Statistical Modeling for Tailings Consolidation Using Index Properties

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Arjun Chandra Paul, candidate for the degree of Master of Applied Science in Environmental Systems Engineering, has presented a thesis titled, *Statistical Modeling for Tailings Consolidation Using Index Properties*, in an oral examination held on November 16, 2011. The following committee members have found the thesis acceptable in form and content, and that the candidate demonstrated satisfactory knowledge of the subject material.

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ABSTRACT

The extraction of mineral resources from the earth generates large volume of mine tailings which are usually disposed hydraulically in tailings pond. To minimize the environmental concerns associated with deposition of mine wastes and reclamation of the containment ponds, the tailings need to undergo an efficient consolidation. The main objective of this research was to develop statistical models for tailings consolidation using index properties based on data in the literature thereby, capturing physicochemical interactions. The first model was developed for groups of tailings (sedimentary clays, residual soils and oil sand tailings) and the second model was developed for all tailings. Results indicated that void ratio varied significantly at low effective stress ($< 5$ kPa) and high hydraulic conductivity ($> 10^{-6}$ cm/s) for sedimentary clays and residual soils, because physicochemical interactions are maximum under these conditions. For oil sand tailings, effective stress ($\sigma'$) and hydraulic conductivity ($k$) were strongly correlated with void ratio due to relative homogeneity in material composition. The effect of process conditions on consolidation behavior was found to be negligible for this class of material. By converting void ratio to liquidity index and normalized void ratio, volume compressibility and hydraulic conductivity data in the literature merged for materials of each group even at low $\sigma'$ and high $k$. This means that the newly developed relationships can better describe tailings behavior even at low $\sigma'$ and high $k$. The volume compressibility coefficients ($A$, $B$) varied linearly with plasticity index ($I_p$) whereas the hydraulic conductivity coefficients ($C$, $D$) followed decreasing power law functions of $I_p$. Strong agreements between modeled data and measured data (published in the literature) were obtained for both void ratio ($R^2 = 0.98$) and hydraulic conductivity ($R^2 = 0.99$).
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LIST OF SYMBOLS

\( v_f \) Fluidization velocity

\( \gamma_s \) Unit weight of soil solids

\( \gamma_w \) Unit weight of water

\( v_{si} \) Initial settling velocity

\( e_m \) Soil formation void ratio or Maximum suspension void ratio

\( e \) Void ratio

\( k \) Hydraulic conductivity

\( u \) Pore water pressure

\( \sigma \) Total stress

\( \beta(t) \) Interactive stress

\( \sigma' \) Effective stress

\( Q \) Flow volume per unit time

\( L \) Sample height

\( a \) Cross sectional area

\( h \) Head difference

\( A, B \) Volume Compressibility Coefficients

\( C, D \) Hydraulic conductivity coefficients

\( C_c \) Compression index

\( I_P \) Plasticity index

\( A_c \) Activity

\( w_L \) Liquid limit

\( w_P \) Plastic limit
LI  Liquidity index

$e/e_L$  Normalized void ratio

$\varepsilon_o$  Permittivity of vacuum

$\kappa$  Boltzmann constant

$D_c$  Dielectric constant of medium

$T$  Temperature

$e_e$  Electronic charge

$n_o$  Ion concentration

$\nu$  Ionic valence

$I/K$  Thickness of double layer

$U_{DLVO}$  Total potential energy

$U_R$  Repulsive potential

$U_A$  Van der Waals attraction potential

$H$  Hamaker constant

$l$  Particle separation distance

$r$  Particle radius

$p$  Solvent permeability

$\varepsilon$  Permittivity

$\zeta$  Zeta potential

$c$  Function of ionic composition

$E, m$  Empirical constants for Casimir-Polder theory

$F, m'$  Empirical constants for Lifshitz theory

$\eta$  Efficient collision coefficient
\( \mu \) Water viscosity

\( t \) Time

\( N \) Particle number

\( \frac{dN}{dt} \) Reduction rate of particle number

\( T_r \) Tortuosity

\( n \) Porosity

\( w \) Water content

\( s \) Solids content

\( A_s \) Specific surface area

\( CEC \) Cation exchange capacity

\( f \) Clay content

\( G_{sf} \) Specific gravity of clay

\( G_{ss} \) Specific gravity of sand

\( e_s \) Maximum void ratio of sand

\( S \) Degree of saturation

\( G_s \) Specific gravity of soil solids

\( \bar{x} \) Sample mean

\( \sigma_s \) Sample standard deviation

\( n \) Sample size

\( t_{(\alpha/2, n-1)} \) Upper critical value of the t-distribution with (n-1) degrees of freedom

\( OLS \) ordinary least squares

\( BLUE \) Best linear unbiased estimator

\( GLS \) Generalized least squares
CHAPTER 1

INTRODUCTION

1.1 Problem Statement

Mining industries place their main focuses on the extraction of valuable mineral commodities from the parent rock. To extract the valuable constituents, certain ore processing steps (crushing, grinding, concentration, leaching, heating and thickening) are followed at mining operations though the extraction process may vary significantly from plant to plant (Edil and Fox, 2000). The finely ground mill residue remaining after the extraction of mineral is referred to as tailings (Bussière, 2007). The extraction of mineral process generates large volume of tailings. Due to the difficulty and long times required to dewater the tailings, it is necessary to understand the characteristics of the tailings.

The tailings are usually disposed hydraulically in confined impoundment areas. During deposition, segregation occurs due to sand dropping out faster and the fines flow to the centre of the tailings pond. In the pond, sand forms the perimeter dykes whereas the fines are in suspension and take a long time to settle. The high water content and slow dewatering rate of the slurries result in unique challenges related to the management of the impoundment facilities for a number of decades (Edil and Fox, 2000). Moreover, tailings dam failure in different parts of the world causes severe public distress due to large amount of contaminant releasing into the environment (Morgenstern and Scott, 1995). Clearly, deposition of mine tailings and reclamation of the containment ponds are the primary issues of concern in geotechnical engineering. To minimize the environmental footprint, the fluid tailings need to undergo an efficient consolidation, that is, extraction of solids from the liquid phase at a rapid rate and up to a high degree
The solid-liquid separation of tailings is governed by physicochemical factors derived from colloid-liquid interactions and applied stress due to internal granular surcharge or upper layer deposition (Azam et al., 2009).

From a geotechnical perspective, tailings can be characterized as relatively homogeneous and fine-grained slurries usually exhibiting low strength, high compressibility, low hydraulic conductivity, excessive pore water pressure and susceptibility to liquefaction (Morgenstern and Scott, 1995). A clear understanding of these properties at the onset of deposition is essential for planning, design, operation and reclamation of the tailings impoundments (Edil and Fox, 2000). Large strain consolidation test is necessary to perform the above aspects and it may take couple of months to complete. This test requires large quantities of sample and sophisticated laboratory equipment. However, consolidation behavior of mine tailings can be predicted by means of consistency limits and indices that use basic geotechnical equipment, small quantities of sample and shorter test times.

1.2 Research Objectives

The main objective of this study was to analyze the consolidation behavior of tailings in conjunction with soil consistency that captures the physicochemical interactions. The specific objectives were as follows:

- To develop void ratio versus effective stress and hydraulic conductivity versus void ratio relationships for three groups of materials (sedimentary clays, residual soils and oil sand tailings) using published data in the literature.

- To correlate the above relationships with soil consistency, that is, with liquidity index and normalized void ratio.
To develop relationships between consolidation coefficients and plasticity index by accumulating data in the literature for all groups of materials.

To validate the above relationships by analyzing the modeled data and the measured data (published in the literature) for both void ratio and hydraulic conductivity.

1.3 Thesis Outline

This chapter is followed by Chapter 2 that introduces the consolidation theory by describing the volume compressibility and the hydraulic conductivity of tailings. Next, the effects of geology and mining operation on tailings properties are reviewed. Thereafter, the colloid-water interaction and the factors affecting tailings consolidation are explained. The chapter closes with a review of geotechnical index properties.

Chapter 3 presents the methodology of the statistical analysis. The construction of a ternary diagram and the development of the statistical models are described.

Chapter 4 presents the results and explains these in light of geotechnical understanding. This chapter begins with the geotechnical index properties of tailings. Next, the classification of fine-grained materials, their characterization and statistical model issues are described. This is followed by the volume compressibility and the hydraulic conductivity relationships for three groups of materials, and then by index based correlations for these groups of materials. Finally, index based relationships for all tailings and validation of these relationships are described.

Chapter 5 presents the summary and conclusions of tailings consolidation models. This is followed by a list of references and appendices.
CHAPTER 2

LITERATURE REVIEW

2.1 General

This chapter begins with the consolidation theory. A brief description of tailings consolidation and the factors affecting the properties of materials are introduced. Colloid-water interactions governed by geology and mining operation are reviewed. Next, the factors affecting consolidation behavior are described to understand the engineering behavior of tailings. Finally, the geotechnical index properties are given to provide a brief overview on basic properties of tailings.

2.2 Consolidation Theory

Figure 2.1 shows the interface height as a function of elapsed time during the settling of a slurry. There are three distinct stages: flocculation, sedimentation and consolidation. Initially, the slurry develops a fabric and there is a relatively short period for flocculation which is characterized by a very small settling velocity of the interface. The development of microstructure depends on the mineralogy and water chemistry both of which govern the solid-liquid interaction. The newly formed flocs settle freely under gravity to undergo a rapid decrease in the interface height. During the settling process, segregation usually occurs, because the heavier particles fall faster (McRoberts and Nixon, 1976).

According to Imai (1980), electrolyte concentration plays an important role in the flocculation stage. An increase in electrolyte concentration leads to an increase in the flocculation of particles which will transit to hindered settling where a sharp interface is developed between suspension and clear liquid above. Segregation at the hindered settling ceases when the mutual interaction between particles is sufficient to agglomerate
Figure 2.1: Schematic of interface height versus time in a vertical column
the different size particles due to decreasing porosity. The particles finally settle at the same rate under gravity (Tan et al., 1990). A transition from particulate to hindered settling is also influenced by the concentration of slurry and the grain size distribution. If the solid concentration increases, this will lead to hindered settling. An increase in particle sizes (silt and fine sand) will result in a lower water content to obtain hindered settling (Tan, 1995).

To understand the solid phase and the liquid phase movement, it is necessary to describe the process of sedimentation and fluidization. In the early stage of settling process, suspended solid particles move downward under gravity through a stationary liquid phase and this process is known as sedimentation. In the latter, liquid flows slowly upwards through the bed of solid particles and this process is referred to as fluidization (Pane and Schiffman, 1997). If the fluid velocity increases, the particles reorient themselves and this process continues until the loosest stable arrangement (a greater cross sectional area to the fluid flow) is developed. The particles are supported by the fluid and kept in suspension with further increase in velocity. This velocity is known as minimum fluidization velocity (\(v_f\)). According to Richardson and Zaki (1954), when the velocity is greater than the \(v_f\), the solid particles remain evenly dispersed in the fluid and a sharp interface is observed between the suspension and the clear liquid above. They found that the velocity of fluidization and sedimentation depends only on the system porosity, and the fluidization velocity at a given porosity is equal and opposite to settling velocity at the same porosity.

According to Pane and Schiffman (1997), hydraulic conductivity of suspensions is measured directly based on fluidization velocity and the initial settling velocity.
Denoting the uniform dispersion of void ratio by $e$, the unit weight of soil solids by $\gamma_s$, the unit weight of water by $\gamma_w$ and the fluidization velocity by $v_f$, the hydraulic conductivity ($k$) is calculated according to the following equation:

$$k = \frac{v_f\gamma_w(1+e)}{\gamma_s-\gamma_w}$$  \[2.1\]

Denoting the initial settling velocity by $v_{si}$, the hydraulic conductivity is calculated according to the following equation:

$$k = \frac{v_{si}\gamma_w(1+e)}{\gamma_s-\gamma_w}$$  \[2.2\]

Pane and Schiffman (1997) observed the following features during the sedimentation test: (i) for higher porosities, the solid-liquid interface seems blurred and undefined due to segregation of soil particles and (ii) for lower porosities, some surface features of the interfaces such as channeling, miniature craters and volcanoes are developed, indicating the initiation of effective stress.

