CENTRIFUGAL MODELLING OF OIL SANDS TAILINGS CONSOLIDATION

by

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ABSTRACT

A large amount of fluid fine tailings (FFT) is stored in tailings ponds and is continuously accumulating from the extraction of bitumen from oil sands ore in northern Alberta. The FFT are high in water content and have a very slow dewatering behavior that requires many years for them to fully consolidate under their own weight. A better understanding of the geotechnical properties of untreated or treated tailings is needed to evaluate different tailings treatment and disposal options. However, evaluating the long-term geotechnical behavior of the tailings using conventional laboratory and field experiments can be time-consuming and relatively expensive. In response to this dilemma, a centrifuge modelling technique is used in this study to model the self-weight consolidation of oil sand tailings. The technique replicates the prototype self-weight stress in a model and models consolidation that may take many years in a field within a few hours of centrifuge run.

A series of centrifuge tests is conducted in the new GeoREF geotechnical beam centrifuge facility at the University of Alberta for modelling the self-weight consolidation of oil sands tailings using consolidation cells equipped with in-flight solids content and pore pressure profile measuring transducers. The repeatability of centrifuge tests and scaling laws is examined by running “model of the model” tests along with duplicate tests. Centrifuge tests are also conducted at the C-CORE centrifuge center at Memorial University of Newfoundland and Labrador, mainly to evaluate the segregation behavior of tailings during high-gravity tests. The concerns of segregation in modelling the self-weight consolidation of oil sands tailings using centrifuge are addressed by defining

segregation boundaries at high centrifugal acceleration and Earth gravitational acceleration. The results form a guide for selecting a non-segregating tailing for centrifuge tests. The applications of formulas that relate the undrained shear strength of tailings with their maximum particles size carrying capacity at different accelerations are evaluated. A wait-time is proposed for tailings prior to spinning them in a centrifuge that minimizes particle size segregation during the centrifuge tests.

The thixotropic behavior of tailings of different solids and fines content are examined and the effects of thixotropy in centrifuge modelling are evaluated. The time domain reflectometry (TDR) is applied for solids content profile measurements in centrifuge tests after examining various measuring technologies for solids content. A series of tests is conducted to evaluate the TDR probe calibration, measuring range, sensitivity and the effect of chemical additions, soil texture and thixotropy. The TDR calibration equation for deriving solids content from TDR dielectric constant readings is proposed for high-water content material. The proposed equation differs from the commonly used calibration equation for higher solids content materials.

Also in the study, a non-contact type laser displacement sensor for tailings interface settlement monitoring is examined and applied to centrifuge tests. A new technique of density profile measuring probe, based on a light scatter technique, is examined in the centrifuge tests program. The consolidation parameters of tailings and kaolinite slurry are determined from centrifuge tests using data collected during the centrifuge flight and at the end of the tests. Large strain consolidation tests are conducted to derive input parameters for numerical models and to compare with centrifuge results. Comparisons of consolidation parameters from the centrifuge and large strain consolidation tests indicate the strain rate effect on compressibility. The strain rates in centrifuge tests and conventional consolidation tests are presented and the effects of strain rates on the compressibility of materials are discussed. The slurry-water interface settlements of tailings are monitored during the centrifuge tests and compared with FSConsol large strain consolidation numerical model prediction. The consolidation rate from FSConsol is found to be slower than the centrifuge results. In addition to the centrifuge tests, the settling, shear strength, permeability and plasticity of oil sands-fines sand mixture tailings at a wide range of solids and fines content are examined at Earth gravitational acceleration.

PREFACE

This dissertation is submitted for the degree of Doctor of Philosophy in Geotechnical Engineering at the University of Alberta. The research described herein is original, and neither this nor any substantially similar dissertation was or is being submitted for any other degree or other qualification at any other university.

A version of Chapter 3 was published in International Journal of Physical Modelling in Geotechnics (IJPMG) [Sorta, A.R., Sego, D.C., & Wilson, W. (2012). Effect of thixotropy and segregation on centrifuge modelling. International Journal of Physical Modelling in Geotechnics (IJPMG), 12(4), 143–161.]. A version of Chapter 4 was published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal [Sorta, A.R., Sego, D.C., & Wilson, W. (2013). Time domain reflectometry measurements of oil sands tailings water content: A study of influencing parameters. Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal, 4(2), 109-119.]. A version of Chapter 5 was submitted for publication in International Journal of Physical Modelling in Geotechnics (IJPMG) [Sorta, A.R., Sego, D.C., & Wilson, W. Centrifugal modelling of oil sands tailings consolidation]. A version of Chapter 6 was published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) [Sorta, A.R., Sego, D.C., & Wilson, W. (2013). Behaviour of oil sands fines-sand mixture tailings. Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal, 4(4), 265-280.]. I was the principal investigator, responsible for all major areas of concept formation, technical apparatus design, data collection and analysis, and manuscript composition. Dr. David Sego and Dr. Ward Wilson were the supervisory authors on these papers and were involved throughout the concept formation and manuscript composition. The thesis explored and fully acknowledged the existing knowledge and references made at the end of each chapter. The personnel and institutions that financially and/or technically supported the research are acknowledged at the end of each chapter.

He is before all things, and by Him all things hold together.

Colossians 1:17

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TABLE OF CONTENTS

LIST OF TABLES

Chapter 6

LIST OF FIGURES

Chapter 2

Chapter 3

Chapter 6

CHAPTER 1. INTRODUCTION

1.1. STATEMENT OF PROBLEM

Millions of cubic meters of extraction tailings are produced annually as a by-product of bitumen extraction from oil sands ore in northern Alberta. Upon deposition of the tailings, the coarse portion (sand) of the extraction tailings segregates and forms beaches and is used to construct containment dykes. The fines particles are highly dispersed during the extraction process, and during the tailings deposition, flow to a large fluid containment to form fluid fine tailings (FFT). The sand is used for dam construction and for tailings treatments and thus does not create significant geotechnical challenges for the oil sands industry. In contrast, however, FFT have generally a very slow rate of consolidation and create numerous environmental and geotechnical challenges.

The long-term behaviour of untreated and treated tailings needs to be determined to evaluate the performance of different tailings treatments and disposal options. Large- and small-scale settling column tests, field pilot tests, and mathematical models based on laboratory-derived soil parameters are commonly used to study the sedimentation/consolidation behavior of FFT or fines-sand mixture tailings. However, the use of these conventional testing methods is inadequate not only because of stress dissimilarities between laboratory tests and field conditions, but also because of the extended testing time required to complete the tests, owing to the slow dewatering behavior of FFT. The use of pilot field tests is limited by the cost and the length of time required obtaining long-term experimental results. The numerical approaches depend on a consolidation test that requires many weeks/months to produce an input for the numerical model. Furthermore, the models are highly sensitive to the consolidation parameters and need long-term prototype scale experimental results for modelling verification.

In this research project, the self-weight consolidation of FFT, flocculated and thickened fines-sand mixture tailings, and untreated fines-sand mixture tailings is investigated using centrifuge modelling. A centrifuge is used in order to reproduce prototype (field) stress conditions in model tests and to simulate consolidation phenomena that may take many years under field conditions but only a few hours in a centrifuge run. However, the use of a centrifuge for the self-weight consolidation modelling of tailings may enhance segregation. Therefore, the effects of segregation in centrifuge modelling need to be explored and addressed before using the centrifuge for self-weight consolidation modelling.

Furthermore, the behaviour of fines and fines-sand mixture tailings is influenced by time-dependent processes such as thixotropy. The reduction of testing duration by use of the centrifuge technique may marginalize the time-dependent process that affects the settling behaviour of these slurry/soft soils, and so the effect of thixotropy on behaviour tailings also needs to be investigated. The centrifuge testing technique is used here to derive material constitutive relations in a shorter time than is needed for conventional testing method, but the technique requires in-flight solids content and pore pressure measuring probes during the centrifuge flight. The development of transducers or sensors that measure soil properties during the centrifuge flight, especially for high water content material, is not as advanced as, for instance, centrifuge machine design, machine control and safety. Thus, probe development and application for centrifuge testing need to be evaluated. At the same time, centrifuge testing methods require verification of scaling laws and test procedures. The behaviour of fine tailings at Earth gravitational acceleration is relatively well studied, but knowledge of the geotechnical behaviour of fines-sand mixture tailings is limited, especially with regard to proportioning the fines and sand to change a mixture's behaviour.

The objectives of the research are to model self-weight consolidation of oil sands tailings and to address some of the concerns in the centrifuge modelling technique.

1.2. OBJECTIVES OF RESEARCH PROGRAM

The main research objectives of this study are to:

- examine segregation related to use of centrifuge in evaluating the settling behaviour of oil sand tailings;
- study the long-term self-weight consolidation behaviour of fluid fine tailings, thickened tailing, and fines-sand mixture tailings at various initial solids content and acceleration levels using a centrifuge modelling technique;
- examine the effect of the time-dependent process on modelling oil sands tailings self-weight consolidation using centrifuge;
- derive material constitutive relationships from centrifuge tests and compare these with material constructive relationships from large strain consolidation tests;
- examine the predictions of large strain numerical models by comparing them with centrifuge modelling results;

- develop probes or apply existing technologies for soil property measurements during centrifuge flights; and
- investigate fundamental behaviour of oil sands fines-sand mixture tailings at various fines-sand ratios at Earth gravitational acceleration to aid in the planning and disposal of fines-sand mixture tailings.

1.3. ORGANIZATION OF THESIS

This thesis is presented in the "paper format" style. The first chapter serves as an introduction, and each subsequent chapter (Chapters 2 to 6) is presented in a paper format, with its own abstract, body of text and bibliography, except for the final chapter (Chapter 7), which presents conclusions and recommendations. Chapters 3, 5 and 6 have previously been published in peer-reviewed journals and are presented here as part of this Ph.D. thesis. The chapters' text, font type, size and margin sizes are formatted for consistent presentation in the thesis, but the content of the chapters is "as published" in the journals. Chapter 4 has been submitted for publication in peer-reviewed journals and is presented here "as submitted".

Chapter 2 presents the basics of the centrifuge modelling principle, the philosophy of using centrifuge, inherent centrifuge modelling errors and limitations, and concerns related to centrifuge modelling techniques. A literature review related to the self-weight consolidation of slurry/soft soil using centrifuge modelling technique is also included in the chapter. The literature review illustrates the practice of modelling the self-weight consolidation of soft soil in centrifuge.

Chapter 3 addresses concerns over segregation and thixotropy in centrifuge modelling. Centrifuge and settling column tests are conducted at various solids and fines content using oil-sand tailings, and segregation boundaries at Earth gravitational acceleration and at high-gravity tests are defined. The effect of thixotropy on centrifuge modelling is examined by measuring the shear strength of tailings and determining the contribution of shear strength to gravity and time-dependent processes. The segregation investigation results serve as a pre-test guideline in selecting a non-segregating material for centrifuge tests in chapter 5.

Chapter 4 presents the examination of time domain reflectometry for solids content measurements of oil sands tailings. The effects of soil texture, temperature, thixotropy and chemical additions on TDR readings and the probe measuring range, accuracy and repeatability are examined. These examinations serve as a resource for the application of the TDR method for centrifuge solids content profile measurements for centrifuge modelling in the next chapter.

In Chapter 5, the self-weight consolidation of oil sands tailings and kaolinite slurry is modeled using a centrifuge. The scaling laws and modelling procedure are verified, and the TDR method is applied for solids content measurements. Consolidation parameters are derived using large strain consolidation and centrifuge test methods, and large strain consolidation numerical model predictions are compared with centrifuge results. The use of a laser displacement transducer for interface settlement monitoring is addressed in this chapter.

In Chapter 6, the behaviour of fines-sand mixture tailings at various initial solids and fines contents is examined. The settling, plasticity, storage capacity, permeability, and shear strength of fines-sand mixtures in a wide range of solids and fines content are presented

In Chapter 7, the final chapter in the thesis, the conclusions from the study are summarized and recommendations for future research are presented.

1.4. PUBLICATIONS RELATED TO THIS RESEARCH

Journal papers and conference papers were published from the results of this research work. The following is a summary of the publications:

Journal Papers

- Sorta, A.R., Sego, D.C., and Wilson, W. (2012). Effect of thixotropy and segregation on centrifuge modelling. International Journal of Physical Modelling in Geotechnics, 12(4), 143–161. (Chapter 3 in this thesis)
- Sorta, A.R., Sego, D.C., and Wilson, W. (2013). Time Domain Reflectometry measurements of Oil Sands Tailings Water Content: A Study of Influencing Parameters. Canadian Institute of Mining Journal, 4 (2), 109-119. (Chapter 4 in this thesis)
- Sorta, A.R., Sego, D.C., and Wilson, W. (2013). Behaviour of Oil Sands Fines-Sand mixture Tailings. Canadian Institute of Mining (CIM) Journal. Canadian Institute of Mining Journal, 4 (4), 265-280. (Chapter 6 in this thesis)
- Sorta, A.R., Sego, D.C. and Wilson, W. Centrifugal Modelling of Oil sands Tailings Consolidation, submitted to International Journal of Physical Modelling in Geotechnics. (Chapter 5 in this thesis)

Conference presentations

- Sorta, A.R. and Sego, D.C. (2010). Segregation related use of Centrifuge in Oil Sands Tailings. Proceedings of the 63rd Canadian Geotechnical Conference, Calgary, Alberta, 656-664.
- Sorta, A.R., Sego, D.C. and Wilson, W. (2012). Time Domain Reflectometry (TDR) Oil Sands Tailings Water Content Measurements: Texture Effect. Proceedings of the 3rd International oil sands tailings conference, Edmonton, Alberta, 183-190.
- Sorta, A.R., Sego, D.C. and Wilson, W. (2014). Centrifuge modelling of oil sands tailings consolidation. Accepted for publication in the proceedings of the 4th International oil sands tailings conference.
- Gupta, M., Zhou, Y., Ho.T., Sorta, A.R., Taschuk, M. T., Sego, D. C., and Tsui, Y. Y. (2012). Solid content of oil sands tailings measured optically. 3rd International oil sands tailings conference, Edmonton, Alberta, 157-163.

CHAPTER 2. CENTRIFUGE MODELLING: MODELLING PRINCIPLE AND LITERATURE REVIEW

ABSTRACT

The purpose of this chapter is to present a general description of the centrifuge modelling principle and inherent centrifuge modelling errors. The philosophies of using centrifuge, centrifuge scaling laws, and the advantages and limitations of centrifuge testing techniques are also briefly described. These descriptions are necessary because the centrifuge modelling technique is not common in the oil sands industry. Previous research on modelling the self-weight consolidation behavior of slurry/soft soils using centrifuge are reviewed. The literature review is intended to illustrate the practice of slurry/soft soils self-weight consolidation modelling using centrifuge.

1. CENTRIFUGE AND CENTRIFUGE MODELLING PRINCIPLE

A centrifuge is a machine that puts an object in rotation around a fixed axis, applying a force perpendicular to a rotational axis. Geotechnical centrifuge testing involves the study of gravity-dependent geotechnical events using small-scale models subjected to acceleration fields that are many times Earth's gravitational acceleration (g). Centrifuge testing is most suitable for geotechnical structures in which gravity is a primary driving force, such as natural and man-made slopes, retaining structures, buried structures, underground excavation, self-weight consolidation, and groundwater contaminant migration. Soil has nonlinear mechanical properties that are dependent on effective stress and stress history, and thus it is important to maintain the same stress in model tests as in the prototype.

Centrifuge testing is carried out to maintain the same stress in soil and its modelling principle is based on self-weight stress similarity between prototype and model.

The self-weight stress in soil is a function of the unit weight and thickness of a soil deposit. The equivalent stress in a prototype and a model can be achieved by decreasing the thickness of the deposit and increasing the unit weight of the specimen in a centrifuge model test. The unit weight of soil can be increased by either increasing the density of the soil or increasing the gravitational acceleration level in model tests. Since an objective model test aims to represent field behavior, the same materials (e.g., materials of the same density) are normally used in models as in prototypes, and thus the same unit weight is achieved by increasing gravitational acceleration in the model. Gravitational acceleration can be artificially increased by rotating the sample in a horizontal plane using a centrifuge. The use of centrifuge is thus to artificially increase the gravitational force in the model by rotating the sample on a nearly horizontal plane. Figure 1 illustrates the centrifuge modelling principle.

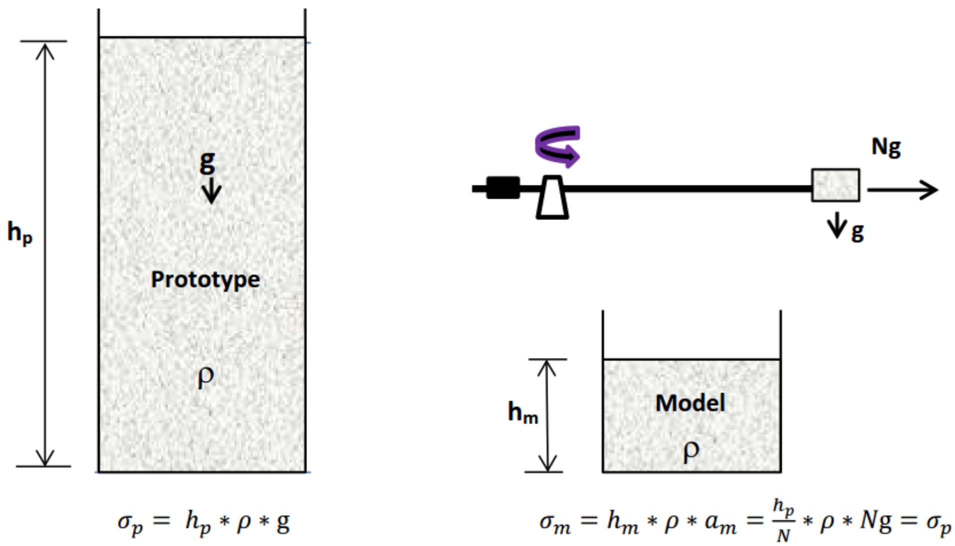

Figure 1. Schematic representation of centrifuge modelling principle, modified from Taylor (1995)

2. PHILOSOPHY OF USING CENTRIFUGE

The principle of centrifuge modelling is to create the same stress in both the model and the prototype. Within this principle, there are four reasons for using a centrifuge, which are: modelling of prototypes, validation of numerical models, parametric studies, and investigating of new phenomena (Ko, 1988).

The modelling of a prototype can be done by constructing a small model that replicates all features of the prototype, including the use of similar materials. The accuracy of a mathematical model can be examined by physically modelling the phenomena in a centrifuge and comparing the mathematical model results with the centrifuge model results. Centrifuge model test results are considered accurate for gravity-dependent events, as long as the results are verified through the modelling of models (Ko, 1988). Because of the ease of conducting centrifuge tests, centrifuge can be used for parametric studies that influence a particular geotechnical structure. Centrifuge modelling can also be used to develop insight into the important aspects and mechanisms of new phenomena, which can be then be used as the qualitative basis for formulating an explanation of the experimental observation (Ko, 1988).

3. CENTRIFUGE SCALING LAWS

In order to correctly replicate a prototype response in a model or interpret model results as they apply to prototype behavior, a proper scaling law must relate the prototype to the model. Table 1 summarizes the scaling law between a prototype and a model in centrifuge modelling.

In centrifuge modelling, small-sized models are used to represent a prototype. The height of the prototype is scaled down to model height by using a height scale factor (1/N). The height scale factor is the ratio of the model height to prototype height. Deformation in a centrifuge model is also 1/N of deformation in a prototype, whereas strain in both the model and prototype are equal. Model height is chosen while considering the height of prototype, centrifuge capacity and pay load volume, and in a consideration of reducing side wall friction and inherent modelling errors.

The primary objective of centrifuge testing is to maintain equal stress between model and prototype, so the stress scale factor between them is one. To maintain the same stress in both the model (σ_m) and the prototype (σ_p), centrifuge acceleration is increased by N, where N is the ratio of prototype to model height

(Equation 1). Like stress, pore pressures in the model and prototype are equivalent.

$$\sigma_m = h_m * a_m * \rho = \frac{h_p}{N} * (N * g) * \rho = h_p * g * \rho = \sigma_p \quad [1]$$

where h_m is model height, a_m is acceleration in the model, h_p is prototype height, g is Earth's gravitational acceleration, N is ratio of prototype height to model height (h_p/h_m) that is equivalent to the ratio of acceleration in centrifuge to Earth's gravitational acceleration ($r\omega^2/g$), and ρ is density of the material.

Equation 2 shows the time-scaling relation between a model and a prototype during the consolidation process. The time-scaling relation was derived without using any specific consolidation theory (Cargill & Ko, 1983; Croce et al., 1985) and is based on a theory that accounts for large deformation (Eckert et al., 1996; Bloomquist, 1982).

$$t_m = \frac{t_p}{N^2} \quad [2]$$

where t_m is elapsed time in the model, t_p is elapsed time in the prototype for an equal degree of consolidation as in the model, and N is the ratio of centrifugal acceleration to Earth's gravitational acceleration or the ratio height of the prototype to the height of model.

Equation 2 implies that the consolidation process that may take many years in a tailings pond can be simulated in a few hours using a centrifuge. For example, consolidation that may take 27.5 years in a prototype can be modeled in 1-day continuous centrifuge flight, if the centrifuge is set to run at 100g. This reduction in testing time is one of the main advantages of using centrifuge to study the consolidation behavior of tailings.

Table 1. Scaling relations between model and prototype

Quantity	Prototype	Model
Length	N	1
Area	N^2	1
Acceleration	1	N
Weight force	N^2	1
Stress	1	1
Strain	1	1
Mass density	1	1
Time (consolidation)	N^2	1
Mass	N^3	1
Velocity	1	N
Hydraulic conductivity	1	N
Time (creep)	1	1

4. INHERENT CENTRIFUGE MODELLING ERRORS

4.1 Vertical stress distribution

Unlike Earth's gravitational acceleration, acceleration in a centrifuge is not uniform but varies across the model height, as shown in Figure 2 (Taylor, 1995). This is because centrifugal acceleration ($a = r\omega^2$) is a function of centrifuge radius(r). The radius, r, is the distance from the center of rotation to an element in a model. Thus the actual vertical stress distribution in the model is not a linear function of depth but rather a function of both radius and depth (Equation 3).

$$\sigma_v = \int_{r_s}^{r_s+h} \rho\omega^2 r dr = \rho\omega^2 \left(r_s * h + \frac{h^2}{2}\right) \qquad [3]$$

where ρ is the density of the material, h is depth below the top surface of the model, ω is angular rotation speed, r_s is the radius from the center of rotation to the top surface of the model, and r is the radius to the point where vertical stress is calculated.

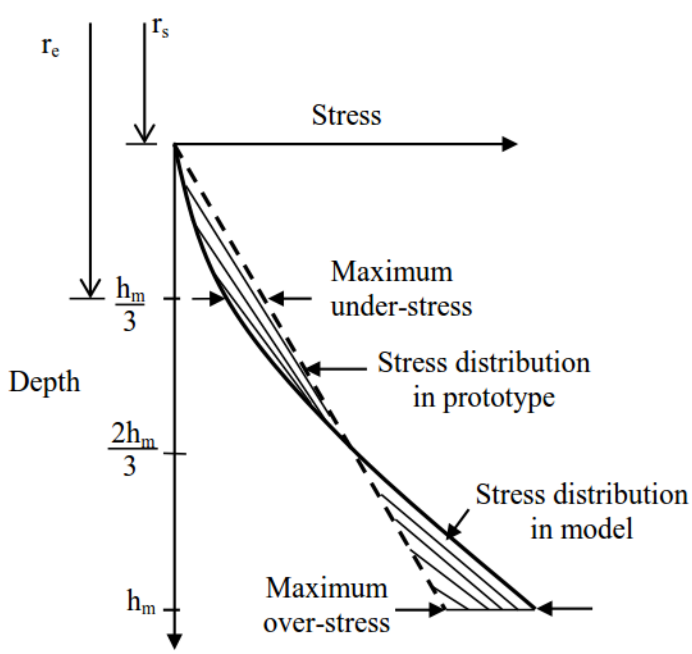

Figure 2. Vertical stress distribution in centrifuge model, modified from Taylor (1995)

A model's vertical stress distribution deviation from the prototype's linear vertical stress distribution is known as the inherent vertical stress distribution modelling error (Taylor, 1995). The vertical stress distribution modelling error is a function of model size relative to the effective centrifuge radius as shown in Equation 4 (see appendix for its derivation). The effective radius is the radius used to calculate the angular rotational speed for centrifuge tests.

$$r_u = r_o = \frac{h_m}{6r_e} \qquad [4]$$

where h_m is model height, r_u is the relative magnitude of under-stress, and r_o is the relative magnitude of over-stress.

In general, the centrifuge is set to rotate at a constant angular rotational speed (ω). In calculating the angular rotational speed, an effective centrifuge radius (r_e) is chosen to minimize the vertical stress distribution error in a model. Schofield (1980) and Taylor (1995) recommended using the effective centrifuge radius, which is the distance from the center of rotation to one-third of the height of the specimen. This recommendation is based on equating the maximum under- and over-stress ratios (Equation 4).

Error in vertical stress distribution is insignificant (<3%) if the model height is less than to 20% of effective centrifuge radius (Taylor, 1995; Fox et. al., 2005). Therefore, to minimize the vertical stress distribution error, model height is normally chosen to be less than 20% of the effective centrifuge radius.

4.2. Horizontal stress distribution

Figure 3 illustrates forces that act in a centrifugation model during the centrifuge flight. Since the model rotates in a circular path, equipotential lines across the model are curved (Townsend et al., 1986). Elements at the center of the model are subjected to a vertical stress only while other elements are subjected to both vertical and horizontal stresses. In a prototype, self-weight stress acts in a vertical direction only, while in a model there is also a horizontal stress component. The presence of the horizontal stress component in a centrifuge model is called the inherent horizontal stress modelling error.

The behavior of a model is a function of the inclination of the resultant acceleration relative to the longitudinal axis (Taylor, 1995). The error introduced due to the curvilinear stress distribution is a function of the model width relative to the centrifuge radius. The effect of the lateral component of acceleration is not significant if the ratio of the model's maximum width to effective centrifuge radius is less than 20% (Hird, 1974). Thus, a model's maximum width is limited to 20% of the effective radius of the centrifuge.

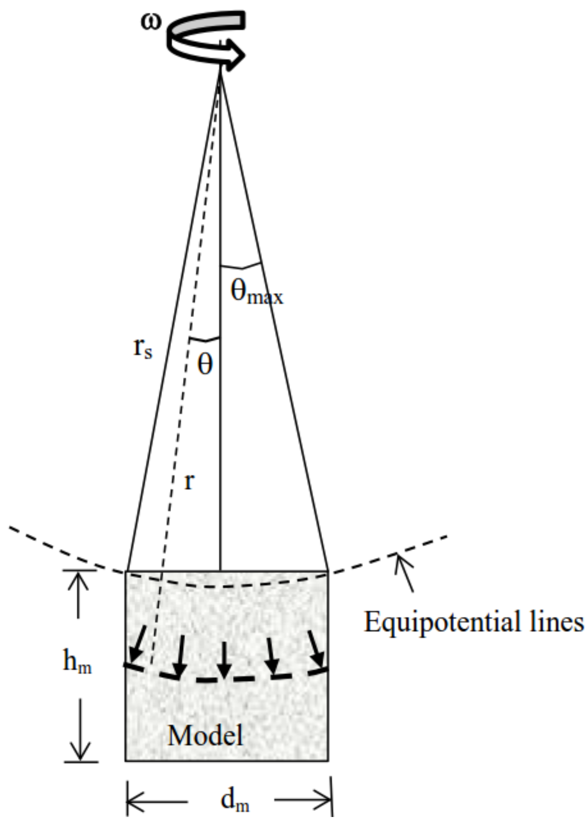

Figure 3. Stress distribution in a centrifuge model, modified from Townsend et al. (1986)

5. MODELLING OF MODELS

An experimental technique known as "modelling of models" has been used in centrifuge testing. The technique was proposed by Ko (1988) and involves running three centrifuge tests on the same material but at different initial heights and acceleration levels so that all models represent the same pseudo-prototype. The principle of the technique is shown in Figure 4. Points A1, A2 and A3 in Figure 4 are model height and acceleration levels in modelling of model tests representing the same 10 m high prototype. Points B1, B2 and B3 represent the same prototype at 100 m high. A comparison of results from the modelling of model tests, either at the end or at any intermediate stage of consolidation, is used to check the internal consistency of centrifuge test results, to study model size effect, or to derive a time relation between a model and its prototype.

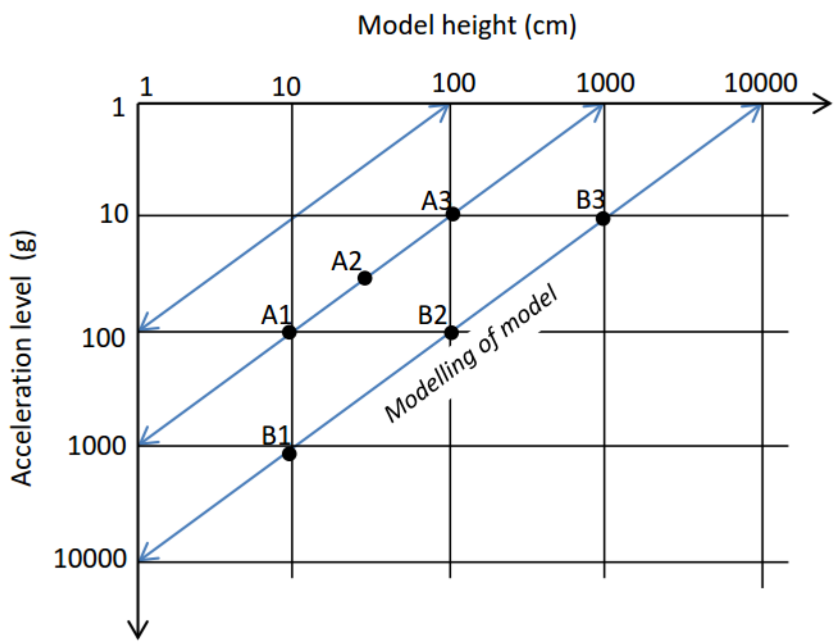

Figure 4. Modelling of model principle, modified from Ko (1988)

6. ADVANTAGES OF CENTRIFUGE TESTING

The advantages of using centrifuge for self-weight consolidation modelling compared to conventional testing are listed below.

- The same magnitude of stress levels is maintained in models as in full-scale prototypes, so no extrapolation is required for the constitutive laws to be applicable at prototype scale.
- Displacement and pore pressure boundary conditions are well-defined; therefore, different drainage conditions (e.g., one-way, two-way or seepage-drainage) can more easily be used in a model study than in prototype scale tests.

- Observations of the complete cross-section of a model can be made, enabling predictions of displacement and strain throughout the entire model.
- Self-weight consolidation and other diffusion processes can be studied in a short period of time.
- Centrifuge modelling is comparatively cheap, better controlled, more easily and accurately instrumented, and has more uniform soil conditions than prototype scale testing.
- Isolates gravity-dependent from gravity-independent phenomena.
- Has a technique for checking the scale effect and consistency of the test results and is particularly useful when no prototype is available for verifying the model test results.
- Has theoretically derived and some experimentally proved scaling laws that can be used to relate model and prototype.
- Is relatively easier to extend from one-dimensional to two- or three-dimensional modelling.
- The effects of various stress histories, stress paths, and geometry conditions can be easily studied.
- Inhomogeneity, layering, and sequence of deposition can be modelled with careful model preparation and testing procedures.

- Can be used to study new phenomena and in-flight measurements of soil properties, and can provide insight into important aspects and mechanisms of the new phenomena.
- Centrifuge modelling is more replicable compared to large strain theory predication, as the theory is highly sensitive to consolidation parameters like permeability. Deriving consolidation parameters for numerical model inputs requires a long testing time.

7. LIMITATIONS OF THE CENTRIFUGE MODELLING TECHNIQUE

Like other soil testing techniques, centrifugal model testing has limitations. It is important to take these into consideration when modelling and interpreting the test data. Some of the limitations are as follows:

- The vertical stress distribution in a centrifuge model is non-linear (Taylor, 1995).
- The radial acceleration field creates a horizontal stress component on soil elements, except for those along the center line of the model (Townsend et al., 1986). The non-linear vertical stress distribution and the presence of the horizontal stress component issue can be minimized by using a model height and width of less than 20% of the effective radius of the centrifuge.
- Centrifuge modelling requires different time-scale factors for different forces to govern a problem. For example, the time scale for weight force differs from that for inertial force or viscous force. Identifying which force is more important and governs a particular problem may help to derive and

use the proper time scale (Croce et al., 1985). It also requires different time-scale factors for dynamic and static events (Taylor, 1995). For example, time scaling for dynamic events is 1:N, but excess pore pressure would be modelled using a time-scale factor of $1{:}N^2$. The dynamic and static events issue may be addressed by increasing the viscosity of the pore fluid (Taylor, 1995).

- This form of testing may enhance the segregation of particles, the formation of dewatering structures, and lateral drainage. It is important to evaluate the segregation behavior of the materials at high-gravity before running centrifuge tests that require long flight hours. A segregating material under high test does not represent the prototype material so does the test result. Coagulant or flocculant additions do not improve the segregation boundary of materials like it improves at Earth's gravitational acceleration.
- The similitude of some dimensionless numbers between the prototype and model cannot be achieved (e.g., Reynolds number and Froude number) (Knight & Mitchell, 1996). The lack of similarity may or may not be significant, depending on the type of geotechnical problems. If the Reynolds number is less than unity in centrifuge tests, for example, Darcy's law is considered valid even if the Reynolds similarity is not achieved (Knight & Mitchell, 1996).

- The influence of long-term chemical effects, thixotropy, and creep are not properly modelled in the model test. This may be a major limitation for materials that are highly influenced by time-dependent phenomena.
- The effect of friction and adhesion between the soil and model container can be significant in some cases, but is not a particular problem for centrifuge modelling. The effects of side friction can be minimized by increasing the width-to-height ratio of the model. Proper lubrication of the internal side wall of a container with a thin layer of high viscosity silicon oil can minimize side-wall friction (Moo-Young et al., 2003). The side-wall friction effect and over-stress at the lower portion of the model due to non-linear stress distribution tend to have the opposite effect (Mitchell & Liang, 1986).
- Modelling the behaviour of high void ratio materials like fluid fine tailings (FFT) is more difficult than low void ratio materials in terms of instrumentation, monitoring, and data interpretation. This is because the tailings have low shear strength and slow dewatering behaviour, and the change in volume of tailings may be controlled by gravity and non-gravity-dependent processes. Modelling requires long centrifuge flight hours. A contact-type of displacement transducer, for example, cannot be used for high water content materials, as the materials do not have sufficient strength to carry the transducer's weight, which increases with centrifugal acceleration.

- Instrumentation for measuring soil properties during test flights is not as well developed as the centrifuge machine design, control, and safety (Zeng, 2001).
- Instruments for centrifuge modelling need to be light-weight and small-sized, and have high sensitivity and range of measurements. Probes for centrifuge tests are normally more expensive than conventional 1 g tests and are not readily available. The amplitude of variation in some physical quantities in the model is small, and so the electrical signals delivered may be weak.
- Centrifuge testing requires instruments that are less affected by gravity or self-weight stress increase.
- Accurate measurement of physical quantities is more important in centrifuge model tests than in prototype or laboratory tests. This is because even a slight error in a centrifuge is scaled up proportionally to centrifuge acceleration level. For example, a 1 mm error in a centrifuge in 100g tests is equivalent to a 100 mm error in a prototype. Manual reading is not an option in centrifuges.
- The model is located in the swing platform of a fast-rotating centrifuge, and the electrical signals in the model measurement must be delivered to the recording instrument fixed on the ground. The delivery of signals could be affected by noise interference from the slip ring (Liu and Jiang, 1988).

- The rate of variation of deformation and pore pressure in geotechnical models is much greater than in the prototype (Liu and Jiang, 1988).
- The rate of strain is higher than in conventional tests, which would have an effect on the properties of materials that depend on strain rate.
- The permeability calculation from a centrifuge is based on a self-weight-induced hydraulic gradient. The hydraulic gradient is not constant along the model height and during the progress of consolidation.
- Geotechnical beam centrifuge facilities are only available in a few research facilities and universities. Installation and operating costs are expensive and the device needs to be housed in reinforced structures that can absorb the impact of a test package hitting at maximum rotational speed.

8. CENTRIFUGAL MODELLING OF THE SELF-WEIGHT CONSOLIDATION BEHAVIOR OF SLURRY/SOFT SOILS: LITERATURE REVIEW

Previous research on modelling the self-weight consolidation behaviour of slurry and/or soft soils using centrifuge is reviewed in this section. The reviewed documents are research articles that were presented in conferences, journals and dissertations. The literature review illustrates the practice of modelling a self-weight consolidation of slurry/soft soils using centrifuge in terms of modelling objectives, instrumentation, and data analysis and interpretation. The full contents of the article are not, however, provided. The reviewed articles are presented here in chronological order of publication.

Blomquist and Townsend (1984) used a 1 m radius beam centrifuge to validate numerical models for predicting the consolidation characteristics of Florida phosphate clay deposits and to determine the time-scaling relation between prototype and model. The centrifuge tests for validating the numerical model were conducted by modelling the self-weight consolidation of phosphatic clay slurry filled in a large metal tank (2.74 m x 4.27 m x 6.7 m) at an initial solids content of 12.6% and a height of 6.32 m. The centrifuge tests were conducted by monitoring the interface settlement of the waste clay using an in-flight camera. The time-scaling relation between the model and prototype was evaluated from centrifuge tests conducted at acceleration levels of 60, 80 and 100 g representing the same prototype (i.e., modelling of models). They also conducted several centrifuge tests on Florida phosphate clay, with and without a sand-capping layer, and then compared these results with large strain numerical model predictions. The input parameters for large strain numerical models were derived from a slurry consolidometer test or were back-calculated from the centrifuge tests.

Blomquist and Townsend's (1984) results indicated that the time-scaling exponent between centrifuge models and prototypes depends on the initial solids content of the slurries and the stage of volume change. At low initial solids content and/or during the initial stage of settling, the time-scaling exponent was found to be around 1 and then increases to 2 as the consolidation progresses. A comparison of the interface settlement of phosphatic clay in a large tank and in a centrifuge model indicates that the time-scaling exponent between model and prototype was 1.6. However, You and Znidarcic (1994) indicated that the time-scaling exponent between model and prototype for both the hindered sedimentation and the consolidation stage should be 2, and that time exponents that differ from the theoretical value of 2 should be associated with changes in soil structures due to the high gravity application in centrifuge. Blomquist and Townsend (1984) compared their centrifuge results with numerical model predictions. The comparison indicated that the numerical model deviated significantly from the centrifuge test results in slurry of low initial solids content (less than 10% solids content for Florida phosphatic clay). Centrifuge tests on capped slurries showed that the final solids content of slurries can be increased by placing a sand cap on the top of phosphatic clay, but the time required to reach the final consolidation volume was found to be too long, due to the decreasing permeability as the consolidation progresses.

Mikasa and Takada (1984) conducted a series of centrifuge tests to investigate the possibility of using a centrifuge to study soft soil undergoing self-weight consolidation. The initial water content of the clay was chosen to be less than twice the liquid limit, to minimize particle segregation under high gravity tests and to consider consolidation of soil without the hindered sedimentation stage. The self-weight consolidation tests were conducted in a two-arm, 1.5 m radius, swinging bucket beam centrifuge by monitoring the interface settlement in flight. The centrifuge test results were compared with the numerical model based on Mikasa's (1963) consolidation theory. The input parameters for the numerical model were derived from centrifuge tests conducted at different initial solids content – namely, from initial interface settlement rates, and from solids content profiles at the end of the tests. Good agreement was found between the centrifuge and numerical model results in terms of time-settlement curves and isochrones of self-weight consolidation.

