis of empirical equations as shown (Omotoso et al., 2007) (Equation 2 and 3):

\[
\% \text{Clay} = \frac{\text{MBI} + 0.04}{14}
\]

Equation 2

where
\[
MBI \left( \frac{\text{meq}}{100\text{g}} \right) = \frac{\text{mls MB-normality of MB}}{\text{weight of dried solids (g)}} \times 100
\]

Equation 3

From this work an observation was made:

“It should be noted that the % Clay calculated with this equation can be greater than 100% based on the properties of the clays and solids being titrated. This calculation often requested by oil sands operators, but not treated as a direct output of the methylene blue test” (Currie et al., 2014).

In Equation 3, the Methylene Blue (MB) value is measured using a procedure which has been proposed by the COSIA Clay Focus Group. In this method, the surface area of the clay sample is measured by dispersing a dried solids sample on filter paper in an acidic environment (usually pH lower than 3) in the presence of a solution of methylene blue made with de-ionized water (typically 0.006M) until a blue halo appears. Titration continues until a permanent halo indicates the presence of methylene blue cation. Then, the volume of methylene blue is recorded and used to calculate the Methylene Blue Index (MBI) using Equation 3. “The methylene blue index (MBI) calculates the millequivalents of MB/100 g of solids titrated” (Currie et al., 2014).

MB interacts with the clays solely due to their cation exchange ability, and can reflect the properties of the clays based on isomorphic substitution. The acidic condition is used to ensure that the amorphous Fe$_2$O$_3$ is not able to absorb MB. Higher MB values reflects to the presence of clays with higher swelling characteristics and higher CEC as for the smectite groups.

The active surface area (SA) of clays, based on the dimensions of the MB molecule, is calculated using Equation 4 (Hang & Brindley, 1970):

\[
SA (m^2/g) = MBI \times 130 \times 0.0602
\]

Equation 4
3.3.2.4. Impact of Clay Content on Fluid Fine Tailings Generation

The various ranges of clay content in oil sands ore, calculated using Equation 2, can be used to assess the processibility of ore in terms of FFT generation, as a critical factor in expanding oil sands operations.

The following studies have been conducted on the use of clay boundaries as another indicator of FFT accumulations:

Boxill (2011) expressed that ores with clay contents greater than 15% are categorized as high clay content ores (Boxill, 2011).

Czarnecki et al. (2005) also presented the results form assaying 142 samples from the Athabasca region to investigate the relationship between the clay sized particles and oil content variation which is shown in Figure 10 (Czarnecki, Radoev, Schramm, & Slavchev, 2005).

Figure 10: Relationship between oil content and clay size particles in Athabasca region (Czarnecki et al., 2005)
A negative degree of correlation was found to exist between clay size and bitumen grade, this being a decrease in bitumen content with an increasing amount of clay minerals. This result is consistent with the observation of Sanford (1983) on oil content as a function of fines particles (Figure 4) (Czarnecki et al., 2005).

Therefore, the combination of the mentioned studies, and data shown in Figure 10, demonstrates linkages between clay content of oil sands ore and fluid fine tailings generation, as follow and as listed in Table 8:

1. Oil sands ores with clay amounts greater than 12 wt. %, which are related to the low grade ore, produce higher amounts of FFT due to less processabilty
2. Oil sands ores with 10 to 12 wt. % clay belong to the medium grade ore class, and generate medium amounts of FFT, and
3. Ores with clay content less than 10 wt.% are categorized as good processing ores and produce lower amounts of FFT

Table 8: Relationship between clay content of oil sands ore and FFT generation

<table>
<thead>
<tr>
<th>Clay Content (%)</th>
<th>FFT Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clay &lt;10</td>
<td>Low FFT</td>
</tr>
<tr>
<td>10&lt; Clay &lt;12</td>
<td>Medium FFT</td>
</tr>
<tr>
<td>Clay &gt;12</td>
<td>High FFT</td>
</tr>
</tbody>
</table>
The results from Table 6, fines boundaries, and Table 8, clay boundaries, as the two main indicators can be used to define the different FFT accumulation streams in the representative block model data.

3.4. Hydraulic Conductivity of Fine Tails

Apart from the mentioned factors as linkages between the fines and clay contents of ores and fluid fine tailings generation, the electro-chemical activity of fines in tailings slurry also affects the settling rate and consolidation behavior of fine tailings and can be used to determine the clay types based on varying hydraulic conductivity. This section has been provided as a guide for future investigation on determining clay type(s) in FFT.

Hydraulic conductivity \((k)\) is a function of flow velocity. During the settling state, the void ratio of solids decreases with time, and leads to a drop in flow velocity. The hydraulic conductivity of fine tails then must be calculated using steady state velocity, and it does not conform to Darcy’s Law (Suthaker & Scott, 1996).

Suthaker and Scott (1996) proposed the following equation (Equation 5) in a power law for measuring hydraulic conductivity as a function of void ratio. This relationship can be used to forecast the consolidation behavior of FFT.

\[
K = 6.16 \times 10^{-9} \times e^{4.468} \quad \text{Equation 5}
\]

where \(K\) is hydraulic conductivity in \(\text{cm/s}\) and \(e\) is the void ratio.
Equation 5 can be used in the prediction of the consolidation behavior of fine tails. A slow rate of consolidation in FFT would be expected if the hydraulic conductivity of fines tails is in the range of $1 \times 10^{-6}$ to $1 \times 10^{-9}$ m/s (BGC Engineering Inc., 2010).

The void ratio in Equation 5 can be expressed by the following equation (Equation 6):

$$ e = \frac{V_v}{V_s} \quad \text{Equation 6} $$

where $V_v$ is the volume of voids and $V_s$ is the volume of solids. These can be expressed by equation 7 and 8:

$$ V_v = V - V_s \quad \text{Equation 7} $$

where $V$ is the sample volume and $V_s$ is derived from Equation 8:

$$ V_s = \frac{M_s}{G_s \times \rho_w} \quad \text{Equation 8} $$

where $M_s$ is the sample weight, $G_s$ is the specific gravity of the mineral grains and $\rho_w$ is the water density.