The sedimentation and consolidation zones are separated by the soil formation line (given in Figure 2.1). This line is characterized by the constant value of void ratio termed as soil formation void ratio ($e_m$) which is the fundamental material property for solid-liquid interaction (Pane and Schiffman, 1997). According to Azam et al. (2009), the $e_m$ is defined as the maximum suspension void ratio that corresponds to the lowest measurable effective stress and the initiation of slurry microstructure. Pane and Schiffman (1997) observed that the solid-liquid interface line moves downward and intersects the soil formation line, indicating the completion of sedimentation test. The slight downward concavity of the soil formation line indicates that the accumulated soil undergoes the self-weight consolidation process while depositing.
Consolidation is the change of soil volume resulting from the expulsion of excess pore water pressure that, in turn, is provoked by the vertical stresses. Terzaghi (1936) proposed the principle of effective stress having two parts: the existence of effective stress and its effect that controls the deformation of soil. Terzaghi’s effective stress concept is applicable for soils with small shearing strain of about 0.001% and it is expressed in the form of a difference between the total stress and the pore water pressure. The rate of excess pore pressure dissipation is governed by the excess pore water pressure gradient and the hydraulic conductivity of the material.

According to Gibson et al. (1967), volume compressibility and hydraulic conductivity are non-linear for soft soils (defined as saturated and normally consolidated soils with large shearing strain of about 0.10 to 1%) such as tailings which undergo large settlements. These authors proposed a non-linear finite strain consolidation theory to account for large settlements of soft soils. This theory was developed by applying the continuity of mixtures, the Darcy-Gersevanov fluid migration relationship through a soil matrix and the Terzaghi’s principle of effective stress for vertical equilibrium (Been and Sills, 1981). Tan (1995) and Azam (2011) proposed that electrochemical forces between solid-liquid interfaces carry some of the overburden force for fine-grained slurries. Therefore, it is necessary to account for the interactive force controlling the three dimensional network of the particles that prevents the free fall of the larger particles and resists the self weight consolidation at low effective stress. Clearly, Terzaghi’s theory needs to be modified for slurries by applying the stress developed due to interactive force which will be subtracted from the difference between total stress and pore pressure. Denoting the pore pressure by $u$, total stress by $\sigma$ and interactive stress $\beta(t)$, a more
appropriate definition proposed by Tan (1995) for effective stress ($\sigma'$) calculation is as follows:

$$\sigma' = \sigma - u - \beta(t)$$  \[2.3\]

Interactive stress, $\beta(t)$ is expected to be very small, and it has no direct contribution on deformation and may be a time dependent factor. When particles are sufficiently close for interaction, interactive stress develops. Initially, this stress is equal to $(\sigma - u)$ and there is no effective stress though the difference between the total stress and pore water pressure exists (Tan, 1995). This means there is a transition point indicating the zero effective stress after the completion of sedimentation until interactive stress is zero. Shodja and Feldkamp (1993) studied that the transition between sedimentation and consolidation occurs progressively and the thickness of a transition zone depends on particle size distribution, packing characteristics and the nature of inter-particle forces. For soft soils, Been and Sills (1981) found that there is a gap between the void ratio (about 6.0 to 7.0) at end of all settling and the void ratio (about 9.0 to 10.0) when the effective stress is first measured.

2.3 Tailings Consolidation

Consolidation behavior of tailings is explained by the volume compressibility and the hydraulic conductivity relationships. The large strain consolidation test is generally performed by applying incremental loads to increase the effective stress on tailings. At the end of each applied load increments, effective stress and void ratio are calculated and the saturated hydraulic conductivity ($k$) is measured directly by applying a constant head difference across the sample. Denoting the flow volume per unit time by $Q$, the sample
height by $L$, the cross sectional area by $a$, and the head difference by $h$, the hydraulic conductivity is calculated according to the following equation:

$$k = \frac{QL}{ah} \quad [2.4]$$

Denoting the empirical constants by $A$, $B$, $C$ and $D$, the constitutive equations for volume compressibility and hydraulic conductivity obtained from the consolidation test can be respectively written as follows:

$$e = A \varepsilon^B \quad [2.5]$$

$$k = C e^D \quad [2.6]$$

The compression index ($C_c$) is the slope of the straight line portion of the loading curve (void ratio versus applied pressure) and it describes the amount of settlement of a soil under loading. Likewise, the hydraulic conductivity is the rate of water migration through a soil that governs the expulsion of the excess pore water pressure during consolidation. Reviewing the literature, it was found that the volume compressibility and the hydraulic conductivity were correlated with the index properties of fine-grained soils. Denoting plasticity index by $I_p$, Wroth and Wood (1978) developed an equation for compression index of clays as follows:

$$C_c = 1.35 I_p \quad [2.7]$$

Denoting the void ratio by $e$, the plastic limit by $w_p$, the plasticity index by $I_p$ and the activity by $A_c$, Carrier (1985) proposed a correlation between compression index and soil consistency for remoulded clays as follows:

$$C_c = 0.329 \left[ e - 0.027 w_p + 0.0133 I_p \times (1.192 + A_c^{-1}) \right] \quad [2.8]$$

Likewise, Carrier and Beckman (1984) reported that the hydraulic conductivity (unit in m/s) for remoulded clays is correlated to the index properties as follows:
\[ k = 0.0174 \left\{ e^{-0.027[(w_p-0.242(I_p))]} \right\} / (1 + e) \]  \[ \text{[2.9]} \]

Berilgen et al. (2006) proposed a correlation between hydraulic conductivity (unit in m/s) and index properties for high water content clays as follows:

\[ k = \exp \left[ -5.51 - 4 \ln (I_p) \right] e^{7.52 \exp \left[ -0.25 (L) \right]} \]  \[ \text{[2.10]} \]

2.4 Factors Affecting Material Properties

2.4.1 Ore Geology

Rock and soil weathering, erosion and transportation of soil materials, depositional processes and post depositional changes in sediments are the main factors to understand the characteristics of any soil deposit (Mitchell and Soga, 2005).

Erosion includes all processes to wear away land surface by mechanical action. The transporting agents such as water, wind and ice are only capable of limited wearing. Average flow velocity is required more to erode the particles than to transport. Particles are eroded if the drag force of fluid is more than the gravitation, cohesive and frictional forces. Movement of sediments depends on the settling velocity of the particles and the laws of fluid motion. The rolling and dragging along the boundary between the transporting agent and the ground surface are required to transport the largest particles. Soluble materials are carried in solution and they can precipitate because of changed conditions. The concentration of sediments is maximum close to the stream bed than near the top. Fine particles are evenly distributed throughout the depth whereas coarser particles are near the bottom (Mitchell and Soga, 2005).

Physical weathering involves the disintegration (caused by wetting and drying or freezing and thawing) and erosion (due to the action of glacier, water and wind). These processes make sand, silt or even smaller than silt size particles with the properties
similar to the parent materials. Conversely, chemical weathering relates to changes of mineral content of parent rock and is caused by the action of percolating water, air and carbon dioxide. The minerals which produce parent rock are converted into different groups of materials and clay minerals. Clay minerals are of colloidal size (< 0.002 mm), and they give cohesion and plasticity properties which are the distinctive characteristics of clays. The nature of clay minerals depends on the parent rock and the weathering environment including well drained site and alkaline or acidic percolating water. For example, parent materials for smectite clay minerals are rock with high alkalinity earth such as igneous rock, volcanic ash and their derivatives pertaining to ferromagnesian minerals and calcic plagioclase. The formation of smectites also depends on the climatic condition in which evaporation exceeds precipitation and there is poor leaching and drainage (Mitchell and Soga, 2005).

Generally, biological activity influences the properties of soil particles. This is done by modifying particle arrangement, weathering of mineral surfaces, mediating oxidation-reduction reactions, and contribution to precipitation and dissolution of minerals. Furthermore, bio-geo-chemical interactions also influence the evolution of earth surfaces, promote the precipitation of cementing agents, accelerate the rate and amount of weathering, cause internal erosion, and alter fines migration through the soil matrix (Mitchell and Soga, 2005).

Unloading due to erosion of overlying sediments by glacial process governs the mechanical over-consolidation. For example, marine clay such as London clay was deposited during the Eocene period. In late Tertiary and Pleistocene time, the erosion occurred. In the late Quaternary period, small reloading took place by new deposition of
gravel after the unloading. There were five major transgressive-regressive cycles recognized during its deposition within the London clay. The post-depositional processes are site specific, because the degree of weathering, desiccation and erosion are dependent on location. The variation in depositional and post-depositional processes results in the complex mechanical behavior (Hight et al., 2003).

Finally, time effects or aging of both cohesive and cohesionless soils were analyzed by Schmertmann (1991). It remains uncertain whether the mechanisms of chemical reactions or physical activity or both lead to the observed increase in pre-consolidation pressure, shear strength (friction angle and cohesion), and material stiffness.

Figure 2.2 shows the soil formation processes. The soil formed by chemical weathering process which remains directly above and in contact with the parent rock is known as residual soils. Some of the residual soils are eroded by rainfall and they flow through rivers and streams. Eventually, these soils redeposit as new sediments at the bottom of lakes and oceans. This process continues for thousands of years and soils are compressed by the weight of layers when additional soil is deposited above the previous layer. The layers become denser and therefore harden. In this process, soil can form a thick layer and this soil is known as sedimentary soils. In some cases, loads on the soil can be reduced due to subsequent geological uplift or erosion processes. In these processes, soil can be normally consolidated (low stresses subjected to soils than loads currently acting on them) and over-consolidated soils (higher loads subjected on soils than the loads currently acting on them). The process related to the sequence of stresses
Figure 2.2: Schematic of soil formation processes (after Wesley 2010)
subjected to soil since its formations is termed as stress history. On the other hand, the particles of residual soils packed together in such a way can make soil skeleton, and their characteristics are quite different from those of simple collection of individual particles (Wesley, 2010).

According to Wesley (2010), the following factors are absent from residual soil, and degree of uniformity and predictability of sedimentary soils are due to these factors:
(i) The sorting processes that occur during erosion, transport and deposition of sedimentary soils can make homogeneous soil. As a result, coarser particles deposit in one place and fine particles deposit in different place.
(ii) Stress history is an important factor to understand the characteristics of sedimentary soils and it divides the soils into normally consolidated and over consolidated.

According to Wesley (2010), the following factors are very important to distinguish the residual soils from sedimentary soils:
(i) Residual soils are usually more heterogeneous compared to sedimentary soils.
(ii) Some residual soils, particularly from those of volcanic origin may have completely different clay minerals which are not found in sedimentary soils. These minerals strongly influence the soil characteristics.

A special class of sedimentary soil is oil sand which is composed of uncemented quartzose sands and fine-grained lithologies. Microscopic layer of water covers the sand grains and bitumen fills the pore spaces. The sand grains (predominantly quartz) were deposited in this way for millions of years and streams flowed from the Rocky Mountains in the west and from the Precambrian Shield in the east. Eventually, the area was known as the location of an ancient inland sea where the sand was spread densely. The sand of
this area was saturated by oil which became originated at depth to the south-west. Oil flowed into the sand deposits. The sands are locked with some fines which are accumulated at the particle contacts, but these fines do not have significant effect on total amount of fines in the tailings stream. Major contribution of the fine materials is generated from interbedded clay-shale which is broken down during the mining and extraction process (Scott et al., 2004).

2.4.2 Mining Operation

Mine tailings are produced from ore processing and extraction of constituents of interest such as uranium, aluminum, phosphate, oil, gold and copper. To understand the nature of mine tailings, the knowledge of the steps of processing and extracting an ore is necessary. According to Edil and Fox (2000), the following steps are used for many ore processes though the extraction processes may vary from plant to plant:

(i) Crushing and Grinding: These steps are fundamental in the milling process and thereafter, different techniques are used to extract the minerals of interest. Crushing is used to reduce the rock size that can be fed into the grinding equipment. Grinding is performed by rod mills to reduce further particle sizes which are on the order of 0.5 mm or less. It is the final operation process in the physical reduction of ore and final gradation depends on the particle breakdown from the grinding and clay content in the ore. For example, copper tailings are composed of silicate particles which are produced from grinding of parent rocks. Particles that are produced from hard rock are usually hard and angular.