Scully et al. (1984) evaluated the self-weight consolidation behavior of Florida phosphatic clay at a high initial void ratio. The objectives of the centrifuge tests were to validate numerical model prediction and to verify time-scaling relationships between model and prototype. Four centrifuge tests were conducted at an initial void ratio of 15 and at different initial model heights and accelerations representing the same hypothetical prototype of a 5 m height (modelling of model). The consolidation parameters for the numerical model input were derived from settling column, step-loading consolidation, constant rate of deformation, and flow pump permeability tests. The time-scaling exponent between the model and prototype was found to vary from 2 to 2.3. The compressibility curve obtained from the step-loading and constant rate of deformation matched the compressibility curve derived from the centrifuge tests (from the solids content profile at the end of the centrifuge test). The numerical model agreed fairly well with the prototype, while the numerical model slightly over-predicted settlement.

Croce et al. (1985) derived scaling relations between a model and prototype for centrifuge modelling by considering the mechanical similarities between them. Rather than using a differential equation or dimensional analysis, they used a mechanical similarity approach because it only requires the proportionality of all forces acting on similar systems. The differential equation approach was considered to depend on oversimplified assumptions for describing geotechnical events, and dimensional analysis approaches require a high degree of physical intuition in selecting physical quantities that have a primary influence on the geotechnical models. In practice, however, it is not always possible to fully satisfy the similarity of all types of forces acting in a similar system. For example, Croce et al. (1985) obtained different time-scaling factors by considering the similarity of all kinds of forces and concluded that a single time-scaling factor cannot be achieved by keeping the similarity of these forces in centrifugal modelling. To derive the proper scaling factor, the similarity forces that govern the problem should be selected. According to Croce et al. (1985), selecting forces that govern the problem is easier than selecting physical quantities for dimensionless analysis. Assuming that the self-weight consolidation of soil is governed by seepage and self-weight forces, Croce et al. (1985) derived a time-scaling exponent of 2 for the self-weight consolidation of soils in a geotechnical centrifuge, and then verified the time-scaling exponent using the modelling of model experimental technique.

Croce et al. (1985) also studied the self-weight consolidation behaviour of soft clay in single- or double-drainage conditions using a centrifuge. The beam centrifuge at the University of Colorado and commercially available kaoline samples with an initial water content of 110% were used for the experiments. Model heights of 5.7 to 9.8 cm were used at different acceleration, representing a 5 m deep prototype. The centrifuge self-weight consolidation results were compared with large strain numerical predictions. Constitutive material relationships for the large strain numerical model were derived from the flow-pump and centrifuge tests. The flow-pump technique was used to derive the hydraulic conductivity-void ratio relationships, while the centrifuge tests provided an effective stress-void ratio relationship from the water content profiles at the end of the tests. Two sets of hydraulic conductivity-void ratio relationships were derived from the flow-pump technique: one from tests conducted at a low hydraulic gradient (0.1-0.2), and the other from tests conducted at a higher hydraulic gradient (1-5). The two sets of hydraulic conductivity-void ratio relationships were derived to investigate the effect of permeability in predicting the rate and magnitude of settlement, while the centrifuge time-settlement curves were used as prototype behaviour for validating the numerical model.

A comparison of centrifuge results with the large strain numerical model prediction indicated that the large strain consolidation theory was in good agreement with the centrifuge test results when permeability-void ratio relationships of a low hydraulic gradient flow-pump technique were used. However, when using a permeability-void ratio relationship of a higher hydraulic gradient, the large strain numerical model over-predicted settlement and excess pore pressure dissipation. The large strain consolidation analysis indicates that the crucial factor for an accurate prediction of consolidation was the non-linearity of the material properties, in particular permeability. Croce et al. (1985) recommended accurate permeability measurements at a low hydraulic gradient due to permeability sensitivity.

Croce et al. (1985) also compared the centrifuge results with conventional theory, using consolidation parameters derived from conventional consolidation tests.

The comparisons indicate that the conventional theory was significantly different from prototype behaviour for predicted settlement and pore pressure dissipation, especially under one-way drainage conditions. A comparison of single and double drainage of the soft clay deposit using the conventional theory indicates that the consolidation time in a single-drained prototype was 5 to 8 times slower than in a double-drained deposit, but the prototype behaviour, as observed in the centrifuge modelling, indicated that it was only 1.5 times slower.

Takada and Mikasa (1986) used a geotechnical beam centrifuge to determine the consolidation parameters of soft clay and to derive scaling relations between model and prototype in self-weight consolidation in centrifuge. A two-armed, 1.75 m radius, swinging bucket beam centrifuge was used. The consolidation parameters of four different types of soils were evaluated from the water content profiles of the model at the end of the self-weight consolidation and from the initial portion of the time-settlement curve of models prepared at different initial water contents. The initial water contents of the samples were chosen to minimize particle segregation during the centrifuge tests.

Shen et al. (1986) modeled the consolidation and surface settlement of a storage tank founded on a soft-soil deposit, using a centrifuge. The modelling involved the filling, storing, and emptying of the storage tank. The model was prepared by first consolidating kaolin clay at Earth gravity, after which a layer of sand was placed on the top of the consolidated clay and a cylindrical tank (unfilled) was placed on the top of the sand layer. The model was then put in the centrifuge and run at an acceleration rate that re-initiated the pre-consolidation stress. The filling, storing and emptying of the tank were modeled by filling and emptying the tank with water during the centrifuge flight. The settlement of the tank, the settlement of the surrounding soil, and the pore pressure in the clay layer were monitored in-flight for each stage of filling, storage and emptying. The results of the centrifuge tests were used to validate numerical model (bounding surface model) for cohesive soils consolidation. The pore pressure responses in the centrifuge tests agreed well with the numerical model prediction, but the numerical model under-predicted the total settlement.

Mitchel and Liang (1986) modelled the consolidation of soft clay under embankment structures using a 1 m radius beam centrifuge. The aim of the centrifuge tests was to evaluate a time-dependent constitutive model that incorporated the combined effects of creep and hydrodynamic consolidation. The clay foundation layer was prepared from kaoline clay in a rectangular box (0.42 x 0.2 x 0.3 m) and instrumented with five pore pressure transducers at different locations in the model. A fine sand embankment was constructed on top of the soft clay layer. The deformation of the clay layer was monitored using a camera mounted near the model that recorded the position of plastic marker beads installed in the clay layer. The clay layer was pre-consolidated at Earth gravity prior to the conducting of the centrifuge tests.

Two different series of centrifuge tests were then conducted. The first series investigated the reproducibility of the testing procedure/results, and the second series investigated the model size effect. In the centrifuge tests, steady-state water flow in the embankment layer was maintained during the centrifuge run. The deformation and pore pressure responses from the centrifuge tests were compared with a plane-strain finite element computer program for analyzing consolidation (CON2D). The numerical model generally predicted the pore pressure but failed to accurately predict the settlement of the clay foundation during the initial stage of consolidation. The long-term settlement, however, matched the centrifuge results. The centrifuge tests conducted to investigate the effect of model size indicated that size does not significantly affect the test results.

Selfridge et al. (1986) investigated the consolidation behavior of Florida phosphatic clay treated with predetermined quantities of lime or gypsum using a beam centrifuge. As lime or gypsum treatment is a chemical process that cannot be adequately modeled in a centrifuge, Selfridge et al. (1986) proposed a method of accelerated curing. Accelerated curing involves placing treated clay in an oven at 40.5 °C for 2 days and then conducting the centrifuge tests. The consolidation behavior of four untreated and twelve treated clay samples was studied by monitoring the interface settlement during the centrifuge run. The results indicated that the lime addition hindered the consolidation of the clay when compared to untreated clay, as lime produces a strong soil skeleton that resists consolidation. In contrast, the addition of gypsum enhanced the consolidation rate by flocculating the particles to increase the drainage and self-weight consolidation. However, the accelerated curing sample preparation procedure produced higher shear strength clays than normally treated clay, which led to difficulties in extrapolating the model results to the prototype.

Beriswill et al. (1987) modeled the self-weight consolidation behavior of Florida phosphatic clays and phosphatic clay mixed with sand using a beam centrifuge of 1 m radius. Modelling of model tests at acceleration levels of 60 and 80g were also conducted to derive time-scaling relations between models and prototypes. The centrifuge tests were conducted by monitoring interface settlement. A metallic ruler attached to Plexiglas containers and pictures taken during the centrifuge flight were used to monitor the interface settlement. The tailings samples were allowed to stand for two days prior to the conducting of the centrifuge tests to develop bonding between particles.

The results of the modelling of model tests indicated that the time-scaling relations between models and prototypes depend on the initial solids content of the sample. At high initial solids content and/or at the final stage of change in volume, the time-scaling exponent was approximately 2, but at low solids content and at the initial stage of the change in volume, the time-scaling exponent was between 1 and 2. A time-scaling exponent of less than 2 was considered to indicate a change in volume dominated by hindered sedimentation rather than consolidation. The modelling of model test results on some of the tailings resulted in a time-scaling exponent of above 2 (2.2-3.1) due to the segregation of particles. Organic rich phosphatic clay resulted in a time-scaling exponent of zero. In centrifuge theory, a time-scaling exponent of zero occurs when viscous forces dominate the settling behavior of soil. The addition of sand improves the settling rate, especially clay of poor settling characteristics. Segregation related to high gravity tests, however, creates challenges in the modelling of clay-sand mixture tailings. Tests conducted on duplicated samples showed that the consistency of centrifuge results depends on the initial homogeneity of the mixtures.

McVay et al. (1987) experimented on obtaining compressibility and permeability relationships of soils from centrifuge tests based on an in-flight measurement of pore pressure and solids content profiles. The pore pressure profiles at different elapsed times during the centrifuge flight were measured using mini pore pressure transducers that were installed in the wall of a Plexiglas consolidation cell at different depths. For the solids content profiles measurement, they first experimented with the electrical resistivity technique and the use of a total stress measuring probe. The two techniques were found unsuitable for the centrifuge tests, so they used a sampling technique for measuring solids content profiles directly. Their sampling technique (multi-sample sampling method) was based on a number of samples (models) prepared at the same initial water content. The samples were placed in equal-size consolidation cells and spun together. The solids content profiles were determined by stopping the centrifuge, taking out one sample at a time and slicing it to determine the solids content profile. The solids content measured at different elapsed times in the centrifuge tests and an assumed excess pore pressure profile were used to derive the permeability and compressibility relationships. The advantage of their approach was that the material constitutive relationship can be derived from a single centrifuge flight with stress conditions similar to those existing in slurry ponds. The disadvantage of the approach was that the stopping and re-running of the centrifuge complicates the pore pressure and stress history of the model.

Townsend et al. (1987) conducted several self-weight consolidation tests using a two-arm, 1 m radius beam centrifuge. The materials used for the centrifuge tests were Florida phosphatic clay, clay-sand mixtures, sand-capped clay, and sand-clay-mixture-capped clay. The centrifuge tests aimed to investigate consolidation enhancement of phosphatic clay when sand was mixed with clay or used as a capping layer. The results of the investigation indicate that sand-capping increased the final solids content of the clay while the clay-sand mixture improved the rate of clay consolidation. The centrifuge results were compared with their closed-form analytical solution (for the magnitude of consolidation). In most of the cases, the centrifuge results were found to be consistent with the analytical solution. The segregation of particles created a challenge in centrifugal modelling of the self-weight consolidation characteristics of the clay-sand mixture. The insufficient bearing capacity of clay enhanced segregation and created challenges in modelling the consolidation of sand-capped clay. Stage capping and submerging the capping layer were found to be useful techniques to minimize bearing capacity failure and segregation. Townsend et al. (1987) recommended an evaluation of the segregation characteristics of clay-sand mixture and sand-capped clay before modelling their self-weight consolidation in centrifuge.

Miyake et al. (1988) examined displacement and time-scaling relations between a centrifuge model and prototype in sedimentation and self-weight consolidation of dredged marine clays. The scaling relations were examined by using the modelling of model centrifuge test procedure, and then confirmed via modelling the sedimentation and self-weight consolidation of dredged marine clays in 6 m high standpipes. The pipes were filled in six stages of 100 cm thickness, and each layer was allowed to fully consolidate before placement of the next layer. The time-scaling exponent between the model and prototype was found to be 1.25 for the sedimentation stage and 2 for the self-weight consolidation stage of change in volume. The displacement scaling exponent was confirmed to be 1 for both the sedimentation and self-weight consolidation stages of change in volume.

Miyake et al. (1988) also compared the filling and consolidation of marine clay filled in 6 m high standpipe with the numerical model. The numerical model was based on Mikasa's (1963) large consolidation theory. The consolidation parameters for the numerical model input were derived from centrifuge tests and from standard consolidation tests. At high initial water content, the numerical model prediction was found to be slow compared to centrifugal model tests. During the filling stage, the numerical model was slow compared to the 1 g standpipe test results. In relatively low water content samples, the numerical model prediction of settlement was higher during and after the filling stage.

Cooke (1991) investigated an effective radius to be used in calculating average acceleration in a centrifuge. The effective radius from the central axis to 40% of the model height was found to minimize the vertical stress distribution error in centrifuge modelling.

Stone et al. (1994) used a beam centrifuge (radius 1.8 m) to study the short- and long-term behavior of gold mine tailings. The centrifuge tests were performed to reproduce the history of stage-filled tailing impoundments, where field data at various stages of filling were available. The stage-filling and consolidation were replicated by successive additions and consolidation of discrete layers of tailings in the centrifuge; the centrifuge was stopped to enable the placement of the successive layers of tailings. The thickness of the deposited tailings and the consolidation time in the centrifuge replicated the thickness of the total tailings deposited between each field measurement.

After modelling the active stage of filling impoundments, the centrifuge tests were continued to assess the long-term behavior of the tailings. Settlement and pore pressure at different depths of sediment were monitored in-flight in the long-term behavior modelling. The field data were compared with the centrifuge tests and with the numerical analysis results. The consolidation parameters for the numerical model input were derived using a row cell oedometer. Both the centrifuge and the numerical analysis results were found to be in good agreement with the field data, both in terms of time-settlement curve and solids content profiles.

Theriault et al. (1995) used a bench-top centrifuge to study the effect of chemical, physical and enzymatic treatments on the dewatering characteristics of oil sands fine tailings with or without residual bitumen. The study shows that the dewatering rate of tailings depends on the treatment method, and that none of the treatment methods have an effect on final sediment volume (tailings concentration after 15 hrs of centrifuge run at 1500 g). These results support the geotechnical observation, where the compressibility curves of materials of different initial composition or treatment methods converge to the same void ratio at high effective stress (>1000 kPa). The performance of the treatment methods was better compared by the elapsed time to reach the final sediment volume or by the dewatering rates rather than by the concentration of the tailings after the high relative acceleration centrifuge tests.

Eckert et al. (1996) used a bench-top centrifuge to derive material constitutive relationships of bitumen free oil sands fine tailings. The constitutive relationships were derived from initial settling rates and from the equilibrium heights of tailings tested in a centrifuge at different acceleration levels and at different initial solids content. Using the materials' constitutive relationship derived from the centrifuge test, Eckert et al. (1996) verified a numerical model by comparing it with the interface settlement of fine tailings filled in a 3 m high standpipe, monitored for 400 days. The numerical model predictions closely matched with the interface settlement of the standpipe, and the slight discrepancy was reasoned to be a wall friction effect. The standpipe diameter was only 2.54 cm. Eckert et al.'s (1996) consolidation model was based on a fluid mechanics approach but is equivalent to Gibson et al. (1967), only differ on coordinated systems used in the formulation of the governing equations.

El-Shall et al. (1996) examined the possibility of using a bench-top centrifuge to derive material constitutive relationships of Florida phosphatic clays. In their centrifuge tests, interface settlement and pore pressure dissipation were not monitored in-flight. Their approach involved preparing samples in a centrifuge bottle, centrifuging these at selected speeds (acceleration level) for a known period of time, stopping the centrifuge and measuring the model height, and restarting the centrifuge and spinning it at the same speed for an equal length of time. The stopping, measuring, and re-running of the centrifuge were repeated five times per predetermined centrifuge rotational speed. The tests were repeated with two other centrifuge rotational speeds. Mathematical manipulation of the data collected during the tests were used to derive the material constitutive relationship and reported to give a comparable result to the conventional techniques of consolidation testing.

King et al. (1996) experimented with measuring the shear wave velocity of soft soils undergoing self-weight consolidation in a centrifuge. A kaolinite slurry was used in the investigation and the tests were conducted at 100 g using a 5.5 m radius C-CORE centrifuge. Piezoelectric bender elements were used to produce and detect shear waves. The piezoelectric (transmitting and receiving element) was installed on the wall of the cylinder, close to the bottom and the shear wave velocities were measured in-flight. Excess pore pressure dissipations were also monitored in-flight by installing pore pressure transducers at various elevations within the consolidating kaolinite. The results of the investigation indicated the possibility of generating and detecting shear waves in consolidating soft soils in a geotechnical centrifuge at high acceleration levels.

Hurley and McDermott (1996) developed an in-flight probe for measuring compressional waves in soft soils undergoing self-weight consolidation in a centrifuge. The investigations were made using kaolinite slurry prepared at an initial geotechnical water content of 537% and tested at 100 g using the C-CORE centrifuge. Four piezoelectric compressional transducers, four pore pressure transducers and an electrical resistivity probe were used in the test. The results indicated that the compressional wave velocity-density relationship of the kaolinite under high gravity was found to be the same as that at Earth gravitational acceleration.

McDermott and King (1998) used a bench-top centrifuge to examine the possibility of using a portable, inexpensive, small diameter (<1 meter) centrifuge for evaluating mine tailings consolidation parameters. Kaolin slurries prepared at different initial solids contents (47-59%) were used in the investigation. A strobe aided with a magnifying glass was used to measure the interface settlement in-flight at ± 0.5 mm accuracy. The initial linear portion of the time-settlement curve and Takada and Mikasa's (1986) equation were used to derive the permeability-void ratio relationship, without accounting for the effect of non-uniform acceleration in the model.

Hurley (1999) studied the development of an in-flight bulk density and compressional wave velocity measuring probe for use in a geotechnical centrifuge. The development was to correlate geophysical and geotechnical properties of soft soils undergoing self-weight consolidation. The compressional wave velocity measurement was made by installing piezoelectric material on the wall of a PVC consolation cell, near the cell's base. The transmitter and receiver of the transducer were oriented 180° apart and the voltage supplied to the transmitter and electrical signals from transmitter was via the centrifuge slip rings.

For bulky density measurement, Hurley (1999) experimented with the electrical resistivity and gamma ray attenuation techniques.

The electrical resistivity technique was found unsatisfactory for centrifuge testing because the method results in questionable porosity/formation factors, significant variation, and non-repeatable resistivity measurements. Because the electrical resistivity technique was found to be unsatisfactory, Hurley (1999) examined the gamma-ray technique for bulk density measurements. A miniature-sized gamma-ray probe installed near the bottom of the column was used for measuring the bulk density of a kaolinite sample undergoing self-weight consolidation in a centrifuge. The gamma-ray technique was based on generating gamma ray radiation on one side of the column and then measuring the amount of gamma ray attenuation through the soil column using a radiation detector on the opposite side.

Hurley (1999) conducted a number of centrifuge tests to calibrate the gamma ray density-measuring probe and to develop a correlation between geotechnical and geophysical parameters (compressional wave velocity and bulk density). The centrifuge results indicated that the gravity effect on the gamma ray source and/or detector was minimal. The density and compressional wave velocity measuring probes operated properly at high acceleration levels. The compressional wave velocity-bulk density relationships derived from the centrifuge tests were in good agreement with published data for kaolin suspension under Earth gravity. However, the use and further development of these probes for an in-flight density/wave velocity measurement cannot be found in any other published articles.

McDermott et al. (2000) used a beam centrifuge to study dewatering structures formed in soft soils undergoing self-weight consolidation. Dewatering structures are localized macrostructures resulting from preferential flow paths or flow channeling during the self-weight consolidation of soft soils and manifest in the formation of boils (small, evenly spaced holes and mounds on the top surface) and vertical conduits at the side surface of consolidating sediment.

Consolidation theories assume that water migrates uniformly under the influence of excess pore pressure gradient and do not account for the formation of dewatering structures in self-weight consolidation. The presence of dewatering structures makes the assumption of uniform pore fluid migration inappropriate (McDermott et al., 2000). Dewatering structures are not limited to centrifuge tests, but the high gravity in centrifuge may enhance the formation of dewatering structures. Low initial density, high hydraulic gradient, segregation of particles, and the breaking and re-arrangement of flocs may be the cause, but the mechanism of dewatering structures formation is unknown (McDermott et al., 2000). Dewatering structures were observed in the McDermott et al. (2000) self-weight consolidation tests in centrifuge test. McDermott et al. (2000) then tried to predict the formation of dewatering structure in a self-weight consolidation test in a centrifuge.

Singh and Gupta (2000) used a bench-top centrifuge to evaluate the coefficient of permeability of silty soils at water content of less than 30%. The coefficient of permeability derived from the centrifuge was compared with a permeability coefficient derived from conventional falling-head and oedometer falling-head, and was calculated from oedometer tests. Their results indicated that the coefficient of permeability of soil in a centrifuge was N times greater than Earth gravitational acceleration, where N is the ratio of acceleration in centrifuge to Earth gravitational acceleration. However, Robison (2002) argued that the coefficient of permeability is a soil property and should therefore be the same both in Earth and high-gravity tests.

Zeng and Lim (2002) investigated the effect of centrifugal acceleration variation along model height in centrifuge modelling. They used the finite element code SIGMA/W with linear elastic and a Cam-Clay model to study centrifugal acceleration variations and model size effect on the accuracy of centrifuge tests. Zeng and Lim (2002) found that the influence of acceleration variation and the effect of model container size depended on the type of geotechnical phenomena modeled in centrifuge (slope stability, self-weight consolidation, foundation) and the type of parameter measured (vertical stress, horizontal stress, settlement).

Moo-Young at al. (2003) used a 6.5 m radius Waterways Experiment Station beam centrifuge to study the self-weight consolidation behaviour and migration of contaminants in sand-capped sediment. The centrifuge tests modeled an in-situ sand-capping technique, using a layer of clean sand placed over contaminated sediment in subaqueous pit disposal. Three centrifuge tests were conducted at accelerations of 50 and 100g. Of the three centrifuge tests, two were conducted at different accelerations representing the same prototype to verify that correct modelling procedure was applied. Contaminant migration was studied by mixing a water-soluble fluorescent dye with the sediment layer and studying the concentration of dye in-flight and at the end of the centrifuge tests. In the tests, settlement of the capped sediment was monitored in-flight using the Linear Variable Differential Transducer (LVDT), and excess pore pressure dissipation at the bottom of the sediment was monitored in-flight using a mini pore pressure transducer. The side walls of the consolidation box were coated with a thin layer of high-viscosity silicone oil to minimize side wall friction. An in-flight water sampling system was designed and used to sample water from an overlaying water layer (i.e., the layer above the sand cap layer).

Moo-Young at al. (2003) interpreted and compared their centrifuge modelling results with the numerical model prediction. The numerical model (Primary Consolidation, Secondary compression, and Desiccation of Dredged Fill [PSDDF]) was found to over-predict settlement up to 20%. The study of dye tracer concentration demonstrated that consolidation-induced advection was found to be the main process of contaminant migration, rather than diffusion.

Fox et al. (2005) developed a one-dimensional large strain numerical model for self-weight consolidation of soft soils in a geotechnical centrifuge. The numerical model was based on the large strain consolidation theory of Gibson et al. (1967) and accounts for the high gravity conditions with an acceleration factor that varies linearly with depth. In contrast to the practice of centrifuge modelling, actual acceleration in centrifuge modelling is not constant but instead increases with specimen depth. Fox et al.'s (2005) numerical model studied the effect of variable acceleration along the model height in self-weight consolidation of soft soils in centrifuge. Fox et al. (2005) used the results of centrifuge tests on Singapore marine clay to verify their numerical model in predicting the self-weight consolidation behaviour of soft soils. The numerical model was found to closely match experimental data. To study the effect of non-uniform acceleration in centrifuge modelling, Fox et al. (2005) ran several numerical simulations by varying model height, effective radius, acceleration level, and the ratio of height to effective radius. The numerical simulations were compared with the centrifuge time-settlement curve, with results indicating that the effect of non-uniform acceleration is strongly controlled by the ratio of initial specimen height to the radius of the centrifuge. Errors in the computed consolidation time-settlement curve were consistently found to be small when this ratio was 20% or less.

In centrifuge modelling, centrifugal acceleration is commonly considered as constant. Angular velocity for spinning the centrifuge is calculated using an effective radius, assuming constant centrifuge acceleration along the model height. The effective radius is commonly taken as the distance from the central axis to one-third of the depth of the model, based on Schofield's (1980) and Taylor's (1995) recommendations. However, their recommendations did not account for density and height changes during the consolidation of soft soils (Fox et al., 2005). The numerical simulation of Fox et al. (2005) indicates that an effective radius to the initial mid-height of the specimen results in a better match to the experimental time-settlement curves.

Sharma and Samarasekera (2007) developed an equation to calculate the hydraulic conductivity from variable head permeability tests in a centrifuge that accounts for linear centrifugal acceleration variation along the model height. The equation recommended that permeability tests be conducted in a small radius centrifuge, where the variation of acceleration along the model height can significantly influence the results. In a large radius centrifuge, hydraulic conductivity from variable head permeability in a centrifuge can be calculated using average acceleration. Average acceleration is normally calculated using the radius from the central axis to mid-height of the sample, but Sharma and Samarasekera (2007) recommended an effective radius from the central axis to mid-height of the water layer rather than to mid-height of the sample.

Znidarcic et al. (2011) examined the self-weight consolidation behavior of oil sands mature fine tailings (MFT) using a beam centrifuge. The centrifuge test was conducted at 45g while monitoring the interface settlement in-flight. A model height of 82 mm was used in the test. The results of these tests were compared with those of the large strain numerical model. The MFT consolidation parameters for the numerical model input were derived from a seepage-induced consolidation test. The interface settlement-time and the void ratio profile at the end of the centrifuge tests were compared with the numerical model, obtaining good agreement. Based on these results, the authors suggested that MFTs behave like regular soil slurry, even during a high-gravity self-weight test in a centrifuge, despite the presence of residual bitumen creating challenges and requiring special attention. The consolidation process of MFT can be described by a nonlinear finite strain consolidation, but consolidation of MFT in ponds may behave differently than in laboratory models. Hydraulic gradient differences between laboratory tests and field conditions were postulated to be the reason for the varying behaviors.

Reid and Fourie (2012) used a bench-top centrifuge to determine the consolidation parameters of soil slurries. The development of the bench-top centrifuge was initiated because geotechnical beam centrifuges are expensive to operate and are limited for commercial application. Kaolin slurry and well- and gap-graded tailings were used in the experiments. Because segregation was observed at high gravity tests in the tailings, a modified test procedure (pre-loading before spinning in centrifuge) was used. The effective stress-void ratio relationships of the materials were derived from the water content profile at the end of the self-weight consolidation. The end of the self-weight consolidation was judged by the full dissipation of excess pore pressure. Wireless transmission-based mini pore pressure transducers installed at the base of the consolidation cell were used to monitor pore pressure dissipation in-flight. The permeability-void ratio relationships were derived from the measured pore pressure dissipation and from using a numerical model that was developed by the authors. In their numerical procedure, the permeability-void ratio (k-e) relationship was assumed and adjusted iteratively to match model pore water pressure dissipation. The k-e relationship was found to be in agreement with row cell tests results.

10. SUMMARY AND CONCLUSIONS

The centrifuge testing method is particularly useful for problems involving self-weight consolidation or other diffusion processes. Self-weight loading is generated automatically by the enhanced weight of the soil, and the diffusion process occurs rapidly due to the small dimension of the model. Centrifuge has many advantages and limitations that need to be considered in the planning, testing and interpreting stages of the model results.

In summarizing the literature review, we can see that most of the self-weight consolidation tests in centrifuge were mainly conducted for deriving time-scaling relations between models and prototypes, examining self-weight consolidation, generating data for numerical model verification, and deriving consolidation parameters. Furthermore, the consolidation parameters were mainly derived from the water content profile at the end of the centrifuge tests and from a number of centrifuge tests conducted on slurries of different initial solids contents. Some centrifuge tests were conducted for special purposes, such as to study dewatering structures formation in self-weight consolidation in centrifuge; to study the effect of effective radius and container size on self-weight consolidation; or to develop an in-flight bulk density or compressional wave velocity measuring probes. Only a few centrifuge self-weight consolidation modelling had field (prototype) data for model test verification; likewise, only a few centrifuge tests were experimented on for modelling the behavior of chemically treated clays. In most of the centrifuge tests, the concern of particle segregation under high gravity test was not examined prior to performing the tests.

The literature review indicates that self-weight consolidation modelling in geotechnical centrifuges has been limited to measurements of settlement and pore pressure only. There are no well-documented density profiles measuring probes in a geotechnical centrifuge. Hurley (1999) experimented on measuring the density of soils undergoing self-weight consolidation in a centrifuge using a mini gamma ray probe near the base of the model, but there is no continuity in the use and refinement of the probe for density profile measuring.

Added to the dearth of information is a disagreement in the literature regarding the time-scaling relation between model and prototype. You and Znidarcic (1994) claim that the time-scaling exponent between model and prototype during sedimentation and self-weight consolidation is 2, whereas other researchers (Bloomquist & Townsend, 1984; Beriswill, 1987) claim that it is between 1 and 2, depending on the soil initial water content and stage of settling. There is also disagreement in the literature on the scaling relation between model and prototype regarding the coefficient of permeability. Some studies indicate it scales up according to the acceleration level, and some indicate that the coefficient of permeability is soil parameter, which does not depend on gravity level. Meanwhile, a comparison of numerical and centrifuge modelling indicates there is good agreement between centrifuge and large strain numerical models, but some of the modelling results suggest that the numerical model deviates significantly from the centrifuge model results, especially at low initial solids content materials. The conventional consolidation theory prediction was found to substantially deviate from the centrifuge results in modelling soft soil self-weight consolidation.

Bench-top centrifuges have been used for modelling self-weight consolidation and for deriving consolidation parameters of soft soils. Despite the limitations of these centrifuges, the consolidation parameters of soft soils derived from a bench-top centrifuge were reported to give the same results as conventional large strain consolidation tests.

In the centrifuge modelling, kaolinite, rather than natural soils, was the most commonly used material. This may be because the use of kaolinite simplifies the extrapolation of model results to a prototype. A larger number of centrifuge self-weight consolidation tests were conducted on Florida phosphate clay than on any other mine waste, but only a few self-weight centrifuge tests were conducted on oil sand tailings using both bench-top and beam centrifuge.

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CHAPTER 3. EFFECT OF THIXOTROPY AND SEGREGATION ON CENTRIFUGE MODELLING

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CHAPTER 3. EFFECT OF THIXOTROPY AND SEGREGATION ON CENTRIFUGE MODELLING

ABSTRACT

In this paper, segregation related to the application of high centrifugal acceleration and the effect of thixotropy in modelling the settling behaviour of slurry/soft soils using a centrifuge are examined. Settling column and centrifuge tests were conducted on slurry/soft soils at various sand fines ratios (SFR) to define a segregation boundary using the ternary diagram. A segregation boundary based on centrifuge and settling column tests are established and the results indicate that the application of high gravity in centrifuge tests prompts and enhances segregation. It is also found that the segregation boundary of high gravity tests is a function of applied acceleration level, grain size of sand, the percentage fines and clay contents. The application of formulas that estimate the maximum size of sand that remain in suspension are evaluated and found conservative at high gravity tests. The shear strength of slurry/soft soils at various SFR and age were evaluated to assess the effect of non-gravity, time-dependent behaviour on strength and settling behaviour of slurry/soft soils. The results of the shear strength tests at various ages and composition indicate that strength gain is mainly due to thixotropy. The gain in shear strength due to thixotropy may not be properly modelled in centrifuge testing and may create difficulty in extrapolating centrifuge test results to prototype.

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1. INTRODUCTION

In Northern Alberta, currently four oil sands operators are extracting bitumen from oil sands deposits using open surface mining and Clark hot water extractions (CHWE) or slightly modified CHWE process (BGC Engineering Inc., 2010). The CHWE process, which is based on the pioneer work of Dr. Karl Clark, involves the use of hot water, steam, air and caustic soda (NaOH) to liberate bitumen from oil sands ore (FTFC, 1995). Each year the bitumen extraction process produces millions of cubic meters of high water content tailings composed of sand, silt, clay and a small amount of residual bitumen. The extraction tailings are conventionally discharged into tailing ponds where coarse particles segregated to form a beach and dykes while the fine tailings are carried in to ponds as thin slurry. The fine tailings in these ponds then sediment to 20% solids content in a few months and to 30% in a few years. After reaching 30% solids content, called matured fine tailings (MFT), the water release rate becomes very slow and may need decades to fully consolidate (FTFC, 1995). The accumulation of this large volume of matured fine tailings, which has very slow water release rates, creates environmental, operational and management concern for the public, regulators, as well as, oil sands operators. To address these concerns diverse research has been conducted since the 1970s. The aims of this research were to reclaim the disposal site to productive use, reduce the production and accumulation of fine tailings, reduce tailings impact on the environment and reduce costs of extraction and management of wastes (FTFC, 1995). Fundamental geotechnical engineering studies in this regard include the study of sedimentation and self-weight

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consolidation behaviour of fines and fine–sand mixture tailings and the evaluation of different disposal options to reclaim the disposal site to productive use.

Conventionally, settling column tests and numerical models based on laboratory-derived consolidation parameters are used to study the sedimentation/consolidation behaviour of fine/fines–sands mixture tailings or to evaluate alternate disposal options. Large- and small-scale stand pipe tests have been used as common methods for studying the sedimentation and self-weight consolidation behaviour of MFT or fines–sand mixtures (Caughill et al., 1993; Jeeravipoolvarn et al., 2009; Scott et al., 1986; Suthaker et al., 1997). The consolidation parameters (void ratio–effective stress–void ratio–permeability relation) are usually determined from large strain consolidation tests combined with settling column tests (Jeeravipoolvarn et al., 2008; Pollock, 1988; Scott et al., 2008). These test methods are well documented and useful in quantifying the consolidation parameters and in understanding the combined process of sedimentation and self-weight consolidation of slurry. However, the tests may require many months or years to complete and does not represent the field (prototype) stress conditions.

The use of centrifuge for studying the sedimentation/self- weight consolidation behaviour of a very slowly dewatering slurry/soft soil, such as oil sands MFT, is essential. Testing time can be significantly reduced by use of centrifuge and the effective stress in the prototype can be easily reproduced in the model by way of the application of a centrifugal acceleration that is many times Earth's gravitational acceleration. The significant reduction in testing time and the

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capability of reproducing field stress condition makes the centrifuge a powerful and attractive method for modelling the sedimentation and self-weight consolidation behaviour of slurry/soil while saving both cost and time.

However, the application of high gravity to a slurry/soft soil composed of fines and coarse particles may enhance segregation. Furthermore, the reduction in the test time may marginalize the time-dependent process that affects the settling behaviour of these slurry/soft soils. The purposes of this paper are to examine segregation related to use of centrifuge in evaluating the settling behaviour of oil sand tailings and to examine the effect of the time-dependent process on using the centrifuge model results to understand behaviour at the prototype scale.

Examination of segregation related to the centrifuge test was approached by defining segregation boundaries of fines and fines–sand mixture tailings using centrifuge and settling column tests while utilising the ternary diagram developed by Scott and Cymerman (1984). The effect of applying high gravity, the effect of particle size and the effects of sand fines ratio (SFR) on segregation boundary are examined.

The influence of time-dependent processes on understanding the settling behaviour of oil sands tailings using centrifuge were examined by measuring the vane shear undrained shear strength of fines and fines–sand mixture tailings at various initial compositions and ages. The strength gains due to time-dependent processes are derived from the total strength gain to assess the effect of time-dependent process on the undrained shear strength of fines and fines–sand

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mixture tailings. The shear strength development with time was also used to establish a wait time before subjecting test samples to a high acceleration field in the centrifuge. The applicability of formulas, which relate shear strength with the slurry maximum sand grain carrying capacity, were evaluated for their application in high gravity tests using the undrained shear strength measured after one day of sample preparation.

2. SEGREGATION RELATED TO CENTRIFUGE MODELLING

Centrifuge has been used to study sedimentation/self-weight consolidation behaviour of slurries and soft soils at the prototype (field) stress condition, to evaluate different reclamation/disposal schemes, to validate mathematical models and to measure consolidation parameters. For example, Beriswill et al. (1987), Bloomquist and Townsend (1984), Selfridge et al. (1986) and Stone et al. (1994) used centrifuge to model sedimentation and self-weight consolidation behaviour of slurries. Centrifuge has been used by Mikasa and Takada (1984), Scully et al. (1984), Croce et al. (1985) and Eckert et al. (1996) to validate a large strain numerical model. Townsend et al. (1986, 1989) and Theriault et al. (1995) used centrifuge for evaluation of different disposal options. McVay et al. (1987) and Takada and Mikasa (1986) used centrifuge for measuring the consolidation parameters of slurry/soft soils.

The concern of segregation during centrifuge modelling has been acknowledged in centrifuge tests (for example, Mikasa and Takada (1984), Takada and Mikasa (1986) and Townsend et al. (1986)). Mikasa and Takada (1984) recognized segregation during centrifuge modelling and used a 'soft soil' with an initial

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consistency that did not allow any particle segregation. The selected initial water content was based on their experience but without clearly established pre-test criteria to guide others. However, they used post-test criteria to verify that segregation did not occur in their tests by examining the shape of void ratio effective stress curve at the end of self-weight consolidation; there was a marked drop in the effective stress–void ratio curve, indicating segregation. Takada and Mikasa (1986) used a sample with an initial water content that was equal or less than twice the liquid limit of the clay to prevent particle segregation in the centrifuge tests. The selection of this criterion was based on their past experiences with testing similar slurries. Townsend et al. (1986), while 'modelling of model' and evaluating the settling behaviour of Florida phosphatic clay consolidation, recognized the problem of segregation related to centrifuge modelling and recommended a further study of the applicability of centrifugal modelling using sand–clay suspensions.

A review of past centrifuge tests reveals that most researchers (McVay et al., 1987; Townsend et al., 1989) recognize the concerns of segregation during centrifuge tests and tried to avoid segregation by using a low water content sample, low centrifugal acceleration or stage loading procedures. There appears to be no well-established guideline for selecting samples that do not segregate during centrifuge tests. This paper aims to study segregation during the application of high gravity in centrifuge test and to establish pre-test guidelines in selecting a non-segregating material for centrifuge tests.

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3. THIXOTROPY AND CENTRIFUGE MODELLING

Thixotropy, from a geotechnical point of view, is defined as the process of softening caused by remoulding, followed by a time-dependent return to the original harder state at constant water content (Mitchell, 2002). Thixotropy is a general occurrence in fine grained materials (Mitchell, 2002). At constant water content the ratio of the undrained strength measured after an elapsed time to the undrained strength measured immediately following remoulding is defined as thixotropic strength gain (Suthaker and Scott, 1997). The thixotropy of a material is a function of several factors such as the clay mineralogy, water content, loading rate, and the type and amount of chemical additives. These factors are discussed in Suthaker and Scott (1997) and Banas (1991). An explanation of the mechanisms of thixotropic strength gain in clay samples can be found in Osipov et al. (1984) and Mitchell (2002).