### 3.5. Uncertainty in Forecasting Tailings Model

The forecasting tailings generation model includes several risks and uncertainties, such as fines and clay content boundaries, for assigning the different tailings streams. This uncertainty may cause a reduction in processed ore by eliminating blocks with higher amounts of FFT production on the basis of these two factors, which might not be accurate and need to be tested for more operations across the Athabasca mineable oil sands.
In addition, it is critical to consider mining limits and equipment or total production rates and cash flow impacts in long term mine planning due to the potential for eliminating high, and probably medium, FFT ore zones in an effort to reduce the total fines generated and improve profitability.

3.6. Summary and Remarks

A comprehensive study on the determination of fines and clay content boundaries as two main indicators in FFT accumulation has been carried out in this chapter. Fines content was made available in the representative block model data from Shell operation but clay content was calculated using the Methylene Blue Index value which was made available in the block model data.

In order to achieve the thesis objectives, the research methodology has been designed to develop a mass balance relation by grouping each block of ore into High, Low and Medium FFT streams on the basis of different ore properties. These two main indicators as fines and clay content were accommodated into the blocks in order to calculate the capability of each block for producing different tailings streams. This categorization was then applied into the representative block model data to roll different geological material types into the different tailings streams in modifying the FTM.

A corresponding tailings model will be evaluated economically in terms of associated cost of tailings treatment (operation cost only) to define the most profitable blocks which will be presented in following section in Chapter 4.
Chapter 4

Development of a Forecasting Tailings Model

The materials characteristics, which were developed in Chapter 3, were applied using representative block model data from the Shell Company to identify the forecasting tailings model (FTM) as a function of different ore facies. Then, the mass balance of clays in processed ore, in different tailings streams and in beaches and dykes were calculated.

This chapter is concerned with verification of the FTM to minimize fluid tailings inventories in the earliest stages of planning with the primary objective of using the most profitable blocks of ore with respect to bitumen grade and FFT accumulations over the mine life. Also, a sensitivity analysis for different variable inputs in FFT production will be done in this chapter.

4.1. Introduction to the Representative Oil Sands Block Model Data

In order to implement the FTM, real block model data was made available. A block model with a total of 2,419,680 blocks, having block dimensions of 50m×50m×1m, was imported in Surpac Software. The blocks with bitumen content greater than 7% were selected as ore based on Alberta’s Directive 082 to implement the FTM (Alberta Energy Regulator, 2016a). The selected blocks contained 4,151 MT of total ore tonnage. The size of the deposit was 12.25km × 9.3km with a height of 178m. Each block was characterized by X_center, Y_center, Z_center, bitumen (%), water (%), fines content (<44µm) (%), MBI, Mg, Ca, Na, K, Cl, SO₄, pH and facies descriptions.

Fines data from drillhole samples was used to estimate the percent fines in the representative geological model. The fines distribution of the entire block model data, blocks with bitumen
greater than 7% were assigned as ore due to the Directive 082, is illustrated in Figure 11. The average fines content in this specific area is 14.3%.

The fines distribution is likely wide since ores in this leased area are delivered from the McMurray (Upper McMurray Formation, typically fines material), Middle McMurray and Lower McMurray (typically very coarse material) geological members.

Figure 11: Fines distributions in the representative model

There is a negative correlation between fines content and bitumen content in the representative model (Figure 12), the same trend as was also shown in Figure 4.

The correlation between the MBI and bitumen content is also shown in Figure 13. A higher value of MBI is related to a lower amount of bitumen which also contains higher amounts of clay.
Figure 12: The correlation between fines and bitumen in the representative model

Figure 13: The correlation between MBI and bitumen in the representative model
4.2. Scope and Limitations of Calculation Methods

A comprehensive literature review on the use of fines and clay boundaries as the two main indicators was conducted in order to calculate the capability of each block for producing different tailings streams. Fines content was made available in the representative block model data. Clay content for each block of ore was calculated using Equation 2 (Omotoso et al., 2007).

The % clay is equivalent to the % of the clay size fraction when the clay mineral composition of the stream is the same as that used to develop the correlation.

In order to calculate the percent clay, blocks with a MBI greater than zero were selected and the total of 787,640 blocks was used to modify the FTM. Then, each block of ore was classified into Low, Medium and High FFT streams using fines and clay content indicators as defined by the following:

1. For Low FFT generation:
   - Blocks with fines percent less than 18% were filtered
   - Among the mentioned blocks, any block with clay content less than or equal to 10% was selected and categorized as a Low FFT stream

2. For Medium FFT generation:
   - Any blocks with fines percent greater than or equal to 18% and less than 25% were filtered
   - Blocks with clay content between 10% and 12% were selected and assigned as a Medium FFT stream
3. For High FFT generation:
   - Fines percent greater than or equal to 25\% were selected
   - Blocks with clay content greater than or equal to 12\% were filtered and specified as a High FFT stream

The above methodology is represented in the schematic flowsheet of Figure 14.
Figure 14: Schematic representation of research methodology
Example data for one block sample from each tailings stream using the described explanation is shown in Table 9. The blocks which were not classified by accommodating fines and clays boundaries are known as Blank.

Table 9: Different tailings streams classified on the basis of fines and clay contents

<table>
<thead>
<tr>
<th>Bitumen %</th>
<th>Fines %</th>
<th>Clay %</th>
<th>MBI MB/100 g of solids titrated</th>
<th>FFT Streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.39</td>
<td>16.17</td>
<td>8.85</td>
<td>123.86</td>
<td>Low</td>
</tr>
<tr>
<td>10.84</td>
<td>19.07</td>
<td>11.60</td>
<td>162.46</td>
<td>Medium</td>
</tr>
<tr>
<td>12.84</td>
<td>25.15</td>
<td>12.03</td>
<td>168.38</td>
<td>High</td>
</tr>
<tr>
<td>10.36</td>
<td>18.28</td>
<td>13.62</td>
<td>190.61</td>
<td>Blank</td>
</tr>
</tbody>
</table>

The modified FTM, after assigning each block into Low, Medium and High FFT streams, was used to calculate the total mass of clay in ore, in beaches and dykes, and in the FFT. The following assumptions were made prior to calculating the total mass of clay in different tailings constructions:

1- Two fines capture rates were applied to the raw mass of total clay in the ore feed. The first rate accounts for the percentage of captured clay in beaches and dykes as 50%. The second rate accounts for suspended clays in fluid fine tailings which is set at 35% of the total mass of clay in the ore. In addition, 15% of the total clay mass in the ore is also assumed to be settled onto the bottom of a pond (Shell Canada Energy, 2012).