(ii) Concentration: It is used to separate the valuable particles from those with little value by using different techniques such as gravity separation and froth flotation. Gravity
separation which is performed with water requires mineral and its parent rock with different specific gravities. The desired minerals are separated and collected. The remaining materials with high water content are discharged into tailings impoundments. The most widely used method is froth flotation which is a highly complex physicochemical process. Particles containing higher mineral move up to the surface of a froth which is skimmed off, and the remaining particles are tailings.

(iii) Leaching: This is used to remove the minerals from the ground particles of an ore by strong acid or alkaline solution. This process can change the physical properties of the tailings. For example, the acid leaching of uranium ore changes the montmorillonite in the ore to kaolinite clay minerals in the tailings.

(iv) Heating: It is sometimes used to extract minerals. For example, the extraction of oil from oil sand involves heating. The remaining materials after extraction of oil are handled in a slurry form.

(v) Thickening: This is the final step of milling process which is used to remove some of water from tailings before discharging into the tailings pond. It is commonly performed by the thickener which consists of a tank with rotating arms. The thickened tailings are usually transported and deposited hydraulically in a tailings pond. The coarser particles settle close to the point of discharge and the fine particles flow towards the centre of the ponds. These fine particles settle slowly and result in large volume of tailings.

2.5 Colloid-Water Interactions

Clay mineralogy and pore water chemistry are the results of geology and mining operation of materials. The main factors affecting soil consistency are water composition (governed by mining operation) and mineral composition (derived from geological
origin). These factors govern the amount of water electro-chemically attached to the particle surfaces (van Olphen, 1977). Mineralogy governs the size, shape and surface characteristics of soil particles. It influences the solid-liquid interaction and separation behavior. The physicochemical interactions at the colloid-water interfaces result in the development of a double layer around the colloid particles (Mitchell, 1976). A detailed description of double layer theory is described as follows:

2.5.1 Double Layer Theory

Electrical double layer consists of stern layer and diffuse layer. The Stern layer is formed by counterions (ions with charge opposite to the colloid) and it is firmly attached to the colloid. In the diffuse layer, the concentration of counterions gradually decreases and that of coions (ions with charge similar to the colloid) steadily increases until charge equilibrium with the liquid is attained (Chapman, 1913). Clay particles in a liquid are characterized by surface electrical charges. They can gain charges from preferential adsorption of certain ions to particle surfaces. The colloid and the surrounding ions develop an electrical potential across the double layer. The electrical potential is maximum at the colloidal surface and progressively approaches zero. Denoting the permittivity of vacuum \( (8.8542 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1}) \) by \( \varepsilon_0 \), the Boltzmann constant \( (1.38 \times 10^{-23} \text{ J K}^{-1}) \) by \( \kappa \), the dielectric constant of medium by \( D_c \), the temperature (K) by \( T \), the electronic charge \( (1.602 \times 10^{-19} \text{ C}) \) by \( e_c \), the ion concentration by \( n_o \), and the ionic valence by \( \nu \); the thickness of the double layer \( (I/K) \) around a colloidal particle is given by following equation (Mitchell and Soga, 2005):

\[
\frac{1}{K} = \left( \frac{\varepsilon_0 \kappa D_c T}{2 e_c^2 n_o \nu^2} \right)^{\frac{1}{2}} \tag{2.11}
\]
The above equation states that the thickness of the double layer varies as follows: (i) inversely with the ionic valence, (ii) inversely with the square root of the ion concentration and (iii) directly with the square root of the product of the dielectric constant and temperature. This means that ionic valence is the main factor affecting the double layer thickness. For example, trivalent ions cause the thinnest double layer, followed by divalent ions and then by monovalent ions (Collis-George and Bozeman, 1970). Similarly, an increase in ion concentration of the pore fluid reduces the double layer thickness. Furthermore, an increase in temperature is associated with a decrease in dielectric constant of the medium, because more energy is required to polarize fluid molecules. Therefore, the combined effect of DT on double layer thickness is marginal. Overall, a decrease in double layer thickness decreases the adsorption capacity of soil particles that, in turn, decreases the consistency limits (Mitchell and Soga, 2005).

Figure 2.3 shows repulsive and attractive energy as a function of distance between particle surfaces. Repulsive force between particles exists because of net negative charge on the surface of clay particles. There is an attractive force which is mainly from Van der Waals force. The Van der Waals force is electromagnetic. The surface potential is related to a lower measurable parameter known as the zeta potential (ζ) that develops between the stern layer and the diffuse layer (Hunter, 1981). The stability of a particle in a suspension depends upon its total potential energy, $U_{DLVO}$ consisting of repulsive potential $U_R$, Van der Waals attraction potential, $U_A$ (Israelachvili, 1992). Denoting the Hamaker constant by $H$, the particle separation distance by $l$, the particle radius by $r$, the solvent permeability by $p$, the function of the ionic composition by $c$ and the permittivity by $\varepsilon$, the total potential energy is given by following equation:
Figure 2.3: Repulsive and attractive energy versus distance between particle surfaces

(after Mitchell and Soga, 2005)
\[ U_{DLVO} = U_R + U_A \]
\[ = 2 \pi \varepsilon r \zeta^2 \exp(-\sigma l) - H / (12 pl^2) \]  

The Van der Waals attractive and repulsive forces reduce to almost zero at a distance away from the solid surface, but the repulsive force or barrier is maximum at a little far from the particle surface where the repulsive potential dominates the Van der Waals attraction. If the barrier is greater than 10 \( kT \) (\( k \) is Boltzmann constant), the collision between two particles developed by Brownian motion is not sufficient to overcome the barrier and the accumulation of particles does not occur (Overbeek, 1977).

2.5.2 Dispersion and Flocculation

Colloidal particles in a suspension undergo Brownian motion and during this movement, they come close to each other. The attraction and repulsion forces between the colloidal particles vary at different rate with separation distance (given in Figure 2.3). According to Casimir-Polder and Lifshitz theories, the repulsion decreases exponentially with distance and the attractive force decreases with the inverse of third or fourth power of particle distance, respectively. Although the Casimir-Polder theory is not exact, it is a good approximation for particle separation less than about 100 nm. Denoting the empirical constants by \( E, F, m' \) and \( m \), the attractive forces are dependent on distance according to the following equations:

\[ F_1 = \frac{Em}{d^3} \]  
\[ \text{Casimir-Polder theory} \]  

\[ F_2 = \frac{Em'}{d^4} \]  
\[ \text{Lifshitz theory} \]  

The repulsive force is sensitive to changes in cation valence, dielectric constant, electrolyte concentration and pH whereas the attractive force may be sensitive only to changes in dielectric constant. The balance of attractive and repulsive force between
colloidal particles determines whether particles would be dispersed or flocculated. If the amount of attractive force is less than that of repulsive force, the net force will be repulsion and the particles will be dispersed from each other. Conversely, flocculated structure will be formed if the net force between the particles acts as attraction. The rate of flocculation depends on the frequency of collision between particles due to Brownian motion. According to Hubbard (2002), the reduction rate of particle number is related to flocculation time and it is determined by using the following equation:

\[
\frac{dN}{dt} = -\left(\frac{4}{3\mu}\right) \eta \kappa T \frac{N^2}{\mu}
\]  

where, \(N\) is the particle number, \(t\) is the time, \(\kappa\) is the Boltzmann constant, \(\mu\) is the water viscosity, \(T\) is the temperature and \(\eta\) is the efficient collision coefficient.

2.6 Factors Affecting Tailings Consolidation

2.6.1 Microstructure

Soil is usually considered as continuum to understand its engineering behavior. Soil is actually composed of discrete particles, particle groups and pore spaces. A better understanding of soil behavior can be obtained if a soil is studied in conjunction with soil microstructure. A variation in soil microstructure can be developed with changes in water content.

Figure 2.4 gives the schematic of different types of fabric in clay suspensions. The mode of particle association in soils is in dispersed or aggregated state. If there is no association between particles, deflocculated structure is formed (given in Figure 2.4a and Figure 2.4b). The edge-to-edge and edge-to-face association form flocculated structure (given in Figure 2.4c through Figure 2.4f). The face-to-edge and edge-to-edge association
Figure 2.4: Mode of particle associations in clay suspensions
of particles form a cardhouse structures which are voluminous. The face-to-face association results in a thicker and larger particle (van Olphen, 1977).

The mechanism of particle association depends on the size, shape and charge of particles, pH, and concentration of ions. A connector of clay between two coarse particles results from a loose cardhouse structure. An array of books is similar to the interweaving bunches of clay between coarse particles. Irregular aggregations consist of a cardhouse microstructure of clay particles whereas regular aggregations are composed of a bookhouse fabric. There are two types of soil matrix (coarse and clay matrix) resulting from a combination of the above features and depending on soil composition. A coarse matrix refers to the coarse grains which touch one another. Soil behavior in a coarse matrix is governed by size, shape, angularity and distribution of the coarse particles. Clay particles take place in the pore spaces between the coarse grains. Conversely, the coarse particles separate from each other in a clay matrix. The engineering behavior of soil in a clay matrix depends on colloid-water interactions.

The fabric of a soil can be represented by three levels of scale such as microfabric, minifabric, and macrofabric (Olsen, 1962; Yong and Sheeran, 1973). A microfabric is composed of particles assemblage and the inter-assemblage pore spaces. Generally, the size of microfabric can be up to a few tens of micrometers. A minifabric consists of the assemblage of a few microfabric units and the interassemblage pore spaces between these units. The size of typical minifabric is in the range of a few hundred micrometers. Macrofabric corresponds to the entire soil mass which contains cracks, fissure and laminations. These types of fabric scales influence the engineering behavior of soil. Creep (time dependent phenomena) is influenced by microfabric and a better
understanding of physicochemical interactions can be achieved by minifabric. Shear strength and consolidation behavior of in-situ soils are influenced by macrofabric.

2.6.2 Tortuosity

Tortuosity means the ratio of the length of actual path of the fluid particles to the shortest length of path in the direction of flow. Tortuosity is an important feature of flow through the porous media. It influences the hydraulic conductivity which is related to the interconnected porosity of soil particles. For a given soil, interconnected void can be visualized as a drainage path through which fluid can flow. Dead end pores or disconnected bubbles within the soil can cause problem to correlate hydraulic conductivity with porosity. Porosity refers to the ratio of volume of voids to total volume in a soil mass, and it measures the void spaces in a soil mass. Tortuosity is always greater than one and it decreases with increasing porosity (Ghassemi and Pak, 2010). According to Koponen et al. (1997), tortuosity varies linearly with porosity. They developed an equation to calculate tortuosity \((T_r)\) from porosity \((n)\) as follows:

\[
T_r = 0.8 \left(1 - n\right) + 1 \tag{2.16}
\]

Tortuosity is fully dependent on configuration of the pores, flow paths and particle’s geometry. An increase of the particles’ height to width ratio results in an increase of the tortuosity that, in turn, decreases the hydraulic conductivity. The effect of particle size on tortuosity disappears if diameter of the particle is larger (Nabovati and Sousa, 2007).

2.6.3 Channeling

Narrow vertical paths are formed as a part of settling and consolidation of fine grained materials and they are referred as channels. When water and very fine particles flow
upwards through the channels, volcanoes (small mounds of accumulated particles) and craters (small depressions) develop. The excess pore pressure dissipation can be enhanced by channeling which can become a part of degree of consolidation (Nam et al. 2008). Channels usually develop below the lower interface of sediment and these channels propagate upwards until they reach at the top of the consolidation layer. For flocculated structure, some channels extend through the suspension zone. Channels close to the lower interface look more distinct and their lengths are generally less than 3 cm. They disappear if sediment is fully consolidated (Nam et al., 2008).

The main factor which controls the formation of channel is referred as flocculation. The flocs do not settle uniformly due to different floc sizes, and the particles tend to merge into flocs because of non-uniform settling behavior. The flocculated materials are attracted to one another, and they pull particles into flocs and away from other particles. Thus, discontinuities and voids are formed between flocs. These discontinuities make least resistance paths to dissipate the excess pore pressure. Eventually, fluid flow makes the discontinuities to merge, forming the vertical channels (Nam et al., 2008).