Skempton and Northey (1952) who studied the thixotropic strength gain of three clay minerals (illite, kaolinite and bentonite) found that kaolinite is the least thixotropic clay mineral. The clay-sized fraction of MFT mainly consists of kaolinite (80%) (FTFC, 1995; Miller et al., 2010). Based on the clay mineralogy, MFT is expected to be the least thixotropic material. However, studies at the University of Alberta by Suthaker and Scott (1997), Miller et al. (2011) and Banas (1991) found that oil sands fine tailings are a highly thixotropic material, higher than most typical clay minerals. It appears that the thixotropic behaviour of the fine tailings is more related to the presence of dispersing agent (sodium hydroxide) and residual bitumen than its clay mineralogy. According to Mitchell

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(2002), kaolinite can be made especially thixotropic by the addition of dispersing agents.

In a thixotropic material, the longer the duration of the test, the greater the thixotropic strength gain (Seed and Chan, 1957). According to Seed and Chan (1957), the effect of thixotropy is a function of test duration. Thus thixotropy has a greater effect in prototype than in centrifuge tests as consolidation in prototype takes much longer than in centrifuge tests. The effect of thixotropy on material behaviour becomes less significant in centrifuge testing by reducing the testing time and the settling behaviour of material in model tests may not be as equally influenced by the time-dependent process as in prototype. This paper studies the time-dependent behaviour of oil sands fines and fines–sand mixture tailings over a wide range of solid and fines content at various ages and studies the effect of time-dependent behaviour on the extrapolation of centrifuge modelling results to prototype.

4. DESCRIPTION AND USE OF TERNARY DIAGRAM

The ternary diagram is a convenient tool to describe numerous properties of slurries composed of fines and coarse material to assess the viability of alternate strategies for managing large- volume tailings that arise in many mining operations (Morgenstern and Scott, 1995; Scott and Cymerman, 1984; Sobkowicz and Morgenstern, 2009). All practical method of treating tailings can be illustrated (Morgenstern and Scott, 1995).

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The ternary diagram is characterized by three axes (Figure 1). The base axis represents the fines content (fines/total dry solids), the left-hand axis refers to the solids content (solids/total mass); and the right-hand side represents the fines–water ratio (fines/(fines + water)) (Azam and Scott, 2005; Scott and Cymerman, 1984; Sobkowicz and Morgenstern, 2009). The three apexes of the diagram denote 100% water (top), 100% sand (bottom left), and 100% fines (bottom right). Fines or fines–sand mixture tailing with a certain amount of water, fines and sand plots as a point on the ternary diagram. The horizontal parallel lines of the diagram are constant solids content lines that represent tailings of the same solids content at different sand fines ratio. The straight lines drawn from the water apex to the base represent a constant fines content lines representing tailings mixture having the same grain size distribution but of different solids content. Straight lines drawn from the sand apex to the right-hand side of the diagram indicate constant fines–water ratio (FWR) lines (Azam and Scott, 2005; Scott and Cymerman, 1984). At constant FWR line, the relative proportion of fines and water is constant, which in many cases determines the geotechnical behaviour of the fines dominated tailings matrix (Sobkowicz and Morgenstern, 2009).

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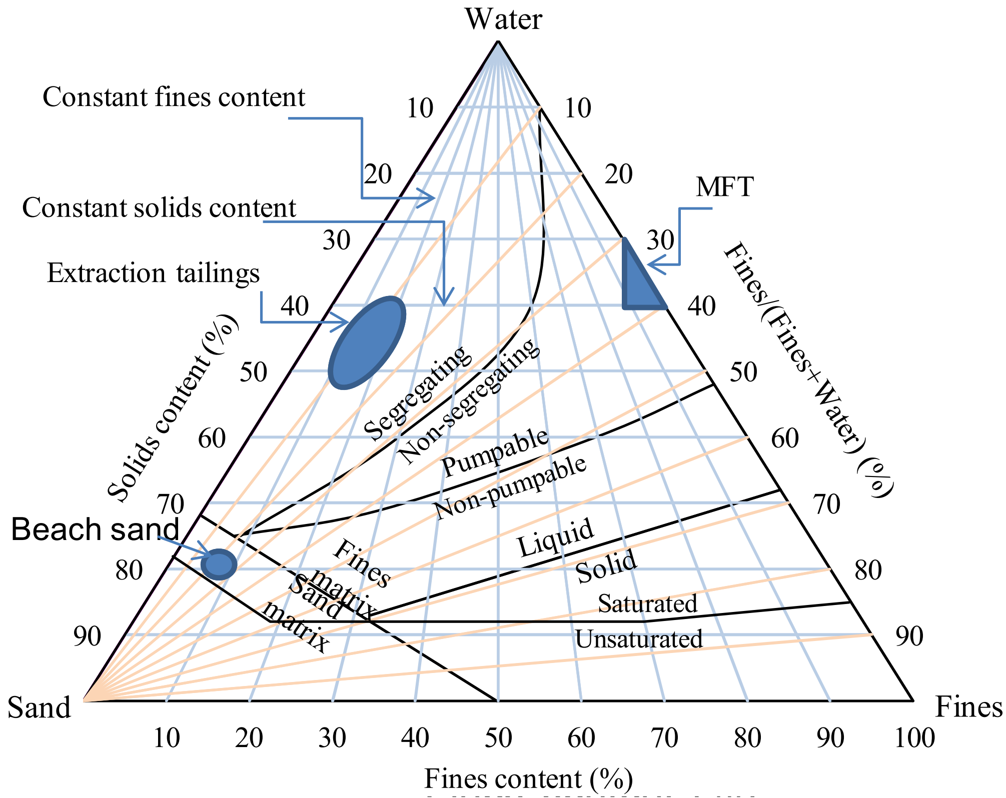

Figure 1. Ternary diagram

The ternary diagram is used to illustrate areas with different geotechnical behaviour such as: segregating against non-segregating, solids against liquids, pumpable against non-pumpable, fines dominated against sand dominated matrix, and saturated against non-saturated tailings (Azam and Scott, 2005; Scott and Cymerman, 1984; Sobkowicz and Morgenstern, 2009). The segregation boundary on the ternary diagram is used to delineate segregating tailings from non-segregating tailings over a wide range of solids and fines content. A non-segregating tailings on the ternary diagram is represented by the tailings composition that lies below the segregation boundary while segregating tailings are represented by tailings composition above the segregation boundary. A non-

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segregating tailing is defined as a tailings mixture in which the fines and sand particles settle together to form a uniform deposit (FTFC, 1995).

In segregating tailings the amount of fines/solids is not sufficient to prevent the separation and the settling of coarse (heavier) particles to the bottom. Increasing the solids content by densification, or increasing the fines content through enrichment of fines tailings, would change a segregating to a non-segregating mixture (Matthews et al., 2002). On the ternary diagram adding solids content through densification is represented by moving along constant fines content lines towards higher solids content, and enrichment of fines is represented by moving along constant solids content line towards high fines content.

Without changing the composition of the mixture, any process/method that moves the segregation boundary towards a higher solids and fines content enhances segregation and any process/ method that moves the boundary towards lower solids and fines content improves the segregation behaviour of the mixture. For examples adding coagulants/flocculants in the mixture would move the boundary towards the direction of low solids and fines content (Matthews et al., 2002). The addition of chemicals would coagulate/flocculate the fines, thereby improving the carrying capacity of the fines, which would lead to a segregating mixture under normal conditions to become non-segregating. Shearing during tailings transportation and dynamic deposition would enhance the segregation behaviour of tailings (Matthews et al., 2002). Under shearing and dynamic deposition, a higher solids and fines content composition mixture would be required to be deposited as a non-segregating mixture. On the ternary diagram the effect of

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shearing and dynamic deposition can be represented by the shift in segregation boundary towards higher solids/fines content.

The segregation boundary on the ternary diagram can be used to easily identify the segregating and non-segregating mixture under different sets of conditions or can be used to guide the amount and method of densification or fines enrichment for changing a segregating mixture to a non-segregating mixture and to select a non-segregating tailing composition for a particular set of tailings treatment, testing or depositional conditions. In this paper, owing to these important applications of the ternary diagram, the effect of high gravity application on the segregation behaviour of oil sands tailings is studied using the ternary diagram.

5. SEGREGATION INDEX (SI)

Segregation index (SI) is used in the oil sands industry as well as in the pipeline solids transport field to describe the segregation behaviour of fines and fines–sand mixture tailings (Scott and Cymerman, 1984). The index reflects the percentage of fines not captured in the mixture. SI is calculated from the solids content profile after letting the tailings settle for a certain length of time. In order to minimize the influence of change in solids content with depth due to sedimentation/self-weight consolidation, the index is evaluated before any significant change in volume occurred in the samples (Scott and Cymerman, 1984). The experimental results of Tan et al. (1990), Scott and Cymerman (1984), Been and Sills (1981), Imai (1981) and Jeeravipoolvarn et al. (2009) indicate that at an early stage of sedimentation/self-weight consolidation, where the change in

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volume is negligible, the solids content profile with depth is constant (vertical). In this early stage of settling any change in solids content from the average is considered due to the sorting particles based on size, and can thus can be used as an index for segregation. For high dewatering behaviour tailings the index needs to be determined immediately following filling the samples in the cylinders. For a very slow dewatering behaviour of tailings, such as oil sand MFT, the index can be calculated after a few weeks of settling or after a few minutes of centrifuge run that would allow enough time for all segregating particles to settle to the bottom without any significant change in volume occurring in the samples.

6. CENTRIFUGE MODELLING PRINCIPLE

Centrifuge modelling is based on the stress similarity between field (prototype) and model. In the centrifuge test, the model of size (1/N) of the prototype and with the same material as a prototype is used. Prototype stress is achieved by the application of a centrifugal acceleration N times Earth's gravitational acceleration on the model placed at the end of a centrifuge arm, thereby achieving stress similarity between prototype and model (Equation 1)

$$\sigma_m = h_m a_m \rho = \frac{hp}{N}(Ng)\rho = \sigma_p \qquad [1]$$

where h_m is model height, a_m is centrifugal acceleration in the model, hp is prototype height, N is height reduction factor (h_p/h_m) or relative acceleration

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($r\omega^2/g$), g is Earth's gravitational acceleration and ρ is density of the material; σ_m is self-weight stress in a model and σ_p self-weight stress in prototype.

A beam type centrifuge is commonly used in modelling the sedimentation and self-weight consolidation of slurries/soils. In beam centrifuge, sedimentation and self-weight consolidation is simulated by placing the one-dimensional sedimentation/self-weight consolidation model at the end of the centrifuge arm and rotating the sample in a horizontal plane at acceleration level of N times Earth's gravitational acceleration (N-g). Owing to the short drainage path in the model, sedimentation/self-weight consolidation phenomena that may take many years under field conditions can be simulated within a few hours using the centrifuge.

7. MATERIALS DESCRIPTIONS

Fines and coarse tailings from Albian Sands Energy Inc. and Syncrude Canada Ltd oil sand operators are used in this study. The fine tailings used are: Albian MFT from 7.5 m depth (Albian_7.5), Albian MFT from 15 m depth (Albian_15), Albian thickener underflow tailings (Albian_TUT), Syncrude MFT (Syncrude) and Syncrude cyclone overflow tailings (Syncrude_COT). The index properties and composition of these tailings are summarized in Table 1 and the grain size distribution in Figure 2. Albian MFTs were used to define a segregation boundary over a wide range of solids and fines content by preparing fines–sand mixture at various solids and fines content whereas Syncrude MFT, Syncrude_COT and Albian_TUT were used to define segregation boundary for an existing sand percentage in the samples. Albian beach sands were used in

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preparing Albian fines–sand mixture tailings. The effect of sand grain size on segregation boundary were investigated by using beach sands of particles passing sieve no. 10 (2 mm), no. 40 (0.425 mm) and no. 60 (0.25 mm). Albian MFTs–sand mixture at various sand fines ratio; Syncrude MFT, Syncrude_COT and TUT at various initial solids content were used in the vane shear tests conducted at various ages.

Table 1. Index properties and composition of materials

Samples	Fines content [%]	Bitumen content [%]	Liquid limit [%]	Plastic limit [%]	Clay content [%]	Clay fines ratio (CFR) [%]	Specific gravity [-]	Clay Dispersion [%]
	Characteristics							
Albian_7.5	99	1.0	53	26	57	58	2.66	100
Albian_15	91	7.0	40	22	38	42	2.44	100
Albian_TUT	70	3.5	35	17	36	51	2.56	55
Syncrude	98	4.5	53	26	56	57	2.52	100
Syncrude_COT	92	2.5	42	19	46	50	2.60	100

The bitumen content, shown in Table 1, was determined by extracting dissolved bitumen from oven-dried samples using toluene solvent in accordance with Dean-Stark extraction method (AOSTRA, 1979). The bitumen content is defined as the mass of bitumen over mass of solids. The fines content is determined by washing specimens through a no. 325 sieve (0.045 mm). The fines content is defined as the mass of solids passing sieve no. 325 (0.045 mm) relative to the mass of solids, consistent with the oil sand industry use. The specific gravities of the fines tailings reported in Table 1 are specific gravities calculated using the equation given by Banas (1991) (Equation 2) for an assumed specific gravity value of 2.70, 1.00 and 1.03 for bitumen free mineral solids, water and bitumen respectively. Based on the index tests results and according to the Unified Soil Classification

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System (USCS), Albian_7.5 and Syncrude are classified as CH while the remaining fine tailings are classified as CL.

$$G_f = \frac{1+b}{\frac{1}{G_{bf}} + \frac{b}{G_b}} \quad [2]$$

where G_f is the specific gravity of the fine tailings, b is the bitumen content by dry mass, G_{bf} is the specific gravity of bitumen free mineral solids and G_b is the specific gravity of the bitumen.

The liquid and plastic limits of the fine tailings were determined according to ASTM testing procedure (D 4318-05; ASTM, 2008a) after reducing the water content of the fine tailings close to liquid limit through self-weight consolidation and incremental loading. The Atterberg test was performed immediately after mixing to minimize the effect of thixotropy on the measured values. The grain size distribution is determined using sieves and dispersed hydrometer tests. Sodium hexametahphosphate (5 g/l) was used for dispersion. Non-dispersed hydrometer tests, without chemical addition and mechanical agitation, were also conducted according to ASTM (D 4221-99R05; ASTM, 2008b) standards to examine the degree of clay dispersion/flocculation of the fine tailings. In both dispersed and non-dispersed hydrometer tests samples were not dried prior to the tests or the residual bitumen was not extracted before hydrometer tests as drying and the high temperature in bitumen extraction process may cause cementation and bonding of particles leading to lower fines content. The degree of clay

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dispersion shown in Table 1 is calculated as the ratio of percentage finer in non-dispersed tests to the percentage finer in dispersed hydrometer tests at grain size of 2 mm. Clay size fraction is defined as particles finer than 2 mm. Except for the Albian thickener underflow tailings (TUT), the grain size distribution of the dispersed and non-dispersed tests indicates that the fine tailings were completely dispersed by the bitumen extraction process. The low degree of dispersion of the Albian_TUT may be associated with the addition of coagulant/flocculent during the fine tailings thickening process.

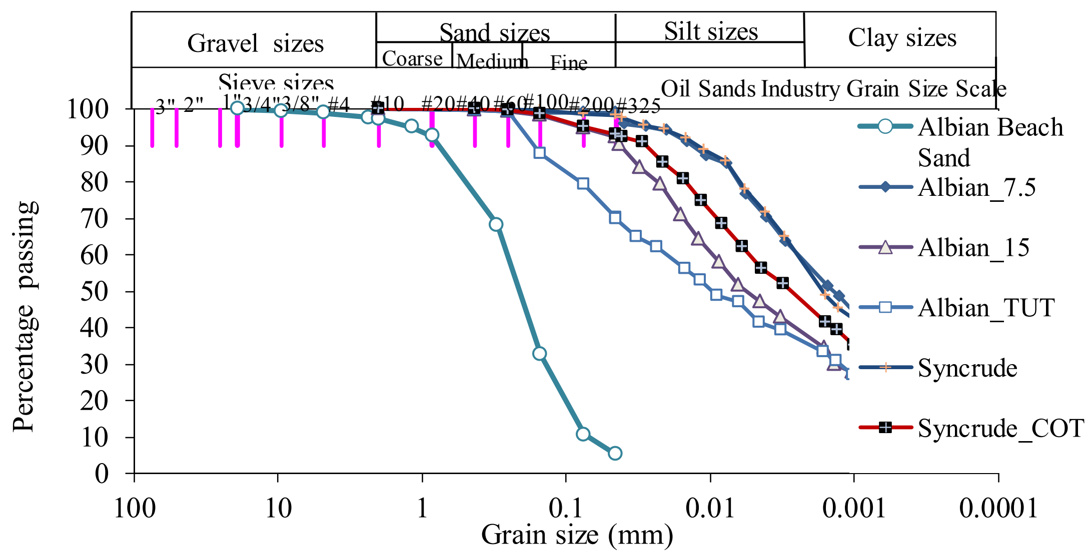

Figure 2. Grain size distribution of the fines and coarse tailings

8. EXPERIMENTS

8.1 Settling column tests

In accordance with the tests procedure developed by Scott and Cymerman (1984), various mixes of fines and fines–sand mixture tailings at different solids and fines content were prepared and left to sediment for a month for use in defining the

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segregation boundary using the ternary diagram. After one month of sedimentation and consolidation the samples were incrementally sampled from the top down and the solids content profile was used to determine the segregation indexes and to define the segregation boundary on the ternary diagram. The segregation index is defined as the sum of the change in density from average density over the whole depth of the sediment divided by the average density and used as a parameter for measuring the sorting of particles. A segregation index of less than 5% is considered non-segregating (Donahue et al., 2008).

Fines–sand mixtures at various solids and fines content were prepared by mixing MFT, pond water and beach sands. The mass of MFT (M_{MFT}), tailings sand (M_{sand}) and pond water (M_{water}) to produce one litre of fines-sand mixture of a desired solid and fines content was calculated using Equation 3.

$$\begin{bmatrix} M_{MFT} \\ M_{sand} \\ M_{water} \end{bmatrix} = \begin{bmatrix} Fines \\ Sand \\ Water \end{bmatrix} \begin{bmatrix} f_{MFT} s_{MFT} & f_{sand} s_{sand} & f_{water} s_{water} \\ (1-f_{MFT}) s_{MFT} & (1-f_{sand}) s_{sand} & (1-f_{water}) s_{water} \\ 1-s_{MFT} & 1-s_{sand} & 1-s_{water} \end{bmatrix} \text{ in 1 L CT} \quad [3]$$

where f_{MFT} and s_{MFT} are the fines and solids content of MFT respectively; f_{sand} and s_{sand} are the fines and solids content of sand (coarse tailings) respectively; and f_{water} and s_{water} are the fines and solids contents of mixing water (usually 0%). M_{MFT}, M_{sand} and M_{water} are the required mass of MFT; sand (coarse tailings) and pond water for making one litre of fines–sand mixture of desired compositions respectively. Fines, sand and water are the mass of fines, sand and water in one litre of the desired fines–sand mixture.

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In preparing fines–sand mixture samples, the MFT stored in pails was first thoroughly mixed to obtain a uniform consistency. Then the required mass of MFT, sand and pond water, calculated using Equation 3, was placed in the mixing pail and thoroughly mixed for 5 min. A double auger mortar mixer (dual-paddle blades) was used for mixing the MFT in the storing pails as well as the fines–sand mixtures tailings in the mixing pail. Fines tailings at different solids content were prepared by mixing MFT and pond water in order to evaluate the segregation behaviour of fine tailings for an existing sand percentage in the prepared samples.

After preparing the samples at various solids and fine content, the samples were placed into a settling column of 1 L capacity (6.3 cm internal diameter cylinders to a height of 32.1 cm) and left to sediment and consolidate for one month. After one month, the decant water was siphoned off and the sediment sampled in a number of layers from the top down. The solids content profile was then determined by drying the sub-samples in an oven at 105°C. The segregation index was calculated from the solids content profile using Equation 4.

$$SI = \frac{\sum \left|(s_i - s_{ave})(H_i - H_{i+1})\right|}{s_{ave}} x100 \qquad [4]$$

where SI is segregation index, s_i solid contents of slice i, s_{ave} is the average solid content after one month of settling over the total height of the sample and $H_i - H_{i+1}$ is the normalized height of slice i.

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To define the segregation boundary at a particular solid content, four settling columns were filled with fines–sand mixture tailings at the same solid content but at four different fines content. The segregation indexes were computed from the solids content profiles after one month of settling. The segregation indexes were then plotted as a function of the initial fines content. The segregation boundary point was then taken as the fines content corresponding to 5% segregation index (95% fines capture index). For the Albian's fines–sand mixture, five to six segregation boundary points were derived from the series of settling columns tests to define the segregation boundary over a wide range of solids and fines contents. The segregation boundary points of the fines tailings were derived from the plot of segregation index against initial solids contents for a segregation index corresponding to 5%.

8.2 Centrifuge tests

The centrifuge used for this study is a swinging platform beam centrifuge of radius 5.5 m (C-CORE centrifuge). Twelve polyvinyl chloride (PVC) cylindrical containers of 100 mm internal diameter and 220 mm height were used to test 12 models in single centrifuge flight (Figure 3(a)). The PVC cylinders were made by coring solid PVC pipe. For safety reason during centrifuge flights, the 12 models were contained in strong rectangular aluminium boxes of internal dimensions 940 x 1180 x 400 mm (Figure 3(b)).

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(a) (b)

Figure 3. Model containers for the centrifuge tests: (a) PVC cylinders for testing 12 models in single centrifuge flight; (b) test package

Like the settling column tests, samples for centrifuge tests at various solids and fines content were prepared by mixing MFT, sand and pond water. After mixing the samples to the desired solid and fine content, the samples were poured into PVC cylinders of 100 mm internal diameter. The heights of the samples (models) were 50 mm to 83 mm, depending on the centrifugal acceleration level used in the centrifuge tests. Centrifugal acceleration levels of 60 times Earth's gravitational acceleration (60g) to 100 times Earth's gravitational acceleration (100g) were used. In computing the centrifugal acceleration ($a = r\omega^2$), the radius was taken from the centre of rotation to one third depth of the sample in accordance with the recommendation of Taylor (1995) and Schofield (1980). After one day of waiting time, the samples were spun to the desired acceleration for an equivalent of 30 days in the prototype. The spin times in the centrifuge are calculated using Equation 5 for the theoretical time exponent of x = 2. The heights of the samples (model height) were chosen to represents a 5 m deep prototype. Model height (h_m)

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corresponding to 5 m prototype is calculated by dividing the prototype height by the level of centrifugal acceleration used.

$$t_m = \frac{t_p}{N^x} \qquad [5]$$

where t_m is model time (spin time in centrifuge), t_p is prototype time, 30 days, N is centrifuge acceleration/Earth gravity acceleration and x is a theoretical time exponent, x = 2.

After the end of centrifuge tests, the samples in the plastic cylinder were subsampled into five to seven layers and the solid content of each layer was determined. The segregation index was then computed from the solid content profiles using Equation 4. The segregation boundary at particular solids content was determined from a plot of fines content against segregation index for a segregation index corresponding to 5% (fines capture index of 95%).

In addition to the solids content profile, in some of the centrifuge tests samples, the fines content profiles at the end of the centrifuge tests were also determined to evaluate segregation. Sub-samples at various depths were obtained and washed using no. 325 (44 mm) sieves. The sand retained on the no. 325 sieve was oven dried at 105 °C and used to determine the fines content profiles. The segregation index based on the fines content profile is then computed using Equation 6. The segregation boundary was then taken as the segregation index corresponding to 5% (fines capture index of 95%). Also, for some of the samples, the grain size

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distribution of sand from a different depth of the sediment after the centrifuge test was analysed to investigate sorting of sand by size and to check that the segregation index values of 5% properly categorize segregating samples from non-segregating samples.

$$SI = \frac{\sum |(f_i - f_{ave})(H_i - H_{i+1})|}{f_{ave}} x100 \qquad [6]$$

where SI is segregation index, f_i fines contents of slice i, f_{ave} is the average fines content over the total height of the sample and $H_i - H_{i+1}$ is the normalized height of slice i.

8.3 Shear tests

Specimens for shear tests were prepared together with the centrifuge test samples. The undrained shear strength of the fines–sand mixes was measured using the Brookfield viscometer (DV-II+ Pro) with the four-sided vane blades and at a vane rotation speed of 0.2 rpm. The apparatus has a measuring capacity of 5 to 1000 Pa. Vane shear tests were conducted using vanes with height twice the diameter, vanes with diameters of 0.6 to 2.2 cm were used. The size of the vanes spindles for a particular test was selected based on the expected shear strength of the samples, smaller vanes for higher strength and larger vanes for relatively small shear strength. The undrained shear strength of fines and fines–sand mixture samples were measured immediately following mixing then after 1, 2, 4 and 24 h and at various times up to a maximum of 189 days.

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9. RESULTS AND DISCUSSIONS

9.1 Settling column tests results

The results of settling tests are summarized by plotting segregation boundaries on the ternary diagram (Figure 4). The boundaries for Albian fines and fines–sand mixture tailings are established at various solids and fines content. For the other tailings used in the study, segregation boundaries are established only for existing sand content in the fine tailings. The segregation boundaries shown in Figure 4 are established from the solids content profile after one month of sedimentation and self-weight consolidations. Tailings compositions above the boundary are segregating while below the boundary they are non-segregating.

As shown in Figure 4, the segregation boundaries vary with the tailings compositions and source. The segregation boundary of Albian_7.5 fines–sand mixture tailings is parallel to 24% FWR for fines content less than 70%; the segregation boundary of Albian_15 m is close to and parallel to a 30% FWR. The segregation boundary of Albian MFT from 7.5 m depth (Albian_7.5) lies above the boundary of Albian MFT from 15 m (Albian_15). The difference in the segregation boundary is likely associated with the difference in percent of clay in the fines. Albian MFT from 7.5 m depth has a clay–fines ratio (CFR) of 58% but Albian MFT from 15 m depth has CFR of 42% (Table 1). In addition to the significant CFR difference, variation in bitumen content, pore water chemistry, fines mineralogy and extraction methods are the other possible reasons for the observed difference in the segregation boundary. Segregation boundary points of

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Syncrude, Syncrude_COT and Albian_TUT are close to the segregation boundary of Albian_7.5 m as the clays–fines ratio is similar to Albian_7.5 (Table 1).

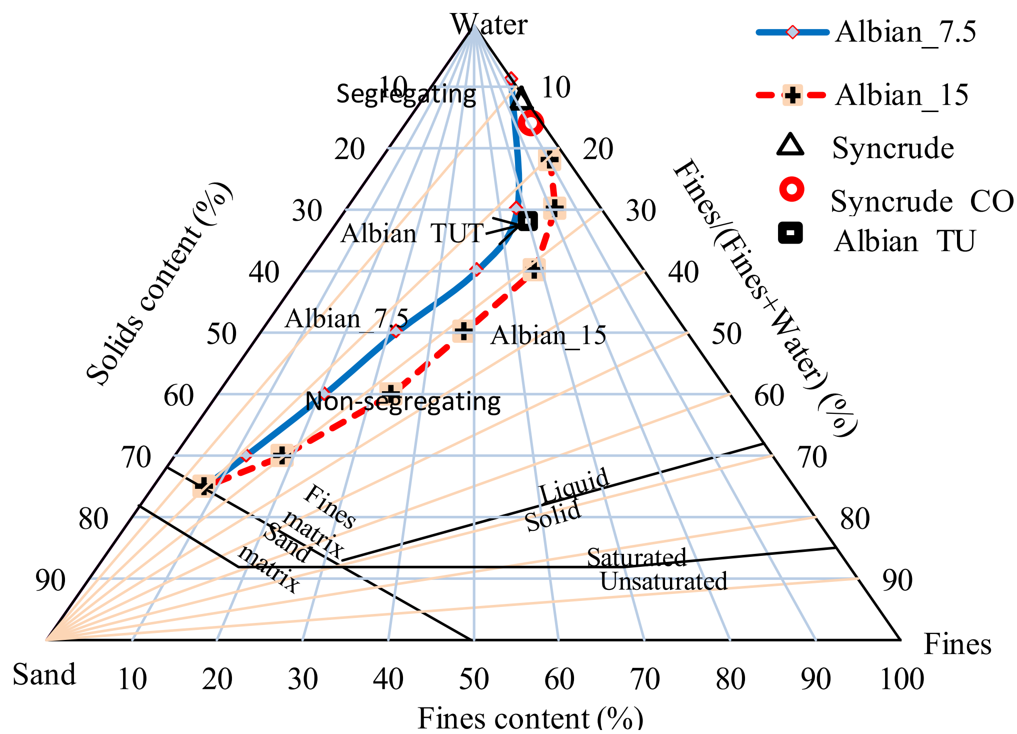

Figure 4. Segregation boundaries from settling column tests

9.2 Centrifuge tests results

The results of centrifuge tests are summarized by plotting segregation boundaries at various acceleration levels in Figure 5. The segregation boundaries established from centrifuge tests are a function of tailings composition, source and acceleration levels. Differences in the segregation boundary between the tailings are exhibited more in centrifuge tests than in settling column tests. The difference in segregation boundary for different tailings (at the same acceleration level) may be associated with variation in water chemistry, fines mineralogy and bitumen

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extraction methods. Like settling column tests, a segregation boundary of tailings with a higher clay–fines ratio lies above the boundary of tailings having a lower clay–fines ratio.

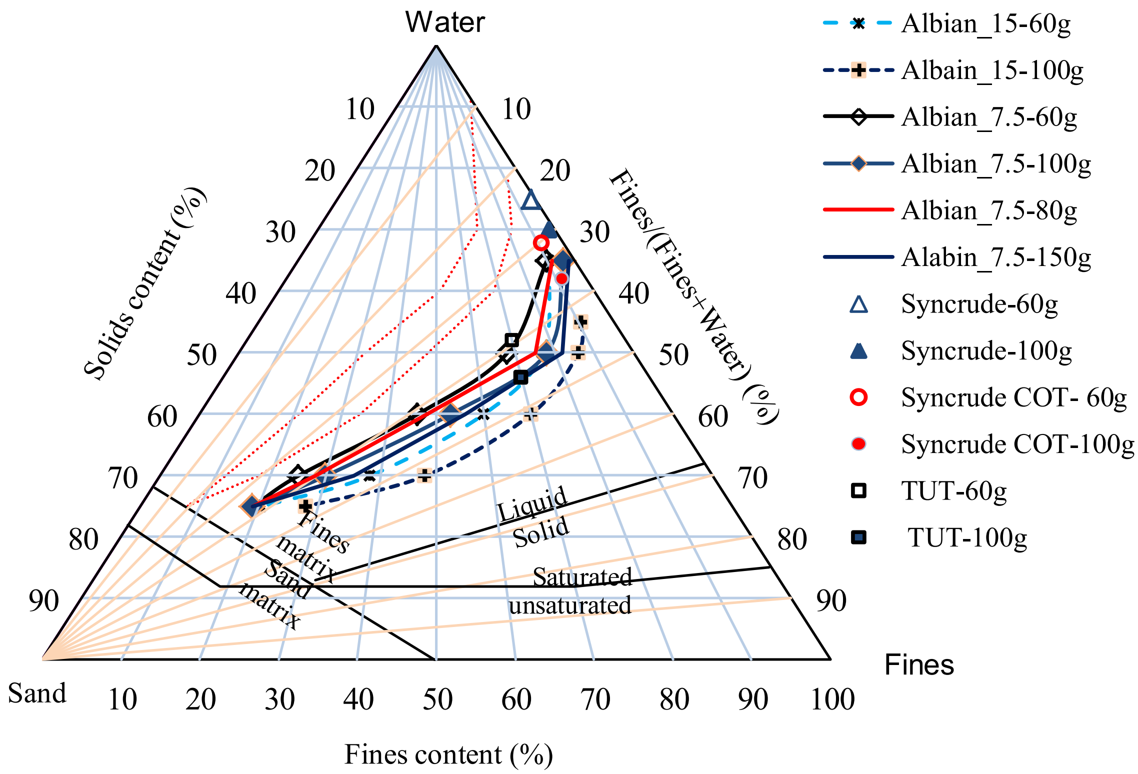

Figure 5. Segregation boundary from centrifuge tests

As shown in Figure 4 and Figure 5, the segregation boundaries from settling and centrifuge tests are different. The segregation boundary from the centrifuge tests shifts towards a higher solids content. The difference may be associated with the application of high acceleration without first increasing the carrying capacity of clay fractions in the mixture. In centrifuge model tests, as the acceleration is applied, the weight of individual grains increases in proportion to the applied acceleration but the fines carrying capacity generally does not change. Fines–sand mixtures that are non-segregating in settling column test (under Earth's gravity

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level) become segregating mixtures under high acceleration levels in the centrifuge. The area bounded by the centrifuge and settling column segregation boundary refers to tailings compositions that segregate as a result of applying high centrifugal force. The segregation related to high gravity makes specimen behaviour in the centrifuge model different from the prototype, limits the composition of materials that can be used in centrifuge tests and limits the range of consolidation parameters that can be derived from the centrifuge tests.

The effects of sand maximum particle size on the centrifuge segregation boundary were investigated by using Albian_15 fines–sand mixtures at different SFR. Beach sands passing 2 mm, 0.425 mm and 0.25 mm were used in making the fines–sand mixtures. Segregation boundaries for the three different maximum size of sands mixture were evaluated from solids content profiles at the end of the centrifuge tests. The effects of sand maximum particle size on the segregation boundary are summarized by plotting the segregation boundary in Figure 6.

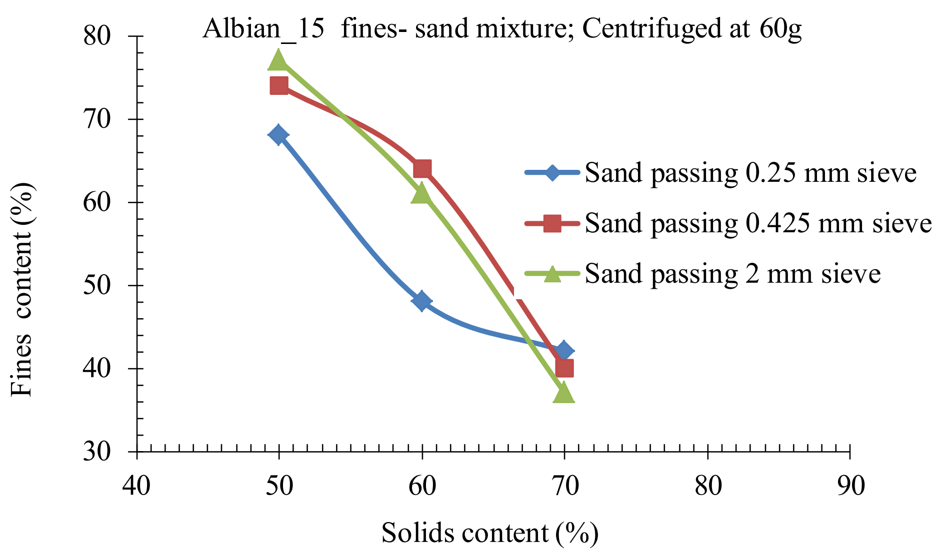

Figure 6. Segregation boundary of fines–sand mixture of different maximum particle size of sand

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As shown in Figure 6, fines–sand mixture with a maximum particle size of 2 mm requires higher percentage of fines than the fines–sand mixture with a maximum particle of sand particle size of 0.25 mm. However, at lower fines and higher solids content, it appears that the particle size distribution of sand has more influence than the maximum particle size of the sand. The particle size distribution of beach sand passing the 0.25 mm is more poorly graded than sands passing 2 mm (Figure 7).

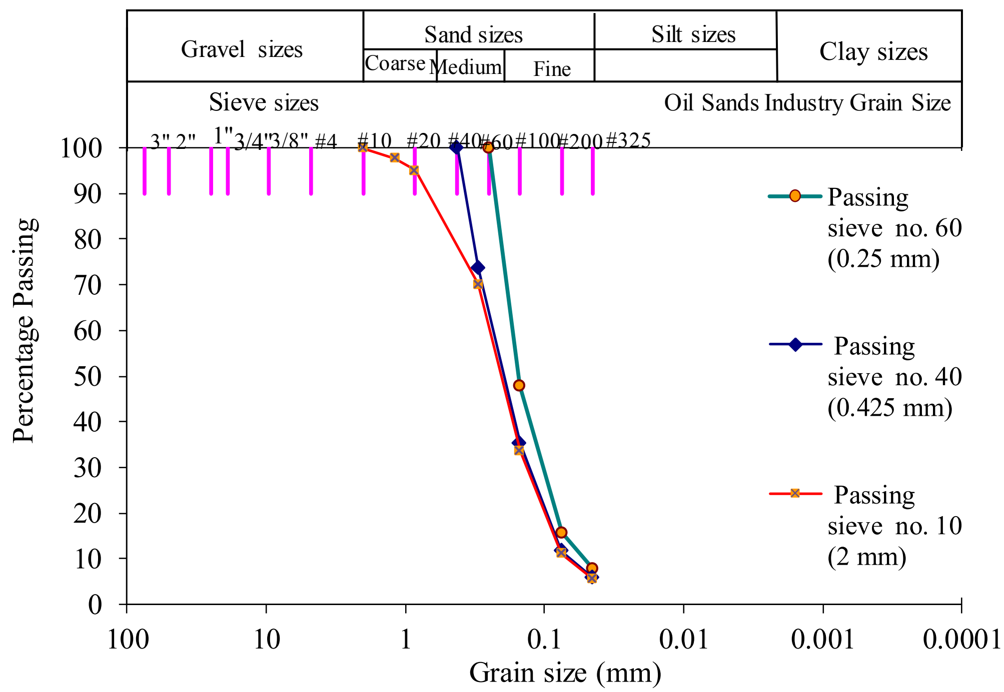

Figure 7. Particle size distribution of Albian beach sand passing sieve no. 10, no. 40 and no. 60

The segregation index (SI) that was used to define the segregation boundaries shown in Figure 4 and Figure 5 were computed from the solids content profiles after one month of sedimentation and consolidation. In order to relate the segregation index computed from solids and fines content profiles and to examine

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how the segregation boundary can be affected by the type of profiles used, both solids and fines content profiles were evaluated following the centrifuge tests. Evaluation of segregation based on the fines content profile is considered more logical than based on the solids content profiles as it directly measures sorting of the coarse fraction from the fines and is less likely to be influenced by the change in density induced during consolidation or less likely to be influenced by the elapsed time to measure the density profile after sample preparation. However, the evaluation of segregation based on the fines content profile is more time-consuming than based on the solids content profile. This is due to the fact that washing each sub-sample that contains residual bitumen is more time-consuming than weighing and drying sub-samples in an oven.

Figure 8 shows the plot of SI as a function of the initial fines of the samples for Albian_15 fines–sand mixture samples at 70% initial solids content, 30–55% fines content after centrifuge tests at 100g. The samples after the tests were sliced to determine the solids and fines content and the segregation indexes were computed from solids and fines content profiles. Figure 8 is a typical plot a series of tests conducted for evaluating segregation based on solids and fines content profiles.