2- The total mass of clay for each block of ore was calculated on the basis of fines and clay percentages.

3- 4% of the ore is assumed to be rejected before entering the CHWE process.
4- The dry density of ore was set at 2.1 t/m$^3$

5- No missing fines were assumed to exist within the pipeline

In the FFT phase, some inputs, such as percent fines which are captured in beaches and dykes on the bottom of tailings pond and in the FFT phase, can be variable based on several operational factors and should be taken into account as an uncertainty to calculate the volume of FFT in the different tailings streams.

Different probabilities of fines distributions from annual tailings management plans reported to the government by oil sands operators should be considered to capture a better understanding of uncertainty associated in this regard.

The total mass of clay in ore, as a percent of the total block mass, in beaches and dykes, and in FFT for each block of ore, was calculated as follows:

\[
\text{Mass of clay in ore} = \text{tonnes of each block} \times \% \text{ fines} \times \% \text{ clay} \times \% \text{ processed ore}
\]

\[
\text{Mass of clay in beaches and dykes} = 50\% \times \text{mass of clay in ore}
\]

\[
\text{Mass of clay in FFT} = 35\% \times \text{mass of clay in ore}
\]

The amount of water in FFT was calculated by setting Equation 9 (fines over fines plus water ratio, FOFW) to 35%, the solids density boundary at which further densification of fines particles in the FFT is avoided (Kasperski & Mikula, 2011):

\[
\frac{\text{Mass of clay in ore}}{\text{Mass of clays in ore} + \text{Mass of water}} = 0.35 \quad \text{Equation 9}
\]
Therefore the water content was calculated using Equation 10:

\[
\text{Water content} = \frac{0.65 \times \text{Mass of clay in ore}}{0.35} \quad \text{Equation 10}
\]

The total mass of FFT production was summed based on the mass of clay in FFT and the water content for each tailings stream.

The above calculation methods for several blocks in different tailings streams were applied and results are shown in Table 10.
Table 10: Total mass of clay calculation for selected blocks in different tailings streams

<table>
<thead>
<tr>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>MBI MB/100 g of solids titrated</th>
<th>Water (%)</th>
<th>Solid (%)</th>
<th>Mass of clay in ore (tonnes)</th>
<th>Mass of clay in Beaches and Dykes (tonnes)</th>
<th>Mass of clay in FFT (tonnes)</th>
<th>Water content (tonnes)</th>
<th>Total FFT (tonnes)</th>
<th>FFT Streams</th>
</tr>
</thead>
<tbody>
<tr>
<td>7.39</td>
<td>16.17</td>
<td>8.85</td>
<td>123.86</td>
<td>6.46</td>
<td>86.15</td>
<td>72.10</td>
<td>36.05</td>
<td>25.24</td>
<td>133.91</td>
<td>159.14</td>
<td>Low</td>
</tr>
<tr>
<td>10.84</td>
<td>19.07</td>
<td>11.60</td>
<td>162.46</td>
<td>5.37</td>
<td>83.79</td>
<td>111.53</td>
<td>55.77</td>
<td>39.04</td>
<td>207.14</td>
<td>246.17</td>
<td>Medium</td>
</tr>
<tr>
<td>12.84</td>
<td>25.15</td>
<td>12.03</td>
<td>168.38</td>
<td>3.3</td>
<td>83.86</td>
<td>152.45</td>
<td>76.23</td>
<td>53.36</td>
<td>283.13</td>
<td>336.49</td>
<td>High</td>
</tr>
<tr>
<td>10.36</td>
<td>18.28</td>
<td>13.62</td>
<td>190.61</td>
<td>3.37</td>
<td>86.27</td>
<td>125.46</td>
<td>62.73</td>
<td>43.91</td>
<td>233.00</td>
<td>276.91</td>
<td>Blank</td>
</tr>
</tbody>
</table>
It is noted that, in this study, the tailings mass balances have been considered from mining operations and extraction units. Outputs from froth treatment plants also will feed the daily tailings balance, but they are beyond the scope of this study to assess.

The distribution of the total mass of clay particles based on calculations involving the processing from mining to tailings of 100 tonnes of ore, for simplification, is illustrated in Figure 15.
Figure 15: Distribution of clay particles from mining to tailings

Total mass of clay in ore = ore tonnage * fines% * clay%
If Fines = 25% and Clay = 12%:

Total mass of clay in 100t of ore = 100t * 0.96 * 25% * 12% = 2.88t Clay in ore

50% of fines are captured in Beaches and Dykes

1.44 t to Beaches and Dykes

1.01t to FFT

Fluid Fine Tailings
35% of fines are suspended

4t to Rejects

15% of Fines are settled
0.43 t to bottom of pond
It is assumed that 4% of the ore is rejected from the extraction process, and 2.88 tonnes of clay in 96t of ore would be entered to the CHWE process using the specified fines and clay contents. Therefore, the total mass of clay in beaches and dykes, using the assumed capture rate, would be 1.44 tonnes, and the total mass of clay in the FFT stream would be calculated at 1.01 tonnes. The remaining clay, 0.43 tonnes, would be settled on the bottom of a pond.

4.3. Modeling Results

Using the above framework, the results from the forecasting tailings model are shown in Table 11. This table indicates how the geological material types are rolled into the fluid fine tailings production zones by grouping ore properties based on fines and clay contents. The estimate of the captured clay quantity for each FFT zone has been calculated in terms of millions tonnes. The total clay in the FFT is reported as approximately 19.3 million tonnes, and by adding water content to that, the total FFT produced is estimated at around 121.8 million tonnes for the entire leased area.
Table 11: Fluid fine tailings materials forecast using the FTM