2.7 Geotechnical Index Properties

2.7.1 Water Content

Water content \( w \) is defined as the ratio of the mass of water in a given volume of soil to that of soil solids in the same volume. It is expressed in percentage. It is determined according to the ASTM D2216–10 Standard Test Methods for Laboratory Determination of Water (Moisture) of Soil and Rock by Mass. Water content is used to calculate solids content \( s \) which is defined as the ratio of the mass of soil solids to the total mass of the
soil. Based on phase relationships, solids content is calculated according to the following equation:

\[ s = \frac{1}{1+w} \]  

[2.17]

2.7.2 Specific Gravity

Specific gravity \((G_s)\) is defined as the ratio of the mass of a unit volume of a material at a standard temperature \((4{^\circ}C)\) to the mass in air of the same volume of gas-free distilled water at the given temperature. Specific gravity is used to calculate void ratio which is referred as the ratio of the volume of voids to the volume of soil solids. It is determined according to ASTM D854–10 Standard Test Methods for Specific Gravity of Soil Solids by Water Pycnometer. To preclude the effect of pre-test drying of residual soils, Fourie (1997) suggested that soil sample is oven dried at temperature of 50 \(^{\circ}\)C.

2.7.3 Grain Size Distribution

Grain size distribution of soils is performed according to ASTM D422–63(2007) Standard Test Method for Particle-Size Analysis of Soils. For high ionic concentration of pore water of slurry, Dusseault and Scott (1983) proposed that the soil sample should be divided into two sub-samples: (i) one part is used for determining dry mass of the soil and (ii) the other is used for grain size distribution. Hydrometer analysis is conducted on dry sample after complete dispersion of soil solids (Lambe, 1951). Approximately 25 g of dry sample is used in the hydrometer test to preclude the effect of hindered settling (Vitton and Sadler, 1997). Soil sample is mixed with dilute alkaline sodium hexametaphosphate which acts as a dispersing agent and the sample is suspended by agitation (Townsend et al., 1971; Wintermeyer and Kinter, 1954). The same materials are used for sieve analysis after washing with distilled water.
The grain size analysis provides two important parameters: (i) fines content (termed as the percentage of mass finer than 0.075 mm in the total mass of soil) and (ii) clay content (referred as the amount of mass finer than 0.002 mm in the total mass of soil solids). Sieve analysis determines the mechanical properties of soil slurry whereas hydrometer analysis explains the physicochemical phenomena at the solid-liquid interfaces.

2.7.4 Consistency Limits

The consistency limits provide important information about the physical and chemical properties of slurries (Carrier and Beckman, 1984). The Liquid limit \((w_L)\) of a soil is the lowest water content above which a soil behaves like a viscous fluid. Likewise, the plastic limit \((w_p)\) of a soil is the water content below which it ceases to be plastic. The plasticity index \((I_p)\) is defined as the difference between the two limits and it describes the range of water content where soil exhibits plasticity properties.

\[
I_p = w_L - w_p
\]  

[2.18]

The consistency limits are usually determined by oven drying the samples at a temperature of 105°C for 24 hours. Such drying conditions can lead to clay aggregation and the formation of silt size particles with an associated loss of plasticity, especially in residual soils. To preclude this effect, Azam et al. (2005) determined the consistency limits of laterite ores at a reduced temperature of 50°C. This temperature may or may not be appropriate for all soils because of an incomplete removal of adsorbed and/or structural water (Holtz and Kovacs, 1981). The standard drying conditions are suitable for oil sand tailings to lower the water content to the liquid and plastic limit ranges, because oil sand tailings take a long time to consolidate naturally and this material is
known to gain a very rapid thixotropic strength which causes higher liquid and plastic limit ranges. To avoid thixotropic hardening and the associated increase in consistency limits, the latter should be determined on samples immediately after their collection (Scott et al., 1985). Thixotropy is termed as an isothermal, reversible and time dependant process where the material stiffens at rest and is liquefied by remoulding.

The consistency limits of fined grained soils depend on the several factors: (i) amount and type of clay minerals, (ii) type of absorbed cation (Das, 1983). The cumulative water adsorption capacity of the soil constituents governs the engineering behavior of the soil. The adsorption capacity of the particles mainly depends on specific surface area \(A_s\) and cation exchange capacity \(CEC\). The specific surface area is a reflection of soil mineralogy and is directly related to the magnitude of the electrical charge whereas the cation exchange capacity refers to the maximum quantity of cations that a soil can possess, at a given pH value, for exchanging with the pore fluid (Mitchell and Soga, 2005). Denoting water content by \(w\) and the unit weight of water by \(\gamma_w\), the adsorbed water can be calculated according to following equation (Lambe and Whitman, 1969):

\[
w = A_s \times \frac{1}{k} \times \gamma_w\]

Table 2.1 gives the specific surface area, the cation exchange capacity and the consistency limits of common clay minerals such as kaolinite, illite and smectite. An increase in specific surface area and/or \(CEC\) results in an increase in both the liquid limit and the plastic limit. Generally, consistency limits are highest for smectite followed by illite and then by kaolinite.
Table 2.1: Specific surface area, CEC and consistency limits of clay minerals

<table>
<thead>
<tr>
<th>Clay Minerals</th>
<th>Specific Surface, $A_s$ (m$^2$/g)</th>
<th>CEC at pH of 7 (cmol+/kg)</th>
<th>Liquid limit (%)</th>
<th>Plastic limit (%)</th>
<th>Plasticity index (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Smectite</td>
<td>700 - 840</td>
<td>70 – 100</td>
<td>140 – 710</td>
<td>54 – 98</td>
<td>67 – 656</td>
</tr>
</tbody>
</table>

Data Sources: Mitchell (1976), Carroll (1959) and Lambe and Whitman (1969).
2.7.5 Liquidity Index

The relative consistency of a soft soil is explained by liquidity index (LI). When \( LI \) is less than 1, soil behaves like a plastic material. Conversely, soil behaves like a viscous fluid when \( LI \) is more than 1.0. For sensitive clays, if the water content is more than \( w_L \), they may be stable in an undisturbed condition, but they can liquefy under sudden shock.

2.7.6 Normalized Void Ratio

Normalized void ratio is defined by a ratio of void ratio and void ratio at \( w_L \). Normalized void ratio is used to define the mutual repulsion of clay particles and the effective pore sizes controlling the fluid flow in volume compressibility and hydraulic conductivity of soils, respectively. According to Russell and Mickle (1970), and Nagaraj et al. (1991), all clays have the following identical properties at the \( w_L \): undrained shear strength (1.7 kPa), pore water suction (6 kPa) and hydraulic conductivity (2.5 \( \times \) \( 10^{-7} \) cm/s). Mitchell and Soga (2005) explained the above-mentioned identical values as follows: (i) the thickness of average adsorbed water on individual particle surfaces is nearly the same, (ii) each aggregate of several particles acts as a single unit that interacts with water as a whole, and (iii) the average intercluster pore size is the same. Similar reasons may be attributed to the plastic limit that has been reported to have undrained shear strength of around 170 kPa (Sharma and Bora, 2003). This means that the engineering behavior of fine-grained soils is derived from the interaction of charged particle surfaces with charges in the pore water. The physicochemical interactions at the solid-liquid interfaces develop due to charged particle surfaces and charges in pore water. This research focuses on consistency-based relationships that are intended to account for the physicochemical interactions and to analyze the tailings consolidation at the onset of deposition.
CHAPTER 3

RESEARCH METHODOLOGY

3.1 General

This chapter gives the research methodology carried out for the present study. Tailings classification is described based on Unified Soil Classification System (USCS) followed by ternary diagram for tailings characterization. Next, a theory of statistical analysis is described. Finally, a detailed description of the statistical analysis is given to understand the modeling for three groups of tailings and for entire tailings using published data in the literature.

3.2 Tailings Classification

Figure 3.1 shows the plasticity chart for USCS. The fine-grained slurries (finer than 0.075 mm) were classified according to Standard Practice for Classification of Soils for Engineering Purposes (Unified Soil Classification System) (ASTM D2487-11). Plasticity chart was made by plotting liquid limit (%) and plasticity index (%). An empirical boundary lines referred as “A” line was drawn to separate the inorganic clays (plotted above “A” line) from silty and organic soils (plotted below “A” line). To define the low and high plasticity soils, a line was drawn at $w_L$ of 50%. A certain zone was used in the plasticity chart to define sand (denoted by CL-ML) when soils with plasticity index ranging from 4 to 7 were plotted above “A” line. There are different symbols used to define the different types of soils. For example, low and high plasticity clayey materials are denoted by CL and CH respectively whereas low and high plasticity silty materials are defined by ML and MH respectively. The low and high plasticity organic soils are denoted by OL and OH respectively.
Figure 3.1: Plasticity chart for USCS
3.3 Tailings Characterization with Ternary Diagram

Figure 3.2 shows the layout of a ternary diagram having three apexes and three axes. The three axes are referred as the solids content (plotted on left hand side), the clay water ratio (reported on the right hand side) and the clay content (given along the base). The three apexes are termed as water, coarse and clay. The clay size fraction is defined as a material finer than 0.002 mm. The parallel horizontal lines represent the constant solid-water ratio lines. The straight lines plotted from water apex to the base represent slurries with constant clay content. Likewise, the straight lines drawn from the coarse apex to the right hand side represent constant clay-water ratio lines.

The ternary diagram describes the boundary between coarse matrix and clay matrix. In a coarse matrix, coarse particles barely touch each other and the clay particles fill up the pore spaces between the coarse particles or sand. Conversely, the sand grains do not touch each other in the clay matrix, but they are suspended. Denoting $f$ as the clay content (by weight), $G_{sf}$ as the specific gravity of clay, $G_{ss}$ as the specific gravity of the sand, $e_s$ as the maximum void ratio of sand (0.9) and $w$ as the water content, the matrix boundary was obtained according to the following equation:

$$f \, (\%) = \frac{100 \, e_s G_{sf} - w G_{sf} G_{ss}}{e_s G_{sf} + G_{ss}} \quad [3.1]$$

Ternary diagram is applied to define the following characteristic boundaries: sedimentation-consolidation boundary (separation between the sedimentation and the consolidation region), segregating-nonsegregating boundary (segregation or preferential settling of solid particles) and solid-liquid boundary (plotted at undrained shear strength of about 2.5 kPa). The key feature of the diagram is clay-water ratio lines that govern the physicochemical interactions between solid-liquid interfaces (Azam et al., 2005).
Figure 3.2: Construction layout of a ternary diagram
3.4 Theory of Statistical Analysis

3.4.1 General

A brief description of the statistical terminology is warranted to develop a basic understanding for the modeling process.

3.4.2 Variables

Variables are things, items, and entities which are measured, manipulated and controlled in research. There are two types of variables such as dependent and independent variables. In experimental research, independent variables are manipulated and the manipulation effects on dependent variables are generally measured. Based on the type of measurement, variables can be classified into four classes such as nominal, ordinal, interval and ratio. Nominal variables allow categories but not ranking or quantification. Ordinal variables can be assessed in terms of ranking but cannot be quantified. Interval variables include measurement of both time and space. They allow both ranking and quantification. Lastly, ratio variables are similar to interval variables but they have an identifiable absolute zero.

3.4.3 Relationships

Relationships between dependent and independent variables are determined by regression analysis and these relationships provide consistent distribution of the magnitude of variables in a sample of observations. The magnitude and reliability of variables characterize a relationship. The magnitude pertains to the size of variation in a relationship whereas the reliability refers to the representativeness of the observed data.

The correlation line between two variables is developed by using ordinary least squares (OLS) method in which the regression estimates a set of coefficients that
minimizes the sum of squared residuals. The coefficient of determination ($R^2$) measures the improvement in prediction of a relationship obtained by using regression analysis. The correlation significance with a given magnitude depends on the sample size and the outliers. Outliers are not representative observations, because they affect the slope of correlation line. Certain outliers can be excluded from the analysis because of their extreme observation. Therefore, conclusions are always made by examining both $R^2$ and standard deviation.

3.4.4 Sample Size

Magnitude and reliability of relationships are interdependent if sample size is constant. The larger the magnitude of relationship between variables, the more reliable is the relationship. The probability of a strong relationship between variables is significantly high for small sample size. If there is no relationship between two variables, the required sample size is appeared to be infinitely large. In experimental studies, the maximum possible values of dependent variables determine the sample size.