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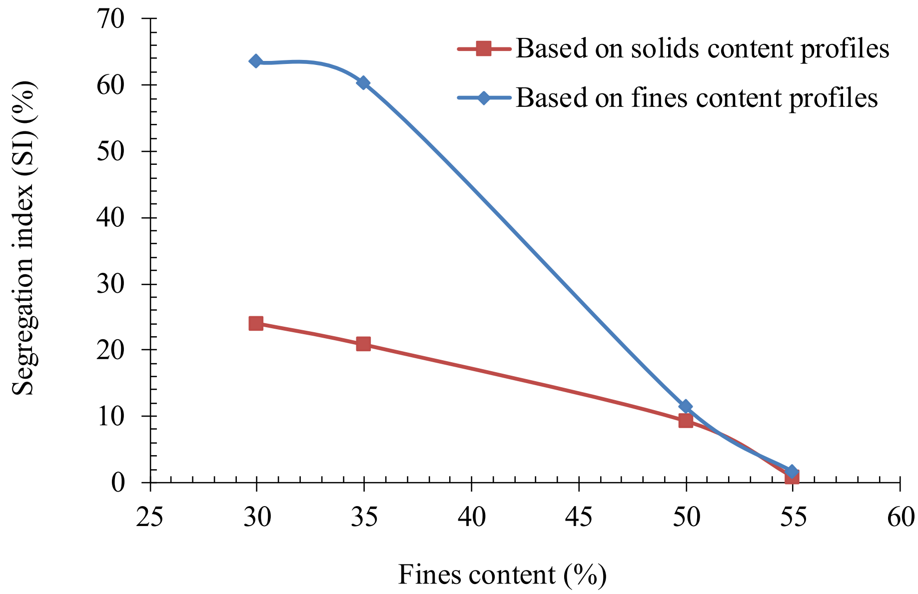

Figure 8. Segregation index of the Albian_15 fines–sand mixture at 70% solids, 30–55% fines content, 100g tests, based on solids and fines content profiles

A summary of 73 samples that were analysed for evaluating segregation index based on solids and fines content profiles is shown in Figure 9. It appears that for a segregation index of less than 5%, both profiles generally estimate more or less the same segregation index. However, for a segregation index of greater than 5%, the segregation indices based on fines content profile are generally greater than those based on solids content profiles. The segregation boundary point (5% segregation index), however, is not significantly influenced by use of either solids or fines content profiles.

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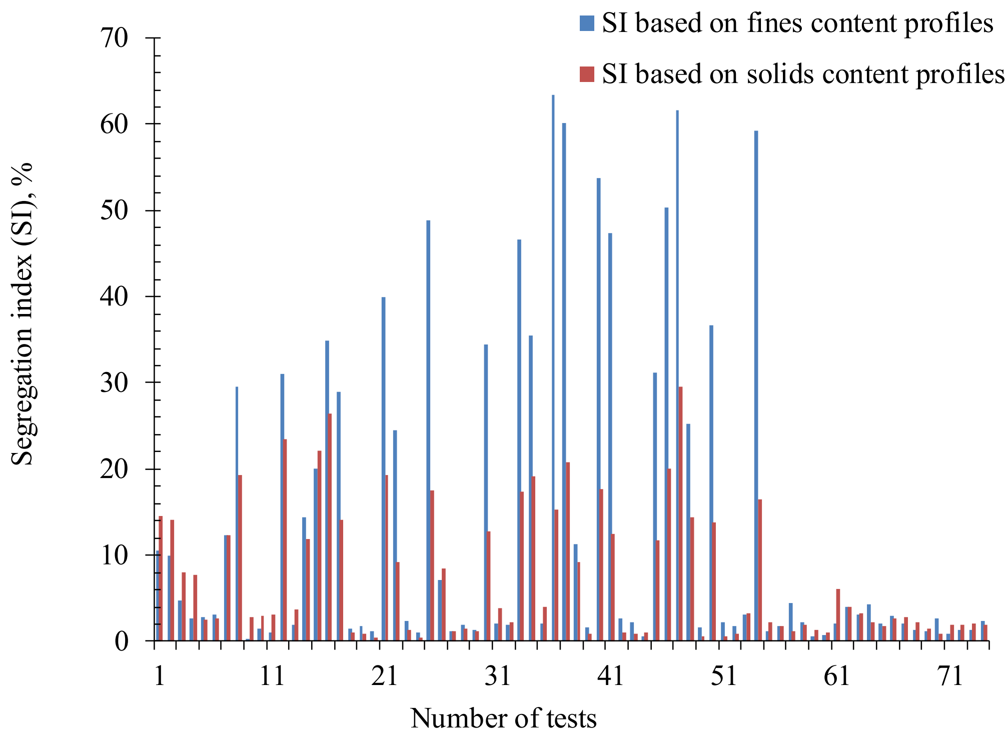

Figure 9. Summary of segregation index based on solids and fines content profiles

In order to assess the characterisation of segregation based on solids or fines content profiles, the grain size distribution of sand taken from a different depth was analysed after the centrifuge tests. Typical grain size distributions of sand at different depths are shown in Figure 10. Based on solids content profiles, Figure 10(a) shows typical grain size distribution of samples classified as non-segregating and Figure 10(b) for segregating. It appears that a segregation index of 5% properly categorizes segregating and non-segregating samples. In addition to characterisation based on the segregation index, visual observation of the test samples showed that segregated mixtures had a layer of bitumen in the top portion

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of the samples, as well as distinct layers of fines and sand and diluted release water above the fines.

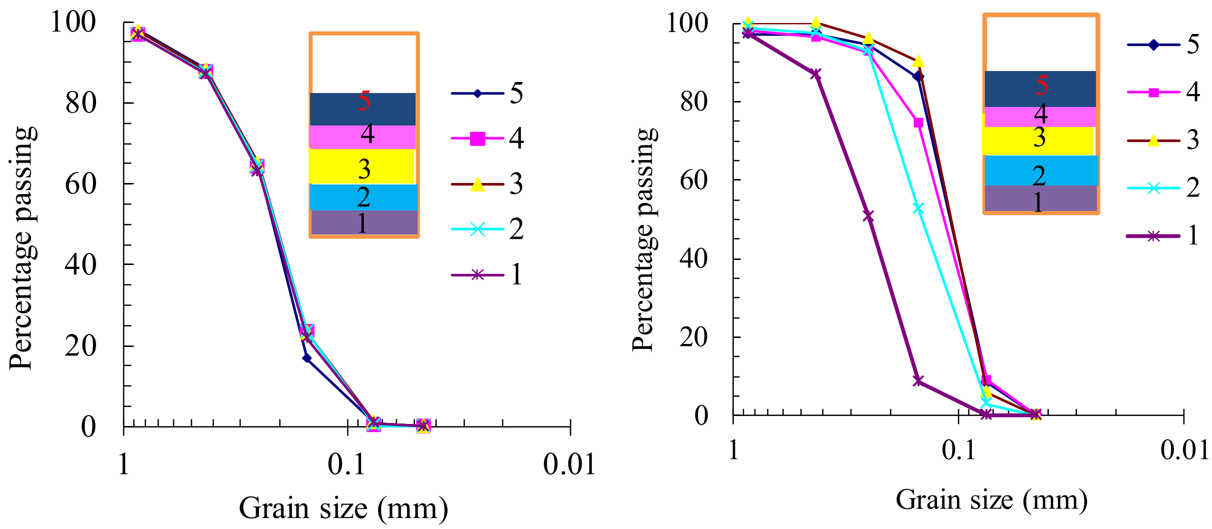

Figure 10. Grain size distribution of sand from different depth of sediment: (a) Albian_15 fines–sand mixture, 50% solids, 80% fines, 60g acceleration, SI < 5; (b) Albian_15 fines–sand mixture, 50% solids, 60% fines, 60g acceleration, SI > 5

The ternary diagrams in Figure 4 and Figure 5 present the results indicating the effect of applying high centrifugal acceleration on the segregation boundaries fines and fines– sand mixture tailings. The ternary diagram is a convenient means for easily identifying or determining at what solids and fines content fines–sand mixture will behave as either a segregating or non-segregating materials. The detailed description and use of this diagram can be found in Azam and Scott (2005). Another approach in the literature for evaluating segregation is by evaluating the maximum size of sand that remains within a suspension. In this approach, the formulas by Weiss (1967) – whose work is cited by Xanthakos (1979) – and Cardwell (1941) – whose work is cited by Morgenstern and Amir-

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Tahmasseb (1965) – are most applicable. The Cardwell (1941) and Weiss (1967) formula that estimates maximum particles diameter of sand that remain in a suspension (slurry) is given by Equation 7.

$$D_{\max} = \frac{mSu}{(\rho_c - \rho_s)a} \quad [7]$$

where S_u is the undrained shear strength of the slurry, ρ_c is the density of sand particles, ρ_s is the density of slurry, a is the gravitational acceleration and m is constant (6 used by Cardwell and 1.5 used by Weiss).

The maximum sizes of sand that remain in suspension under Earth's gravity and under high acceleration level were computed using the formulas suggested by Cardwell (1941) and Weiss (1967). The shear strength measured after one day of sample preparation was used in computing the maximum size of sand. The computed maximum size of sand that remains in suspension under Earth's gravity and under high acceleration field for the Albian_7.5 fines–sand mixture is summarized by plotting the maximum size of sand as a function of FWR (fines/(fines + water)) of the samples (Figure 11).

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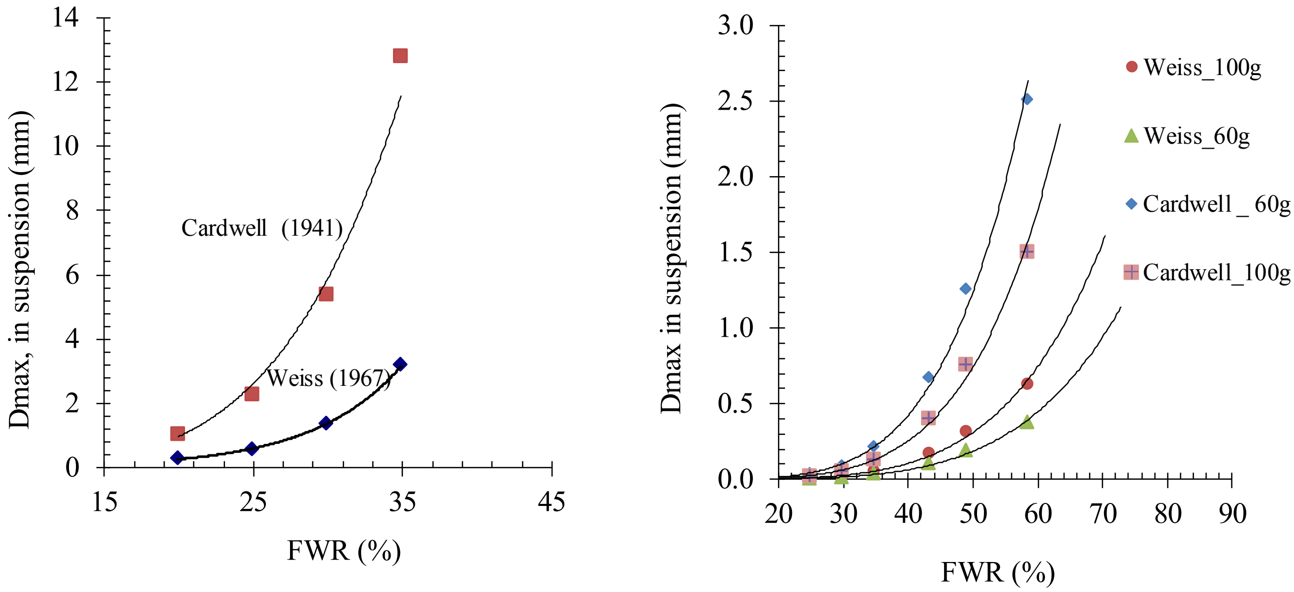

(a)

(b)

Figure 11. Maximum size of sand that remains in suspension, Albian 7.5 fines–sand mixture tailings: (a) under Earth's gravity; (b) under high-acceleration field in centrifuge

For the Albian_7.5 fines–sand mixture, the Cardwell (1941) formula estimated that fines–water ratios of 23% are required to support 2 mm diameter sand particles under Earth's gravitational acceleration (Figure 11(a)). This is in close agreement with the settling columns test result in which a FWR (fines/(fines + water)) is parallel to a segregation boundary of 24% (Figure 4). The Weiss (1967) formula on the other hand estimates a 33% FWR for supporting 2 mm diameter sand particles under Earth's gravity. According to the Cardwell formula a FWR of 55% at 60g and a FWR of 62% at 100g are required to support sand particles having of 2 mm diameter. However, as shown in the centrifuge segregation boundary the slurries can support 2 mm of sand at FWR of less than 45%.

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According to Weiss (1941) a FWR of greater than 70% is required for supporting 2 mm diameter sand particles. This analysis suggests that the evaluation of segregation based on Cardwell (1941) and Weiss (1967) under high acceleration fields is highly conservative. The Cardwell (1941) formula can be used for the characterisation of segregation of fines–sand mixture samples under Earth's gravity whereas the Weiss (1967) formula is conservative in estimating the maximum size of sand that remains in a suspension under Earth's gravity.

9.3 Shear tests results

Figure 12 shows the undrained shear strength against fines void ratio after 1 day of sample preparation for all materials used in this study. The strength of the fines–sand mixture is plotted as a function of fines void ratio and the relation is best described using a power relation (or linear relation in log strength against log fines ratio plot) (Figure 12). The fines voids ratio is used instead of void ratio or solid contents because the strength of the fines–sand mixture varies with the percentage of fines contained in a sample at the same solids content (void ratio).The fines void ratio is defined as the volume of voids relative to the volume of fine and computed from void ratio and fines content using Equation 8.

$$e_f = \frac{eG_f}{fG_s} \quad [8]$$

where e_f is the fines void ratio, e is the void ratio, G_f is the specific gravity of fines; f is the fines content and G_s is the specific gravity of solids. The specific

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gravity of the fines–sand mixture was calculated from specific gravity of fines and specific gravity of sand (2.65) using a formula given by ASTM D-854-05 (ASTM, 2008d) standard for combining the specific gravity of soil and the specific gravity of aggregates.

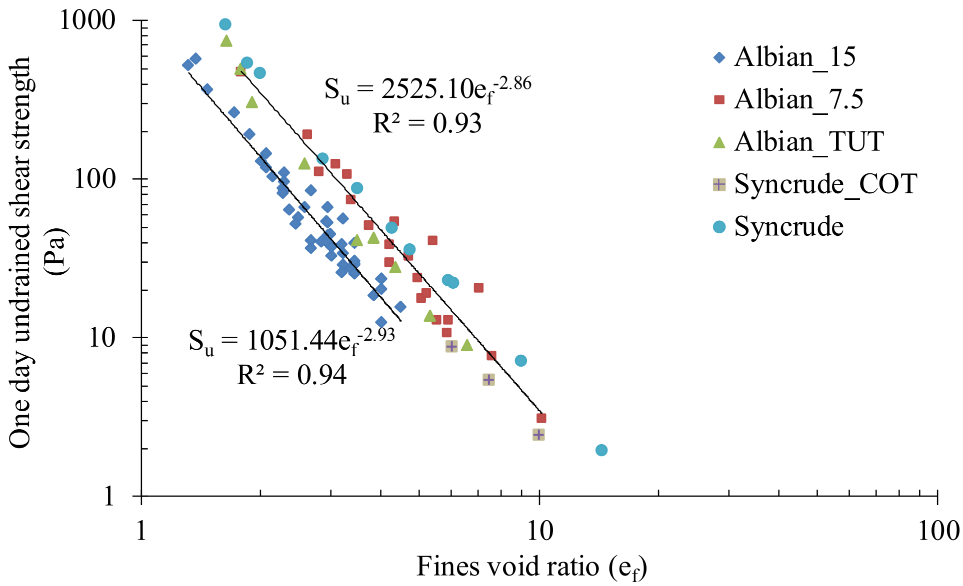

Figure 12. Shear strength of fines and fines–sand mixtures tailings after one day of sample mixing

As shown in Figure 12, the undrained shear strength against fines void ratio is a function of the fines tailings source. The variation of shear strength between different tailings (for the same fines void ratio) is likely associated with the variation of the clay content relative to fines content.

The undrained shear strength of the Albain_15 fines–sand mixture at 47.3% solids content, 60 to 90% fines content, as a function of elapsed time is given in Figure 13. Figure 13 is a typical result of a series of tests conducted on samples prepared at the same initial solids content but at different fines content and tested at

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different age of the samples. Considering the slope of the shear strength–time plot in Figure 13, the rate of shear strength gain in one day following sample preparation is greater than the rate of shear strength gain after one day. The strength gain within one day is solely due to a time-dependent process as there is no volume change during this period. In all of the samples used in this study, the period to which there is no change in volume after letting the samples settle (induction period) is greater or equal to one day. After the induction period the increase in shear strength is attributable both to the decrease in water content and the effect of the time-dependent process.

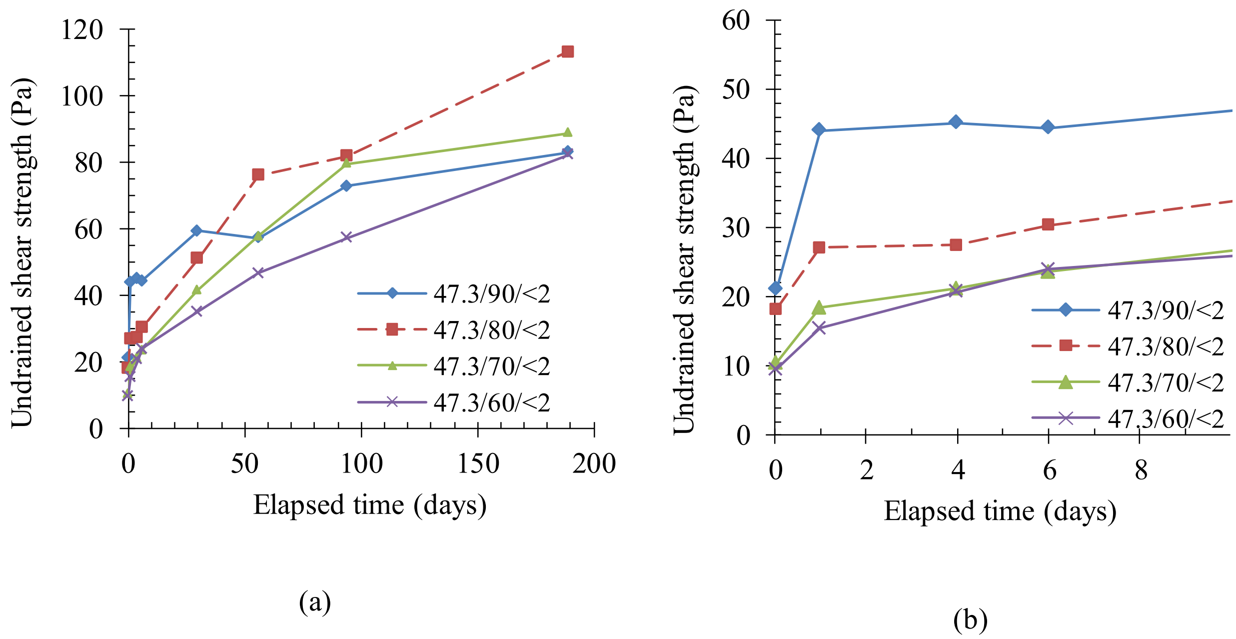

Figure 13. Shear strength development of the Albian_15 fines– sand mixture, 47.3% initial solids content, 60–80% fines content, 2 mm maximum size sand particles: (a) for 189 days; (b) for 10 days

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The change in shear strength in one day relative to the strength measured immediately following mixing is summarized in Figure 14. The gain in shear strength in one day varies from 5 to 150% of the strength immediately following mixing with a general trend of increasing with increase in fines void ratio (Figure 14). As the carrying capacity of the fines fraction is a function of the slurry shear strength, and as there is significant shear strength gain in one day, letting samples to rest for one day before subjecting them to a high acceleration field in a centrifuge reduces the potential of segregation during centrifuge tests. Thus, one day waiting time is suggested for materials used in this study. The wait time is an elapsed time immediately after mixing to a time the samples are subjected to a high acceleration field in a centrifuge and is less than or equal to the induction period. The wait time is based on reducing the potential for segregation in centrifuge tests based on the rate of shear strength development during the induction period. The waiting time is a function of the dewatering behaviour of the material, the composition of the material, and the type and amount of chemical additives used for enhancing the dewatering behaviour of the tailings being tested.

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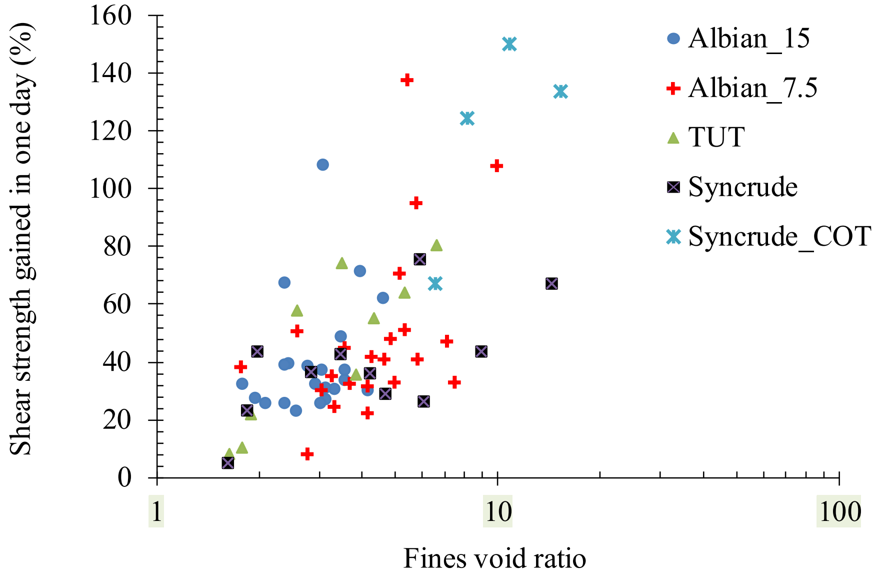

Figure 14. Shear strength gained in one day relative to the strength measured following sample mixing

Figure 15 shows the strength of the Albain_15 fines–sand mixture at 50% solids content, 60 to 80% fines content, at various elapsed times. Figure 15 presents a series of shear tests conducted at various ages of fines and fines–sand mixture samples. The solid lines represent the measured shear strength while the dotted line represents the shear strength estimated owing to change in volume only. The initial mass of each sample, the initial void ratio of the sample and the amount of water released at different elapsed time are used to calculate the fines void ratio at different elapsed time. The fines void ratio calculated at different elapsed time and the S_u–e_f relationship immediately following mixing are used to estimate the strength gain of sample resulting from a decrease in water (change in volume). The strength due to the time-dependent process is then taken as the measured

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strength minus the shear strength increase resulting from a decrease in water content.

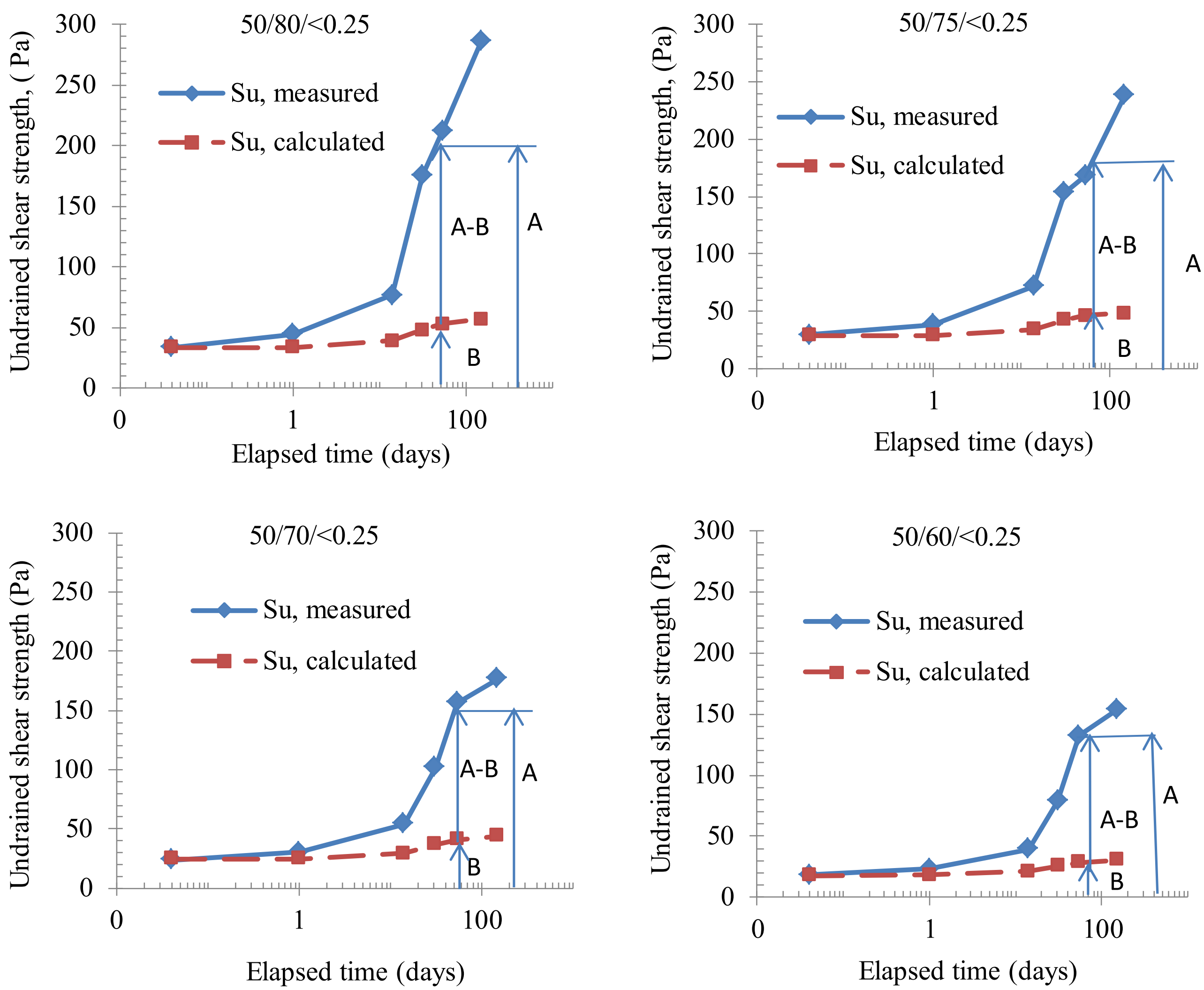

Figure 15. Strength of the Albian_15 fines–sand mixture sand as a function of elapsed time, 70% initial solids content, 60–80% fines content, 0.25 mm maximum size of sand.

In Figure 15, line A refers the total strength gain after sample preparation, line B refers the strength gain due to change in volume at a particular time. Line A–B is the strength due to time-dependent processes. The strength represented by the line

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A–B is greater than that of B, indicating that the strength gain due to time effects is much greater than that due to the change in volume (decrease in water content). In other words, the strength gain is more dependent on the non-gravity time-dependent process than the gravity-dependent process. The ratio of strength gain due to the time-dependent process (thixotropy) relative to the total strength gain after mixing is summarized in Figure 16. The thixotropic strength (ratio of strength gain due to thixotropy relative to the total strength gain) is a function of the tailings composition and age but is greater than 0.62 with a mean value of 0.9 and a confidence interval (95%) of 0.1. The significant contribution of strength gain with elapsed time due to a non-gravity time-dependent process may create difficulty in extrapolating centrifuge modelling test results to the prototype. This is because the settling of soft soils that may take many months/years to consolidate in a prototype can be modelled in a few hours of the centrifuge run without properly accounting for the effect of time-dependent process associated with strength gain.

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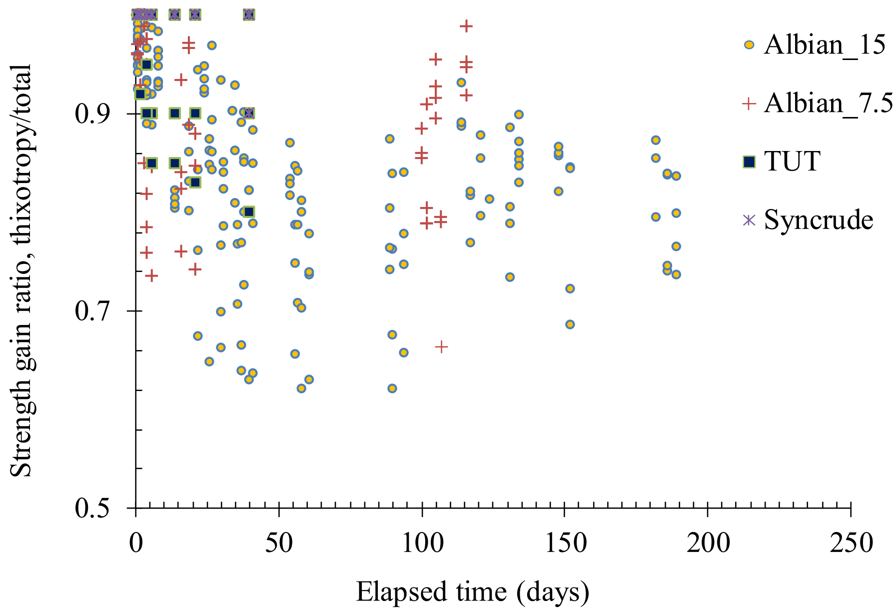

Figure 16. Thixotropic strength relative to total strength as a function of elapsed time

10. CONCLUSION

Settling and centrifuge tests were conducted on oil sand fines and fines–sand mixture tailings to define the segregation boundary. Segregation boundaries derived from the settling and centrifuge tests are used to show the effect of applying high centrifugal acceleration on segregation behaviour of fines and fines–sand mixture tailings. The effects of a time-dependent process on modelling the settling behaviour of fines and fines–sand mixture were investigated by measuring the undrained shear strength of fines and fines–sand mixture tailings over a wide range of composition and ages.

Based on settling column, centrifuge and vane shear test results the following conclusion can be made.

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- Segregation boundaries from settling and centrifuge tests depend on tailings source compositions and gravity levels thus are not the same for all oil sand tailings.
- The application of centrifugal acceleration which is many times the Earth's gravitational acceleration without increasing the carrying capacity of fines enhances the segregation of fines and fines–sand mixture tailings.
- The area bounded by static (settling column test) and centrifuge segregation boundary on the ternary diagram refers to tailings composition that will segregate during the application of high acceleration in the centrifuge testing.
- The significant shift of segregation boundary of centrifuge tests from settling column test limits the compositions of materials that can be used for centrifuge tests and the ranges of consolidation parameters that can be derived from centrifuge tests.
- Particle segregation related to high-g tests would make the behaviour of material in a model different from the prototype.
- Solids and fines contents from the settling columns and centrifuge tests can be used for segregation evaluation and tailings composition with a segregation index of less than 5% can be considered as a non-segregating sample.
- The measured shear strength of the fines–sand mixture at different initial void ratio and age indicates that oil sands fines and fines–sand mixture tailings are highly thixotropic material.

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- The thixotropic behaviour of the material creates difficulty in extrapolating centrifuge tests results to the prototype.
- Allowing oil sands fines–sand mixture tailings to rest for one day before centrifuge tests reduces the potential of segregation in centrifuge testing.
- The equations of Cardwell (1941) and Weiss (1967) that predicts maximum particle size that remain in slurry are both conservative under high acceleration level.

Modelling the settling behaviour of MFT requires many days of continuous centrifuge run. Geoenviromental problems (clay barrier performance, solute transport and light non-aqueous liquid fate phase) require a continuous centrifuge run for many days in order to model prototype performance over several days (Mitchell, 1998). It is essential first to examine the segregation behaviour of samples under high gravity before conducting centrifuge tests that may require a continuous centrifuge run for many days in an expensive facility. The segregation behaviour can be evaluated in a few minutes of centrifuge runs without the need of in-flight instrumentation and monitoring. For the evaluation of segregation, multiple samples can be placed in single centrifuge tests, saving both energy and cost. The solids or fines content profiles at the end of the test can be used for the evaluation of segregation.

Centrifuge modelling is sometimes used to verify mathematical models. The close agreement between the mathematical model and the centrifuge tests results is used as a justification for the use of the mathematical model or the centrifuge

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modelling technique. However, the close agreement of the mathematical model and centrifuge model does not guarantee the application of the mathematical model/centrifuge testing to prototype- scale problems. This is because neither the mathematical nor centrifuge model may incorporate the non-gravity time-dependent material behaviour and may not account properly for the full complexity of the material's non-homogeneity, boundary condition and stress history that could affect the settling/strength behaviour of the materials in prototype compared to the material tested in the centrifuge test. Careful model preparation and testing procedures may reduce the effect of non-homogeneity and stress history in modelling prototype using small size models (Mitchell and Liang, 1986). A method that properly accounts non-gravity time-dependent behaviour is required to assist the extrapolating centrifuge model results to the prototype.

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Notation

a	acceleration
a_m	centrifugal acceleration in the model
b	bitumen content by dry mass
D_{max}	maximum particles diameter of sand that remain in a suspension (slurry)
e	void ratio
e_f	fines void ratio
f	fines content
f_{MFT}	fines content of matured fine tailings (MFT)
f_{sand}	fines content of sand (coarse tailings)
f_{water}	fines of mixing water
g	earth gravitational acceleration
G_b	specific gravity of the bitumen
G_{bf}	specific gravity of bitumen free mineral solids
G_f	specific gravity of the fine tailings
G_s	specific gravity of solids
h_m	model height
h_p	prototype height
$H_i – H_{i+1}$	normalized height of slice i
m	constant for Cardwell and Weiss equations
M_{MFT}	mass of MFT for making one litre of fines–sand mixture

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M_{sand} mass of sand for making one litre of fines–sand mixture

M_{water} mass of water for making one litre of fines– sand mixture

N the ratio of prototype height to model height or relative acceleration ($r\omega^2/g$)

s_{ave} average solid content

s_i solid contents of a slice i

s_{MFT} solids content of matured fine tailings MFT

s_{sand} solids content of sand (coarse tailings)

s_{water} solids contents of mixing water

SI segregation index

S_u undrained shear strength of the slurry

ρ bulk density of a material

ρ_c density of sand particles

ρ_s density of slurry

σ_m self-weight stress in a model

σ_p self-weight stress in prototype

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CHAPTER 4. TIME DOMAIN REFLECTOMETRY MEASUREMENTS OF OIL SANDS TAILINGS WATER CONTENT: A STUDY OF INFLUENCING PARAMETERS

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CHAPTER 4. TIME DOMAIN REFLECTOMETRY MEASUREMENTS OF OIL SANDS TAILINGS WATER CONTENT: A STUDY OF INFLUENCING PARAMETERS

ABSTRACT

Temperature, solute, texture, and thixotropic effects on time domain reflectometry (TDR) measurements of water content in oil sands tailings are investigated. Results indicate that TDR water content measurements are influenced by temperature, residual bitumen, and percent clay in the tailings. A correction of 0.03–0.10/ °C must be applied to the apparent dielectric constant (Ka) to account for the effect of temperature. The Ka-volumetric water content relationships of slurries differ significantly from the commonly used Topp calibration equation. The age of the tailings and the addition of phosphogypsum did not influence TDR water content measurements.

1. INTRODUCTION

Oil sands bitumen extraction in northern Alberta produces large volumes of extraction tailings, a warm aqueous mixture of sand, silt, clay, residual bitumen, and naphtha at a pH of 8–9 (Chalaturnyk, Scott, & Ozum, 2002). The extraction process involves the use of hot water, steam, and caustic soda (NaOH) to liberate bitumen from oil sands ore. In conventional tailings disposal, the tailings are discharged directly to tailing ponds where the coarse particles separate to form beaches and dikes, and the remaining fines form a thin slurry (6–10% solids) and are carried to ponds. Improved tailings disposal methods further process tailings in a hydrocyclone and thickener before discharging to tailings ponds. The

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hydrocyclone recovers residual bitumen and separates the coarse and fine portions of the tailings. The fine portion of the tailings is then processed in a thickener to increase its solids content and recover warm extraction waters.

The fine portion of tailings generally exhibits a slow rate of consolidation and is a prime concern to the management of mining operations. Cost effective, fast, and real-time tailings water content measurements are needed to properly understand the sedimentation/consolidation characteristics of the tailings; to evaluate long- and short-term disposal and reclamation options; and to identify when process modifications are needed in oil sands bitumen extraction plants or tailings treatment units.

Traditional methods such as percent dry mass, neutron probe, and γ-ray and X-ray probes are time consuming and expensive for measuring continuous water content profiles (Herkelrath, Hamburg, & Murphy, 1991). Time domain reflectometry (TDR) has been used quite extensively to measure the water content of soils in water resource, soil physics, agricultural, and geotechnical engineering professions (Benson & Bossher, 1999). TDR is an electromagnetic technique that measures the apparent dielectric constant (Ka) of soil via the travel time of an electromagnetic wave within the soil. The technique is non-destructive, cost effective, fast, easily automatable, and sufficiently accurate for short- or long-term water content monitoring (Herkelrath et al., 1991; Benson & Bosscher, 1999). The strong contrast in the apparent dielectric constant between water and soil solids makes TDR a viable method for water content measurements (Topp, Davis, & Annan, 1980; Benson & Bosscher, 1999). The Ka of water is

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approximately 81 (at 20 °C), whereas soil solids vary in value from 3 to 7 (Topp et al., 1980; Drnevich, Ashmawy, Yu, & Sallam, 2005); it is this contrast that permits the relative determination of solids and water content.

Time domain reflectometry can have important applications in the oil sands industry for both field and laboratory measurements. In the field, the temporal and spatial variations in water content in tailings ponds and disposal pits can be monitored continuously by installing TDR probes at different depths and locations. Installing TDR probes at strategic locations along extraction tailings streams facilitates monitoring of the variability in water content in the extraction tailings. The solids content of cyclone overflow, cyclone underflow, and thickener underflow tailings (TUT) can be monitored and controlled by use of TDR probes installed at the intake and discharge points of these tailings treatment units. Probes installed at different depths and locations in in-situ (field trial) tests can be used for fast and continuous water content measurements. Because water content can be related to shear strength and degree of consolidation, TDR measured water content can be used to indirectly monitor the progress of consolidation and the development of shear strength in storage ponds and disposal pits. In the laboratory, TDR can be used to monitor the water content profile of tailings during sedimentation and self-weight consolidation tests (e.g., settling column and centrifuge tests) for a better understanding of the settling behaviour of tailings and for deriving consolidation parameters from the self-weight consolidation tests.

The composition of oil sands tailings varies with the quality of ore and the extraction method and its efficiency (FTFC, 1995). Tailings temperature varies

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depending on the age, location, and depth within storage ponds. Oil sands tailings are known to be a thixotropic material and they contain residual bitumen. Several types of chemicals are used to improve the dewatering and segregation characteristics of tailings (Matthews, Shaw, Mackinnon, & Cuddy, 2002). The presence of residual bitumen, the addition of solute, and variations in composition and temperature can affect TDR measurements of water content. Because of the important potential application of TDR in the oil sands industry and the variability of tailings composition and temperature, the study reported in this paper focuses on examining these influences on the measurement of water content in oil sands tailings. The objectives of the study are to define and examine the Ka- water content relationship in oil sands fines and fines-sand mixture tailings and to investigate the effect of tailings texture, residual bitumen, temperature, thixotropy, and the addition of solutes on TDR water content measurements. Identifying and quantifying the influential parameters can broaden the use of TDR for measuring the water content of oil sands tailings both in laboratory and field applications.

2. METHODS

2.1. Description of materials

Oil sands fines tailings from Albian Sands Energy Inc., commercially available kaolinite, and Devon silt were used to study the effect of soil texture on TDR water content measurements. The Albian tailings are

- mature fine tailings (MFT) from the Muskeg River mine tailings pond collected at depths of 7.5 m (Albian_7.5) and 15 m (Albian_15);

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• Albian TUT; and

• fines-sand mixtures with sand contents of 50% (AL_50) and 70% (AL_70).