<table>
<thead>
<tr>
<th>Tailings Zones</th>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>Count#</th>
<th>Mines Ore (MT)</th>
<th>Blocks (%)</th>
<th>Clays in FFT (MT)</th>
<th>Water in FFT (MT)</th>
<th>Total FFT (MT)</th>
<th>Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low FFT</td>
<td></td>
<td></td>
<td></td>
<td>533,302</td>
<td>2,688</td>
<td>68</td>
<td>4.4</td>
<td>23.5</td>
<td>28.0</td>
<td>23</td>
</tr>
<tr>
<td></td>
<td>Fines &lt; 18</td>
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<td></td>
<td>533,302</td>
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<td></td>
<td></td>
<td></td>
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<tr>
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<td>Clay ≤ 10</td>
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<td>533,302</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Min</td>
<td>7</td>
<td></td>
<td>0.29</td>
<td>68</td>
<td>4.4</td>
<td>23.5</td>
<td>28.0</td>
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<td></td>
</tr>
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<td>10.00</td>
<td>10.00</td>
<td>23.5</td>
<td>28.0</td>
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<td>Mean</td>
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<td>4.21</td>
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<td>High FFT</td>
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<td></td>
<td></td>
<td>65,791</td>
<td>332</td>
<td>8</td>
<td>7.5</td>
<td>39.9</td>
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<td>Fines ≥ 25</td>
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<td>65,791</td>
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<td>Medium FFT</td>
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<tr>
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<td>102.5</td>
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</tr>
</tbody>
</table>
It is noted that the maximum weight percent clay in Table 11 is higher than 100% which is related to the Methylene Blue Index values as a function of clay calculation for oil sands samples.

The methylene blue titration of clays has become a principal tool to assess the properties of different tailings streams. However, the principal factors affecting the test results in terms of a capability for generating reliable data with good precision are still under investigation (Currie et al., 2014).

A major challenge in the methylene blue titration procedure is to identify the endpoint of MB titration by operators, and a condition cannot be detected through an automated procedure that is currently used and causes error.

Currie et al. (2014) indicated that the relative error in the MBI measurement could be considered to be 30% to 40%. They also found that a particularly important factor was not the solids content, was the clay to water ratio (CWR) within oil sands samples. Therefore, it is important to understand the effect of clays on operations, and emphasizes the need to have a reliable test method for MB titrations (Currie et al., 2014).

Currie et al. (2014) stated:

“Alternative endpoint detection procedure on the use of spectroscopy has been suggested by Oil Sands Research and Innovation Network (OSRIN), 2014. The proposed method has an ability to assess whether the MB is interacting on the external or internal surface of clays. The result from this study is very attractive since it can enhance the information about the properties of clays in different sample type and much more detail can be mined from the titration data than simply MBI values”
In order to avoid overestimation of the clay mass, statistical studies have been done to calibrate the final mass of clay as done by the following:

1) 4.8% of the total ore blocks have clay content greater than the fines percent (37,731 ore blocks)
   - 0.22% of the total ore blocks in this class belonged to High FFT
   - 1.70% of the total ore blocks in this class belonged to Low FFT
   - 2.87% are categorized as the Blank FFT stream

2) The differences between clay and fines contents are summarized in Table 12

The percentages are calculated on the basis of blocks having clay contents greater than fines.
Table 12: Clay fines difference in the representative block model data

<table>
<thead>
<tr>
<th>Clay-Fines Ranges (%)</th>
<th>Number of Blocks</th>
<th>Blocks for Clay&gt;Fines (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-10</td>
<td>10,271</td>
<td>27%</td>
</tr>
<tr>
<td>10-20</td>
<td>6,786</td>
<td>18%</td>
</tr>
<tr>
<td>20-30</td>
<td>4,891</td>
<td>13%</td>
</tr>
<tr>
<td>30-40</td>
<td>3,182</td>
<td>8%</td>
</tr>
<tr>
<td>40-50</td>
<td>2,438</td>
<td>6%</td>
</tr>
<tr>
<td>50-60</td>
<td>2,066</td>
<td>5%</td>
</tr>
<tr>
<td>60-70</td>
<td>1,746</td>
<td>5%</td>
</tr>
<tr>
<td>70-80</td>
<td>1,260</td>
<td>3%</td>
</tr>
<tr>
<td>80-90</td>
<td>1,045</td>
<td>3%</td>
</tr>
<tr>
<td>90-100</td>
<td>799</td>
<td>2%</td>
</tr>
<tr>
<td>&gt;100</td>
<td>3,209</td>
<td>9%</td>
</tr>
</tbody>
</table>

According to Currie et al. (2014) clay fines differences less than 20% can be ignored, which corresponds to about 45% of the total blocks having clay contents greater than fines in Table 12.

3) 2.63% of the total ore blocks belonged to the class having more than 20% difference between clay and fines. The percentages of these blocks in the different tailings streams are provided as follow:

- only 0.07% are categorized as High FFT
- 0.67% belonged to Low FFT, and
- 1.89% of the total ore blocks are related to the Blank FFT stream
4) The dominant facies in the Blank FFT streams are located in the Middle McMurray Formation at the Estuarine Channel, Tidal Channel and Distributary Channel with less than 10% interbedded clay content due to the stratigraphic sequences in the leased area. These interbedded clay minerals with higher surface active clay content may cause misleading MBI values and thereafter may lead to overestimation of the clay content using Equation 2.

“It is noted that a pure bentonite would show a % clay content of ~730 (Kaminsky & Omotoso, 2011)

All the mentioned studies indicate that clay masses for some blocks have been overestimated due to unreliable MBI values. The actual clay contents of these blocks need to be investigated and a comparison between measured and calculated clay contents needs to be calibrated. This study is beyond the scope of the thesis structure and the author has tried to address this issue.

However, in order to avoid the overestimation of clay mass, the following steps were carried out to calibrate the overestimated clays with higher clay content:

1. A relationship between fines and clay for blocks having clay less than fines was provided. (Figure 16)

2. A relationship was applied to the blocks consisting of clay contents higher than fines, this occurring for approximately 2.63% of the total ore blocks

3. Blocks having differences less than 20% followed Equation 2 for clay content calculation, differences between fines and clay less than 20% were ignored (Currie et al., 2014)
The results from the above studies are provided in Table 13.