3.4.5 Confidence Interval

The purpose of taking a sample from population data and examining a statistic is to rough estimate the mean of the population. The issue related to the analysis how well the sample statistics determines the underlying population value. A confidence interval explains this issue, because it gives a range of values instead of a particular value for the mean. The narrower the interval, the more precise the estimates. The range of interval is mainly influenced by two factors: (i) sample size and (ii) standard deviation. A more precise estimate is obtained by increasing the sample size. The data with large standard deviation generate wider intervals than data with smaller standard deviation.
3.5 Modeling for Groups of Tailings

3.5.1 General

Figure 3.3 shows the schematic of statistical model for three groups of fine-grained slurries (sedimentary clays, residual soils and oil sand tailings). Based on published volume compressibility and hydraulic conductivity data in the literature, the relationships of void ratio with effective stress and hydraulic conductivity for each group of materials were developed. This was followed by deriving index based correlations in terms of liquidity index \((LI)\) and normalized void ratio \((e/e_L)\).

3.5.2 Data Collection and Conversion

Published consolidation data in the literature in terms of void ratio versus effective stress and hydraulic conductivity versus void ratio were provided in the Appendices. In this study, the materials obtained from the literature were divided into three groups: sedimentary clays, residual soils and oil sand tailings, because geological process and mining operation commonly generate these groups of materials. Additionally, most of the materials are either sedimentary or residual soils, and a special class of sedimentary soils is the oil sand tailings in which bitumen is present alongside fine-grained materials.

Volume compressibility data of phosphatic clay and speswhite kaolin, and hydraulic conductivity data of pelagic clay were not available in the literature. Consolidation data in the literature were plotted in terms of void ratio versus effective stress and void ratio versus hydraulic conductivity. Index based correlations for groups of tailings were developed by changing void ratio into \(LI\) and \(e/e_L\). Assuming that the degree of saturation \((S)\) equals 100% in slurries, and denoting the void ratio by \(e\), the specific gravity of soil solids by \(G_s\), the slurry water content \((w)\) was obtained according to the
Figure 3.3: Flow chart of statistical model for groups of tailings

- Volume Compressibility Data (Appendices)
- Hydraulic Conductivity Data (Appendices)
- Index Properties (Table 4.1)
- Best Fits for Tailings Groups (Table 4.2, 4.3)
  - e versus σ' (Fig 4.5)
  - e versus k (Fig 4.6)
- Void Ratio Conversion to LI & e/eₐ
  - LI versus σ' (Fig 4.7)
  - e/eₐ versus σ' (Fig 4.8)
  - LI versus k (Fig 4.9)
  - e/eₐ versus k (Fig 4.10)
- Plasticity Chart (Fig 4.1)
following equation:

\[ w = \left( \frac{\varepsilon}{\gamma_0} \right) \]  \[ [3.2] \]

Denoting liquid limit by \( w_L \) and plastic limit by \( w_P \), this water content was scaled using the liquidity index of soils according to the following equation:

\[ LI = \frac{w - w_P}{w_L - w_P} \]  \[ [3.3] \]

Denoting the void ratio at \( w_L \) by \( e_L \), normalized void ratio is calculated according to the following equation:

\[ \frac{e}{e_L} = \frac{w}{w_L} \]  \[ [3.4] \]

### 3.5.3 Consolidation Relationships

Consolidation data in the literature for three groups of materials were plotted on \( e \) versus \( \sigma' \) and \( e \) versus \( k \) graphs. The best-fits based on the OLS method were obtained for each group of materials.

### 3.5.4 Index Based Correlations

Regression analyses were performed to correlate the effective stress (published in the literature) with \( LI \) and \( e/e_L \). The best-fits for each group of materials were obtained on the OLS method. Likewise, the hydraulic conductivity correlations in terms of \( LI \) and \( e/e_L \) were performed.

### 3.5.5 Model Reliability

Reliability of an estimate utilizes the confidence interval which is calculated from the observation. Denoting the sample mean by \( \bar{x} \), sample standard deviation by \( \sigma_s \), upper critical value of the t-distribution with (n-1) degrees of freedom by \( t_{(\alpha/2,n-1)} \) and sample size by \( n \), confidence limits are defined according to following equation:
The margin of error \( \frac{t(\alpha/2,n-1) \sigma}{\sqrt{n}} \) is referred to the value added or subtracted from the sample mean which determines the interval length. Although the choice of confidence interval is somewhat arbitrary, 95\% and 99\% intervals are usually used in practice. This study considers 99\% confidence interval, because it is more reliable of an estimate than 95\% confidence interval. Additionally, this interval covers the 99\% of normal distribution curve. This means the probability of observing value outside of this area is less than 0.01\%.

**3.6 Modeling for All Tailings**

**3.6.1 General**

Figure 3.4 shows the schematic of statistical model for all tailings. Based on published volume compressibility and hydraulic conductivity data in the literature, the relationships of void ratio with effective stress and hydraulic conductivity for each type of materials were developed. Finally, index based correlations in terms of consolidation coefficients \((A, B, C \text{ and } D)\) and plasticity index were developed.

**3.6.2 Data Collection**

Consolidation data and index properties published in the literature were provided in the Appendices. These data were used to develop index based relationships for all of the materials.

**3.6.3 Consolidation Relationships**

Consolidation data in the literature for each type of materials were drawn on \( e \) versus \( \sigma' \) and \( e \) versus \( k \) graphs. The best-fits for each type of materials in terms of \( e \) versus \( \sigma' \)
Figure 3.4: Flow chart of statistical model for entire tailings materials
Table 3.1: Constitutive equations of consolidation data in the literature for different types of materials

<table>
<thead>
<tr>
<th>Slurry Type</th>
<th>e versus $\sigma'$ Relationships</th>
<th>k versus e Relationships</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Sedimentary Clays</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China Clay</td>
<td>$e = 3.29 \sigma'^{0.16}$</td>
<td>$k = 1.81 \times 10^{-8} \exp^{5.45}$</td>
<td>Znidarcic et al., 1986</td>
</tr>
<tr>
<td>Georgia Kaolin</td>
<td>$e = 2.25 \sigma'^{0.17}$</td>
<td>$k = 1.16 \times 10^{-7} \exp^{4.86}$</td>
<td>do</td>
</tr>
<tr>
<td>Phosphate Slime</td>
<td>$e = 11.34 \sigma'^{0.29}$</td>
<td>$k = 1.16 \times 10^{-9} \exp^{3.50}$</td>
<td>Roma, 1976</td>
</tr>
<tr>
<td>Phosphatic Clay</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Speswhite Kaolin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Pelagic Clay</td>
<td>$e = 4.50 \sigma'^{0.12}$</td>
<td></td>
<td>Marine Geotechnical Consortium, 1985</td>
</tr>
<tr>
<td>(b) Residual Soils</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laterite</td>
<td>$e = 6.45 \sigma'^{0.09}$</td>
<td>$k = 5.76 \times 10^{-14} \exp^{10.26}$</td>
<td>Azam et al., 2009</td>
</tr>
<tr>
<td>Bauxite</td>
<td>$e = 2.34 \sigma'^{0.11}$</td>
<td>$k = 5.02 \times 10^{-8} \exp^{5.24}$</td>
<td>Cooling, 1985</td>
</tr>
<tr>
<td>Uranium</td>
<td>$e = 1.55 \sigma'^{0.07}$</td>
<td>$k = 1.74 \times 10^{-7} \exp^{13.8}$</td>
<td>Matyas et al., 1984</td>
</tr>
<tr>
<td>(c) Oil Sand Tailings</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore A–C, SRPW</td>
<td>$e = 3.26 \sigma'^{0.22}$</td>
<td>$k = 2.85 \times 10^{-9} \exp^{3.73}$</td>
<td>Miller et al., 2010a</td>
</tr>
<tr>
<td>Ore A–NC, TARW</td>
<td>$e = 2.91 \sigma'^{0.22}$</td>
<td>$k = 1.45 \times 10^{-9} \exp^{4.22}$</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–C, SRPW</td>
<td>$e = 3.08 \sigma'^{0.25}$</td>
<td>$k = 2.69 \times 10^{-9} \exp^{5.28}$</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–C, TARW</td>
<td>$e = 3.07 \sigma'^{0.23}$</td>
<td>$k = 2.59 \times 10^{-9} \exp^{4.19}$</td>
<td>do</td>
</tr>
<tr>
<td>Ore A–NC, UARW</td>
<td>$e = 3.42 \sigma'^{0.20}$</td>
<td>$k = 2.13 \times 10^{-9} \exp^{4.16}$</td>
<td>do</td>
</tr>
<tr>
<td>Desanded</td>
<td>$e = 3.46 \sigma'^{0.23}$</td>
<td>$k = 8.46 \times 10^{-9} \exp^{3.41}$</td>
<td>Lord and Liu, 1998</td>
</tr>
<tr>
<td>Cyclone Overflow</td>
<td>$e = 3.27 \sigma'^{0.18}$</td>
<td>$k = 5.96 \times 10^{-9} \exp^{4.10}$</td>
<td>Jeeravipoolvarn et al., 2008</td>
</tr>
</tbody>
</table>

Extraction Process: C, caustic and NC, non-caustic; Pore Water: SRPW, syncrude recycled pond water; TARW, treated Athabasca river water; UARW, untreated Athabasca river water. Consolidation Test: CRD, constant rate of deformation; FZ, fluidization; LSCD, large strain consolidation; OM, oedometer; LSCRS, large strain controlled rate of strain.

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(except phosphatic clay and speswhite kaolin) and $e$ versus $k$ (except pelagic clay) were obtained based on the OLS method.

3.6.4 Index Based Correlations

Table 3.1 gives the constitutive equations of consolidation data in the literature for each material. The volume compressibility coefficients ($A, B$) and the hydraulic conductivity coefficients ($C, D$) were obtained from the constitutive equations. Next, regression analyses were performed to correlate these coefficients with the plasticity index. The plasticity index was selected because it represents the range of water content (between the liquid and the plastic limit) that is operative in the tailings impoundments.

3.6.5 Model Validation

The index-based correlations were used to calculate the modeled void ratio and the modeled hydraulic conductivity. Each of these parameters was plotted against the corresponding measured data in the literature for model validation. The best-fits in terms of modeled data versus measured data (published in the literature) were obtained using the OLS method. Finally, the line of equality was drawn on these graphs. The main feature of equality line was to describe the distribution of data on either side of the line.
CHAPTER 4

RESULTS AND DISCUSSIONS

4.1 General

This chapter first describes geotechnical index properties, followed by tailings classification, and then by tailings characterization using ternary diagram. Finally, results obtained from the statistical models are discussed.

4.2 Geotechnical Index Properties

Table 4.1 gives the geotechnical index properties published in the literature of the fine-grained slurries. The specific gravity \( G_s \) of sedimentary clays ranged from 2.6 to 2.77, which is the typical range for such materials (Wesley, 2010). Conversely, residual soils showed higher \( G_s \) values due to the presence of ferrous minerals such as goethite and hematite in the laterite (Azam, 2005), and gibbsite and hematite in the bauxite (Newson et al., 2006); the higher \( G_s \) (in comparison with sedimentary clays) of uranium tailings was attributed to the high amount of muscovite (Naamoun, 2003). Finally, the low \( G_s \) (2.55 ± 0.1) for oil sand tailings was due to the presence of bitumen \( (G_b = 1.03) \) with variations attributable to the variable amount of bitumen in the various samples (Miller et al., 2010b).