The Muskeg River mine tailings pond is located approximately 75 km north of Fort McMurray in northern Alberta. The fines-sand mixtures were prepared by mixing Albian beach sand with Albian_15. The beach sand is the coarse portion of tailings that segregated in discharged tailings in Muskeg River mine tailings pond. Devon silt and commercially available pulverized kaolinite mixed with deionized water were used to study TDR water content measurements of slurries with no residual bitumen for comparison with oil sands tailings containing residual bitumen. Silt-rich and clay-rich fine tailings were prepared using Albian_15 to study the influence of soil texture on TDR water content measurements. The silt-rich and clay-rich MFT specimens were prepared by diluting Albian_15 to 5% solids and letting the slurry settle and form layers of material with different compositions; the top portion was clay-rich sediment whereas the middle layer yielded silt-rich fine tailings. The physical characteristics of the materials are summarized in Table 1. Fines and fines-sand mixture oil sands tailings equilibrated at temperatures of 15–75 °C were used to study the effect of temperature on TDR water content measurements. Albian_7.5 and Albian_15 were used to study the effect of thixotropy, and TUT and AL_70 were used to study the effect of the addition of phosphogypsum (PG).

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Table 1. Characteristics of materials

Material	Bitumen (%)	Sand (%)	Silt (%)	Clay (%)
TUT	3.5	35	30	35
Clay rich MFT	2.8	2	44	54
Silt rich MFT	2.5	5	55	40
Kaolinite	0.0	2	36	62
Albian_15	7.0	9	49	42
Albian_7.5	1.0	1	42	57
Devon silt	0.0	20	55	25
AL_50	3.0	50	27	23
AL _70	2.2	70	16	14

2.2. Time domain reflectometry measuring principle

The TDR measurement principle is based on generating fast time pulses that propagate along coaxial cables to a TDR probe in the soil (Benson & Bosscher, 1999). Due to the difference in the impedance characteristics of the metallic TDR probe and the soil, waveforms are reflected along the cable to the analyzer as illustrated in Figure 1; the first inflection appears when the pulse from the metallic probe makes contact with the soil and the second inflection occurs when the signal travels back from the soil to the metallic probe (O'Connor & Dowding, 1999). The Ka of the soil/slurry can then be determined using the apparent distance between the inflection points (La) and the physical length of the TDR probe (L; Figure 1, equation 1). The water content of a sample is subsequently derived using the soil-specific or "universal" calibration equation of Ka and water content of soil (equation 2; Benson & Bosscher, 1999; Topp et al., 1980).

$$Ka = (\frac{La}{L})^2 \qquad (1)$$

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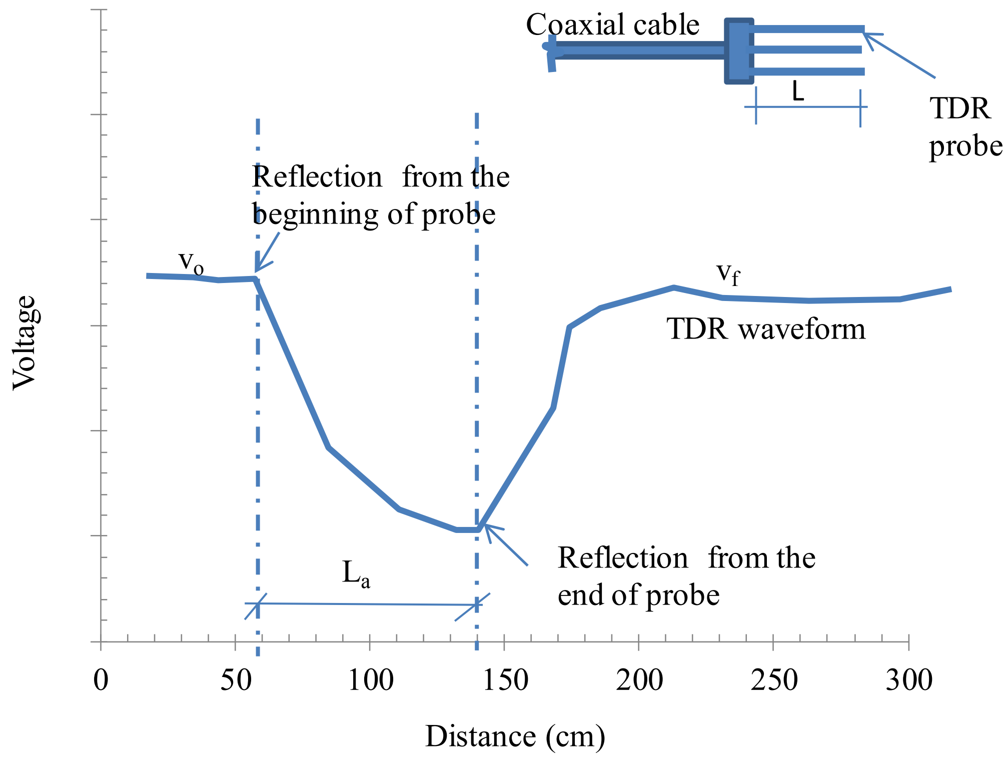

Figure 1. The TDR probe and waveform (modified from Benson and Bosscher, 1999).

2.3. Time domain reflectometry components

The components of the TDR measuring system used in this study are shown in Figure 2 (Campbell Scientific Inc., TDR100 Time-Domain Reflectometry systems). The TDR device includes a reflectometer, a TDR probe (rods), coaxial cable, a multiplexer, a data processor, and a data logger (Figure 2). The TDR probe (rods/waveguide) consists of three metal rods used to measure the Ka when inserted into slurry/soils. The reflectometer generates the pulses and the multiplexer is used to monitor multiple probes using single reflectometry (Benson

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& Bosscher, 1999). The RS-232 ports were used to transfer data to a desktop computer.

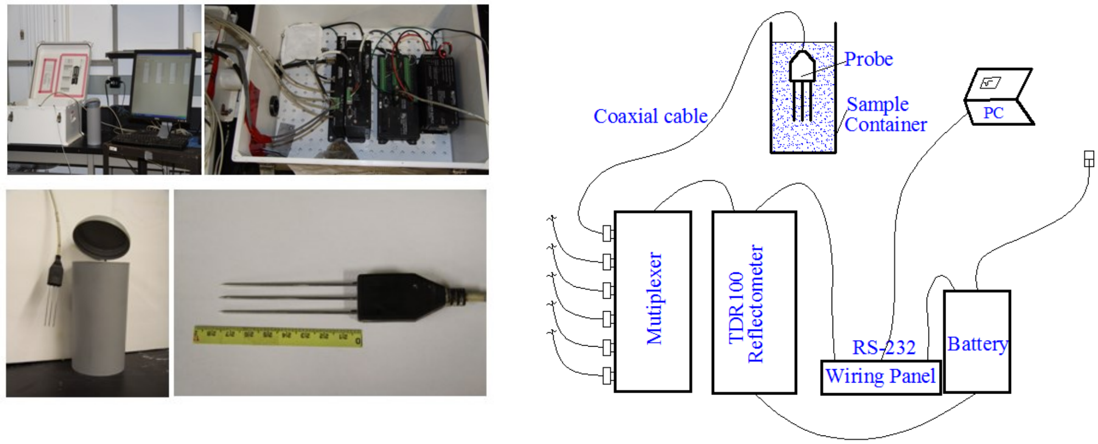

Figure 2. Photographs of TDR components and schematic setup of soil moisture measurement for the TDR technique

3. SOIL/SLURRY TEXTURE EFFECT

Topp et al. (1980) established an empirical relationship between Ka and volumetric water content of soil (equation 2), which set the foundation for the use of TDR for soil water content measurements. The equation was derived from tests conducted on four types of agricultural soils (sandy loam to heavy clay) and glass beads. The equation is considered “universal” and was later adapted by the ASTM D 6565 (2005) standard. Following Topp’s equation, different forms of calibration equations have been proposed based either on tests conducted using different materials or on the principles of mixing the Ka of air, water, and solids according to their volume proportion. For example, based on tests conducted on different types of soils, Herkelrath et al. (1991), Ledieu, de Ridder, de Clerck, and Dautrebande (1986), and Nadler, Dasberg, and Lapid (1991) proposed different

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forms of calibration equations. Mixing formulas were for example suggested by Dobson, Ulaby, Hallikainen, and El-Rayes (1985), Roth, Schulin, Fluhler, and Attinger (1990), and Whalley (1993). The mixing law suggested by Roth et al. (1990), based on three phases (water, air, and solids) and the assumption of no interaction between water and soil, is given in equation 3. Wright, Yoder, Rainwater, and Drumm (2001) summarize some of the calibration equations proposed by different researchers.

$$\theta_v = 4.3x10^{-6} Ka^3 - 5.5x10^{-4} Ka^2 + 2.92x10^{-2} Ka - 5.3x10^{-2} \quad (2)$$

where θ_v is the volumetric water content (the ratio of volume of water to total volume of soil) and Ka is the apparent dielectric constant

$$Ka = [\theta_v K_W^2 + (1-n)K_s^\beta + (n-\theta_v)K_{air}^\beta)^{1/\beta} \quad (3)$$

where K_a is the apparent dielectric constant; θ_v is the volumetric water content (the ratio of volume of water to total volume); n is the soil porosity; K_w, K_s, and K_{air} are dielectric constants of water, soil solids, and air, respectively; and β is a geometric factor that depends on the spatial arrangement of the mixture and its orientation in the electric field.

Even though calibration equations are available in the literature, most are based on much lower water content than is common in oil sands tailings. The equation proposed by Topp et al. (1980), for example, is limited to a volumetric water

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content of less than 53% (solids content greater than approximately 68%) and most of their soil samples were less than 40% volumetric water content (solids content greater than approximately 79%). Many researchers (e.g., Jacobsen & Schjønning, 1993; Ponizovsky, Chudinova, & Pachepsky, 1999; Drnevich et al., 2005; Y u & Drnevich, 2005) have evaluated different forms of the calibration equation, but their studies were also limited to a volumetric water content of 50% or less. Previous studies reported extensively in the literature concentrated on soils with volumetric water content less than 50% because TDR was used more often in geotechnical earth works (e.g., engineered landfill) and agricultural soil science professions, where partially saturated materials are common.

The accuracy of TDR measurements depends on the calibration equation (Ka-water content relationship) and it is important to derive soil-specific calibrations or use a calibration equation that best describes the materials being studied (Gong, Cao, & Sun, 2003; Yu & Drnevich, 2005). The objective of the study in this research is to evaluate the suitability of calibration equations suggested in literature for oil sands tailings and/or to propose calibration equations that best describe the Ka-water content of oil sands tailings. The effects of soils texture, solute concentration, residual bitumen, and temperature on the calibration equation are also addressed in the investigation.

The calibration procedure consists of preparing nonsegregated samples at different initial solids content and measuring their Ka by fully inserting the TDR probes into the samples. Materials with initial solids content of 15–78% were used in the investigation. Nine types of material were used (Table 1). For each

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material, 6–14 samples were prepared at different solids content. For each sample, 6–9 TDR measurements were taken to investigate the repeatability and reliability of the TDR readings. The averages of the TDR readings were used to correlate the Ka to the water and solids contents of the samples.

Three rod metal TDR probes were used for the tests (Campbell Scientific Inc CS640 model). The free length of the TDR probes, the length of the probe that has direct contact with the surrounding soils, was 75 mm. The rods were 1.6 mm in diameter and spaced 8 mm apart. The spacing and the radius of the rod fulfill the Knight (1992) recommendation that the ratio of the radius of the rod to the spacing between the inner rods should be greater than 0.1 and the radius of the rod should be as large as the average pore size of the material.

Samples for calibration tests were contained in PVC cylinders 205 mm in height and 96 mm in diameter. According to Topp and Davis (1985), the sensitive region of the TDR probe is a cylindrical surface surrounding the probe with a diameter 1.4 times the spacing between the rods. The area just beyond the tip of the probe does not affect TDR measurements (Baker & Lascano, 1989). The size of the container used for the tests was greater than the size of the influence zone; the container diameter was 12 times the spacing of the rods and the height of the container was approximately three times the length of the probe. TDR readings were taken by fully inserting the probe into the sample in a way that minimized air gaps and the boundary effects of the soil containers. The probes are extremely sensitive to the area immediately surrounding the probe and the presence of air

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along the rods causes a significant underestimate of the Ka of the material (ASTM D 6565, 2005).

Measurements of the Ka-volumetric water content relationship of samples used in the study and the calibration equation proposed by Topp et al. (1980) are shown in Figure 3. The results indicate that the Ka-volumetric water content relationship of slurry/soft soil deviates significantly from the widely used Topp et al. (1980) equation at volumetric water content greater than 45% (solids content less than approximately 75%).

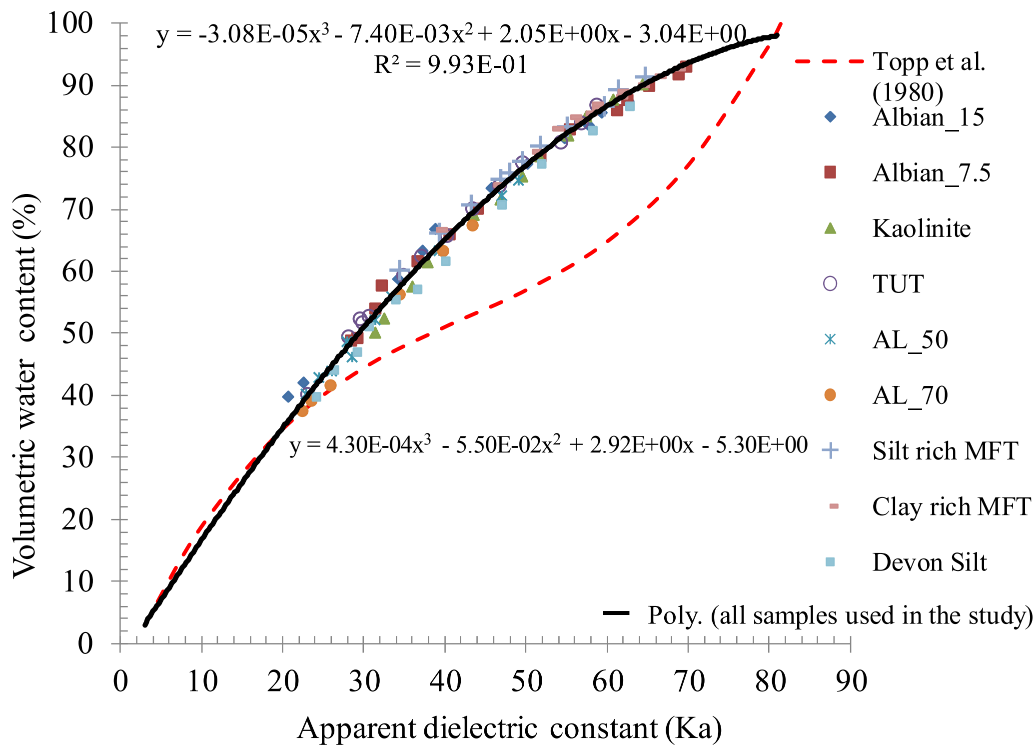

Figure 3. Apparent dielectric constant–volumetric water content relationship for all materials used in the study.

The use of Topp's calibration equation for predicting the volumetric water content of tailings would result in values as much as 28% lower than the actual water

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content (Figure 4). The error increases with an increase in volumetric water content of the samples, but tends to decrease for volumetric water content above 83% (solids content of less than approximately 32%), as shown in Figure 4. The decrease in error for volumetric water content greater than 83% occurs because Topp's equation is constrained to pass through the Ka of water (81.5, 100% water content), though the volumetric water content of their soil samples was less than 53% (greater than approximately 68% solids).

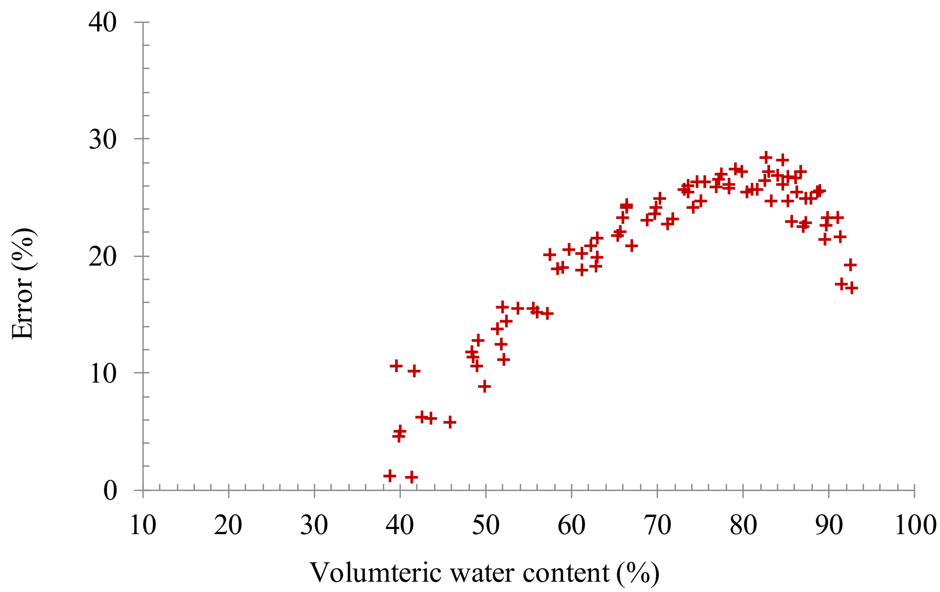

Figure 4. Measured relative error for the Topp et al. (1980) equation for calculating the volumetric water content of slurries and soft soils.

Whalley (1993) and Herkelrath et al. (1991) suggested a linear form for the calibration equation that relates the volumetric water content to the square root of the Ka of the soil (√Ka; equation 4). The constants a and b in equation 4 are derived from regression analyses of laboratory test results, though in general, constants a and b are approximately 12 and 18, respectively. The linear form of

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the calibration equation gives the same results as Topp's polynomial equation when a = 11.81 and b = 18.41 (Yu, Warrick, Conklin, Young, & Zreda, 1997). Theoretical investigations by Ledieu et al. (1986) and Herkelrath et al. (1991) suggest that the calibration equation describing the relationship between volumetric water content and the travel time should be linear. The results in Figure 5 indicate that linear forms of the calibration equation are applicable for the materials used in this study but with the constants a = 15.6 and b = 34.1, significantly different from the values reported in literature. The results indicate that the constants a and b differ between high and low water content materials.

$$\theta_v = a\sqrt{K_a} - b \qquad (4)$$

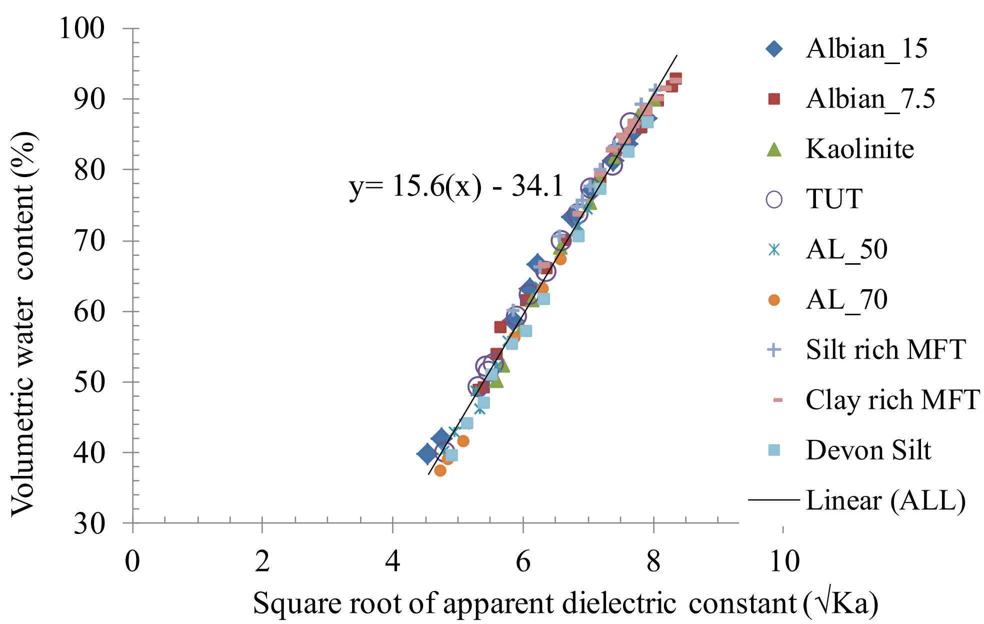

Figure 5. Square root of apparent dielectric constant versus volumetric water content relationship

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A closer look at the Ka-volumetric water content of the materials in Figure 3 indicates that the relationship depends on the texture of the material. At a given volumetric water content, high clay and/or high bitumen materials tend to have a lower Ka than high sand to fines ratio oil sands tailings or nonbitumen materials (Devon silt and kaolinite). AL_15 is high in bitumen whereas AL_7.5 is clay-rich oil sands tailings—both have lower Ka values than the high sand content oil sands tailings (AL_70 and AL_50). The Ka is a measure of the ease with which molecules can be polarized and oriented in an electric field (O'Connor & Dowding, 1999). The presence of residual bitumen in the fines and the diffuse double layer near the clay surface may limit the orientation and polarization of these molecules, leading to a lower Ka for high clay and/or high bitumen content tailings. The coating and bonding of bitumen on soil solids may affect the interaction of water with soil particle surfaces, leading to a lower Ka compared to the value of the dielectric constant for bitumen. The Ka of bitumen is 2.7 at 25 °C (Read & Whiteoak, 2003), close to the value for soils solids.

The dependency of the calibration equations on soil type is consistent with the findings of Driksen and Dasberg (1993) and Bohl and Roth (1994). Because the Ka of soil is a function of particle-specific surface, particle shape, and the interaction between the soil surface and water, TDR water content is soil-type dependent (Driksen & Dasberg, 1993). Based on tests conducted on 34 samples, Bohl and Roth (1994) concluded that the Ka versus water content relationship varies over a wide range depending on the soil type. O'Connor and Dowding

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(1999) indicate that there is no universal calibration equation that can be applied for all materials to give an absolute measurement of water content.

For geotechnical applications in the oil sands industry, the Ka is better correlated with the gravimetric water or solids content than the volumetric water content of soil/slurry. The Ka versus solids content relationship of the oil sands tailings is presented in Figure 6. The solids content (S) of the tailings can be related using apparent dielectric constant with a linear equation, but the slope and intercept of the equation depends of the texture of tailings.

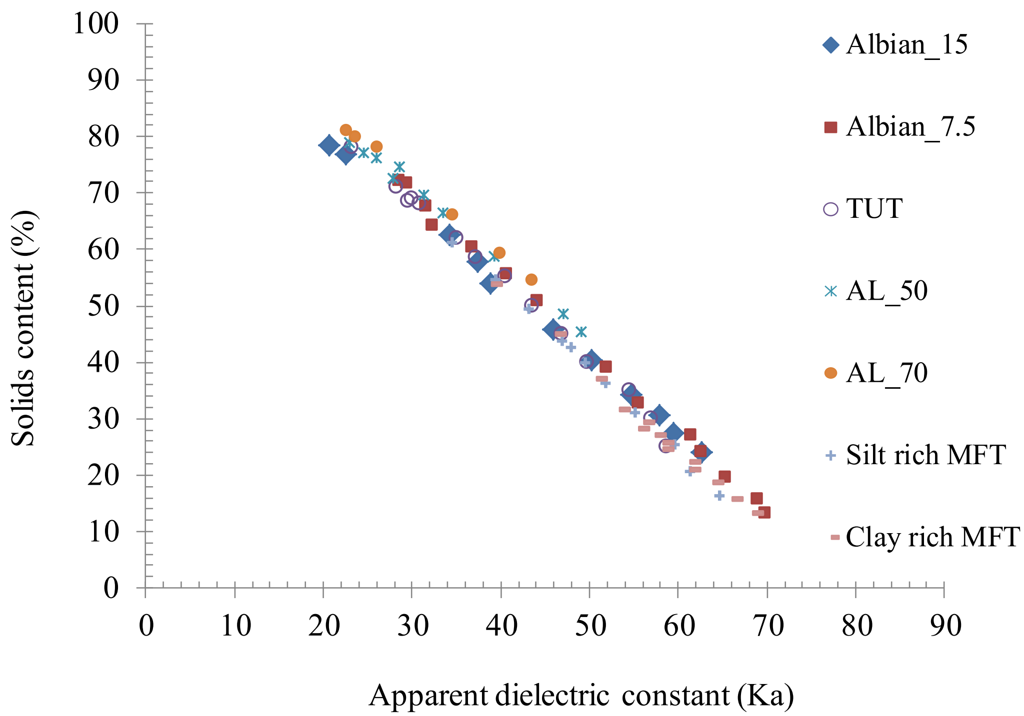

Figure 6. Apparent dielectric constant–solids content relationship of oil sands tailings

The repeatability of TDR measurements at different solids content was evaluated (Figure 7). The standard deviation for solids content measurements from repeated

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TDR measurements is less than 0.6%, but the standard deviation in TDR solids content measurements tends to increase to 1% when the solids content of the tailings is less than 25%.

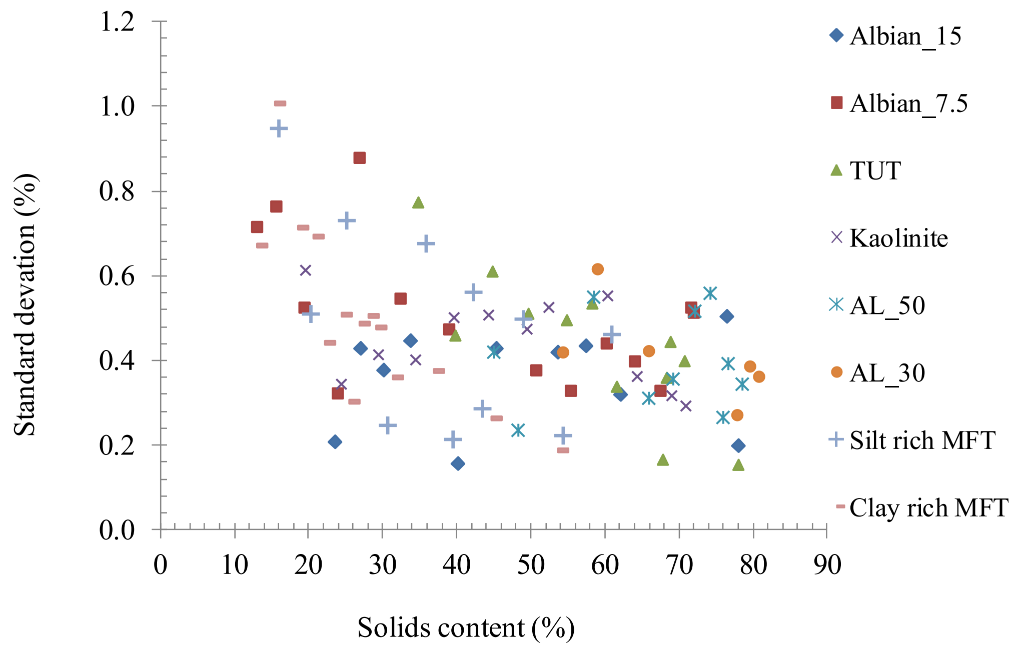

Figure 7. Standard deviation in solids content measurement using TDR.

4. TEMPERATURE EFFECT

Bitumen extraction in the oil sands industry uses a hot water–based extraction process, whereby the bitumen is extracted from the oil sands ore using water at temperatures close to 80 °C (FTFC, 1995). The temperature of the resulting tailings is greater than the surrounding ambient temperature. Temperatures in tailing ponds, extraction tailings streams, thickener underflow, and cyclone underflow streams vary significantly. Tailings temperature also varies depending on the stage of extraction/tailings treatment, depth within the pond, tailings age,

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and changes in the surrounding temperature. Because tailings temperature varies significantly in the field, it is important to investigate the effect of temperature on the TDR water content measurements, so that the TDR can be used under varying temperatures for measuring the water content of tailings.

The effect of temperature on TDR water content measurements of oil sands tailings was investigated by varying temperature in the tailings from 15 to 75 °C. Watertight containers were filled with tailings of different compositions and placed in a bath (Fisher Scientific refrigerated and heated bath) filled with a mixture of laboratory grade ethylene glycol and filtered tap water. The top surface of the fluid was covered by hollow plastic balls (38 mm diameter) and the external surfaces of the unit were covered with polystyrene to insulate the reservoir from temperature losses. The schematic of the test setup is shown in Figure 8. After letting the samples equilibrate to the surrounding liquid temperature, the Ka and temperature of the tailings were measured. Five types of oil sands tailings (TUT, Albian_15, Albian_7.5, AL_50, and AL_70) were used to study the effect of temperature on TDR water content measurements.

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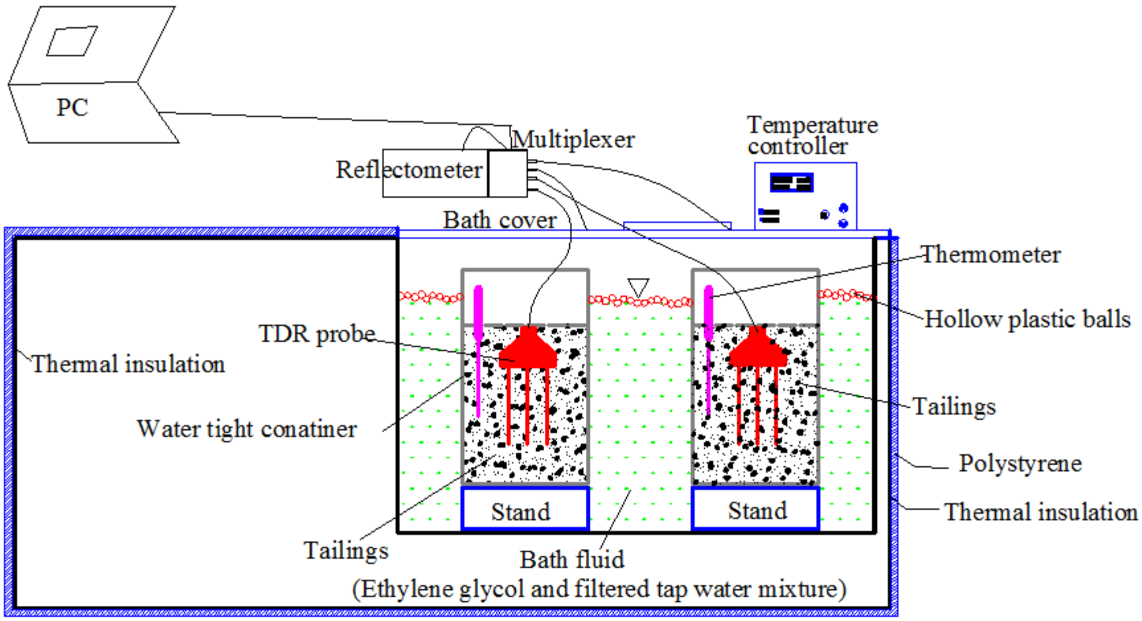

Figure 8. Schematic drawings of the test setup for studying the temperature effect on TDR water content measurements.

The effects of temperature on TDR water content are shown in Figures 9 and 10. Figure 9 shows the Ka of TUT at different test temperatures. Figure 10 shows the Ka as a function of temperature for four types of tailings. The Ka of the tailings decreased with an increase in temperature, indicating that TDR water content measurements are temperature dependent. The Ka decreased at a rate of 0.03–0.1/°C, depending on the solids content of the tailings. Low solids content tailings tended to be more affected by the temperature than high solids content tailings. The results indicate that the effect of temperature is not significant especially in laboratory test condition where there is a small change in temperature variation.

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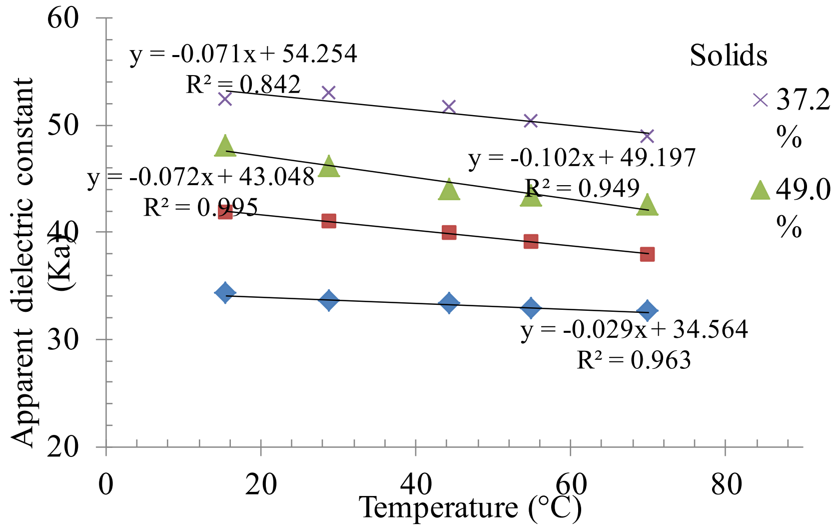

Figure 9. Apparent dielectric constants of TUT at different temperatures.

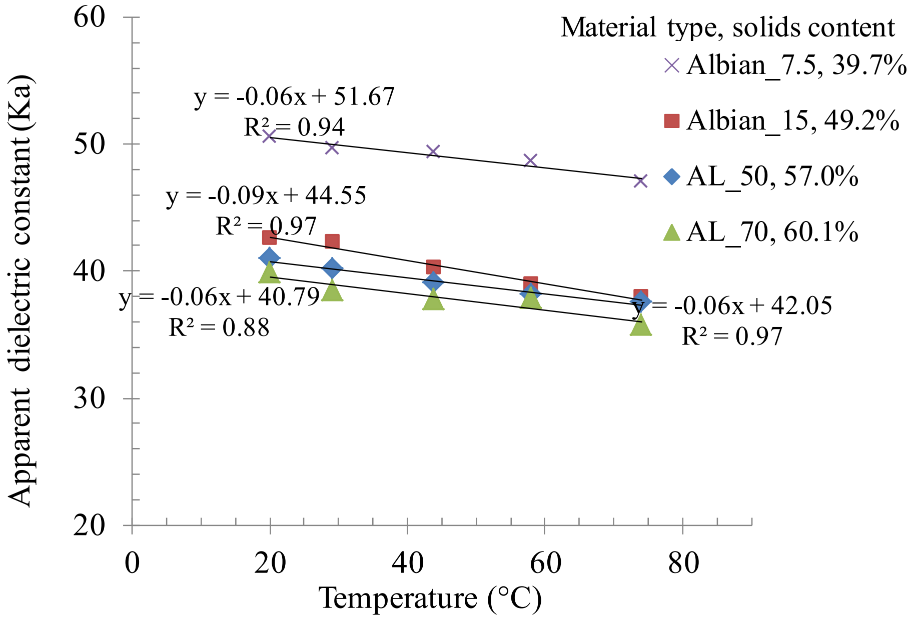

Figure 10. Apparent dielectric constants of tailings at different temperatures.

There is no consensus in the literature regarding the effect of temperature on TDR water content measurements, not only in terms of magnitude but also in terms of the sign (i.e., Ka increases or decreases with an increase in temperature; O'Connor & Dowding, 1999). Pepin, Livingston, and Hook (1995), Gong et al.

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(2003), and Schanz, Baille, and Tuan (2011) indicate that temperature has an effect on the Ka-water content relationship of soils, whereas Topp et al. (1980) and Halbertsma, Van den Elsen, Bohl, and Skierucha (1995) indicate that temperature does not have a significant effect on the Ka of fine-grained soils. Van Loon, Smulders, van den Berg, and van Haneghem (1995) suggest that the Ka decreases with an increase in temperature at high water content, but increases with increasing temperature at low water content.

According to equation 5, the Ka of water decreases with an increase in temperature (Weast, Astle, & Beyer, 1986); however, the Ka values of solids particles and air are nearly constant over a wide range of temperatures (Roth et al., 1990; Weast et al., 1986). This indicates that the effects of temperature on the tailings are related to the dependence of the Ka of water on temperature and the effect of temperature on water-solids interactions.

The effect of temperature on TDR measurements also depends on the water content and the type of materials (Schanz et al., 2011). The effect of temperature is more complicated for fine-grained soils than coarse-grained soils (Gong et al., 2003; Schanz et al., 2011). This is due to the presence of absorbed water on clay surfaces and the fact that temperature has a different effect on the Ka of free and absorbed water. With an increase in temperature, the free water within the soil decreases the Ka while bound water increases the Ka of the soil (Schanz et al., 2011). The results in Figures 9 and 10 indicate that the effect of temperature on tailings is similar to that on water. This can be attributed to the ratio of bound to free water being small in high water content materials; thus the behaviour of the

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tailings depends more on the temperature effect on the free water in the pores of the tailings.

$$K_w = 78.54\left[1-4.579x10^{-3}(t-25)+1.19x10^{-5}(t-25)2-2.8x10^{-8}(t-25)^3\right] \quad (5)$$

where Kw is the apparent dielectric constant of water and t is the temperature in degree centigrade.

5. COAGULANT/FLOCCULENT

The oil sands industry uses different types of coagulant/flocculent to improve the dewatering and segregation characteristics of oil sands tailings. In oil sands composite tailings, gypsum ($CaSO_4$-$2H_2O$), lime (CaO, $Ca(OH)_2$), acid-lime (H_2SO4-CaO), sulphuric acid (H_2SO4), sodium aluminate ($Na_2Al_2O_3$), alum (48% $Al_2(SO4)_3$-$14.3H_2O$), lime-CO_2, CO_2, and organic polymers (polyacrylamides) have been tested to improve the segregation and dewatering behaviour (Matthews et al., 2002). Gypsum is a commonly used coagulant to produce nonsegregating fines-sand mixtures of tailings because of its effectiveness, ready availability, and ease of handling (Matthews et al., 2002). The Ka of free water is close to 81, whereas the Ka of absorbed water varies from 6 to 30, depending on how closely the water is bound to the clay surface (Gong et al., 2003). If the addition of coagulant/flocculent changes the ratio of absorbed to free water, the TDR water content measurements could be affected by the amount and type of solutes added to promote water release from the tailings. To examine the effect of gypsum on TDR water content measurements, the Ka values of TUT and AL_70 (fines-sand mixture of 70% sand) with the addition of various amounts of phosphogypsum (PG) were examined. TUT prepared at a solids

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content of 33% and AL_70 prepared at a solids content of 62% were examined by varying the PG concentration while keeping the temperature and solids content of the samples the same. PG addition from 0 to 5000 mg/kg of tailings was used in the investigation. The Ka of TUT at different solids content with PG addition (900 mg/kg) and without PG addition was also investigated to address the effect of PG addition on TDR water content measurements.

Figure 11 presents the Ka of TUT at 33% solids content and AL_70 at 62% solids content with different PG dosages. Figure 12 shows the Ka-solids content relationship of TUT with and without the addition of PG. The addition of PG up to 5000 mg/kg does not affect the Ka of the tailings, indicating that the addition of PG would not affect tailings water content measurements using TDR. The reason the TDR water content is not affected by the addition of PG may be that the amount of PG added in composite tailings is too small to affect the TDR water content measurements. At low solute concentrations, solutes do not affect the TDR water content measurements (Topp et al., 1980). The results in Figures 11 and 12 also indicate that the addition of PG does not affect the ratio/distribution of absorbed and free water in tailings. Soil electrical conductivity affects TDR measurements as the ions presence in the soil solution provides a path for electrical conduction between TDR probe rods (Mojid et al., 2003). The average electrical conductivity of the oil sands tailing is 0.24 S/m (Guo, 2012). The calibration curve of commercial kaolinite mixed with de-ionized is close to the calibration equation of oil sand tailings indicating the concentration of ions in the samples are low to affect the TDR solids content measurements. Furthermore, the

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addition of solute (gypsum) does not change the calibration equation. It also indicate that, the concentration of ions even after adding gypsum is too low to affect the solids content measurements for a given probe length and TDR system.