Figure 16: Fines versus clay content relationship for blocks with clay less than fines
Table 13: Fluid fine tailings materials using the FTM after calibration

<table>
<thead>
<tr>
<th>Tailings Zones</th>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>Mined Ore (MT)</th>
<th>Blocks (%)</th>
<th>Clays in FFT (MT)</th>
<th>Water in FFT (MT)</th>
<th>Total FFT (MT)</th>
<th>Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low FFT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fines &lt; 18 Clay ≤ 10</td>
<td>533,302</td>
<td>533,302</td>
<td>533,302</td>
<td>2,688</td>
<td>68</td>
<td>4.4</td>
<td>23.4</td>
<td>27.8</td>
<td>23</td>
</tr>
<tr>
<td>Count#</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>0.29</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>19.10</td>
<td>17.99</td>
<td>10.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>12.44</td>
<td>9.90</td>
<td>4.17</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High FFT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fines ≥ 25 Clay ≥ 12</td>
<td>65,791</td>
<td>65,791</td>
<td>65,791</td>
<td>332</td>
<td>8</td>
<td>7.5</td>
<td>39.5</td>
<td>47.0</td>
<td>39</td>
</tr>
<tr>
<td>Count#</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>25</td>
<td>12.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>16.35</td>
<td>87.49</td>
<td>85.93</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>8.61</td>
<td>33.21</td>
<td>18.63</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium FFT</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>18 ≤ Fines &lt; 25 10 &lt; Clay &lt; 12</td>
<td>23,728</td>
<td>23,728</td>
<td>23,728</td>
<td>120</td>
<td>3</td>
<td>1.0</td>
<td>5.2</td>
<td>6.2</td>
<td>5</td>
</tr>
<tr>
<td>Count#</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>18</td>
<td>6.29</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>16.69</td>
<td>24.99</td>
<td>7.49</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.02</td>
<td>21.34</td>
<td>6.85</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Blank</td>
<td>164,819</td>
<td>164,819</td>
<td>164,819</td>
<td>831</td>
<td>21</td>
<td>6.4</td>
<td>33.9</td>
<td>40.3</td>
<td>33</td>
</tr>
<tr>
<td>Count#</td>
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<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>0.8</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>17.91</td>
<td>80.9</td>
<td>40.48</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.46</td>
<td>20.17</td>
<td>9.56</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>3,970</td>
<td>100</td>
<td>19.2</td>
<td>102.0</td>
<td>121.2</td>
<td></td>
<td></td>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

63
After the calibration process, the total quantity of FFT was estimated at around 121.2 million tonnes, only 0.5% less than the amount predicted without considering the overestimated clay mass using Equation 2, which was expected from the fewer blocks involved.

The total FFT forecast to be produced using a clay content calculated as a fixed percent of fines content or from historic FFT production metrics for this specific block model data are estimated at 89 million tonnes (Table 14) versus 121.2 million tonnes using the defined FTM approach. This underestimation of the total FFT, without using FTM, demonstrates the fact of unexpected growth of fluid fine tailings in Athabasca’s oil sands mining. Previously, the oil sands industry had anticipated that the total FFT accumulations may reach over one billion cubic meters by 2020, whilst this amount has already been accumulated in tailings ponds. Part of this over accumulation is due to limitations in existing forecasting methods.
Table 14: Fluid fine tailings materials forecast without using the FTM

<table>
<thead>
<tr>
<th>Tailings Zones</th>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>Mined Ore (MT)</th>
<th>Blocks (%)</th>
<th>Clays in FFT (MT)</th>
<th>Water in FFT (MT)</th>
<th>Total FFT (MT)</th>
<th>Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>All- Without FTM</td>
<td>787.640</td>
<td>787.640</td>
<td>787.640</td>
<td>3,970</td>
<td>100</td>
<td>14.11</td>
<td>75</td>
<td>89</td>
<td>100</td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>0.29</td>
<td>0.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>19.10</td>
<td>87.49</td>
<td>129.70</td>
<td>3,970</td>
<td>100</td>
<td>14.11</td>
<td>75</td>
<td>89</td>
<td>100</td>
</tr>
<tr>
<td>Mean</td>
<td>11.63</td>
<td>14.34</td>
<td>7.08</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
By the FTM approach, more than 39% of the total FFT produced is associated with the High FFT zone, as expected, due to the higher amount of fines and clay contents of this stream. Only 8% of ore blocks in the proposed FTM belong to the High FFT stream.

The contribution of the Low FFT zone in the block model data is around 68% of the total ore feed, while only 23% of total FFT accumulations will be generated from these blocks over the mine life.

As is illustrated in Table 13, 21% of geological ore blocks are classified as non FFT stream by accommodating current conditions. These blocks can be classified, on the basis of the same clay boundaries for the different tailings streams, as the most influential factor in FFT production. Therefore, the blank category has been assigned into the group of High, Low and Medium FFT inventory streams on the basis of clay content (Table 15).

The results, using the above categorization (Table 15), show that 7% of the total ore blocks in the Blank stream are classified in the High2 FFT zone.
Table 15: Fluid fine tailings materials forecast for NA blocks in the FTM

<table>
<thead>
<tr>
<th>Tailings Zones</th>
<th>Count#</th>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>Mined Ore (MT)</th>
<th>Blocks (%)</th>
<th>Clays in FFT (MT)</th>
<th>Water in FFT (MT)</th>
<th>Total FFT (MT)</th>
<th>Mass (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low2 Clay ≤ 10</td>
<td>74,002</td>
<td>74,002</td>
<td>74,002</td>
<td></td>
<td>373</td>
<td>9.4</td>
<td>2.2</td>
<td>12</td>
<td>14</td>
<td>35</td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>8.94</td>
<td>0.02</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>17.48</td>
<td>64.02</td>
<td>10.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.47</td>
<td>22.11</td>
<td>7.76</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>High2 Clay ≥ 12</td>
<td>54,301</td>
<td>54,301</td>
<td>54,301</td>
<td></td>
<td>274</td>
<td>7</td>
<td>2.8</td>
<td>15</td>
<td>18</td>
<td>44</td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>0.8</td>
<td>12.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>17.71</td>
<td>36.46</td>
<td>79.54</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.46</td>
<td>18.34</td>
<td>15.91</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium2 10 &lt; Clay &lt;12</td>
<td>36,516</td>
<td>36,516</td>
<td>36,516</td>
<td></td>
<td>184</td>
<td>4.6</td>
<td>1.3</td>
<td>7</td>
<td>8</td>
<td>21</td>
</tr>
<tr>
<td>Min</td>
<td>7</td>
<td>0.93</td>
<td>10.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Max</td>
<td>17.91</td>
<td>80.9</td>
<td>12.00</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mean</td>
<td>10.47</td>
<td>18.97</td>
<td>10.91</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Sum</td>
<td>831</td>
<td>21</td>
<td>6.4</td>
<td>34</td>
<td>40</td>
<td>100</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
The combination of results from Table 13 and Table 15 indicate that 15% of the total ore feed, assigned to the High FFT zone, contributes to produce more than 54% of the total FFT produced for the entire leased area.