The consistency limits varied over a wide range due to the presence of different types of clay minerals. This was particularly true for sedimentary clays, for which the \( w_L \) ranged from 44% to 162% and the \( w_P \) from 25% and 54%: the higher values associated with high water adsorbing minerals, as described earlier in Table 2.1. Conversely, the \( w_L \) varied from 32% to 83% and the \( w_P \) from 27% to 42% for residual soils. The consistency
<table>
<thead>
<tr>
<th>Slurry Type</th>
<th>$G_s$</th>
<th>$w_L$ (%)</th>
<th>$w_p$ (%)</th>
<th>$I_p$ (%)</th>
<th>USCS Symbol</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>(a) Sedimentary Clays</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China Clay</td>
<td>2.66</td>
<td>53</td>
<td>32</td>
<td>21</td>
<td>MH</td>
<td>Znidarcic et al., 1986</td>
</tr>
<tr>
<td>Georgia Kaolin</td>
<td>2.6</td>
<td>44</td>
<td>25</td>
<td>19</td>
<td>CL</td>
<td>do</td>
</tr>
<tr>
<td>Phosphate Slime</td>
<td>2.77</td>
<td>100</td>
<td>40</td>
<td>60</td>
<td>CH</td>
<td>Roma, 1976</td>
</tr>
<tr>
<td>Phosphatic Clay</td>
<td>2.74</td>
<td>162</td>
<td>44</td>
<td>118</td>
<td>CH</td>
<td>Pane and Schiffman, 1997</td>
</tr>
<tr>
<td>Speswhite Kaolin</td>
<td>2.6</td>
<td>53</td>
<td>32</td>
<td>21</td>
<td>MH</td>
<td>do</td>
</tr>
<tr>
<td>Pelagic Clay</td>
<td>2.69</td>
<td>140</td>
<td>54</td>
<td>86</td>
<td>MH</td>
<td>Marine Geotechnical Consortium, 1985</td>
</tr>
<tr>
<td>(b) Residual Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laterite</td>
<td>3.16</td>
<td>83</td>
<td>42</td>
<td>41</td>
<td>MH</td>
<td>Azam et al., 2009</td>
</tr>
<tr>
<td>Bauxite</td>
<td>3.05</td>
<td>54</td>
<td>40</td>
<td>14</td>
<td>MH</td>
<td>Cooling, 1985</td>
</tr>
<tr>
<td>Uranium</td>
<td>2.81</td>
<td>32</td>
<td>27</td>
<td>5</td>
<td>ML</td>
<td>Matyas et al., 1984</td>
</tr>
<tr>
<td>(c) Oil Sand Tailings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore A–C, SRPW</td>
<td>2.55</td>
<td>50</td>
<td>26</td>
<td>24</td>
<td>CH</td>
<td>Miller et al., 2010b</td>
</tr>
<tr>
<td>Ore A–NC, TARW</td>
<td>2.51</td>
<td>50</td>
<td>31</td>
<td>29</td>
<td>CH</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–C, SRPW</td>
<td>2.48</td>
<td>52</td>
<td>27</td>
<td>25</td>
<td>CH</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–NC, TARW</td>
<td>2.45</td>
<td>58</td>
<td>28</td>
<td>30</td>
<td>CH</td>
<td>do</td>
</tr>
<tr>
<td>Ore A–NC, UARW</td>
<td>2.5</td>
<td>55</td>
<td>28</td>
<td>27</td>
<td>CH</td>
<td>do</td>
</tr>
<tr>
<td>Desanded</td>
<td>2.65</td>
<td>57</td>
<td>25</td>
<td>32</td>
<td>CH</td>
<td>Lord and Liu, 1998</td>
</tr>
<tr>
<td>Cyclone Overflow</td>
<td>2.53</td>
<td>50</td>
<td>21</td>
<td>29</td>
<td>CH</td>
<td>Jeeravipoolvarn et al., 2008</td>
</tr>
</tbody>
</table>

Extraction Process: C, caustic and NC, non-caustic;
Pore Water: SRPW, syncrude recycled pond water; TARW, treated Athabasca river water; UARW, untreated Athabasca river water.
limits between the materials in this group were seen in a narrower range due to the presence of non-clay minerals. According to Dolinar and Trauner (2005), non-clay minerals have much smaller surface areas and less affinity for water that, in turn, results in low consistency limits. In this group, laterite ore is coated by sesquioxides of iron and aluminum (caused by weathering process). A small amount of sesquioxides minerals govern the engineering behavior of this material due to their mobility and solubility. Sesquioxides have a positively charged surface. Conversely, clay particles have negatively charged surface that attracts cations. Most of the cations are exchangeable and replaced by other cations. Cations exchange in laterite ore depends on the type and amount of clay minerals and sesquioxides coating. Such coating tends to inhibit the electro-chemical activity of clay minerals that, in turn, subdues liquid and plastic limit in residual soils (Azam, 2005). Finally, the $w_L$ for oil sand tailings varied from 50% to 60% and the $w_P$ from 21% to 31%. As the kaolinite was the main clay mineral in this group, the consistency limits were generally on the high side for this mineral (Table 2.1). This is attributed to lubrication from bitumen that allowed quick slope failure and delayed material crumbling during the liquid limit and the plastic limit test, respectively.

The above consistency limits depend on the type of water used during testing, but data on the water composition in the literature were not available for all of the materials. Generally, the consistency limits are highest for deionized water, followed by distilled water, and then by decant water. The effect of water composition derived from the chemical-rich nature of the extraction process in the oil sand tailings was found by Miller et al. (2010b). The consistency limits for ore A–C, SRPW ($w_L = 50\%$ and $w_P = 26\%$) were lower than those for ore A–NC, TARW ($w_L = 60\%$ and $w_P = 31\%$). This is because,
about three times higher sodium concentration in the ore A–C, SRPW compared to ore A–NC, TARW caused a decrease in double layer thickness that reduced the adsorption capacity of the particles, that, in turn, decreased the consistency limits.

4.3 Tailings Classification

Figure 4.1 shows the materials published in the literature on the plasticity chart. Most of the soils plotted close to the A-line and in the high liquid limit zone. Sedimentary clays ranged from low to high plasticity clayey soils (CL and CH respectively) and high plasticity silty soils (MH). Residual soils were classified as low plasticity silty soils (ML) and high plasticity silty soils (MH). Sesquioxide coating of the clay minerals rendered the clays less electro-chemically active and the materials behaved as silty soils (Azam et al., 2005). Lastly, the oil sand tailings were classified as high plasticity clayey materials (CH). Despite the presence of significant amount of kaolinite, the relatively high plasticity of oil sand tailings was attributed to bitumen coating and lubrication. Overall, the variability in the index properties of the tailings was attributed to the variable solid-liquid interactions. Derived from the geological background (mineralogical composition of the solids) and the mining operation (the pore fluid composition), these interactions governed the consolidation behavior of slurries (Carrier and Beckman, 1984).

4.4 Tailings Characteristics

Figure 4.2 gives the characteristic zones of three groups of materials. Sedimentary clays and residual ores were plotted in different zones of the ternary diagram because of their different geological origins. Although oil sand tailings are a special class of sedimentary clays, they were not plotted in the zone of sedimentary clays due to their cardhouse microstructure and bitumen residues.
Figure 4.1: Data on plasticity chart
Figure 4.3 shows the effective stress lines at different values for sedimentary clays, residual soils and oil sand tailings. It was found that for a given group of materials, the effective stress lines at any values were parallel to each other. The effective lines appeared to be parallel to clay-water ratio lines with increasing clay content. This means physicochemical interactions are maximum at high clay content. In addition, the effective stress at a given solids content was maximum for oil sand tailings, followed by residual soils, and then by sedimentary clays.

Figure 4.4 gives the hydraulic conductivity lines at different magnitudes for sedimentary clays, residual soils and oil sand tailings. Hydraulic conductivity at a given solids content was maximum for sedimentary clays followed by residual soils, and then by oil sand tailings. This is because dewatering rate of oil sand tailings is very low though the clay content is low compared to other groups of materials. The unique features of the various material types are explained later in this chapter.

### 4.5 Large Strain Consolidation

Table 4.2 gives the ranges of consolidation data in the literature obtained by using different types of test apparatus and procedures. Most of the tests were started at $\sigma' < 1$ kPa and were terminated at effective stress of up to 450 kPa: the uranium tailings were tested between 20 kPa and 900 kPa. The void ratio and hydraulic conductivity for the majority of the materials ranged between 10 and 1 and between $10^{-4}$ cm/s and $10^{-9}$ cm/s, respectively. The variation in the tailings consolidation behavior of different sample types might be attributed to variations in the geological origin, the ore beneficiation process, and the field disposal practice (Morris et al., 2000). According to Mitchell (1976) and Di Maio et al. (2004), the volume compressibility of fine grained slurries depends on solids
Figure 4.2: Characteristic zones of investigated materials
Figure 4.3: Effective stress lines at different values for groups of materials
Figure 4.4: Hydraulic conductivity lines at different values for groups of materials
Table 4.2: Ranges of consolidation data published in the literature

<table>
<thead>
<tr>
<th>Slurry Type</th>
<th>Test Type</th>
<th>$\sigma'$ (kPa)</th>
<th>$e$</th>
<th>$k \times 10^{-6}$ (cm/s)</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>min – max</td>
<td>min – max</td>
<td>min – max</td>
<td></td>
</tr>
<tr>
<td>(a) Sedimentary Clays</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>China Clay</td>
<td>CRD</td>
<td>0.9 – 95</td>
<td>1.5 – 3.3</td>
<td>0.20 – 44</td>
<td>Znidarcic et al., 1986</td>
</tr>
<tr>
<td>Georgia Kaolin</td>
<td>CRD</td>
<td>0.7 – 55</td>
<td>1.1 – 2.5</td>
<td>0.32 – 46</td>
<td>do</td>
</tr>
<tr>
<td>Phosphate Slime</td>
<td>LSCRS</td>
<td>0.9 – 160</td>
<td>5.3 – 14</td>
<td>0.02 – 25</td>
<td>Roma, 1976</td>
</tr>
<tr>
<td>Phosphatic Clay</td>
<td>FZ</td>
<td>---- – ----</td>
<td>2.8 – 14</td>
<td>0.1 – 20</td>
<td>Pane and Schiffman, 1997</td>
</tr>
<tr>
<td>Speswhite Kaolin</td>
<td>FZ</td>
<td>---- – ----</td>
<td>1.0 – 3.7</td>
<td>0.09 – 10</td>
<td>do</td>
</tr>
<tr>
<td>Pelagic Clay</td>
<td>CRD</td>
<td>0.7 – 413</td>
<td>1.9 – 4.0</td>
<td>---- – ----</td>
<td>Marine Geotechnical Consortium, 1985</td>
</tr>
<tr>
<td>(b) Residual Soils</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Laterite</td>
<td>LSCD</td>
<td>0.80 – 64</td>
<td>4.6 – 6.3</td>
<td>0.25 – 21</td>
<td>Azam et al., 2009</td>
</tr>
<tr>
<td>Bauxite</td>
<td>CRD</td>
<td>0.12 – 400</td>
<td>0.6 – 3.3</td>
<td>0.003 – 32</td>
<td>Cooling, 1985</td>
</tr>
<tr>
<td>Uranium</td>
<td>OM</td>
<td>20 – 900</td>
<td>1.0 – 1.4</td>
<td>0.25 – 300</td>
<td>Matyas et al., 1984</td>
</tr>
<tr>
<td>(c) Oil Sand Tailings</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ore A–C, SRPW</td>
<td>LSCD</td>
<td>0.02 – 80</td>
<td>1.1 – 9.0</td>
<td>0.004 – 10</td>
<td>Miller et al., 2010a</td>
</tr>
<tr>
<td>Ore A–NC, TARW</td>
<td>do</td>
<td>0.02 – 80</td>
<td>1.1 – 9.6</td>
<td>0.002 – 20</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–C, SRPW</td>
<td>do</td>
<td>0.02 – 80</td>
<td>1.1 – 9.6</td>
<td>0.004 – 9</td>
<td>do</td>
</tr>
<tr>
<td>Ore B–C, TARW</td>
<td>do</td>
<td>0.02 – 80</td>
<td>1.1 – 8.6</td>
<td>0.006 – 20</td>
<td>do</td>
</tr>
<tr>
<td>Ore A–NC, UARW</td>
<td>do</td>
<td>0.02 – 80</td>
<td>1.1 – 9.1</td>
<td>0.003 – 20</td>
<td>do</td>
</tr>
<tr>
<td>Desanded</td>
<td>do</td>
<td>0.38 – 170</td>
<td>1.2 – 5.1</td>
<td>0.006 – 0.3</td>
<td>Lord and Liu, 1998</td>
</tr>
<tr>
<td>Cyclone Overflow</td>
<td>do</td>
<td>0.09 – 450</td>
<td>1.0 – 4.9</td>
<td>0.007 – 0.8</td>
<td>Jeeravipoolvarn et al., 2008</td>
</tr>
</tbody>
</table>

Extraction Process: C, caustic and NC, non-caustic;
Pore Water: SRPW, syncrude recycled pond water; TARW, treated Athabasca river water; UARW, untreated Athabasca river water.
Consolidation Test: CRD, constant rate of deformation; FZ, fluidization; LSCD, large strain consolidation; OM, oedometer; LSCRS, large strain controlled rate of strain.
(mineralogical composition of soils and content of organic materials), the pore water chemistry, the morphology (soil fabric and physicochemical interactions), and the state condition (temperature, stress path and stress history). Likewise, the hydraulic conductivity measurements depend on the following (Azam, 2011; Suthaker and Scott, 1996; Das, 1983; Olsen et al., 1985): the solids (clay content and mineralogy), the liquid (viscosity and density), morphology (slurry microstructure and time-dependent pore space re-distribution) and the test condition (hydraulic gradient and initial solids content).