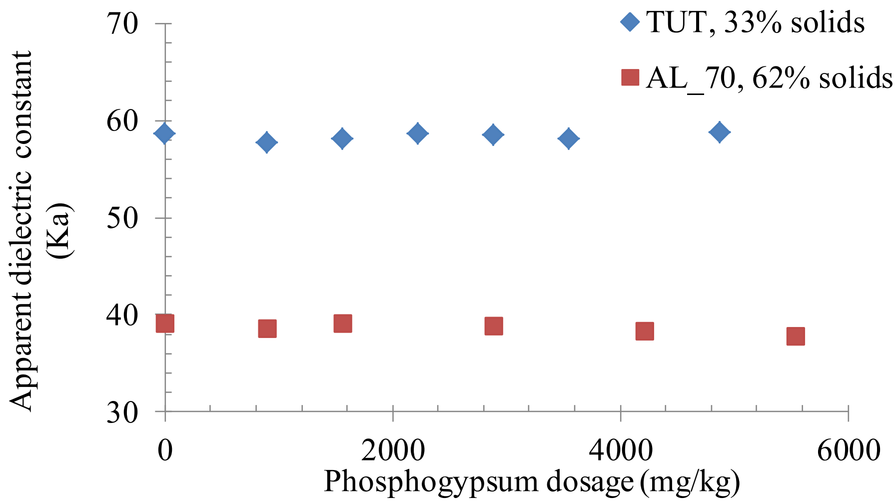

Figure 11.Apparent dielectric constant of TUT and AL_70 tailings at different PG dosages

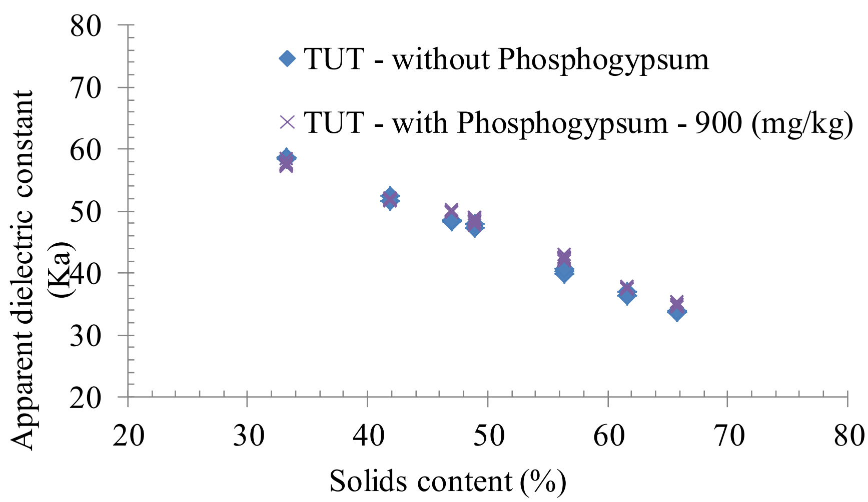

Figure 12. Apparent dielectric constant of TUT at different solids constant with 900 mg/kg PG and without PG addition.

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6. THIXOTROPIC CONSIDERATIONS

In laboratory and field applications, TDR can be used to measure the water content of tailings over long periods of time. Oil sands fines and fines-sand mixture tailings are thixotropic materials (Suthaker & Scott, 1997; Miller, Scott, & Sego, 2011; Sorta, Sego, & Wilson, 2012). To examine the effect of thixotropy on TDR measurements, Albian_7.5 and Albian_15 samples prepared at solids contents of 39.5% and 50.6%, respectively, were placed in Plexiglas cylinders 100 mm in internal diameter to a depth of 820–850 mm (Figure 13). The water content of the tailings in the Plexiglas cylinder was monitored using TDR for 45 days. The tests were designed to monitor the water content of the tailings by keeping the solids content of the sample constant, so that any change in TDR measurements would be associated with the time/age effect. The initial solids content and the height of the samples were chosen to increase the length of the drainage path and minimize the change in water content due to settling within the investigation period. Mature oil sand fine tailings are known to have extraordinarily slow dewatering rates and the change in volume at these solids contents is expected to be small given the short investigation period.

The Ka of Albian_7.5 and Albian_15 as a function of time is shown in Figure 14. The results indicate that the Ka of the tailings at different ages is more or less constant; indicating that the age of tailings does not affect the TDR water content measurements of tailings.

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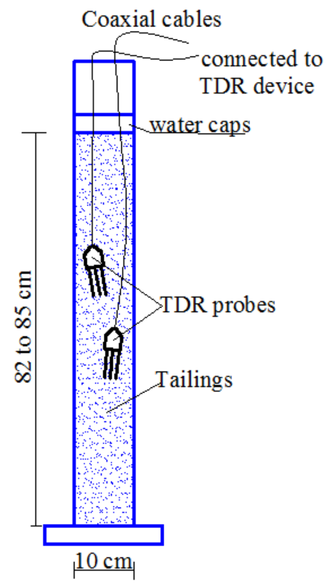
(a)



(b)

Figure 13. a) Photograph of test setup to study thixotropic effect on TDR measurements; b) Schematic representation of tests setup shown in (a).

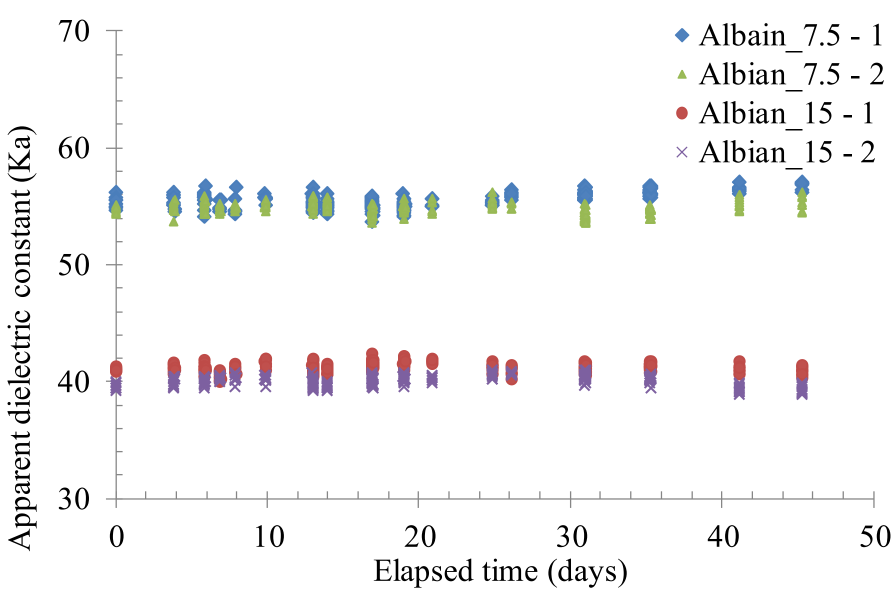


Figure 14. Apparent dielectric constant of Albian_7.5 and Albian_15 as function of time.

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7. CONCLUSIONS

Samples at various solids contents and fines contents were prepared to study the various factors that influence TDR measurements of water content. The results indicate that TDR can be used to measure the water content of oil sands tailings over a wide range of solids content. Detectable measurable inflections were observed over all ranges of solids content and for all materials used in the study. The TDR method was found to have good repeatability in measuring the water content of the tailings. The use of TDR avoids the inherent radiation hazards faced when using the X-ray and neutron methods and the method provides reliable direct results that minimize the cost of tailings sampling for water content monitoring. Site-specific calibration is an important element for the use of TDR and this paper highlights the parameters that could affect the calibration equations.

The study shows that the use of calibrations that were derived for very high solids content and unsaturated materials would result in a significant underestimation of water content when applied to very high water content materials. The percentage of clay and bitumen in tailings was also found to affect TDR water content measurements. The temperature of tailings slightly affects the TDR water content measurements.. The results of tests conducted at different tailings ages indicate that the reflection of electromagnetic waves does not depend on the age of the samples and it can be concluded that TDR can be used for long-term monitoring of oil sands tailings water content without the need to correct for the age of the

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tailings. The addition of PG to tailings did not affect TDR water content measurements.

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CHATER 5. CENTRIFUGAL MODELLING OF OIL SANDS TAILINGS CONSOLIDATION

This paper is submitted to publication in International Journal of Physical Modelling in Geotechnics (IJPMG). It is presented here "as submitted" as part of this Ph.D. thesis as Chapter 5.

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CHATER 5. CENTRIFUGAL MODELLING OF OIL SANDS TAILINGS CONSOLIDATION

ABSTRACT

The self-weight consolidation of oil sands tailings and kaolinite slurry are modelled using a new geotechnical beam centrifuge located at the University of Alberta (GeoREF centrifuge). The centrifuge is used to create a prototype-effective stress regime in the model, and centrifuge tests are conducted at different initial compositions at acceleration levels of 40 to 100g. The objectives of the centrifuge tests are to study long-term consolidation behavior, derive consolidation parameters, verify modelling procedures, and evaluate displacement and density probe applications for centrifuge testing. The interface settlement, pore pressure, and solids content profiles of the consolidating materials are monitored in-flight. The use of time domain reflectometry (TDR) for solids content profile monitoring and a laser displacement sensor (LDS) for interface surface settling monitoring are evaluated. Large strain consolidation parameters determined from a large strain consolidation test (LSCT) apparatus and from in-flight monitoring of solids content and pore pressure are compared. The paper describes the modelling aspect as well as the instrumentation and monitoring of the centrifuge tests. The centrifuge results are presented, discussed, and compared with large strain numerical models using parameters from large strain consolidation testing.

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1. INTRODUCTION

Large volumes of fluid fine tailings (FFT) are produced during extraction of bitumen from oil sands deposits in northern Alberta. The bitumen extraction involves open-surface mining, ore conditioning, hot water and steam addition, settling, flotation, and aeration with a by-product of extraction tailings, which is a warm aqueous mixture of sand, silt, clay, residual bitumen and naphtha at a pH of 8-9 (Chalaturnyk et al., 2002). The extraction tailings are transported via pipelines and discharged into large fluid containments (tailing ponds). Upon deposition, mainly the coarse portions segregate and form beaches/dykes, while most of the fine particles (<45 μm) flow to the tailings ponds to form FFT. FFT is a high water content material composed of silt and clay particles with a small amount of residual bitumen. As of 2012, about 850 million m^3 of FFT is stored in tailings ponds, covering an area of 176 km^2 (Weber, 2013; Fair & Beier, 2012).

FFT has a very slow settling behavior and requires many years to fully consolidate. Physical, chemical or other tailings treatment technologies are required to improve the dewatering characteristics and dispose of the tailings in an environmentally acceptable manner in dedicated disposal areas. Studying the long-term consolidation behaviour of treated and/or untreated tailings is important to understand its consolidation behaviour and the effectiveness of tailings treatment options. This includes gaining knowledge of the rates and magnitude of self-weight consolidation in predicting the storage capacity of impoundments; the rate of clear water production; and the land reclamation and re-use options (FTFC, 1995; Eckert et al., 1996).

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This paper studies the long-term self-weight consolidation behaviour of oil sands tailings such as FFT, thickened and flocculated FFT-sand mixture tailings (thickened tailings [TT]) and FFT-sand mixture tailing (fine-sand mixture tailings [FSMT]) using a centrifuge modelling technique. The centrifuge is used because of the slow dewatering behaviour of the tailings (which may require several months or even years to complete) and the self-weight stress dissimilarity between models and prototypes in conventional tests (such as settling columns [standpipe] tests). The study also aims to verify the centrifuge modelling application for high water content materials and to develop an in-flight instrument so that the performance of tailings treated methods can be evaluated while using geotechnical beam centrifuge in the future. The objectives of the tests are also to examine the possibility of deriving large strain consolidation parameters (void ratio-effective stress and hydraulic conductivity-void ratio relationships) from centrifuge tests based on data collected during the centrifuge flight.

The centrifuge tests were conducted at various initial compositions and initial heights and gravity. The initial compositions of the materials were selected to be non-segregating material under high-gravity tests, based on a previous study (Sorta et al., 2012) conducted using these materials. The initial solids content of the tested materials varied from 37-75% and the initial height from 10-24 cm. Interface (slurry-water interface) settlement, solid contents and pore pressure profiles were monitored in-flight. Time domain reflectometry (TDR) for in-flight solids content measurement and laser displacement sensors (LDS) for tailings interface settlement monitoring were examined for centrifuge tests. Based on

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measured solids contents and pore pressure profiles, the tailings consolidation parameters were derived from centrifuge tests and compared with parameters derived from large strain consolidation tests (LSCT) (slurry consolidometer). The centrifuge tests results were compared with a large strain numerical model (FSConsol slurry consolidation program) prediction using LSCT consolidation parameters as inputs to this numerical model.

2. DESCRIPTION OF MATERIALS

The materials used for this study are oil sands tailings and Edgar Plastic Kaolin (EPK) clay. The oil sands tailings are from Albian Sands Energy Inc.: FFT (AL-7.5 and AL-15), flocculated thickened tailings of 50 and 60% fines (TT-50 and TT-60), and a mixture of FFT and beach sand (fines-sand mixture tailings, FSMT). The geotechnical properties of the materials are summarized in Table 1. The initial solids content of the materials are chosen to be higher than the solids content of the materials on the centrifuge segregation boundary.

Table 1. Descriptions and geotechnical properties of materials used in the study

Material Designation	Material Description	Bitumen (%)	LL (%)	PL (%)	Fines (%)	Clay (%)
Kaolinite	Edgar Plastic Kaolin (EPK) clay	0.0	52	31	98	61
AL-7.5	Albian FFT from 7.5m depth	1.0	53	26	99	57
AL-15	Albian FFT from 15m depth	7.0	40	22	91	38
TT-50	Thickened tailings, 50% fines	3.1	26	16	50	26
TT-60	Thickened tailings, 60% fines	3.3	30	17	60	31
FSMT	Fines and sand mixture tailings	1.5	17	16	20	10

LL = Liquid limit; PL=Plastic limit; bitumen content is defined as the mass of bitumen in the tailings relative to total solids mass; fines content is defined as particles less than 45 micrometer; and clay is particles less than 2 micrometers.

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3. CENTRIFUGE MODELLING PRINCIPLE AND SCALING LAWS

The centrifuge test is a model-sized experiment under the body force of self-weight. The centrifuge modelling principle is based on creating the same self-weight stress in the model as in a prototype by accelerating a model in a centrifuge N times Earth's gravitational acceleration (g). The same material is used in the model as in the prototype, but the model height is N times shorter. Due to shorter drainage lengths, consolidation in the model is much faster than in the prototype. Furthermore, the centrifuge model is easier to monitor and record soil response in, and is more economical and time-saving than prototype-type scale tests. Several researchers (e.g., Cargill & Ko, 1983; Croce et al., 1985) have derived various scaling laws between models and prototypes. Scaling laws are used to correctly model a prototype using the centrifuge or to interpret model results in relation to prototype behavior. Table 2 summarizes the theoretical scaling laws relevant to large strain consolidation modelling and derivation of consolidation parameters from centrifuge tests.

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Table 2. Summary of theoretical scaling laws relevant for self-weight consolidation modelling

Property	Model	Prototype
Length	1	N
Acceleration	N	1
Density	1	1
Time, consolidation	1	N^2
Time, creep	1	1
Settlement (deformation)	1	N
Strain	1	1
Strain rate	N^2	1
Pressure	1	1
Hydraulic gradient	1	1
Flow velocity	N	1
Hydraulic conductivity	N	1
Intrinsic permeability	1	1
Viscosity	1	1
Reynolds number	N	1

N is the ratio of prototype height to model height or the ratio of acceleration in centrifuge (a_m) to Earth gravitational acceleration (g).

4. DESCRIPTION OF CENTRIFUGE

The centrifuge tests were conducted using the GeoREF geotechnical beam centrifuge that is installed in the Natural Resources Engineering Facility (basement floor), University of Alberta, Canada. The centrifuge is a one-beam, 50 G-Tonne centrifuge of 2 m radius to the base of a swinging platform. The maximum payload capacity of the centrifuge is 935 kg-m, the maximum payload volume is 0.6 m wide x 0.8m length x 0.9 m height, and the maximum speed is

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281 rpm. The weight of the test package is balanced by adjusting the position of the counterweight on the opposite side of the arm. Fine balancing of the weight is achieved by transferring oil between chambers at opposite ends of the beam and using compressed air during the flight (TBS, 2012; Zambrano-Narvaez & Chalaturnyk, 2014). A strong axisymmetric metal tube of 0.49 m in diameter and 0.5 m in height is available to enclose the consolidation cell, transducers, and cameras. Two center cabinets are available near the center of the axis of rotation to place in-flight computers, TDR data loggers, and power supplies. The cabinets are designed to position instruments in a low-gravity environment. All safety-related machine functions such as speed, automatic balancing, drive overload protection, access interlocks, and start and stop sequences are controlled by the system, based on an industrial programmable logic controller (PLC). Signals, electric power, and fluid services are transferred on and off the beam rotor by means of rotary stack assemblies fitted to the bottom and top of the centrifuge shaft (TBS, 2012). A cooling system installed on the roof and on the floor is used to control the temperature of the centrifuge room. Three video cameras (two mounted on the wall of the centrifuge room and one on the centrifuge close to the center cabinets) monitor the safety of the centrifuge and the test package, and an accelerometer placed on the swinging platform is used to monitor the acceleration of the centrifuge. Figure 1 shows the general arrangement of the GeoREF centrifuge at rest (hanging position). Details of the centrifuge can be found in Zambrano-Narvaez and Chalaturnyk (2014).

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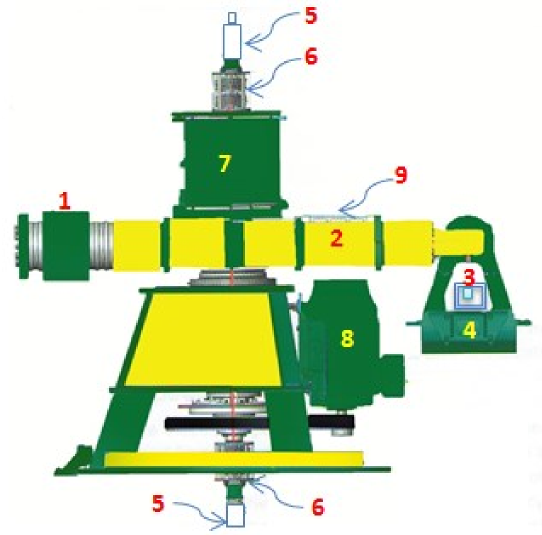

1- counter weight, 2- metal tube (beam), 3-test package, 4-swing platform, 5- rotary unions, 6- slipping rings, 7-center cabinet, 8-drive motor, 9-data acquisition system (DAS)

Figure 1. General arrangement of GeoREF geotechnical beam centrifuge, modified from TBS (2012)

5. SCOPE OF AND SETUP OF CENTRIFUGE TESTS

A total of 12 centrifuge tests were conducted at an acceleration level of 40 to 100g. Table 3 summarizes the types of centrifuge tests conducted, as well as the test designation, the initial compositions of tested materials, and the instrumentation of the model. All of the centrifuge tests were conducted at GeoREF except for CT001, which was conducted at the C-CORE centrifuge facility. CT002 was run to replicate CT001. CT003 and CT004 were conducted to check the integrity of the test package and the effect of high gravity on pore pressure and TDR transducers. CT005-CT0012 tests were conducted for modelling verification, modelling self-weight consolidation, and deriving consolidation parameters. In all of the tests, the centrifuge runs continuously, with no stopping or restarting. The flight duration of the tests depends on the material

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properties and acceleration level. CT001 and CT002 were run for nearly 8 hours, CT003 and CT004 were run for less than 1 hour, CT011 was run for close to 48 hours, and the remaining centrifuge tests were run continuously until excess pore pressure fully dissipated. All tests conducted on kaolinite and tailings were carried out under one-way drainage conditions, with drainage towards the top of the model. Interface settlement, pore pressure profiles, and solids content profiles at different elapsed times were monitored in-flight. In-flight cameras and a laser displacement sensor (LDS) for interface settlement, time domain reflectometry (TDR) for solids content profile, and miniature and standard-size pore pressure for pore pressure measurements were used. The temperature of the centrifuge chamber was monitored with a temperature probe positioned close to the motor. Additional temperature probe was used in CT010-CT012 tests for model temperature monitoring using probes close to the model. Figure 2a-c shows schematic drawings and pictures of consolidation Cell #2, transducers, and camera set-up positions in the swinging platform at the rest-position. The details of these in-flight measurements are described in the following sections.

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Table 3. Initial materials properties, acceleration level and instrumentation of centrifuge tests

Centrifuge Test code	Material Designation	Initial Solid (%)	Relative Acceleration	Initial Height (cm)	Flight Duration (hrs)	Instrumentation	Consol. Cell
CT001	AL-15	46.5	80	10.0	8	INS-1	Cell #1
CT002	AL-15	46.5	80	10.0	8	INS-2	Cell #1
CT003	Water	0	100	14.0	0.75	INS-3	Cell #2
CT004	AL-15	56.5	100	15.0	0.75	INS-3	Cell #2
CT005	Kaolinite	43.9	100	10.0	6.4	INS-3	Cell #2
CT006	Kaolinite	43.9	80	12.5	10.3	INS-3	Cell #2
CT007	Kaolinite	43.9	60	16.7	16.3	INS-3	Cell #2
CT008	TT-50	61.3	100	12.0	46.1	INS-3	Cell #2
CT009	FSMT	75.0	40	24.0	15.7	INS-3	Cell #2
CT010	AL-15	46.5	60	13.4	53.5	INS-4	Cell #2
CT011	AL-7.5	37.0	70	12.3	48.5	INS-4	Cell #2
CT012	TT-60	61.6	90	13.5	41.3	INS-4	Cell #2

Instrumentation: **INS-1** is one in-flight camera (Canon G7 camera); INS**-2** is two webcams; **INS-3** includes five miniature pore pressure transducers (MPPT), one standard laboratory size pore pressure transducer (SPPT), five TDR probes, one Imaging Development Systems (IDS) camera, one light scatter density probe (LSDP), and one webcam; **INS-4** includes five MPPT, one SSPT, five TDR probes, one temperature probe, two webcams, one IDS camera, one LSDP, and one laser displacement sensor(LDS).

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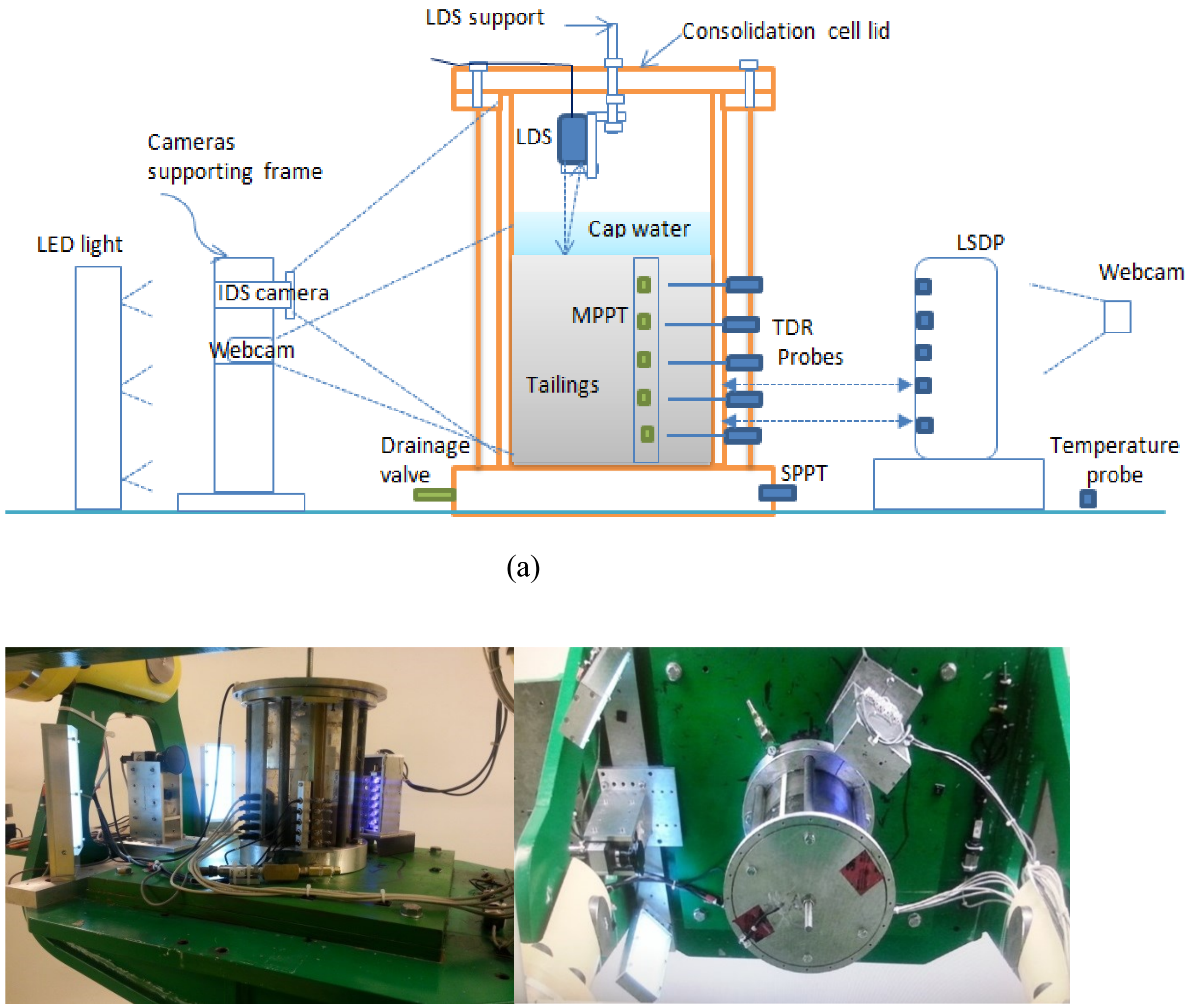

(a)

(b) (c)

Figure 2. (a) Schematic of the test setup, (b) Centrifuge test package setup, at rest position, (c) Centrifuge test package, in-flight position.

6. DESCRIPTION OF CENTRIFUGE CONSOLIDATION CELL

The consolidation cell for CT001 and CT002 is a Plexiglas cylinder of 250 mm internal diameter, 500 mm length and a wall thickness of 25 mm (Cell #1). The base plate for Cell #1 is made of a solid steel plate 12.5 mm thick. Cell #1 has no ports for pore pressure and solids content profile measurements. Centrifuge tests were conducted under one-way drainage and only monitored interface settlement

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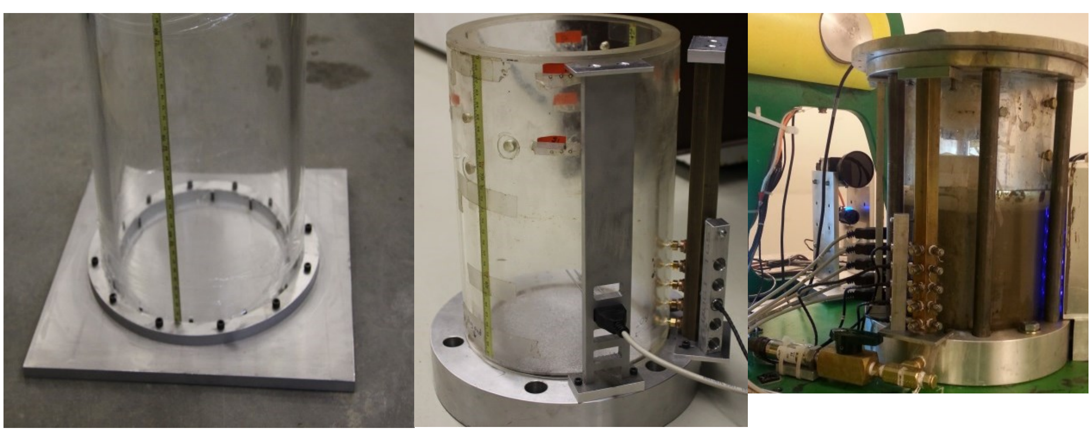
(Figure 3a). All other centrifuge tests were conducted using a Plexiglas cylinder 300 mm in height, 168 mm in internal diameter, and 19 mm in wall thickness (Cell #2) (Figure 3b-c). Cell #2 has five TDR probes and six pore pressure ports to measure solids contents and pore pressure profiles, respectively. The use of transparent Plexiglas in both Cell #1 and Cell #2 allows for observation of the changes in solid liquid interface at different elapsed times. The thicknesses of the Plexiglas cylinders were designed to resist high-gravity hoop stress and to minimize horizontal strain during consolidation. The base plate for Cell #2 is 50 mm thick and made of steel. It has drainage grooves and vertical/horizontal holes for pore pressure measurement at the bottom of the model and allowed for draining water from the consolidation cell. The cylinder and the base plate of Cell #2 are held together using six steel rods threaded at the ends. O-rings were used at the base of the cells to render them watertight. The top and base plates of Cell #2 have flanges that provide support both for the transducers and the lid of the consolidation cell.



(a) (b) (c)

Figure 3. (a) Consolidation Cell #1; (b) consolidation Cell #2, unassembled; (c) consolidation Cell #2 filled with tailings

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The diameters of Cell #1 and Cell #2 were chosen to minimize side-wall friction and to satisfy modelling criteria. Bloomquist's (1982) self-weight consolidation studies on Florida Phosphate clay indicate that side-wall friction effects are minimal for Plexiglas cylinders with diameters of 100 mm or more after performing tests in 50, 100 and 140 mm diameter containers at 60g. Furthermore, Sill's (1998) test results at Earth gravity indicate that the behaviour of materials in a 100 mm diameter standpipe was similar to that of larger diameter standpipes. Modelling criteria require a model's maximum width to be less than 20% of the centrifuge effective radius so that the effect of the lateral component of acceleration is minimal (Hird, 1974). The cell height of Cell #1 or Cell #2 is larger than the model height used for tests, the extra height enabling space for spillage protection, the water cup, and the LDS setup.

7. IN-FLIGHT MEASUREMENTS

7.1 Interface settlement measurement

Metric rulers with millimeter graduations attached on the external wall of the Plexiglas cylinder and in-flight cameras were used for interface settlement monitoring. The top surface of the cap water layer was also monitored to adjust the total stress associated with water lost through evaporation during the flight. The in-flight cameras are IDS camera (Imaging Development Systems digital industrial camera) and webcams. Two LED bar lights placed on the right and left sides of the cameras were used to provide uniform light around the model. Images taken at different elapsed times were received by the computer in the control

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room and used to plot the interface settlement as a function of elapsed time. The camera mounts have aluminum frames that can be positioned close to or far away from the model by moving the mount horizontally or vertically. Because the IDS camera has lockable connectors and lenses, the image quality was not affected by high gravity application; nevertheless, the webcam lens does need to be supported and locked in position. The application of LDS for tailings interface settlement monitoring in centrifuge tests was measured in CT011 and CT012 tests, the results of which are presented in section 14.

7.2. Pore pressure measurement

Five miniature pore pressure transducers (MPPTs) and one general purpose pore pressure transducer (SPPT) were utilized to measure pore pressure profiles during the centrifuge flight. The five MPPTs were installed along the model height spaced at a 2 cm vertical distance starting from 1.6 cm above the base (at 1.6, 3.6, 5.6, 7.6 and 9.6 cm above the base). The SPPT (Omega PPT-30 Psi) was installed at the bottom of the column. The MPPTs are from Durham Instruments (EPRB1-NU33-3.5B) and have high accuracy, minimal size and weight, and rugged all stainless steel construction that satisfies the requirements of pore pressure transducers for centrifuge testing. Druck-PDCR81 MPPT was commonly used for measuring pore pressure in centrifuge modelling. The product line of PDCR81 is discontinued and no longer available (http://www.proconsystems.com), and thus it was not possible to take advantage of the probe’s many years of experience in previous centrifuge testing.

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The MPPTs were not directly installed on the Plexiglas cylinder wall but rather were installed using a hexagonal brass rod at 2 cm vertical spacing, as shown in Figure 3. This is to prevent the cracking of the Plexiglas cylinder by over-tightening when the probe is installed on the cylinder wall, and for ease of saturating the pore pressure line. The hexagonal brass rod has four ports per transducer location. These ports were used to connect to the pore pressure ports of the cell and the pore pressure transducer, and to de-air and saturate the pore pressure line. Besides facilitating the de-airing of the pore pressure line at the start of the experiment, the use of the hexagonal brass rod allows for easy removal, replacement and provided support of the transducers. An aluminium frame for the MPPTs and an aluminium plate for the SSPT were used as a support for the transducers to minimize any effects that centrifuge testing might have on the transducers' responses.

High air entry porous stone and filter paper were used at the top and front of the transducers. The porous disks were de-aired by boiling and stored in water before use in the centrifuge tests. The porous disks and the filter paper were smoothed flush with the inside wall of the consolidation cell for the MPPTs. Centrifuge tests CT003 and CT004 were used to check the integrity of the test setup, to evaluate the pore pressure transducers' performance, and to check probe calibration under high gravity in the centrifuge. The pore pressure responses from CT003 are shown in Figure 4. The transducers are not affected by gravity and the calibration factors at Earth gravity were found valid. There was no leaking from the fittings.

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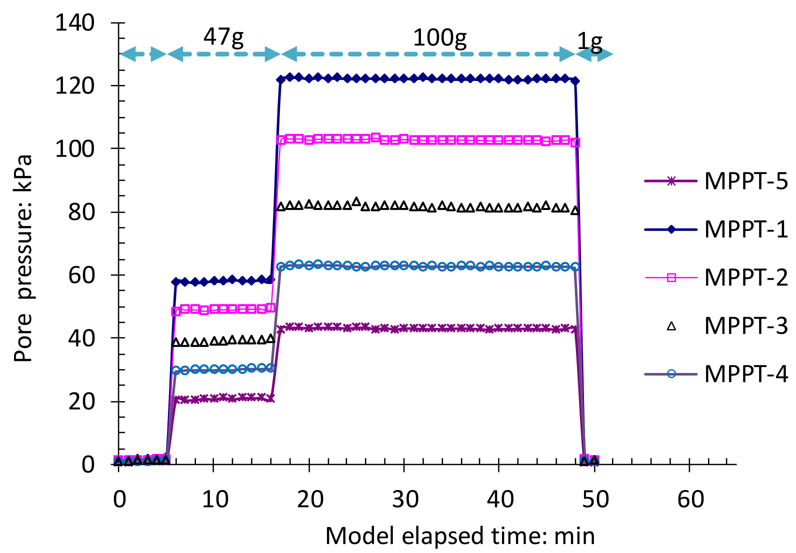

MPPT-1 at 1.6, MPPT-2 at 3.6, MPPT-3 at 5.6, MPPT-4 at 7.6 and MPPT-5 at 9.6 cm above the base

Figure 4. Pore pressure response of MPPT's in centrifuge test CT003

7.3. In-flight solids content measurement

The solids content profiles of the models were monitored using TDR. The TDR method, which relies on a strong dielectric contrast between soil grains and water, was selected after examining different solids content/density/total stress measuring technologies for in-flight solid content or total stress measurements of high water content materials in centrifuge. The examined methods include: - gamma-ray, X-ray, total pressure probe, heat pulse, neutron probe, image analysis, TDR, sampling and electrical resistivity technique. The examination was based on a laboratory investigation, a review of the measuring method, sample size requirement and accuracy of measurement, and an investigation into the possibility of using the methods in centrifuge model tests. A new measuring

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technique based on the light scatter was also evaluated in this centrifuge test program.

TDR probe calibration tests and the effect of temperature, thixotropic and soils textures were investigated at Earth-gravity to examine the suitability, accuracy and measuring ranges. The calibration was made by inserting TDR probes in oil sands tailings and kaolinite prepared at different solids content. The detail of this investigation can be found in Sorta et al. (2013a), with results indicating that the TDR can be used to measure the solids content of tailings over a wide range of solids content with acceptable measuring accuracy. The accuracy and measuring range, the small size and weight of the probes, and the easy adaptation of the method for the centrifuge make the TDR a suitable method for in-flight solids content profile monitoring in centrifuge.

The TDR probes were installed through the wall of a centrifuge consolidation cell at a spacing of 2 cm, starting from 1.6 cm above the base. The TDR probes were re-calibrated for use in the centrifuge test. The re-calibration was necessary to examine the effect of the change in physical length of the probes and the probe installations on a Plexiglas cylinder wall. The physical length of the TDR probes was changed in the probe signal analyzing program, and the offsets were adjusted by filling the consolidation cell with water and adjusting the offset values in the program so that the TDR readings equal the dielectric constant of the water. Next, the probes were re-calibrated by filling the cell with tailings and kaolinite slurry at different solids content. The volumetric water content-dielectric constants relationships from this calibration were then compared to the previous calibration

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results obtained by Sorta et al. (2013a). The re-calibration results were found to be the same as the previous results (Figure 5), indicating that the TDR responses are not affected by the probe installation through the wall of the consolidation cell.

The effect of high gravity on TDR response was examined by measuring the dielectric constant of water and tailings at Earth gravity and in centrifuge. The centrifuge consolidation cell was filled with water and spun for 45 minutes up to 100g (test CT003). The cell was then filled with AL-15 and spun up to 100g (test CT004). The dielectric constants of water and AL-15 at Earth and high gravity tests in the centrifuge are shown in Figure 6. The results indicate that the TDR response is not affected by high gravity application in centrifuge. The tailings were chosen for their high solids content (~56%) and low permeability so that the spinning would not change the initial solids content profile during the tests.

The use of a light scatter density probe (LSDP) for measuring the solids content of tailings during self-weight consolidation in centrifuge is explored through collaboration with the Electrical Engineering Department of the University of Alberta. The measuring method is based on an empirical relationship between the intensity of light scattered and the solids content of known samples. The LSDP consists of a laser diode facing the sample surface and a photodiode facing the same point at a 20° offset angle. As the point is illuminated by the laser spot changes in solids content, the light intensity detected by the photodiode will vary. The photodiode signal can then be used to detect any changes in the solids content. The preliminary investigation results at Earth gravitational acceleration

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were presented in Gupta et al. (2012); however, a detailed presentation of the results, measuring principle, and measuring accuracy are beyond the scope of this chapter.