Apart from environmental impacts like footprint size, water consumption, leakage of toxic tailings into aquifers and greenhouse gas emissions, the reduction in total FFT produced by eliminating blocks belonging to the High FFT zone has a significant impact on cost saving issues in terms of tailings management plans for becoming a self-supporting solids and tailings storage facility.

“Same as reduction in cost which happened in 1990s, through a move towards replacing the dragline and bucketwheel reclaimers with truck and shovel power, and replacing the conveyor belt into hydrotransport system of oil sands to the processing plant (National Energy Board, 2004).”

This model is the most promising strategy to reduce tailings processing by targeting the mining areas, since there is still no “silver bullet” in tailings technology to speed up the reduction of tailings pond size for final remediation and closure.

Furthermore, FTM can be applied for different environmental deposition of oil sands individually, and therefore unplanned maintenance costs of tailings disposal are minimized. This strategy may increase operating cost and reduce production capabilities due to the need for selective mining and the need for proper equipment. However that reduction probably will have a small effect for mine plan production due to the small percentage of impacted blocks realized in the representative model in this study. These blocks also tend to be lower grade with poor recovery characteristics. However long term mine planning needs to be investigated by setting
appropriate operational strategies around the mining life cycle and ensuring proper equipment selection.

4.5. Financial Calculation Methodology

The main aim of this evaluation is to conduct an assessment of the associated cost of the tailings inventory on the basis of differences in ore feed. This cost can be a factor to define the actual profitable ores in open pit optimization practice. In order to do that, the modified forecasting tailings model was employed to determine the economic viability of oil sands development by considering tailings accumulations.

Unfortunately, cost model data was not made available to conduct a project economic evaluation in terms of a discounted cash flow in this study. Therefore, a project was evaluated using the Economic Block Valuation (EBV) approach in terms of total tailings treatment cost based on Canadian constant dollars in 2015, with and without implementing the FTM by following the listed assumptions:

- Tailings treatments costs were generally considered to cost in the range of $5-$15 per tonne of fluid fine tailings (Thorley, 2015). Research into commercially viable methods of tailings treatment is ongoing and the variation in costs considered will account for different treatment methods.
- Three tailings treatments costs were assigned: a low cost at $5 per tonne of FFT, a medium cost at $10 per tonne of FFT and a high cost at $15 per tonne of FFT for all tailings streams without and with implementing FTM
- The EBV approach was applied to the entire block model data
The Economic Block Valuation (EBV) process is used to define profitable blocks of ore not only based on the bitumen grade but also by considering the associated cost of fluid tailings accumulation for each block individually.

The results can be used to define more accurate ore classification as per Directive 082 (Alberta Energy Regulator, 2016a) (where ore is considered to be material that generates a profit) with respect to fluid tailings generation and bitumen value. This has the potential to have a significant impact on the sustainable development of oil sands mining in long-term mine planning and optimization practice.

The power of the EBV process is that it is extendable to consideration of other mining and processing costs that can have a value assigned on the basis of available block model data.

Traditional cut-off grade approaches in mining consider only a single criterion (ore grade or recoverable ore grade). EBV methods are widely used outside of the oil sands mining industry in defining the mineable pit limit.

The results using the EBV approach, shown in Table 16, indicate that the potential tailings treatment cost (operating cost only) for 89 million tonnes of the total FFT production over the mine life would be estimated at between 445 and 1,335 million dollars without using the FTM approach.

With the proposed FTM approach, a 15% reduction in mined ore, categorized as the High FFT, resulted in a 53% cost saving and FFT reduction.

There would also be a $646,000,000 cost saving in the associated operating cost of tailings treatment, on the basis of medium cost, by eliminating the High FFT ores. This cost saving amount would be equal to 11,600,000 sold barrels of oil at $40/bbl.
Table 16: Economic evaluation for tailings zones using the FTM in constant dollars

<table>
<thead>
<tr>
<th></th>
<th>Ore Feed (MT)</th>
<th>FFT Generation (MT)</th>
<th>Tailings Treatments in $M</th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low Cost</td>
<td>Medium Cost</td>
<td>High Cost</td>
<td></td>
</tr>
<tr>
<td>Total-Without FTM</td>
<td>3,970</td>
<td>89</td>
<td>445</td>
<td>890</td>
<td>1,335</td>
<td></td>
</tr>
<tr>
<td>Total-With FTM</td>
<td>3,970</td>
<td>121.2</td>
<td>606</td>
<td>1,212</td>
<td>1,818</td>
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<tr>
<td>Low FFT Zone</td>
<td>3,061</td>
<td>42.0</td>
<td>210</td>
<td>420</td>
<td>629</td>
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</tr>
<tr>
<td>Medium FFT Zone</td>
<td>304</td>
<td>14.6</td>
<td>73</td>
<td>146</td>
<td>219</td>
<td></td>
</tr>
<tr>
<td>High FFT Zone</td>
<td>605</td>
<td>64.6</td>
<td>323</td>
<td>646</td>
<td>969</td>
<td></td>
</tr>
</tbody>
</table>

The preliminary study indicates that the reduction in bitumen produced is low, the percent of impacted blocks is small and they tend to be lower-grade with poor recovery, and that reduction will impact total mine production. Therefore, the impact of eliminating high fluid fine tailings generation blocks merits further investigation in determination of the final pit limit and the long term production plan on the theoretical tailings model.

The main aim of doing this is to realize that the input ore tonnage, head grade and Net Present Value (NPV) fluctuations are penalized by fluid tailings generations.

The results from this study may have an impact on ore classification criteria by considering minimum fines and clay contents in ore classification with respect to fluid tailings generation apart from the bitumen cut off grade which was set at 7% by regulators and operators many years ago and which may not be a minable and optimum cutoff grade.

Also it would be possible to evaluate the profitability of the blocks with less than 7% bitumen and lower clay contents based on the associated cost of tailings by using the proposed FTM.