4.6 Statistical Model Issues

There are many possible ways (ordinary least squares method, weighted least squares method and two-stage least squares method) to describe relationships between variables. In this study, the main focus of statistical analysis was to develop strong relationships between variables. Conventionally, the constitutive equations for volume compressibility and hydraulic conductivity can be expressed in the following form:

\[ e = A \sigma' B \]  \hspace{1cm} [4.1]
\[ k = C e^D \]  \hspace{1cm} [4.2]

Notice that Equation 4.1 for volume compressibility has an independent variable (effective stress, \( \sigma' \)) and it has dependent variable (void ratio, \( e \)) which correlates with another variable (hydraulic conductivity, \( k \)) in Equation 4.2. The test procedure in the literature for determining \( \sigma' \), \( e \) and \( k \) will be discussed to understand whether the above equations can be simultaneous equations. In a simultaneous equation model, variables that remain fixed are termed as exogenous or independent variables. Conversely, variables that change values and have their own equations are called dependent or
endogenous variables. Two-stage least squares method is appropriate to estimate coefficients in a simultaneous equation model. In the consolidation test, effective stress and its corresponding void ratio are determined after each load increments. Constant head hydraulic conductivity test is performed at the end of each loading step, and hydraulic conductivity is measured at different void ratio. This means void ratio in Equation 4.1 is not the corresponding void ratio in Equation 4.2. A more appropriate way to describe consolidation data is as follows:

\[ e_1 = A \sigma^B \]  
\[ k = C e_2^D \]

Based on the test condition, the above equations are not simultaneous equation and two-stage least squares method cannot be used. This is because ordinary least squares (OLS) method is appropriate to describe consolidation data and it is best linear unbiased estimator (BLUE).

4.7 Limitations of Statistical Analysis

Ordinary least squares (OLS) method assumes that the variance of the error term is constant and is referred to as homoscedasticity, the magnitude of error is expected to be zero, and the errors are statistically independent from one another. For published data in the literature, the variance of error for each group of materials was not constant in the present study when the correlations of void ratio with effective stress and hydraulic conductivity were developed based on OLS. Data scatter in the volume compressibility and the hydraulic conductivity relationships increases with decreasing effective stress and increasing hydraulic conductivity, respectively. The variance of error term (known as heteroscedasticity) is the by-product of violations of assumptions. Heteroscedasticity has
the following consequences for the OLS estimation: the estimated standard deviation is wrong and the OLS is no longer BLUE, that means OLS does not provide the estimate with the smallest variance (Barreto and Howland, 2006). If the form of heteroscedasticity is known, it can be corrected based on generalized least squares (GLS). The GLS is a procedure in which appropriate data transformation is performed before running OLS to deal with heteroscedasticity and it minimizes a weighted sum of squared residuals. If heteroscedasticity is present, GLS always will yield estimators that are BLUE. In some cases, weighted least squares method can be used to provide estimators equivalent to those developed by GLS (Berry and Feldman, 1985). In this study, void ratio data is converted to liquidity index and normalized void ratio before running the OLS to preclude the effect of heteroscedasticity for finding the estimator with the minimum variance for a given sample size.

Assuming that the residual errors are normally distributed, the 99% confidence interval was developed to show a range of modeled data in the volume compressibility and hydraulic conductivity relationships. The results showed that the most of the data were not in the range of 99% confidence interval. This means the variance of errors in the statistical analysis were not normally distributed. This is because void ratio data in the literature were converted to $LI$ and $e/e_L$ to develop normal distribution in the errors.

4.8 Modeling for Groups of Tailings

4.8.1 Consolidation Relationships

4.8.1.1 Volume Compressibility

Figure 4.5 shows void ratio versus effective stress data in the literature for the groups of materials: sedimentary clays, residual soils and oil sand tailings. Each material group data
Figure 4.5: Void ratio versus effective stress
fitted best to a decreasing power law relationship such that the data scatter was highest for sedimentary clays ($R^2 = 0.22$), followed by residual soils ($R^2 = 0.46$), and then by oil sand tailings ($R^2 = 0.98$). When the effective stress was less than approximately 5 kPa, void ratio varied significantly indicating the considerably high compressibility for sedimentary clays and residual soils. This is because physicochemical interaction between solid-liquid interfaces is predominant at low effective stress. It is governed by water chemistry, mineralogy and microstructure which vary widely for different types of materials. Conversely, there was a strong relationship between effective stress and void ratio for oil sand tailings because of relative homogeneity. Furthermore, the 99% confidence interval was wider at low effective stresses (where physicochemical interactions are predominant) and gradually narrowed down with increasing effective stress.

4.8.1.2 Hydraulic Conductivity

Figure 4.6 shows void ratio versus hydraulic conductivity data in the literature for the materials groups: sedimentary clays, residual soils and oil sand tailings. Each material group data fitted best to a increasing power law relationship such that the data scatter was highest for sedimentary clays ($R^2 = 0.09$), followed by residual soils ($R^2 = 0.49$), and then by for oil sand tailings ($R^2 = 0.97$). For sedimentary clays and residual soils, void ratio varied widely when the hydraulic conductivity was more than approximately $10^{-6}$ cm/s whereas void ratio was strongly correlated with hydraulic conductivity for oil sand tailings. Furthermore, the 99% confidence interval was wider at high void ratio (where physicochemical interactions are predominant) and gradually narrowed down with decreasing void ratio.
Figure 4.6: Void ratio versus hydraulic conductivity
4.8.2 Index Based Correlations

Based on the poor relationships of $e$ versus $\sigma'$ and $e$ versus $k$ data in the literature for sedimentary clays and residual soils, index based correlations were developed in this study to consider the influence of physicochemical phenomena.

4.8.2.1 Volume Compressibility

Figure 4.7 and Figure 4.8 give the volume compressibility correlations in terms of liquidity index versus effective stress and normalized void ratio versus effective stress, respectively. All of the curves followed negative slopes and power laws were found to best describe the correlations. Two trends were observed in the liquidity index versus effective stress curve: (i) a steep slope at low effective stresses of up to 2.5 kPa, and (ii) a flat slope for $\sigma' = 2.5 – 1000$ kPa. This is because the constitutive relationships had to include the entire settling process: sedimentation, transition, and consolidation. This is similar to soils generally encountered in geotechnical engineering practice. If the water content of slurries is more than liquid limit ($LI > 1$), the properties of slurries are dominated by the physicochemical interaction and the data is associated with a little scatter. Conversely, if $LI$ is less than 1.0, physicochemical interactions subdued significantly. Similar trends were observed for the normalized void ratio versus effective stress correlations.

Table 4.3 gives the co-efficient of determination ($R^2$) for the selected materials. It can be summarized that the normalized void ratio was strongly correlated with effective stress compared to $LI$ versus $\sigma'$. Morris (2003) observed that the correlation between $e/e_L$ and effective stress for fine-grained slurries was statistically stronger than other correlations. This is because the effective pore size governs the fluid flow through soils.
Figure 4.7: Liquidity index versus effective stress
Figure 4.8: Normalized void ratio versus effective stress
<table>
<thead>
<tr>
<th>Groups of Materials</th>
<th>Correlations</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary Clays</td>
<td>$LI = 4.71 \sigma^{0.34}$</td>
<td>0.73</td>
</tr>
<tr>
<td>Residual Soils</td>
<td>$LI = 4.34 \sigma^{0.16}$</td>
<td>0.64</td>
</tr>
<tr>
<td>Oil Sand Tailings</td>
<td>$LI = 3.38 \sigma^{0.31}$</td>
<td>0.93</td>
</tr>
<tr>
<td>Sedimentary Clays</td>
<td>$e/e_L = 2.70 \sigma^{0.21}$</td>
<td>0.64</td>
</tr>
<tr>
<td>Residual Soils</td>
<td>$e/e_L = 2.03 \sigma^{0.10}$</td>
<td>0.78</td>
</tr>
<tr>
<td>Oil Sand Tailings</td>
<td>$e/e_L = 2.33 \sigma^{0.21}$</td>
<td>0.95</td>
</tr>
</tbody>
</table>
The new consistency based correlations are best applicable for tailings with measurable effective stresses, that is, at least 1 kPa. Furthermore, 99% confidence interval was wider at low effective stresses (where physicochemical interactions are predominant) and gradually narrowed down.

4.8.2.2 Hydraulic Conductivity

Figure 4.9 and Figure 4.10 show the hydraulic conductivity correlations in terms of liquidity index versus hydraulic conductivity and normalized void ratio versus hydraulic conductivity, respectively. All of the consistency-based parameters were found to increase with increasing hydraulic conductivity and power laws were found to best describe the correlations. For the groups of materials, the hydraulic conductivity was strongly correlated with the normalized void ratio and the liquidity index. Carrier and Beckman (1984) showed that the liquidity index strongly correlates with the normalized hydraulic conductivity, $k(1+e)$ for fine-grained soils.

Table 4.4 gives the co-efficient of determination ($R^2$) for the selected materials. The hydraulic conductivity correlations generally showed more scattered data with an associated lower $R^2$ values. This can be attributed to several factors affecting the hydraulic conductivity of slurries such as variation in flow velocity with time, the hydraulic gradient, the initial solids content, and the clay content (Suthaker and Scott, 1996). The systemic errors in the determination of hydraulic conductivity during testing were further studied by Olsen et al. (1985) who suggested that flow through slurries is time-dependent and can be due to one or more of the following reasons: (i) undissolved air in the equipment and/or specimen, (ii) equipment compliance depending on the material fabrication and applied gradients, (iii) inertia required to move the pore fluid.
Figure 4.9: Liquidity index versus hydraulic conductivity
Figure 4.10: Normalized void ratio versus hydraulic conductivity
Table 4.4: Hydraulic conductivity correlations for group of tailings

<table>
<thead>
<tr>
<th>Groups of Materials</th>
<th>Correlations</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sedimentary Clays</td>
<td>$L_I = 150 , k^{0.30}$</td>
<td>0.70</td>
</tr>
<tr>
<td>Residual Soils</td>
<td>$L_I = 38 , k^{0.19}$</td>
<td>0.36</td>
</tr>
<tr>
<td>Oil Sand Tailings</td>
<td>$L_I = 810 , k^{0.37}$</td>
<td>0.91</td>
</tr>
<tr>
<td>Sedimentary Clays</td>
<td>$e/e_L = 29 , k^{0.20}$</td>
<td>0.57</td>
</tr>
<tr>
<td>Residual Soils</td>
<td>$e/e_L = 11 , k^{0.15}$</td>
<td>0.73</td>
</tr>
<tr>
<td>Oil Sand Tailings</td>
<td>$e/e_L = 121 , k^{0.26}$</td>
<td>0.95</td>
</tr>
</tbody>
</table>
and (iv) time-dependent changes in pore space distribution. Using identical equipment
and test conditions for oil sand tailings, Suthaker and Scott (1996) showed that the last
reason is most likely cause of the observed hydraulic conductivity measured during
tailings consolidation.

Irrespective of the extensive scatter in the hydraulic conductivity data (published
in the literature), two trends were clearly visible in the consistency based correlations: (i)
a steep slope for \( k = 10^{-4} \) to \( 10^{-7} \) cm/sec and (ii) a flat slope for \( k = 10^{-7} \) to \( 10^{-9} \) cm/sec. As
described earlier, the constitutive relationships include the entire settling process:
sedimentation, transition, and consolidation (Azam et al., 2009). Furthermore, the 99%
confidence interval was found to be wider at high hydraulic conductivity (where
physicochemical interactions are predominant) and gradually narrowed down with
decreasing hydraulic conductivity.