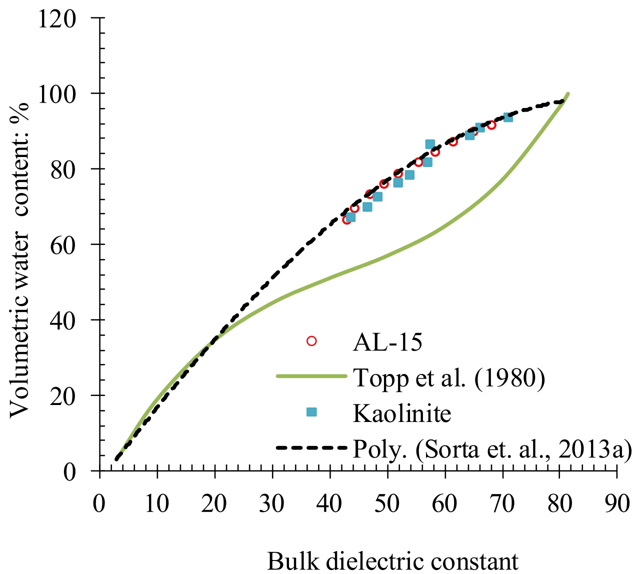

Figure 5. Calibration of TDR probes installed on centrifuge consolidation compared without probe installation

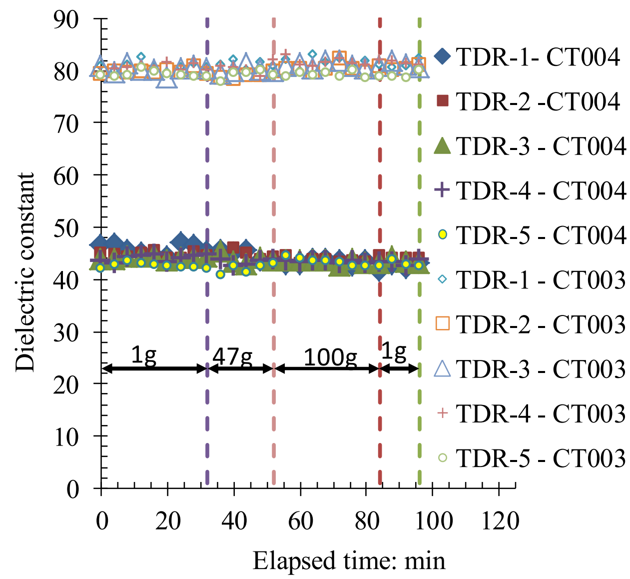

Figure 6. Dielectric constant of water and AL-15 at Earth and high-gravity in centrifuge

8. BRIEF CENTRIFUGE TEST PROCEDURE

FFT and TT samples for the centrifuge tests were prepared to the desired solids content by adding or removing process water. FSMT were prepared by mixing FFT with beach sand to reach the desired solid and fine contents. Kaolinite samples were prepared by mixing the EPK clay powder with distilled water. Before filling the cell with tailings or kaolinite slurry, the consolidation cell was filled with de-aired water and the pore pressure lines were saturated by allowing water to pass through the pore pressure ports. After draining the de-aired water, the samples were then poured into a Plexiglas cylindrical consolidation cell to a

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height of 10-24 cm and stirred using a round-ended plastic rod to remove entrapped air. Modelling criteria requires model height to be less than 20% of the radius of centrifuge. For the kaolinite, the centrifuge tests were run immediately after filling; but for the oil sands tailings, tests were conducted after one day of filling. Waiting one day before conducting centrifuge tests improves the segregation behaviour of tailings without changing their initial solids content (Sorta et al., 2012). Interface settlement and pore pressure data were recorded every 1 minute, TDR readings were taken every 4 minutes, and temperature was recorded every 10 minutes. After the centrifuge tests, the water that was released was siphoned off and the sediment was sliced into a number of layers to determine the solids content profile by oven drying. The rebound of the sediment due to stress relief after stopping the centrifuge was measured to be less than 1% of the initial height and was neglected during the data analysis.

9. SAFETY OF TEST PACKAGE

Centrifuge tests CT003-CT004 were used for checking the integrity of test packages and for checking probe calibration and the gravity effect of probe responses. Figure 7 and Figure 8 show the test setups during the test flights. In-flight monitoring and after-test observations indicate that the test packages are safe, with no leaks or deformation of transducer or camera components. Tests CT003 and CT004 indicate that centrifuge tests can be conducted without enclosing the test package in the round tub of the metal housing. The space requirements of cameras, LED light bars, and transducers' setups required centrifuge tests CT005-CT0012 to be conducted without enclosing the test

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package in a metal round tub, which was designed and made available to protect sudden spills or failure of the test package.

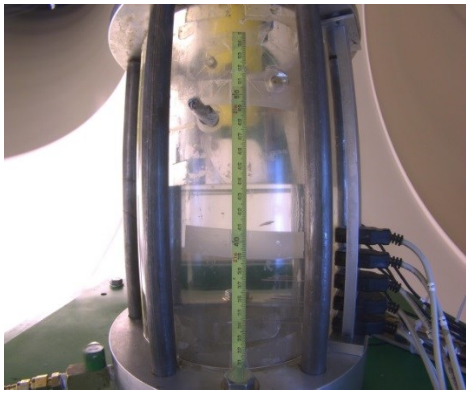

Figure 7. Test CT003 setup

Figure 8. Test CT004 setup

10. REPEATABILITY OF CENTRIFUGE TEST AND VERIFICATION OF SCALING LAWS

Centrifuge tests CT001, CT002, CT005-CT007, CT008 and CT0012 are used to check centrifuge test repeatability and to verify centrifuge scaling law. These centrifuge runs are necessary because the GeoREF centrifuge facility is new and so there is a need to verify that correct modelling procedure is followed. Three types of verification tests were carried out: repeating tests conducted in other centrifuge facilities, modelling of models tests, and running centrifuge tests on TT samples to compare with the trend of results obtained at Earth gravitational acceleration.

Self-weight consolidation of AL-15 was conducted at Memorial University of Newfoundland and Labrador using a 5.5 m radius C-CORE centrifuge. Details of the centrifuge and the centrifuge facility can be found in Phillips et al. (1994). The test was conducted at 80g for close to 8 hours. The initial height and solids

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content of the tailings were 10 cm and 46.5%, respectively. The self-weight consolidation test was then repeated using the GeoREF centrifuge at the University of Alberta (test CT002). The material type, initial solids content, initial height, relative acceleration and the consolidation cell in both facilities were kept the same. The interface settlement was monitored using in-flight cameras in both facilities. The centrifuge test setups in both facilities are shown in Figure 9 and Figure 10 and the models interface settlement-time plots are shown in Figure 11. As Figure 11 demonstrates, the interface settlements from the two models are close, indicating that the test is repeatable and the correct modelling procedure was followed.

As part of centrifuge modelling verification, two centrifuge tests were conducted on thickened tailings of 60 and 50% fine (TT-60 and TT-50) at an acceleration of 90 and 100g (tests CT008 and CT0012). The initial void ratio of the tailings and the prototype height were kept the same. Tests using fine-sand mixture tailings at Earth gravitational acceleration indicate that the behaviour of fine-sand mixture tailings (such as shear strength, plasticity, rate of settling, and segregation) depend more on fines void ratio (volume of voids/volume of fines) than on void ratio (volume voids/volume of solids) (Sorta et al., 2013b). The magnitude of ultimate settlement, however, depends more on the thickness of the deposits and the initial void ratio than on the fines void ratio. Centrifuge tests CT008 and CT0012 conducted on thickened tailings started at the same initial void ratio and were subjected to the same self-weight stress. They were thus expected to give the same ultimate settlement if the scaling relation was valid and the correct

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modelling procedure followed. The centrifuge tests on the two materials were run until the end of consolidation while monitoring the interface settlement, solids and pore pressure profiles. Figure 12 shows the average void ratio as a function of time for the two thickened tailings. The average void ratio is computed from the height of the interface, which was measured at different elapsed times. The settling rates of the two tailings are different but the ultimate settlements are close, indicating that the modelling procedure is acceptable and the deformation scaling relation in Table 2 is valid.

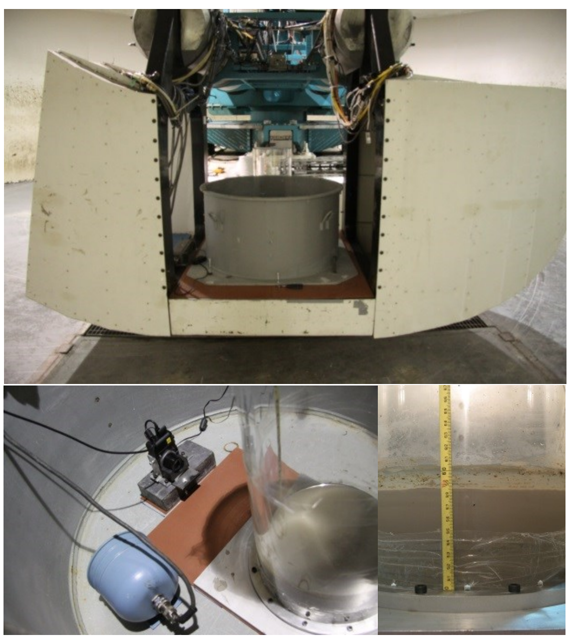

Figure 9. Centrifuge test setup in C-CORE

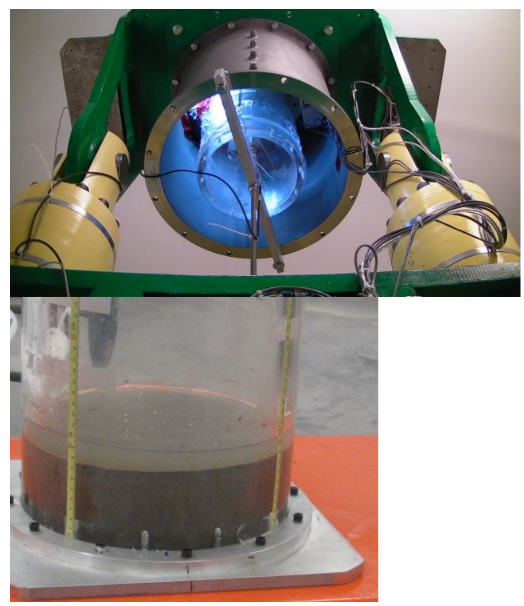

Figure 10. Centrifuge test setup in GeoREF

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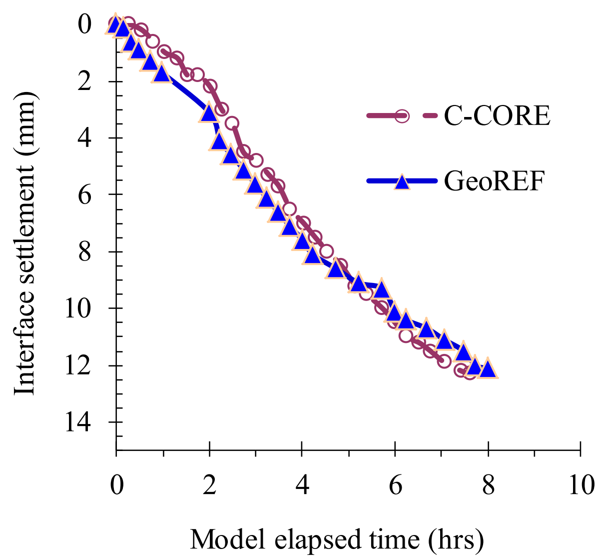

Figure 11. Interface settlement of AL-15 at 80-g centrifuge test at C-CORE and GeoREF

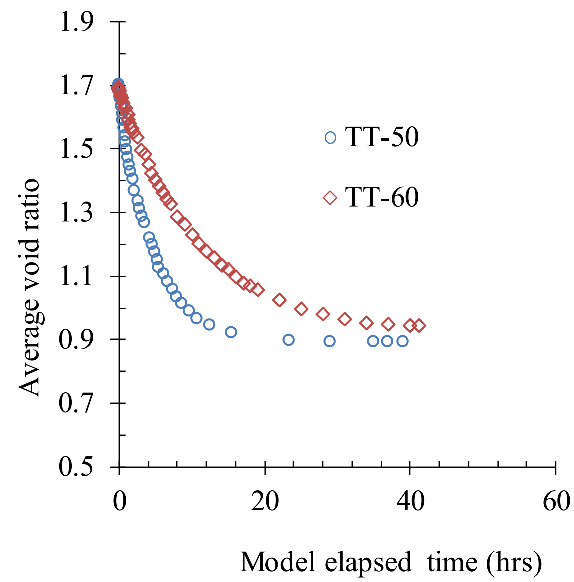

Figure 12. Interface settlement of TT-50 and TT-60, CT008 and CT012 tests

Three centrifuge tests (CT005-CT007) were conducted on kaolinite clay slurry to verify the similitude between different experiments and/or to verify the scaling relation between the model and the prototype. The three tests were conducted at accelerations of 60, 80 and 100g. The initial solids content of the slurry was kept the same for the three tests (close to 44%). The initial height of the slurry was chosen to represent the same 10 m-high pseudo prototype. The three tests represent the same prototype but are modeled at different accelerations. They are thus expected to give the same prototype response, if correct modelling procedure was followed and centrifuge scaling factors are valid. This model verification technique is known as ''modelling of models'', after Ko (1988). The interface settlement, pore pressure and density profiles were monitored in-flight in the three tests. The centrifuge was run until the interface settlements ceased and excess

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pore pressure fully dissipated. At the end of the tests, the solids content profiles were determined by slicing the sediments.

Figure 13 shows the compressibility (void ratio-effective stress relationship) of the kaolinite models after the centrifuge tests. The strains at the end of consolidation from the three modelling of the model are shown in Table 4. The compressibility curves and strains at 100% consolidation of the three tests are close, indicating that the same prototype response can be found for the end of the consolidation. The same magnitude of ultimate settlement points to the height or deformation scaling relation between the model and prototype as being the same as the theoretical value in Table 2.

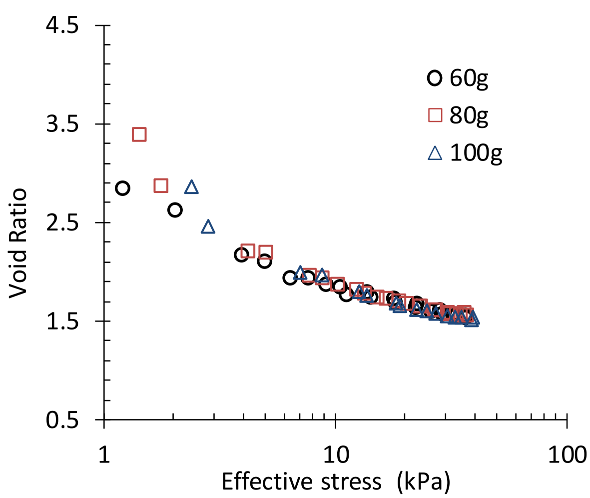

Figure 13. Compressibility of kaolinite from the modelling model test

Table 4. Strain at the end of consolidation from the modelling of model test

Relative acceleration factor	Strain at 100% consolidation (%)
60	34.1
80	34.6
100	35.1

Equation 1 shows the consolidation time scaling relation between the model and prototype. It implies that the prototype consolidation time at a given degree of

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consolidation is the same as the centrifuge tests conducted at different accelerations and heights representing the same prototype. The exponent x in Equation 1 is the time scaling exponent. The theoretical time scaling exponent is 2 for consolidation and 0 for creep type of settlement (Table 2).

$$t_p = t_{m1} * N_1^x = t_{m2} * N_2^x = t_{m3} * N_3^x \qquad [1]$$

where t_p is elapsed time in the prototype, t_{m1}, t_{m2} and t_{m3} are elapsed times for a particular degree of consolidation, and N_1, N_2 and N_3 are relative acceleration levels in the three modelling of the model tests.

The time-scaling exponent from the modelling of the model test is calculated at different degrees of consolidation using Equation 1. The results are given in Table 5. The time-scaling exponent varies with the degree of consolidation, but the average is close to the theoretical time-scaling exponent of 2, as shown in Table 5. Figure 14 shows the degree of consolidation versus prototype elapsed time for the three tests, using the time-scaling exponent of 2. For x=2, the prototype responses from the three tests are very close for consolidation less than 60%; however, they vary with the gravity level used in the centrifuge for consolidation greater than 60%.

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Table 5. Time-scaling exponent from modelling of model tests at different degrees of consolidation

% consolidation	Time scaling exponent 100 and 80g	100 and 60g	80 and 60g
25	1.47	1.18	0.95
40	1.24	1.47	1.65
50	1.15	1.60	1.93
75	2.58	2.68	2.75
90	2.87	2.61	2.40
100	2.28	2.31	2.34
Average	1.93	1.97	2.00

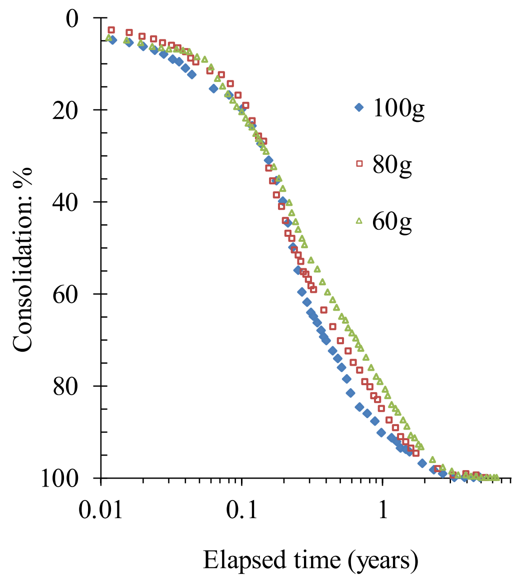

Figure 14. Degree of consolidation as function of prototype elapsed time; model extrapolated using time scaling exponent of 2

Prototype consolidation time differences among the three tests at various degrees of consolidation are shown in Figure 15 using the time scaling exponent of 2. Figure 16 presents the consolidation time differences between tests conducted at different relative accelerations as a percentage of time for 100% consolidation. The prototype elapsed time difference between the tests is less than 2% for a degree of consolidation less than 60%, but varies from 2 to 21% for consolidation above 60%. The time difference between 60 and 100g (40g difference) tests is greater than 60 and 80g (20g difference). Tests of 80 and 100g at a given degree of consolidation indicate that the rate of consolidation may depend on the relative acceleration in the centrifuge. The extrapolation of prototype consolidation time

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from the centrifuge (for example, from a test of 25g [scale of 25]) may differ from a test conducted at 100g (scale of 100).

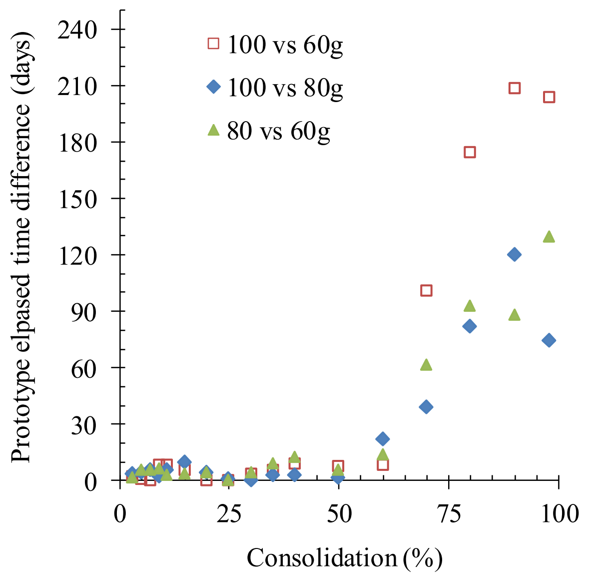

Figure 15. Prototype time difference between modelling of model test using time exponent of 2

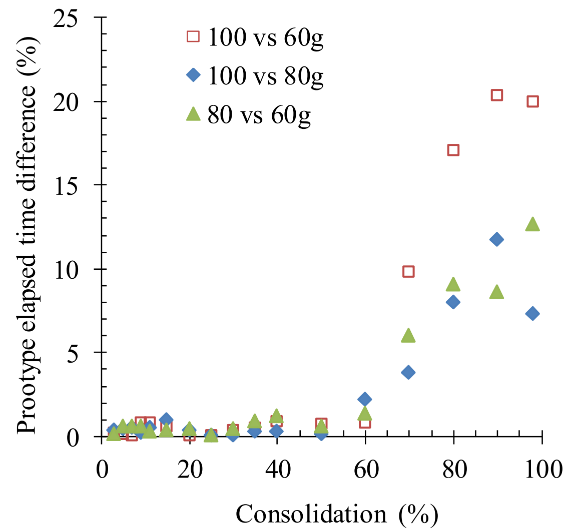

Figure 16. Prototype time difference between modelling of model test as percentage of time for 100% consolidation using time exponent of 2

The time-scaling exponents of 1.5 to 2.5 were used to investigate the effect of time-scaling exponents on prototype consolidation times. Figures 17 shows the degree of consolidation as a function of the prototype elapsed time of kaolinite samples tested at 80g for x=1.5, 1.9, 2.1 and 2.5. The elapsed time for full consolidation is less than 1 year when x=1.5, close to 3 years when x = 1.9, close to 8 years when x=2.1, and close to 100 years when x=2.5. The results shown in Figure 17 indicate that consolidation time estimates from the centrifuge tests are highly dependent on the time-scaling exponent.

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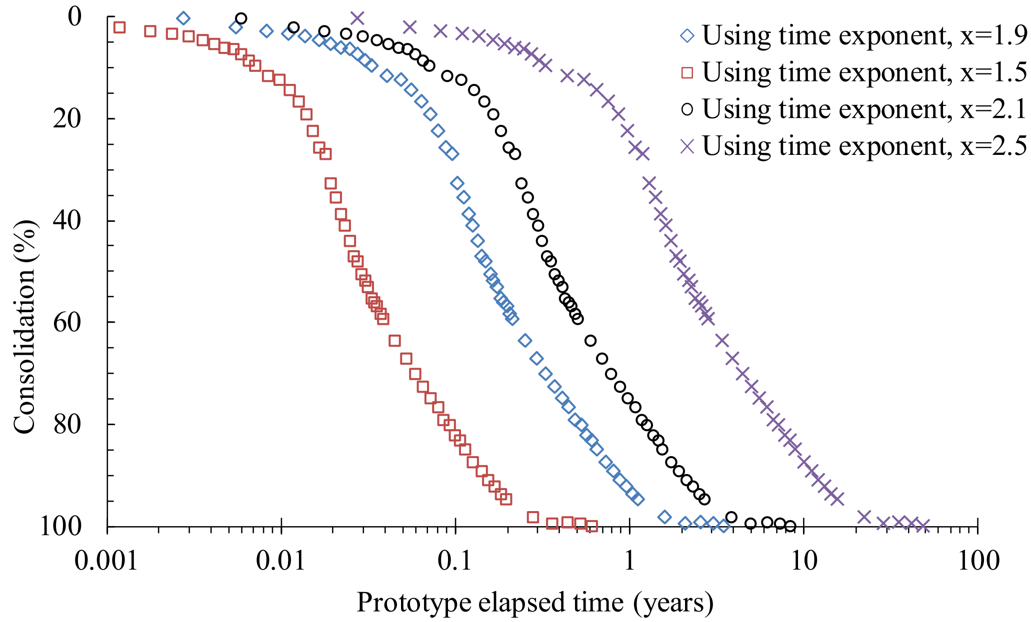

Figure 17. Effect of time scaling exponents on extrapolating model results - CT006-80g test

Angular acceleration in centrifuge is calculated from the constant angular speed and the effective radius of the centrifuge. Unlike Earth gravity, acceleration in a centrifuge is not constant and varies within the height of a model, resulting in a nonlinear stress profile in the model. The model at the top portion is under stressed, while that at the bottom portion is over stressed compared to the prototype stress. To minimize the stress profile differences between the model and the prototype, Schofield (1980) and Taylor (1995) recommended an effective radius from the center of rotation to one-third depth, while Cooke (1991) recommended to a depth of 0.4. The effect of effective radius definition on consolidation rates and magnitude is investigated by varying the effective radius from the center of rotation to one-third depth, to one-half depth, and to the bottom of the model. Figure 18 shows the prototype settlement versus consolidation time based on three definitions of effective radius, with the centrifuge spinning at a

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constant speed of 172 rpm (CT005 test). Figure 18 indicates that the consolidation rate and magnitude of the slurry is only slightly affected by effective radius used especially when the effective radius is to one-third or to one-half the depth of the model. Thus, the effect of the effective radius definition is minor compared to that of the time-scaling exponent.

Acceleration in a centrifuge is normally calculated using an effective radius based on the initial model height. The acceleration is considered constant during the entire process of self-weight consolidation. However, the distance from the centers of rotation to one-half and one-third depth of the model (the effective radius) changes during the consolidation progress. The material used in this study is high water content material that strains up to 35%. Moreover, the effect of radius change during consolidation is considerable and may affect the interpretation of model results. The effect of effective radius change on consolidation rate and magnitude was investigated and is shown in Figure 19. The centrifuge was spun at 172 rpm and the initial height of the model was 16.7. The constant re is the effective radius to the center of the model based on the initial height of the model and kept constant. The variable re is the effective radius to the center of the current height of the model. The model height is updated by subtracting the change in height from the initial height of the model. The results in Figure 19 indicate that updating the change in effective radius does not significantly affect either the rate or magnitude of settlement.

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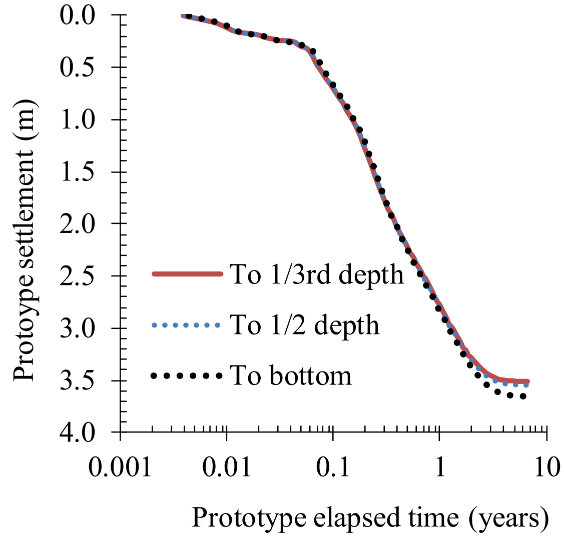

Figure 18. Effect of effective radius definition on estimation of consolidation time, CT005 test

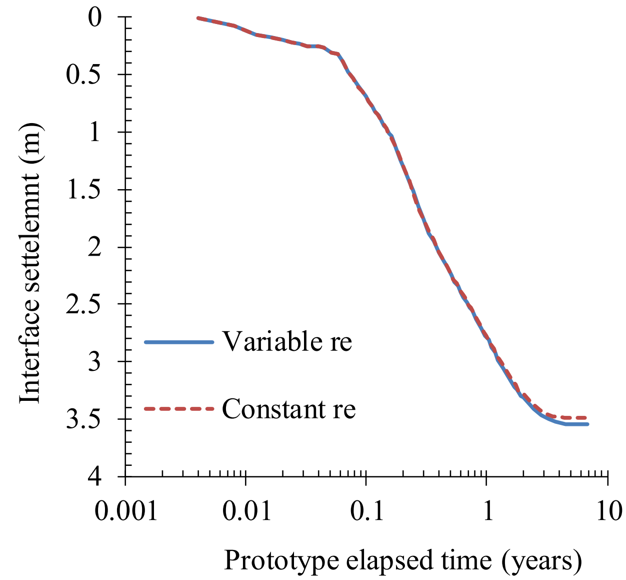

Figure 19. Effect of effective radius on extrapolating model results, effective radius at the center, constant and varies with consolidation progress, CT005 test

The results in this section demonstrate that the testing procedure is acceptable and that the deformation scaling relation between the model and prototype is similar to the theoretical values. The analyses of modelling of model experiments indicate that the theoretical time-scaling exponent falls short of satisfying the scaling relation between the model and the prototype at certain stages during consolidation. Similar to the results of this study, previous modelling of model experiments by Scully et al. (1984) and Bloomquist and Townsend (1984) also reveal that time-scaling is not constant and shows a trend towards increasing relative to the degree of consolidation. Croce et al.'s work (1985) suggests that the time exponent is 2.0 for the centrifugal modelling of the consolidation kaolinite clay. Their results, however, are for relatively low initial void ratio sample, and the scaling law was evaluated only at a 50% and 100% of

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consolidation, not over the whole stage of consolidation. From this, we can surmise that the time-scaling exponent appears to be dependent on the degree of consolidation and the relative acceleration used in modelling. Despite knowing that it has a limitation in predicting the rate of settlement, the theoretical value of 2 is used for centrifuge test results analysis in the next sections.

11. TYPICAL PORE PRESSURE AND VOID RATIO RESPONSE DURING SELF-WEIGHT CONSOLIDATION

Figure 20 shows the pore pressure measured during the test flight at different model depths. The pore pressure transducers are designated from 0 to 5, the bottom one is 0, and the topmost is 5. Figure 20 indicates that pore pressure increases with acceleration and decreases with time. The magnitude of the pore pressure is a function of acceleration and initial solids content, as well as height and the location of the pore pressure transducers. The solids content at different depths as a function of elapsed time during the self-weight consolidation is shown in Figure 21. The solids content is calculated from TDR readings using probe calibration equations. The probes are designated from 1 to 5, with the lowest location designated as TDR 1 and the topmost as TDR 5. Figure 21 shows the void ratio profile at different elapsed times. The void ratio is calculated from the measured solids content assuming full saturation. The void ratio at the top of the model is assumed to be equal to the void ratio measured from the topmost TDR probe, and the void ratio at the bottom is calculated so as to obtain the same height of solids at different elapsed times during the consolidation, using Equation 2. The excess pore pressure profiles at different elapsed times are shown in Figure

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22. The excess pore pressures were calculated by subtracting the hydrostatic pressure from the observed total measured pore pressure. Figure 23 shows void ratio profiles at different elapsed times. Figures 20 and 22 indicate that there is a rapid dissipation of pore pressure immediately after applying the centrifugal acceleration along the model depth, suggesting that the settlement is a consolidation-type settlement.

$$H_s = \sum \frac{H_i}{(1+e_i)} \qquad [2]$$

H_s is the height of solids, H_i is the height of soil element and e_i the void ratio of soil element.

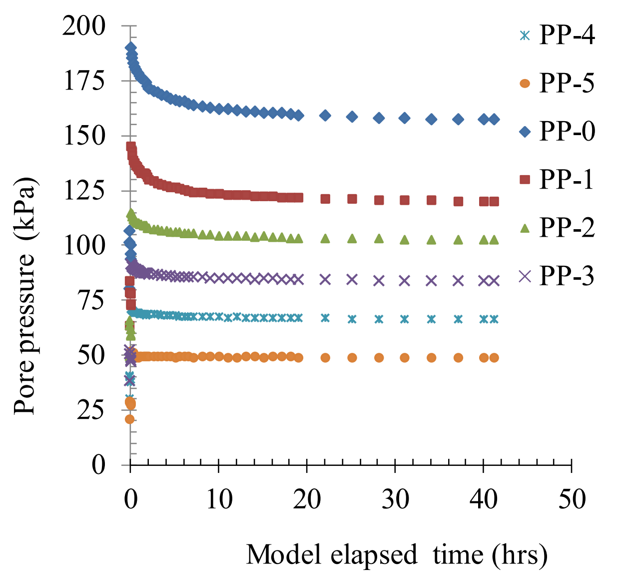

Figure 20. Pore pressure measured at different depths of the model during centrifuge flight - TT-60 (CT0012 test)

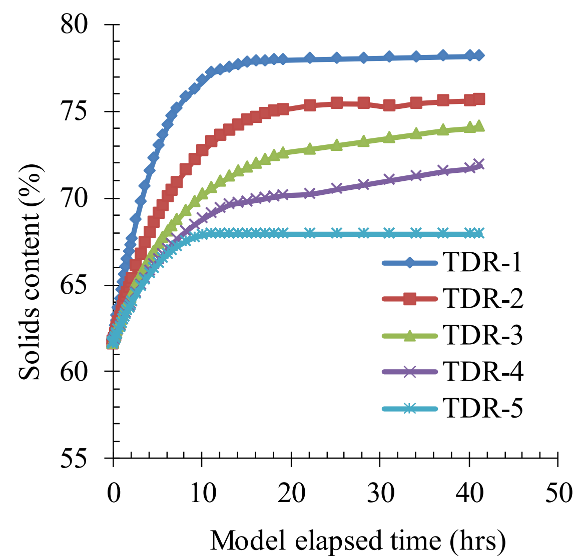

Figure 21. Solids content measured at different depths of the model during centrifuge flight – TT-60 (CT0012 test)

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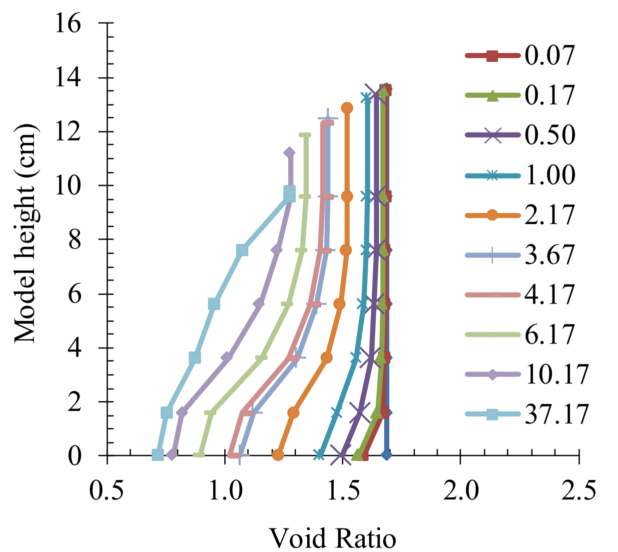

Figure 22. Void ratio profiles at different elapsed times during centrifuge flight - TT-60 (CT0012 test)

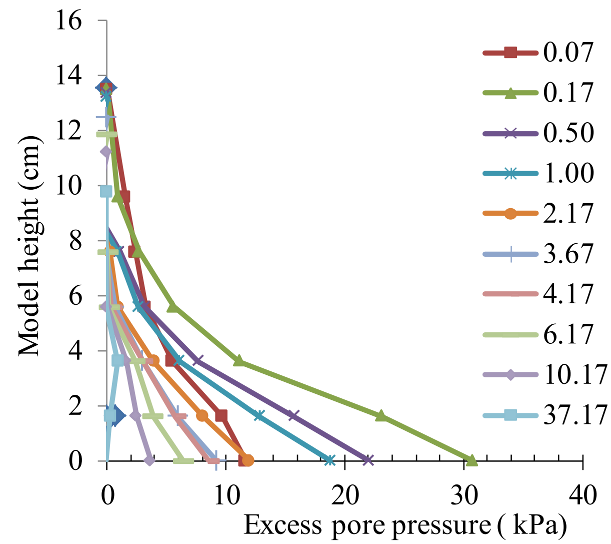

Figure 23. Excess pore pressure profiles at different elapsed times during centrifuge flight - TT-60 (CT0012 test)

12. CONSOLIDATION PARAMETERS FROM LSCT

In conventional soil mechanics, the magnitude and rate of settlement under an imposed load is predicted using the classical Terzaghi theory (1923). Consolidation parameters (coefficient of consolidation, compression index and pre-consolidation pressure) are determined from a standard one-dimensional incremental loading (oedometer) test (ASTM D2435-04). The classic Terzaghi theory assumes infinitesimal strain, linear compressibility and constant permeability. The theory and the laboratory testing method do not apply for a slurry/soft soil that undergoes large changes in volume under self-weight or imposed stress.

Large strain consolidation numerical models, based on the large strain consolidation theory of Gibson et al. (1967), are commonly used in predicting the rate and magnitude of settlement of slurry/soft soils that undergo large changes in

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volume. The theory accommodates non-linear behavior that allows for large deformation and considers the effects of self-weight. Compressibility (void ratio-effective stress relationship) and permeability (hydraulic conductivity-void ratio relationships) of the materials are used as input parameters for the numerical models. Testing methods that accommodate large deformations have been utilized in evaluating the large strain consolidation parameters, such as: large strain consolidation test (LSCT) apparatus (Pollock, 1988; Suthaker, 1995); seepage consolidation apparatus (Abu-Hejleh et al., 1996; Imai, 1979); constant rate of deformation (Scully et al., 1984; Znidarcic et al., 1986); and centrifuge (Mcvay et al., 1987; Takada & Mikasa, 1986). The large strain consolidation parameters of the materials used in this study are evaluated using the LSCT apparatus, with the aim of using the parameters for large strain numerical model input and for comparing with large strain consolidation parameters derived from using centrifuge.

The LSCT apparatus has been used in the oil sands industry for deriving tailings consolidation parameters. This apparatus and test method were developed at the University of Alberta. The test involves pouring slurry of a high initial void ratio into a large strain consolidation cell and then loading the sample incrementally, starting from the self-weight. The change in height of the sample under the loading and the excess pore pressure dissipation at the base are monitored. When the excess pore pressures fully dissipate, additional loads are added, doubling the existing load. At the end of each loading step, a constant head permeability test is conducted to derive the permeability coefficient corresponding to void ratio. The

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permeability tests are conducted by keeping the hydraulic head small in order to avoid hydraulic fracturing or consolidation due to seepage forces. Usually, the LSCT are conducted under one-way drainage conditions, with free drainage on the top. The bottom valve is used for monitoring pore water pressure at the base of the sample and to allow upward water flow for the permeability tests. The consolidation parameters are derived from deformation measured under each loading steps and the constant head permeability tests conducted at the end of each loading steps. The large strain consolidation covers the consolidation parameters from the void ratio at the end of self-weight consolidation to void the ratio corresponding to a maximum stress applied on the sample. Scott and Jeeravipoolvarn (2008) recommended a combination of compressibility standpipe, hydraulic standpipe, and LSCT for deriving the consolidation parameters of tailings over a large range of void ratios. The compressibility standpipe is for deriving effective-stress void ratio relation at higher void ratios than LSCT, based on the water content profile measured at the end of the self-weight consolidation. The hydraulic standpipe test is for deriving the hydraulic conductivity-void ratio relationship at high void ratios, based on the initial interface settlement rate of slurries filled in hydraulic conductivity standpipes at various initial void ratios.

The consolidation parameters of FSMT, TT-50, TT-60 and kaolinite samples were evaluated using the LSCT apparatus. Large strain consolidation parameters for AL-7.5 are available in the literature (Zhang, 2012). Figure 24 summarizes the compressibility and Figure 25 summarizes the permeability of the tested materials. The LSCT results will later be compared with consolidation parameters

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derived from the centrifuge tests and will be used in the large strain numerical model.

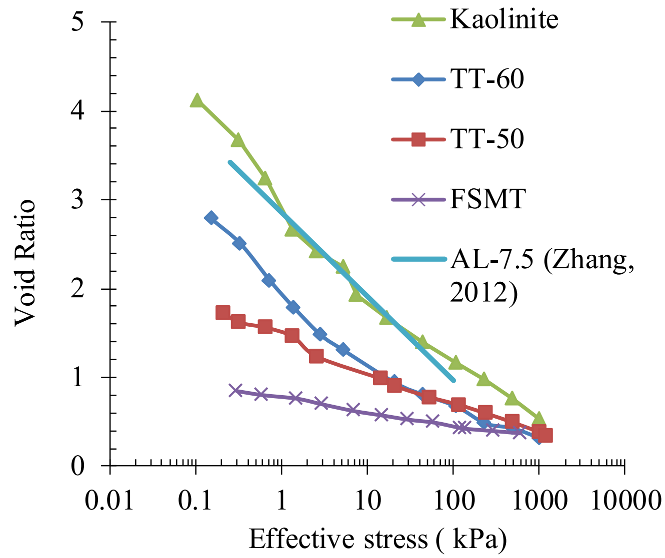

Figure 24. Compressibility of Kaolinite, TT-60, TT-50 FSMT, and AL-7.5 from LSCT

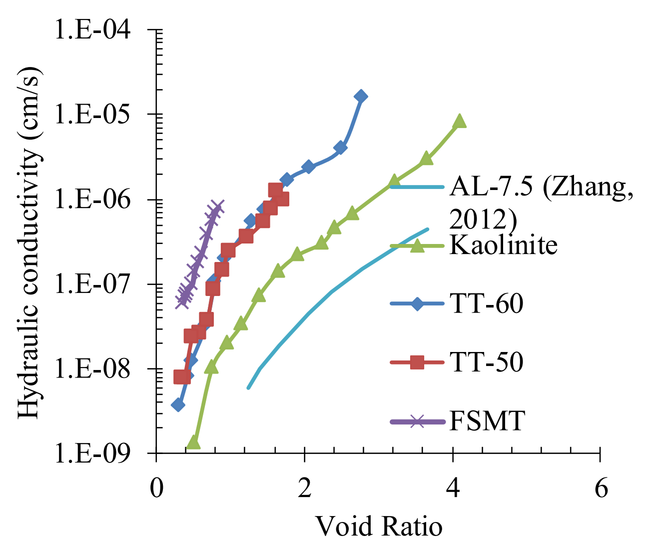

Figure 25. Permeability of Kaolinite, TT-60, TT-50, FSMT, and AL-7.5 from LSCT

13. CONSOLIDATION PARAMETERS FROM CENTRIFUGE TESTING

Centrifuge has been used for evaluating the consolidation parameters of soft soils (e.g. by Mikasa & Takada, 1984; Takada & Mikasa, 1986). The water content profile at the end of a centrifuge test are commonly used to derive the void ratio-effective stress relationship, and the initial settlement rates of models prepared at various initial void ratios are used to derive the hydraulic conductivity-void ratio relationship (e.g., Takada & Mikasa, 1986). However, this approach requires a number of centrifuge model tests to be conducted at various initial void ratios for evaluating the hydraulic conductivity-void ratio relationship (Mcvay et al., 1987).