Furthermore, a decrease in production results in an increase in supply cost. Therefore the impact of eliminating 15% of the total ore feed also should be investigated, through the new mining cost model, as a supply cost in order to make a final financial decision.
Supply costs, composed of mining, extraction and upgrading operations, are highly sensitive to capital costs, world oil prices and currency exchange rates between Canada and the United States. Due to Suncor’s preliminary analysis through to 2012, the impact on supply costs will be approximately $0.20 to $0.27 per barrel (National Energy Board, 2004).

4.6. Sensitivity Analysis

As was indicated in Figure 5, ranges of fines content, as an indicator used to assign the different FFT streams, is more sensitive than clay content (Figure 10). Therefore, a sensitivity analysis was performed on the fines indicator to modify another FTM which is called the FTM2 in this study.

The new fines boundaries for the FTM2 and the primary FTM are illustrated in Table 17. The clay content boundaries remained the same in both forecasting tailings models.

Table 17: Fines content boundaries in the FTM2 and the primary FTM

<table>
<thead>
<tr>
<th>Tailings Streams</th>
<th>Fines Content in FTM2</th>
<th>Fines Content in Primary FTM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low FFT</td>
<td>Fines &lt; 10</td>
<td>Fines &lt; 18</td>
</tr>
<tr>
<td>Medium FFT</td>
<td>10 ≤ Fines &lt; 20</td>
<td>18 ≤ Fines &lt; 25</td>
</tr>
<tr>
<td>High FFT</td>
<td>Fines ≥ 20</td>
<td>Fines ≥ 25</td>
</tr>
</tbody>
</table>

Data included in Table 18 shows the results for the FTM2. The same categorization as for the FTM were used in the FTM2 for blocks which are not assigned to any tailings streams (NA).
Table 18: Fluid fine tailings materials forecast in the FTM2

<table>
<thead>
<tr>
<th>Tailings Zones</th>
<th>Bitumen (%)</th>
<th>Fines (%)</th>
<th>Clay (%)</th>
<th>Count#</th>
<th>Min</th>
<th>Fines &lt; 10</th>
<th>Clay ≤ 10</th>
<th>Count#</th>
<th>Min</th>
<th>Fines ≥ 20</th>
<th>Clay ≥ 12</th>
<th>Count#</th>
<th>Min</th>
<th>Fines ≤ 20</th>
<th>Clay &lt; 12</th>
<th>Mean</th>
<th>Fines</th>
<th>Clay</th>
<th>Mean</th>
<th>Fines</th>
<th>Clay</th>
<th>Mean</th>
<th>Fines</th>
<th>Clay</th>
<th>Mean</th>
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<tbody>
<tr>
<td>Low FFT</td>
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<tr>
<td>Fines &lt; 10</td>
<td>300,900</td>
<td>300,900</td>
<td>300,900</td>
<td>1,517</td>
<td>7</td>
<td>0.29</td>
<td>0.00</td>
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<td>1.2</td>
<td>6.4</td>
<td>7.6</td>
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<td>Clay ≤ 10</td>
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<td>Max</td>
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<td>Mean</td>
<td>11.36</td>
<td>16.12</td>
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<td></td>
<td></td>
<td>3,970</td>
<td>100</td>
<td>18.7</td>
<td>99.4</td>
<td>118.2</td>
<td>100</td>
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</tbody>
</table>
A small change in fines boundaries resulted in:

- less blocks being classified as Low FFT zones in the FTM2, these being 38% compared to 68% in the FTM
- more blocks being classified as High FFT zones using the FTM2, these being 12% compared to 8% in the FTM
- a 15% reduction in mined ore as blocks belonging to High FFT zones, resulting in a 52% reduction in total FFT produced in the FTM2, or approximately the same as that for the primary FTM

The same results from the FTM2 demonstrate that economic evaluation is not sensitive to these new fines boundaries, and it would provide a 52% cost saving and FFT reduction on fluid fine tailings treatment over the mine life (Table 19).

Table 19: Economic evaluation for tailings zones using the FTM2 in constant dollars

<table>
<thead>
<tr>
<th></th>
<th>Ore Feed MT</th>
<th>FFT Generation MT</th>
<th>Tailings Treatments in $M</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Low Cost</td>
</tr>
<tr>
<td>Total-Without FTM</td>
<td>3,970</td>
<td>89</td>
<td>445</td>
</tr>
<tr>
<td>Total-With FTM</td>
<td>3,970</td>
<td>118.2</td>
<td>591</td>
</tr>
<tr>
<td>Low FFT Zone</td>
<td>3,123</td>
<td>42.1</td>
<td>210</td>
</tr>
<tr>
<td>Medium FFT Zone</td>
<td>287</td>
<td>14.3</td>
<td>72</td>
</tr>
<tr>
<td>High FFT Zone</td>
<td>560</td>
<td>61.8</td>
<td>309</td>
</tr>
</tbody>
</table>
4.7. Summary and Remarks

The simulated realizations on the representative block model were used to measure the effect of potential tailings generation with respect to the different ore facies. Two new variables or indicators were integrated into the geological block model data to quantify the effect of fines content and clay indicators.

The boundary of these two indicators is defined by extensive literature review to better understand the link between ore properties, clay content, and fluid fine tailings production. The results can be used to define a more accurate ore classification criteria after verifying the planning and equipment selection processes.

Three zones of tailings accumulations were assigned as Low, High and Medium FFT in the Forecasting Tailings Model (FTM) based on fines and clay contents of an ore. A 15% reduction in mined ore categorized as the High FFT zone resulted in 53% FFT reduction and cost savings.

The preliminary study indicates that the reduction in bitumen produced probably will have a small effect on total mine production, due to the percent of impacted blocks, however it needs to be investigated in future studies in terms of operational strategies and with use of proper equipment.

This framework does not depend on the nature of the deposits, and therefore it can be applied across all the mined areas in Athabasca’s oil sands.

The sensitivity analysis was performed on different fines content ranges to develop the New Forecasting Tailings Model (FTM2). The FFT volume for each tailings stream was impacted in the FTM2, however the economic evaluation would remain approximately constant.
Chapter 5
Summary, Conclusion and Recommendations

This research has developed theoretical frameworks and mathematical formulations for a Forecasting Tailings Model (FTM). The proposed FTM calculates the potential fluid tailings generation on the basis of different ore facies considering fines and clay content indicators in the ore. The main aim of this simulated model is to forecast tailings accumulations and to evaluate the associated tailings costs over the oil sands production process which will improve the economic and environmental performance of oil sands mining operations.