4.9 Modeling for All Tailings

4.9.1 Index Based Correlations

Figure 4.11 and Figure 4.12 show correlations for volume compressibility coefficients (\( A \)
and \( B \)) and hydraulic conductivity coefficients (\( C \) and \( D \)) with the plasticity index data in
the literature, respectively. Both of the former coefficients were found to vary linearly
with plasticity index: coefficient \( A \) showed a positive slope and an \( R^2 = 0.86 \) whereas
coefficient \( B \) showed a negative slope and an \( R^2 = 0.60 \). Conversely, both of the latter
coefficients were found to decrease with increasing the plasticity index according to
power law functions with an \( R^2 = 0.68 \) for coefficient \( C \) and \( R^2 = 0.61 \) for coefficient \( D \).

Berilgen et al. (2006) developed the correlations of consolidation coefficients with
plasticity index and liquidity index for high water content clays, but the newly developed
Figure 4.11: Volume compressibility coefficients versus plasticity index

$A = 0.065 \ (I_p + 21.5)$
$R^2 = 0.86$

$B = -0.004 \ (I_p + 22.8)$
$R^2 = 0.60$
Figure 4.12: Hydraulic conductivity coefficients versus plasticity index

- Coefficient C: $C = 1.06 \times 10^{-5} I_p^{-2.24}$ with $R^2 = 0.68$
- Coefficient D: $D = 16.23 I_p^{-0.40}$ with $R^2 = 0.61$
correlations were based on plasticity index and covered a wide variety of fine-grained slurries.

4.9.2 Validation

Figure 4.13 and Figure 4.14 give the modeled void ratio versus the measured void ratio (published in the literature) and the modeled hydraulic conductivity versus the measured hydraulic conductivity (published in the literature), respectively. In both of the plots, the data were almost equally distributed on either side of the line of equality and the $R^2$ were found to be 0.93 and 0.99. Clearly, the plasticity index correlated well with the consolidation coefficients.

Table 4.5 provides the summary of tailings consolidation model. Modeled void ratio was determined using the relationships between volume compressibility coefficients and $I_P$. Likewise, modeled hydraulic conductivity was determined from the correlation of hydraulic conductivity coefficients with $I_P$. Results indicate that plasticity index can best describe the tailings consolidation behavior. The steps of tailings consolidation model are quite useful in practical purposes for preliminary tailings impoundment designs.
Figure 4.13: Modeled void ratio versus measured void ratio
Figure 4.14: Modeled hydraulic conductivity versus measured hydraulic conductivity
Table 4.5: Summary of tailings consolidation model for all tailings

<table>
<thead>
<tr>
<th>Material Property</th>
<th>Determination Procedure</th>
<th>Validation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquid Limit ($w_l$)</td>
<td>ASTM D4318 – 10</td>
<td></td>
</tr>
<tr>
<td>Plastic Limit ($w_p$)</td>
<td>ASTM D4318 – 10</td>
<td></td>
</tr>
<tr>
<td>Plasticity Index ($I_p$)</td>
<td>$w_l - w_p$</td>
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</tr>
<tr>
<td>Coefficient A</td>
<td>0.065 ($I_p + 21.5$)</td>
<td></td>
</tr>
<tr>
<td>Coefficient B</td>
<td>-0.004 ($I_p + 22.8$)</td>
<td></td>
</tr>
<tr>
<td>Modeled Void Ratio ($e$)</td>
<td>$A \sigma^B$</td>
<td>$e_{mod} = 0.93 \ e_{meas}$; $R^2 = 0.93$</td>
</tr>
<tr>
<td>Coefficient C</td>
<td>$1.06 \times 10^{-5} I_p^{-2.24}$</td>
<td></td>
</tr>
<tr>
<td>Coefficient D</td>
<td>$16.23 I_p^{-0.46}$</td>
<td></td>
</tr>
<tr>
<td>Modeled Hydraulic Conductivity ($k$)</td>
<td>$C e^D$</td>
<td>$(\log_{10} k)<em>{mod} = 1.01 (\log</em>{10} k)_{meas}$; $R^2 = 0.99$</td>
</tr>
</tbody>
</table>
CHAPTER 5

CONCLUSIONS

The main conclusions of this research are described as follows:

- Consistency limits for sedimentary clays covered a wide range due to the presence of various clays. Sesquioxide coating of clays and dominance of non-clays resulted in lower liquid and plastic limits for residual soils. Higher consistency limits for oil sand tailings were due to residual bitumen that imparts thixotropy and lubrication.

- In the ternary diagram for tailings characterization, the effective stress lines and the hydraulic conductivity lines for a given group of materials were parallel to the clay-water ratio lines at high content (more than 60%). This suggests that physicochemical interactions govern the consolidation properties of tailings.

- The void ratio versus effective stress relationship and the hydraulic conductivity versus void ratio relationship were found to be unique for each material type because of the predominance of physicochemical interaction phenomena at the solid-liquid phase boundaries.

- For sedimentary clays and residual soils, void ratio varied significantly at low effective stress (less than 5 kPa) and high hydraulic conductivity (more than $10^{-6}$ cm/s), because physicochemical interactions (governed by water chemistry, microstructure and mineralogy) are maximum under these conditions.

- For oil sand tailings, effective stress and hydraulic conductivity were strongly correlated with void ratio due to relative homogeneity in material composition.

The effect of process conditions on tailings consolidation behavior was found to
be negligible for this class of material.

- By converting void ratio to liquidity index and normalized void ratio, the volume compressibility and hydraulic conductivity data merged for materials of each group even at low $\sigma'$ and high $k$. This means that the newly developed relationships can better describe tailings behavior even at low $\sigma'$ and at high $k$.

- The volume compressibility coefficients ($A, B$) varied linearly with $I_p$ whereas the hydraulic conductivity coefficients ($C, D$) followed decreasing power law functions of $I_p$. Strong agreements between measured and modeled data were obtained for both void ratio ($R^2 = 0.93$) and hydraulic conductivity ($R^2 = 0.99$).
REFERENCES


Edil, T.B. and Fox, P.J. 2000. *Geotechnics of high water content materials*, ASTM International Publisher, West Conshohocken, PA, USA.


APPENDIX A

This appendix provides the published volume compressibility and hydraulic conductivity data in the literature for sedimentary clays in the form of tables and figures.
Table A.1: Volume compressibility data in the literature for sedimentary clays

<table>
<thead>
<tr>
<th></th>
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<tr>
<td><strong>Effective Stress (kPa)</strong></td>
<td><strong>Void Ratio</strong></td>
<td><strong>Effective Stress (kPa)</strong></td>
<td><strong>Void Ratio</strong></td>
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<tr>
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</table>
Figure A.1: Void ratio versus effective stress relationship of china clay

Figure A.2: Void ratio versus effective stress relationship of georgia kaolin
Figure A.3: Void ratio versus effective stress relationship of phosphate slime

Figure A.4: Void ratio versus effective stress relationship of pelagic clay
Table A.2: Hydraulic conductivity data in the literature for sedimentary clays

<table>
<thead>
<tr>
<th>China Clay</th>
<th>Georgia Kaolin</th>
<th>Phosphate Slime</th>
<th>Phosphatic Clay</th>
<th>Speswhite Kaolin</th>
</tr>
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<td>Hydraulic Conductivity x 10^{-6} (cm/s)</td>
<td>Void Ratio</td>
<td>Hydraulic Conductivity x 10^{-6} (cm/s)</td>
<td>Void Ratio</td>
<td>Hydraulic Conductivity x 10^{-6} (cm/s)</td>
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<td>0.20</td>
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<td>1.68</td>
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<td>0.52</td>
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Figure A.5: Hydraulic conductivity versus void ratio for china clay

Figure A.6: Hydraulic conductivity versus void ratio for georgia kaolin
Figure A.7: Hydraulic conductivity versus void ratio for phosphate slime

Figure A.8: Hydraulic conductivity versus void ratio for phosphatic clay
Figure A.9: Hydraulic conductivity versus void ratio for speswhite kaolin
APPENDIX B

This appendix provides the published volume compressibility and hydraulic conductivity data in the literature for residual soils in the form of tables and figures.
Table B.1: Volume compressibility data in the literature for residual soils

<table>
<thead>
<tr>
<th>Effective Stress (kPa)</th>
<th>Void Ratio</th>
<th>Effective Stress (kPa)</th>
<th>Void Ratio</th>
<th>Effective Stress (kPa)</th>
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<td>Uranium Tailings</td>
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Figure B.1: Void ratio versus effective stress for laterite ore

Figure B.2: Void ratio versus effective stress for bauxite tailings
Figure B.3: Void ratio versus effective stress for uranium tailings
Table B.2: Hydraulic conductivity data in the literature for residual soils

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<tr>
<th>Laterite Ore</th>
<th>Bauxite Tailings</th>
<th>Uranium Tailings</th>
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<td>(Azam et al., 2009)</td>
<td>(Cooling, 1985)</td>
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<td>Hydraulic Conductivity x $10^{-6}$ (cm/s)</td>
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<td>Hydraulic Conductivity x $10^{-6}$ (cm/s)</td>
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Figure B.4: Hydraulic conductivity versus void ratio for laterite ore

Figure B.5: Hydraulic conductivity versus void ratio for bauxite tailings
Figure B.6: Hydraulic conductivity versus void ratio for uranium tailings
APPENDIX C

This appendix provides the published volume compressibility and hydraulic conductivity data in the literature for oil sand tailings in the form of tables and figures.
Table C.1: Volume compressibility data in the literature for oil sand tailings

<table>
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<tr>
<th>Ore A–C, SRPW (Miller et al., 2010a)</th>
<th>Ore A–NC, TARW (Miller et al., 2010a)</th>
<th>Ore B–C, SRPW (Miller et al., 2010a)</th>
<th>Ore B–NC, TARW (Miller et al., 2010a)</th>
<th>Ore A–NC, UARW (Miller et al., 2010a)</th>
<th>Desanded (Lord and Liu, 1998)</th>
<th>Cyclone Overflow (Jeeravipoolvarn et al., 2008)</th>
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<td>Effective Stress (kPa)</td>
<td>Void Ratio</td>
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Extraction Process: C, caustic and NC, non-caustic;
Pore Water: SRPW, syncrude recycled pond water; TARW, treated Athabasca river water; UARW, untreated Athabasca river water.
Figure C.1: Void ratio versus effective stress for Ore A–C, SRPW

Figure C.2: Void ratio versus effective stress for Ore A–NC, TARW
Figure C.3: Void ratio versus effective stress for Ore B–C, SRPW

Figure C.4: Void ratio versus effective stress for Ore B–NC, TARW
Figure C.5: Void ratio versus effective stress for Ore A–NC, UARW

Figure C.6: Void ratio versus effective stress for desanded oil sand tailings
Figure C.7: Void ratio versus effective stress for cyclone overflow tailings
Table C.2: Hydraulic conductivity data in the literature for oil sand tailings

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<tr>
<th>Extraction Process</th>
<th>Pore Water</th>
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<th>Void Ratio</th>
<th>Hydraulic Conductivity $\times 10^6$ (cm/s)</th>
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<th>Hydraulic Conductivity $\times 10^6$ (cm/s)</th>
<th>Void Ratio</th>
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Extraction Process: C, caustic and NC, non-caustic;
Pore Water: SRPW, syncrude recycled pond water; TARW, treated Athabasca river water; UARW, untreated Athabasca river water.
Figure C.8: Hydraulic conductivity versus void ratio for Ore A–C, SRPW

Figure C.9: Hydraulic conductivity versus void ratio for Ore A–NC, TARW
Figure C.10: Hydraulic conductivity versus void ratio for Ore B–C, SRPW

Figure C.11: Hydraulic conductivity versus void ratio for Ore B–NC, TARW
Figure C.12: Hydraulic conductivity versus void ratio for Ore A–NC, UARW

Figure C.13: Hydraulic conductivity versus void ratio for desanded oil sand tailings
Figure C.14: Hydraulic conductivity versus void ratio for cyclone overflow tailings