5.1. Summary of Research Contributions

FFT cannot be discharged to the environment. Significant research is ongoing into FFT treatment technologies. The goal of this thesis was to establish a method by which FFT generation could be calculated based on currently available ore properties (i.e. the block model data).

The research methodology was designed to group each block of ore into High, Low and Medium FFT streams to modify the Forecasting Tailings Model (FTM) based on the fines (<44µm-sized particles) content, clay content (using MBI as a proxy), host reservoir environments of deposition and ore facies description as the main indicators in fluid fine tailings generation and lower rate segregation of FFT. The streams are classified by the following:

- Low FFT streams: Fines < 18% and Clay ≤ 10%
- Medium FFT streams: 18% ≤ Fines < 25% and 10% < Clay < 12%
- High FFT streams: Fines ≥ 25% and Clay ≥ 12%
The stated methodology was incorporated into representative block model data from an operating oil sands mining venture for preliminary assessment of the model. The mass of clay for each FFT stream has been calculated using the capture rates in mass balance relations between ore feed and FFT accumulation as a function of different ore properties on the basis of a 2012 Annual Tailings Plan- Jackpine Mine (JPM).

The modified FTM was evaluated economically using an EBV approach to determine the associated cost of potential tailings generation using different costs of FFT treatment per tonne for different tailings streams, these being:

- $5/t FFT as a tailings treatment applied as low cost for all FFT streams
- $10/t FFT was applied as medium cost for all FFT streams
- $15/t FFT was applied as high cost for all FFT streams

The EBV approach was applied to the entire block model data, without consideration of a mining limit. The impact of using an EBV process versus the criteria of Directive 082 was assessed.

A sensitivity analysis has been performed to investigate the influence of fines content on modifying FTM.

### 5.2. Limitations

There are limitations in the work presented that need to be addressed.

The work does not consider a mining limit or total production and cash flow impacts. However, given the preliminary results, a comprehensive study, including mining limits, and detailed capital and production cost estimates, is indicated.
The use of MBI as an indirect measurement of clay content to calculate clay (% mass) should be limited to indicate that a block may produce disproportionately more or less clay than average. Future work should be completed in an attempt to better address this issue.

In the current study, in order to avoid overestimation of the clay mass, the calibration method has been applied to blocks having clay fines differences greater than 20%. This assumption was made on the basis of research by Currie et al. (2014) on the relative error generated in the MBI measurement procedure.

5.3. Conclusions

The role of clay present in the ore is critical to understanding the formation of FFT in the oil sands industry, including both mass and type(s), and should be considered in forecasting tailings production.

When clay content of individual blocks is examined it becomes apparent that tailings production should be considered as a highly variable component of the processing cost. A multi-variable detention of ore (incorporating material-specific costs as well as profits) may improve the overall profitability of mine plans versus consideration of bitumen content alone.

The representative block model data in this study indicates that the total FFT inventory, using historic FFT production data, yields estimates of around 89 million tonnes versus 122 million tonnes using the newly defined FTM approach (Table 13). Part of this over accumulation is due to limitations in existing forecasting methods.

Despite these stated limitations, the results of this study indicate that a small subset of blocks (the High FFT zone, representing 15% of the total mined ore) contributes to a disproportionately
large portion of FFT production (53% of the total FFT accumulations) and may not be economic when specific tailings costs are considered.

Using the EBV approach, the potential tailings treatment cost (operating cost only) was estimated at between $445M to $1,335M without implementing the FTM. With the proposed FTM, a 15% reduction in mined ore categorized as the High FFT materials, resulted in 53% FFT reduction and cost savings over the mine life.

Therefore, the proposed FTM can change the deposition strategy in Directive 082 by accommodating fines and clay indicators in mined oil sands ore classification and facilitating an ore control process aiming to reduce the quantity of FFT produced.

High, and potentially Medium, FFT ore zones (classified as ore using Directive 082 criteria) should be considered as potential waste in the strategic mine planning process in an effort to reduce total fine tailings generated and improve profitability.

Furthermore, a reduction in bitumen loss through mining the low fines and low clay ores improves overall rates of recovery, and reduces water usage and greenhouse gas generation.

The results from this study can be used to define a more accurate ore classification technique, where ore is considered to be material that generates a profit with respect to both FFT generation and bitumen value. This has the potential to have an impact on the sustainable development of oil sands mining in long term mine planning and optimization practice.
5.3. Recommendations and Future Studies

The following recommendations are made:

- Due to limited publically available data in the area of the thesis focus, more laboratory analysis and research to satisfy the fines and clay content boundaries in developing the FTM is recommended. In this regard, future work to improve the MBI technique and the use of MBI data to indicate clay content (type and mass) would be beneficial.

- A methodology to incorporate clay type(s) and content should be implemented in the current ore classification process due to the impact of different clay types on FFT generation and the resulting economic and environmental costs.

- The modified theoretical forecasting tailings model in this study should be tested against historic tailings production data where possible. This would require use of a block model and incorporation of MBI data, if available.

- The profitability of blocks with less than 7% bitumen and lower clay contents can be evaluated based on the associated cost of tailings using the proposed FTM. The result from this investigation can be used to determine an actual minable and optimum bitumen cutoff grade. The 7 wt.% bitumen cutoff grade has been arbitrarily set by regulators and operators many years ago.

- The determination of the final pit limit and full mine plan based on the modified tailings model (FTM) is recommended to realize the input ore tonnage, head grade and NPV fluctuations which can be penalized by fluid tailings generation.

- The use of proper equipment in terms of choosing a selective mining method by eliminating High FFT ores in surface mined ore needs to be investigated.
A project economic evaluation in terms of a discounted cash flow should be conducted using cost model data on the basis of linkages between a predictive model for tailings generation, water use, and greenhouse gas production, and ore properties including facies, bitumen content, clay content, etc.

This new mining cost model should be used in strategic mine planning to incorporate explicit consideration of environmental cost into the mining and processing decision.

There are several risks and uncertainties in modifying the FTM such as determination of fines and clay boundaries in FFT streams, ability to meet production targets due to eliminating blocks categorized in High FFT zone and capture rates to calculate the mass of clays in various constraints. Therefore, more real block model data from different operations should be analyzed using the FTM and EBV methods which have been presented in this thesis.
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