In this study, the large strain consolidation parameters of oil sands tailings and kaolinite slurry are determined from a centrifuge test instrumented with density

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and pore pressure transducers, without the need for running a number of centrifuge tests on the same material at different initial solids contents. The advantages of this approach are that the consolidation parameters can be evaluated from a single model test and the relationship can be determined from a number of data points. The method does, however, require in-flight solids content and pore pressure profile measuring probes. Centrifuge technology does not yet have a reliable solids content profile measuring apparatus. Thus, several different solids content measuring methods were examined and time domain reflectometry (TDR) was used for in-flight solid contents profile measurements. The LSCT method requires many days or months to complete, depending on the permeability and initial solids content of the tailings. The objective of the centrifuge test is to examine the derivation of the large strain consolidation parameters of tailings from the centrifuge in a shorter time than that required for LSCT.

Centrifuge tests CT005-CT012 were conducted by monitoring the interface settlement, solids and pore pressure profiles. Based on the interface settlement, measured solids content and pore pressure profiles at various elapsed times, and using a generalized Darcy's law, principle of continuity and use of material coordinate system, the large strain consolidation parameters of tailings and kaolinite were derived from the centrifuge tests.

To compute the void ratio-effective stress and hydraulic conductivity-void ratio relationships, the model is divided into five equal thicknesses, and the effective stress and hydraulic conductivity are calculated at the nodes of these elements.

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The material nodes are calculated using the initial height and initial void ratio using Equation 3.

$$h_i = \frac{(i-1)}{5} * \frac{Ho}{1+e} = \frac{(i-1)}{5} * H_s \qquad [3]$$

where Ho is the initial height of the model, eo is the initial void ratio of the material, Hs is the solids thickness of the material, and i is an integer varying from 1 to 6. The material coordinate of i=1 indicates that 0% of the solids are below that material node and i=6 indicates that 100% of the solids are below that material node. The material coordinates for i=2 is 20%; i=3 is 40%; i=4 is 60%; and i=5 is 80% solids below the material node. The base of the model is represented by i=1 (h_i=0) while the top of model is represented by i=6 and equals the solids thickness of the material (Hs). At time t=0, the material nodes are known and are spaced equally. When a new distribution of void ratio is obtained, the location of the material node in the real coordinates system (updated Lagrangian coordinates) changes. The effective stress and hydraulic conductivity are calculated by keeping track of the location of each material node and by using the measured pore pressure distribution, solids content profile and interface settlement.

The effective stresses at a material node in the tailings or kaolinite are calculated using Equation 4.

$$\sigma_i' = a_m * (G_s - 1)(H_s - h_i)\gamma_w - u_i \qquad [4]$$

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where σ'_i is the effective stress at material nodes at different elapsed times, a_m is the acceleration in the centrifuge (model), H_s the height of solids, G_s is the specific gravity of the material,γ_w is the unit weight of water, and u_i is the excess pore pressure at the material nodes at different elapsed times.

The void ratio at material coordinate points at different elapsed times can be calculated from the measured solids content profiles. Thus, void ratio-effective stress at each of the material nodes at different elapsed times can be determined.

The hydraulic conductivity (k) at each material node at different elapsed times can be calculated using Equation 5. The derivation of the hydraulic conductivity from the centrifuge test is based on the generalized Darcy's law, the equation of continuity, and the use of updated Lagrangian coordinates. The use of this coordinate system is necessary, since the computations of hydraulic conductivity are based on the displacement of material points in the specimen. Darcy's law is valid for laminar flow and requires the Reynolds number to be less than unity. In centrifuge modelling, the similitude of the Reynolds number between the prototype and model cannot be achieved (Knight & Mitchell, 1996). The Reynolds number is scaled by the number of accelerations used in the centrifuge. However, if the Reynolds number is less than unity, Darcy's law is considered valid in the centrifuge. For the materials used in this study, the Reynolds number is found to be less than unity for up to 200g tests.

$$k = \frac{v_i}{HG} \quad [5]$$

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where v_i is the solid velocity and is approximated as the change in the position of the material nodes divided by the elapsed time, and HG is the hydraulic gradient that is calculated from the excess pore pressure profile in the region close to the material node under consideration.

Figure 26-37 presents the compressibility and permeability of the materials from the centrifuge tests. For comparison, the large strain consolidation test results are included in the figures. The compressibility curves are found by connecting the void ratio-effective stress of soil elements along the model profile at particular elapsed times. The hydraulic conductivity is calculated using Equation 5 for a hydraulic gradient around the mid-depth of the model. The hydraulic conductivity is then divided by the number of acceleration used in the test to compare with the LSCT results. All of the test results indicate that the permeability of the centrifuge is generally higher than that of the LSCT results, and that the compressibility at the end of the tests is similar to the LSCT test results. In contrast, compressibility during the test flights is above that of LSCT. As the settling progresses, the in-flight compressibility moves towards compressibility at the end of the test. Depending on the stage of consolidation, the compressibility variation indicates that the compressibility of a given material is not a unique function of void ratio. The following paragraphs in this section explain why there is no unique compressibility during the progress of settling.

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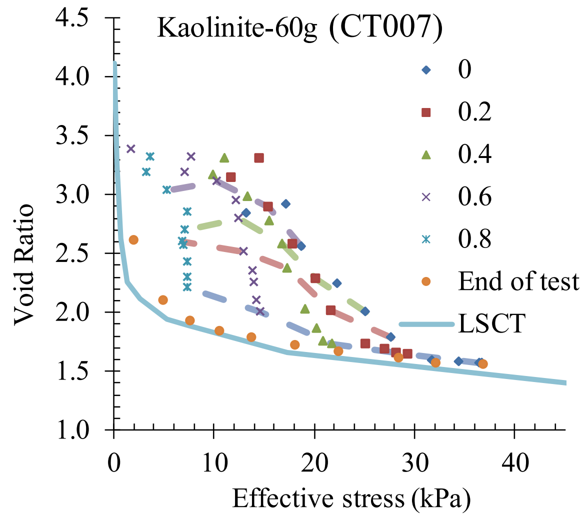

Figure 26. Compressibility of Kaolinite from centrifuge and LSCT

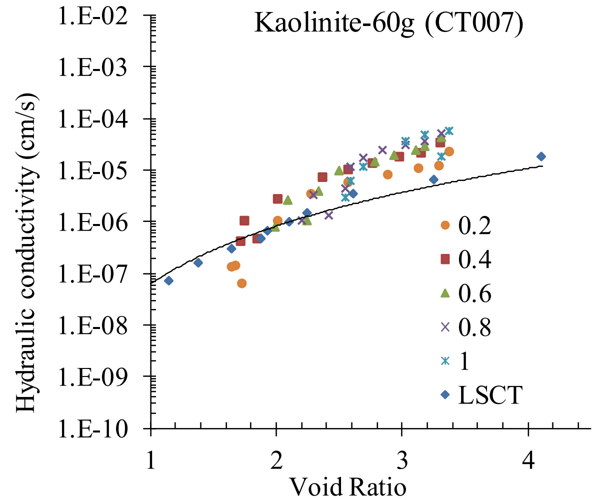

Figure 27. Permeability of kaolinite from centrifuge and LSCT

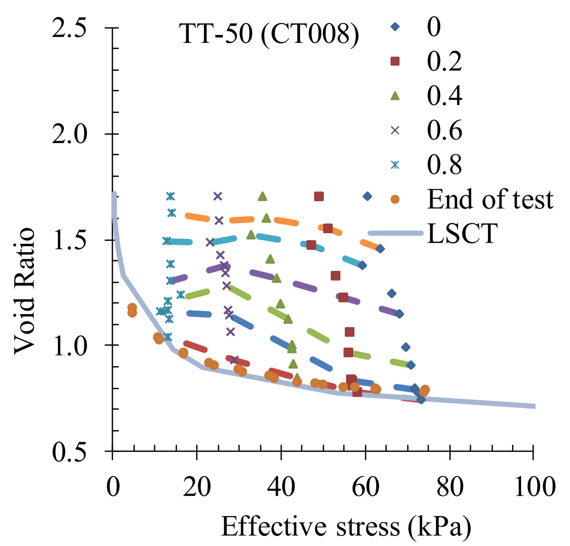

Figure 28. Compressibility of TT-50 from centrifuge and LSCT

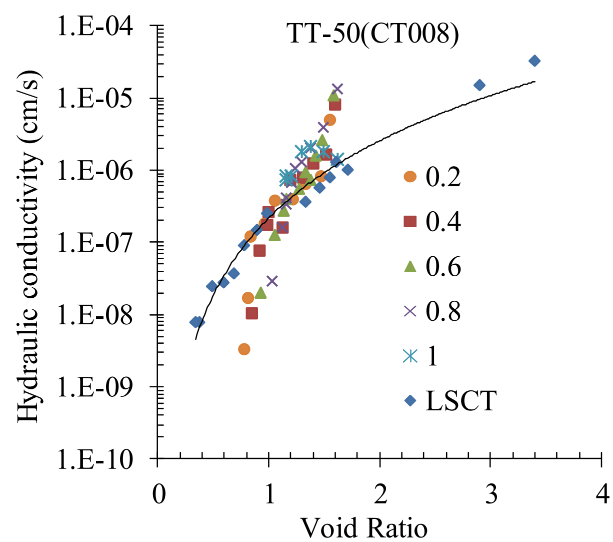

Figure 29. Permeability of kaolinite from centrifuge and LSCT

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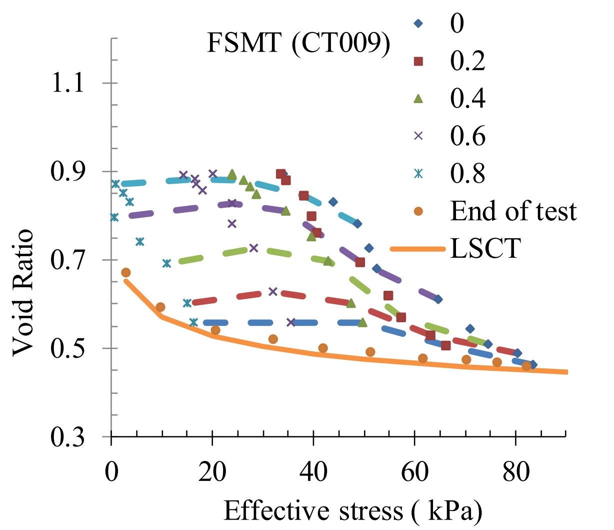


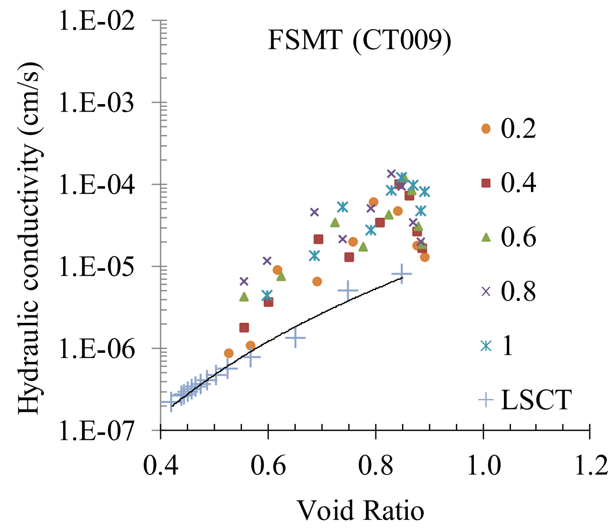
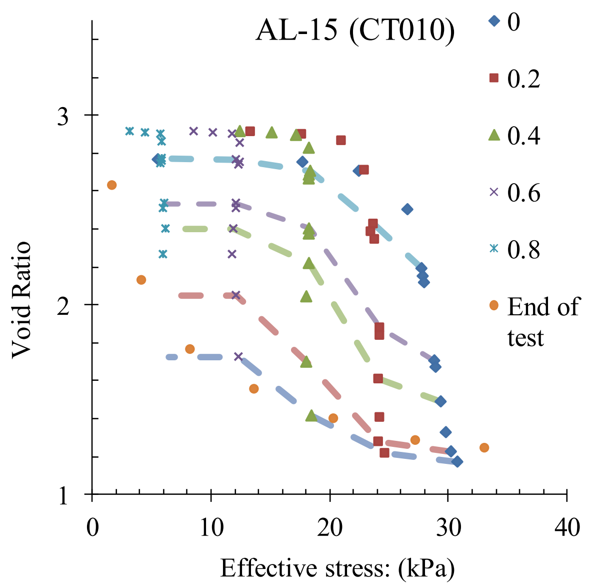


Figure 30. Compressibility of FSMT from centrifuge and LSCT

Figure 31. Permeability of FSMT from centrifuge and LSCT



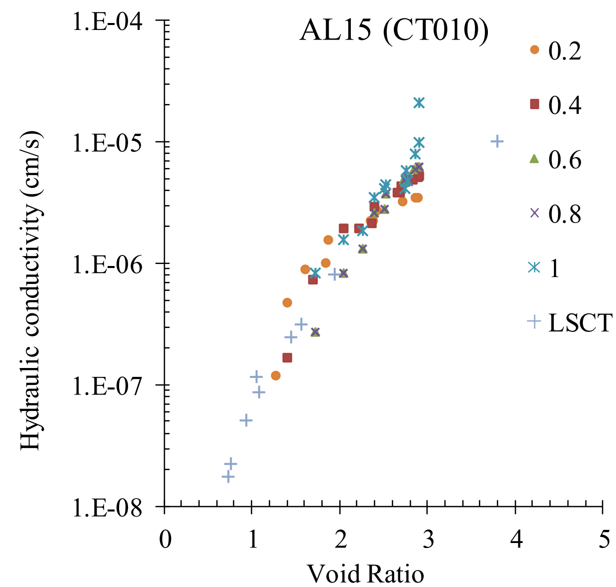


Figure 32. Compressibility of AL-15 from centrifuge and LSCT

Figure 33. Permeability of AL-15 from centrifuge and LSCT

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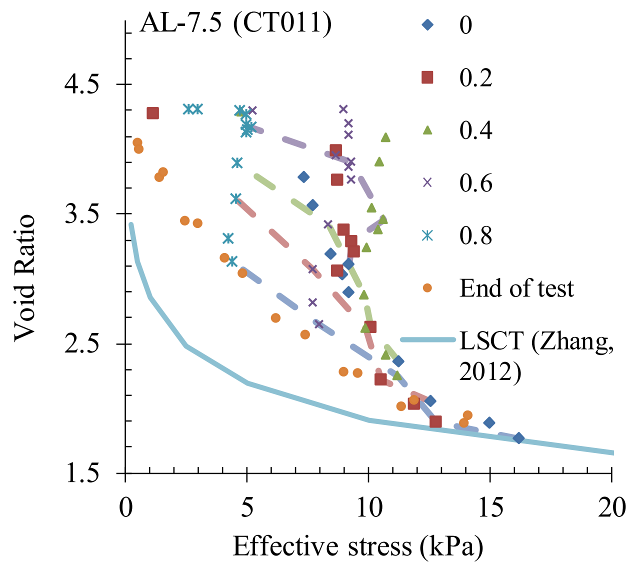

Figure 34. Compressibility of AL-7.5 from centrifuge and LSCT

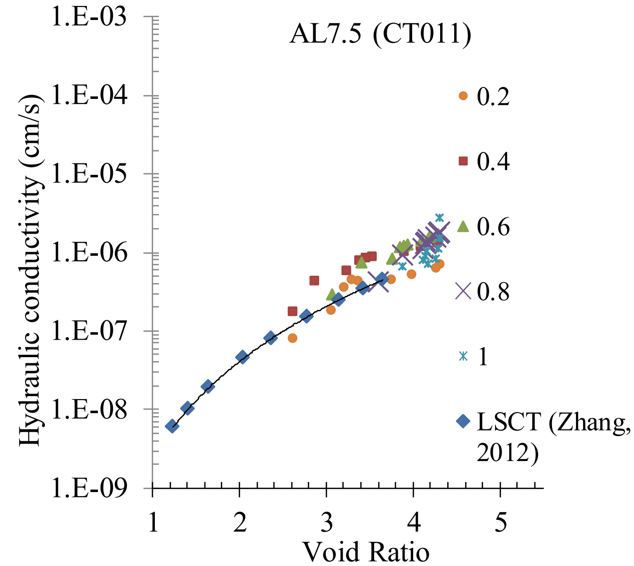

Figure 35. Permeability of AL-7.5 from centrifuge and LSCT

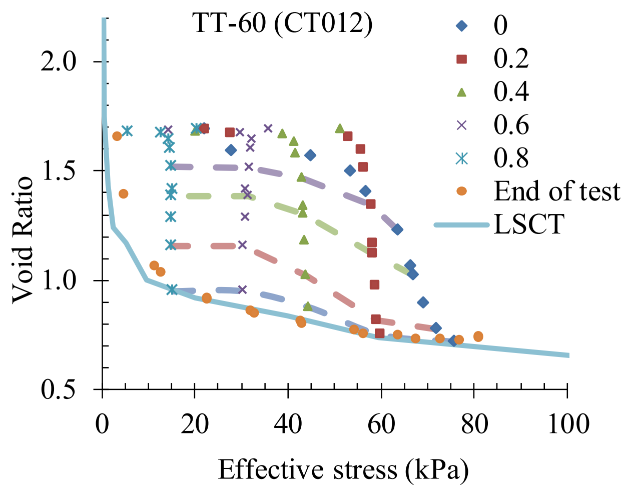

Figure 36. Compressibility of TT-60 from centrifuge and LSCT

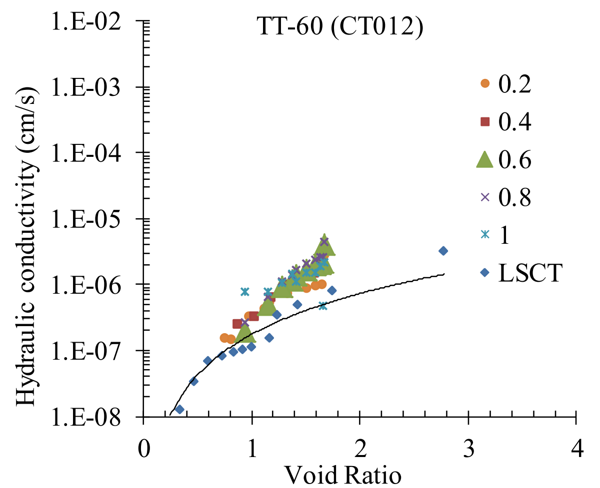

Figure 37. Permeability of TT-60 from centrifuge and LSCT

The classical large or infinitesimal strain theory of consolidation assumes a unique compressibility (effective stress-void ratio relationship) for a given soil. Leroueil (1996) found that the compressibility of soil is not a unique function of

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void ratio but depends on numerous factors, such as strain rate, temperature, stress path, and some restructuring factors. Šuklje (1957) originally proposed a model (the isotaches method) that includes strain rate effect on the behaviour of soil. Based on the constant rate of strain (CRS), controlled gradient, multiple-stage loading and creep tests, Leroueil et al. (1985) showed that the compressibility of soil depends on strain rate. Because the strain rates normally used in CRS tests are usually greater than those used in conventional consolidation tests (oedometer test), CRS compressibility is generally above oedometer tests. Leroueil et al. (1986) and Imai and Tang (1992) also showed that the effective stress-void ratio, followed by an element in the soil, depended on the position of the element relative to the drainage boundary (or depended on the actual strain rate profile within the deposit).

Boudali et al. (1994), Imai and Tang (1992), and Kim and Leroueil (2001) proposed a model that stipulates compressibility dependence on strain rate and/or temperature. Leroueil (1996) indicated that all stress-strain curves obtained at various strain rates and temperatures come into a unique one when they are normalized with respect to the preconsolidation pressure corresponding to the strain rate and the temperature used in each test. Typically, preconsolidation pressure decreases by 1% per 1°C temperature increases (Leroueil, 1996). Most of the previous laboratory investigations and modelling of the effect of strain rate and temperature are focused on small strain consolidation, and the existing results do not indicate that the observed behaviour is limited or depend on strain magnitude.

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Equation 6 shows the strain rate relationship between the model and the prototype. For a centrifuge test at 10 to 100g, Equation 6 indicates that the strain rate in centrifuge model is 2-4 orders of magnitudes higher than the prototype. Table 6 summarizes the average strain rates and the maximum strain rates observed during centrifuge tests CT005-CT0012. The table also lists the range of strain rates in the odometer and CRS tests, and the average strain in LSCT as a comparison. Figure 38 shows the measured strain rate in the centrifuge tests as a function of model elapsed time. Figure 39 and Figure 40 compares the average strain rate from LSCT and the strain rate from the centrifuge test for kaolinite and thickened tailings, respectively. The average strain in LSCT is calculated from the average strain at different loading stages (Figure 41). Table 6 and Figures 38 to 41 reveal that the strain rates observed in centrifuge tests are generally higher than those in conventional tests. Figure 38 indicates that higher strain rates occur during the initial stage of settling and that the strain rate decreases as the consolidation progress. Because of the viscous fluid behaviour, higher strain rates mobilize higher effective stresses, and thus compressibility is well above the compressibility from the LSCT at the initial stages of settling. Furthermore, as the consolidation progresses, the strain rate decreases and the compressibility is correspondingly lowered. Near the end of consolidation, the strain rate approaches that of LSCT, the strain rate within the model also is more uniform, and the compressibility converges to that of LSCT. The data analyses and existing laboratory results in the literature cited above indicate that the strain rate effect can be considered to explain the non-unique compressibility during the test

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flights. Centrifuge differs from conventional CRS tests not only because of the higher strain rate but also because the strain rate is not constant during the test. The temperatures of the centrifuge room were 5 to 8°C above the room temperature, depending on the test duration and centrifuge acceleration. The pore pressure and TDR readings compensated for the changes in temperature, and thus the strain rate effect is believed to be more dominant than the temperature effect for the observed non-unique compressibility during the tests.

$$\frac{\dot{\varepsilon}_m}{\dot{\varepsilon}_p} = \frac{\frac{\partial \varepsilon_m}{\partial t_m}}{\frac{\partial \varepsilon_p}{\partial t_p}} = \frac{\partial t_p}{\partial t_m} = N^2 \qquad [6]$$

where $\dot{\varepsilon}_m$ is the strain rate in the model, $\dot{\varepsilon}_p$ is the strain rate in the prototype, ε_m is the strain rate in the model, ε_p is strain rate in the prototype, tm is consolidation time in the model, tp is consolidation time in the prototype, and N is the ratio of acceleration in centrifuge and Earth gravitational acceleration.

The dewatering rate (i.e. the strain rate) of oil sands FFT in a tailings pond is much slower than under laboratory test conditions. Without considering time-dependent effects such as thixotropic, the centrifuge test results imply that compressibility is dependent on strain rate. Thus, pond compressibility is expected to be lower than LSCT laboratory curves. The same void ratio can be reached at much lower effective stress in the tailings ponds than in laboratory tests. On the other hand, treated and flocculated tailings have a higher dewatering rate. So, if void ratios and pore pressures are monitored as the consolidation

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process progresses, the effective stress-void ratio relationships are expected to be higher than LSCT laboratory curves.

Table 6. Summary of strain rate in centrifuge and conventional consolidation tests

Material Designation	Centrifuge Test Code	Centrifuge Tests, Strain Rates: 1/s maximum	average	minimum	LSCT average strain rates:1/s	CRS* typical strain rates: 1/s	Oedometer** typical strain rates: 1/s
Kaolinite	CT005	4.05E-04	1.02E-04	5.39E-07			
Kaolinite	CT006	3.39E-04	7.45E-05	2.26E-07	1.28E-06		
Kaolinite	CT007	1.72E-04	3.96E-05	1.69E-07		1E-06 to	5E-08 to
AL-7.5	CT011	5.52E-05	5.49E-06	7.14E-07	N/AV	4E-06	5E-06
AL-15	CT009	2.5E-05	4.60E-06	2.40E-07	N/AV		
TT-50	CT012	4.26E-05	1.24E-05	8.45E-08	1.59E-07		
TT-60	CT008	1.50E-05	4.62E-06	1.39E-07	1.87E-07		
FSMT	CT010	1.41E-04	1.64E-05	1.18E-07	1.32E-06		

N/AV- not available, *(Leroueil, 1988), **(Leroueil, 1996)

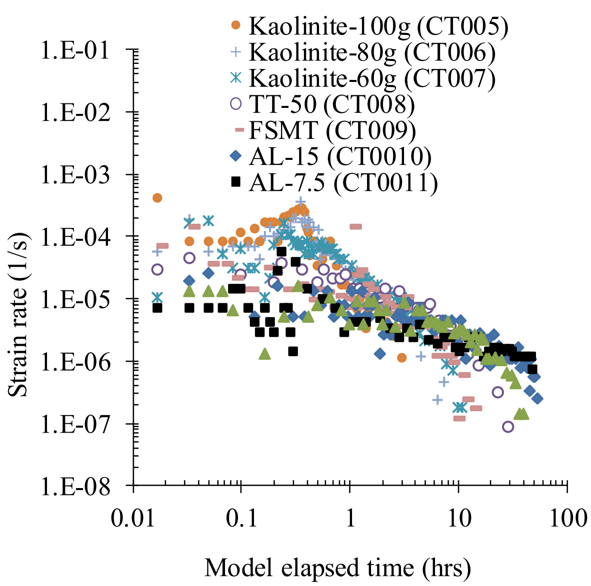

Figure 38. Stain rates in centrifuge models at different elapsed times

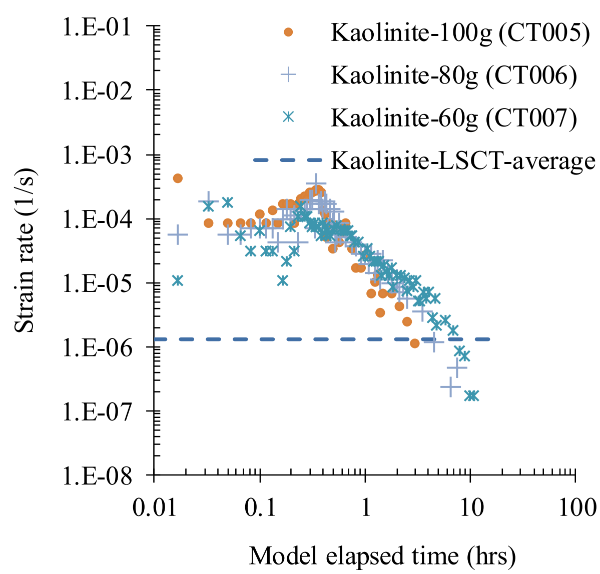

Figure 39. Kaolinite strain rate in centrifuge and LSCT tests

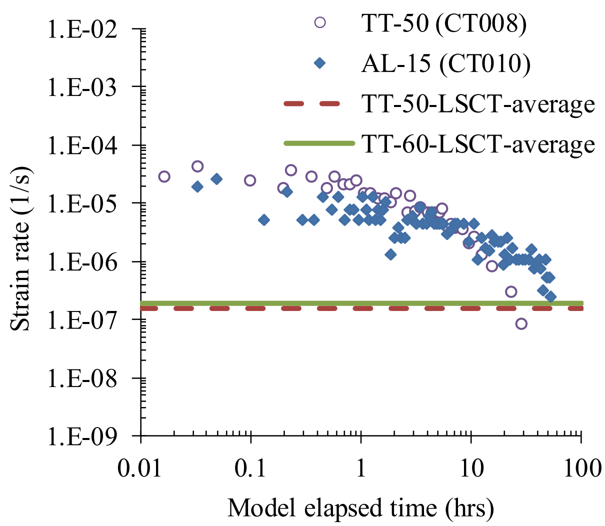

Figure 40. TT-50 and TT-60 strain rates in centrifuge and LSCT tests

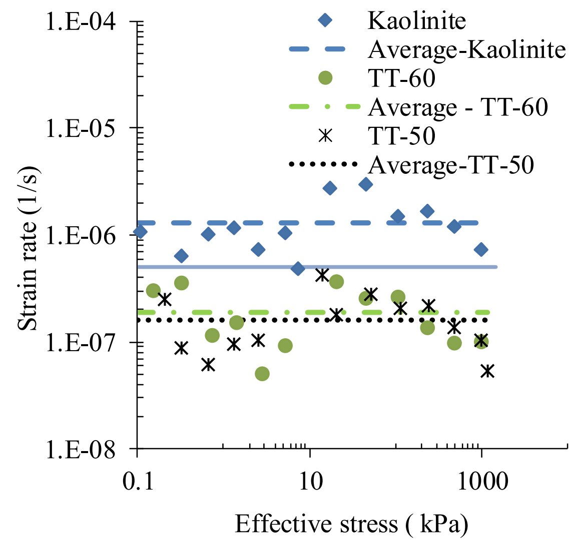

Figure 41. Kaolinite, TT-60 and TT-50 strain rates at different stages of loading

14. LASER DISPLACEMENT SENSOR (LDS) FOR INTERFACE SURFACE SETTLEMENT MONITORING OF TAILINGS IN CENTRIFUGE

Changes in soil thickness in conventional soil testing are normally measured using contact-type transducers, such as the linear variable differential transformer (LVDT). An LVDT is a precise method for measuring displacement over the design range of movement. However, contact-type transducers are too heavy to be supported by tailings in the centrifuge tests. This is because the tailings have very low shear strength and the weight of the transducer increases with the application of gravity in the centrifuge. Non-contact-type displacement measuring devices are thus more suitable for the interface settlement monitoring of high water content materials in a centrifuge. Different types of cameras, fixed in position or flying with a model, have been used for interface settlement monitoring. The images acquired during the test are processed to give the

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interface settlement, but the long data processing time and reduced measuring accuracy are some of the limitations imposed by the cameras. Moreover, the maximum acceleration that the cameras can withstand limits the maximum speed that can be used for the centrifuge testing.

The self-weight consolidation of a slow dewatering behaviour material like oil sands FFT requires a continuous centrifuge run for many hours or days. However, running multiple models in a single centrifuge flight can save both energy and costs (Mitchell, 1998). The number of models that can be tested per flight depends on the size of the consolidation cell, the payload volume of the centrifuge, and the space requirements of the transducers and cameras. In-flight cameras need to be placed at some distance from the model to measure the interface settlement. Space is also required for the cameras' supporting frames and lamps. This need for space usually means that only one model can be run at a time. In contrast, an LDS can be set up at the top of the consolidation cell and requires less space than the camera setup. Thus, the use of an LDS may increase the possibility of running multiple samples in a single centrifuge test. Furthermore, the resolution of measurements and the data processing time of an LDS are better than the use of cameras and a millimeter-graduated metric ruler.

In light of the benefits of the LDS, its use for interface monitoring of the self-weight consolidation of tailings in a centrifuge is examined in this study. The principle of LDS measurement is that light beam from a light source is directed on the object, and the reflected light beam is sensed by the receiving lens. The reflected light and the position-sensitive detector components of the sensor are

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used to determine the position of the object. In a conventional application of LDS, the light source passes through a medium of air to reach the object and reflect back to the sensor. In self-weight consolidation, there is normally a layer of water above the tailings/slurry surface (cap water), and thus the light beam must passes through air and liquid media before reaching the tailings surface and reflecting back to the sensor. The change in the angle of reflection of the light beam passing through two different medium could affect the range, performance and calibration equation of the sensor.

Some preliminary tests were conducted at Earth gravity to calibrate the laser displacement sensor (Keyence IL-100 model) and to investigate the effect of light passing through air and liquid media. Figure 42 shows a typical response from the calibration tests. Figure 43 shows consolidation test monitoring using LVDT and LDS using the LSCT apparatus. Figure 44 shows the LVDT and LDS readings from a consolidation test conducted using the LSCT apparatus. The test results at Earth gravity indicate that while a laser can be used to measure the interface settlement with high resolution, the calibration constant slightly varies with the position of the probes relative to the surface and the height of the cap water. If the initial and final heights of the soil surface are known for the given setup, the sensor reading can be multiplied by a single calibration constant that fits the initial and final height of the tailings surface. The clarity of the cap water also affects the LDS. During self-weight consolidation, the composition of released water is expected to remain constant and does not affect LDS, unless

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there is particle segregation that can allow fines particles to migrate and change the clarity of the cap water.

Centrifuge tests CT0011 and CT0012 were instrumented with the LDS together with in-flight cameras for the interface settlement monitoring. The tests were done on TT-60 at 90g and AL-7.5 at 70g. The laser sensor was supported on the lid of the consolidation cell, as shown in Figure 45, and the LDS readings are compared with the camera readings, as shown in Figures 46 and 47. The voltage reading of the LDS was multiplied by a constant so that it fits with the initial and final height of the tailings. The results indicate that laser displacement sensors can be used for interface settlement monitoring of tailings in a centrifuge. The sensor has a higher resolution and requires less data processing time than in-flight camera images. However, as the LDS needs to be at some distance from the tailings surface, for a light beam projected to be reflected back and received for measurement. Thus the consolidation cell should have a free board (i.e., space above the water layer).

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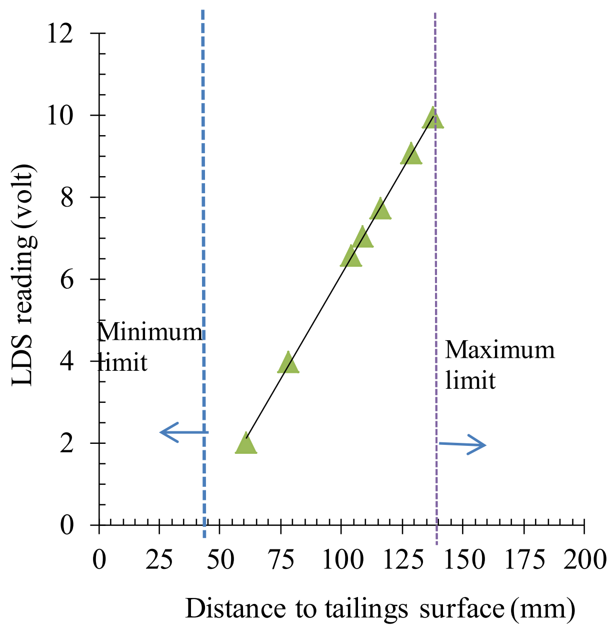

Figure 42. Laser displacement sensor Model 1, calibration at Earth gravity

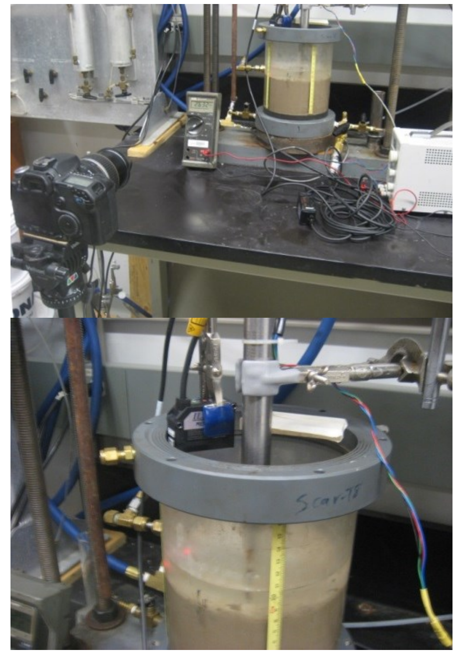

Figure 43. LDS and LVDT setup in LSCT apparatus

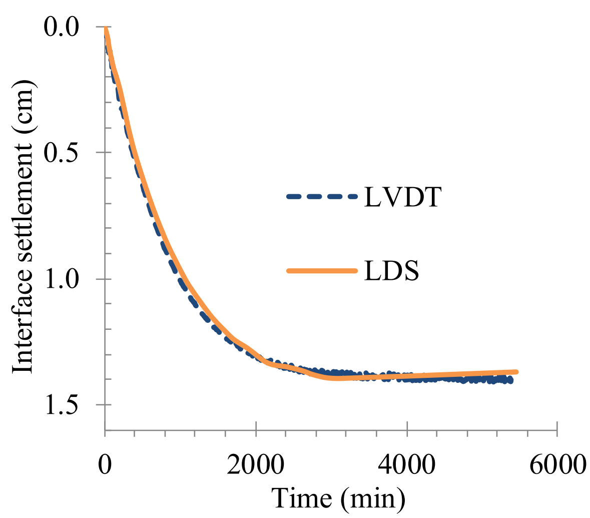

Figure 44. interface surface monitoring in large stain consolidation test apparatus using LVDT and LDS

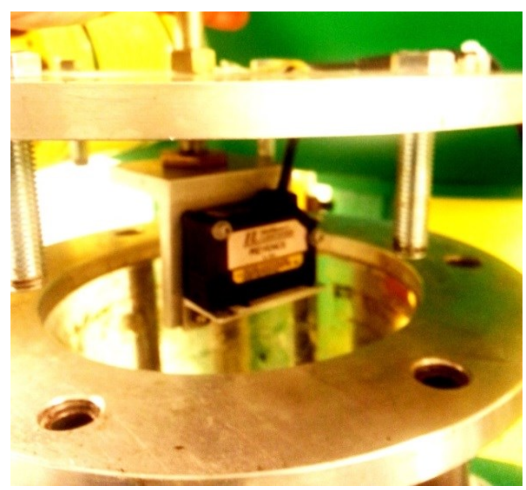

Figure 45. LDS supported in centrifuge consolidation cell lid

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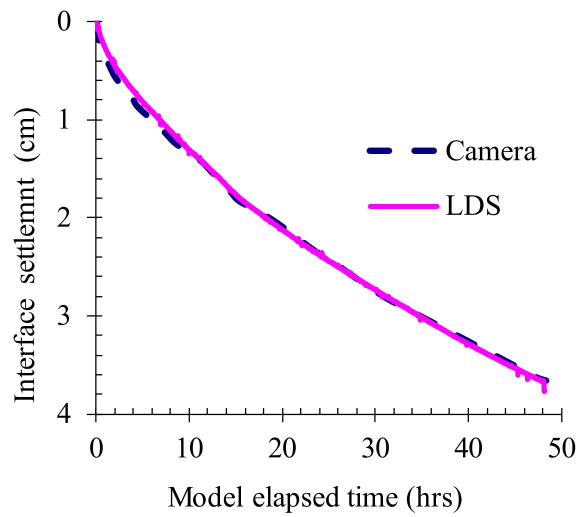

Figure 46. Interface settlement monitored using in-flight camera and LDS- CT0011 test

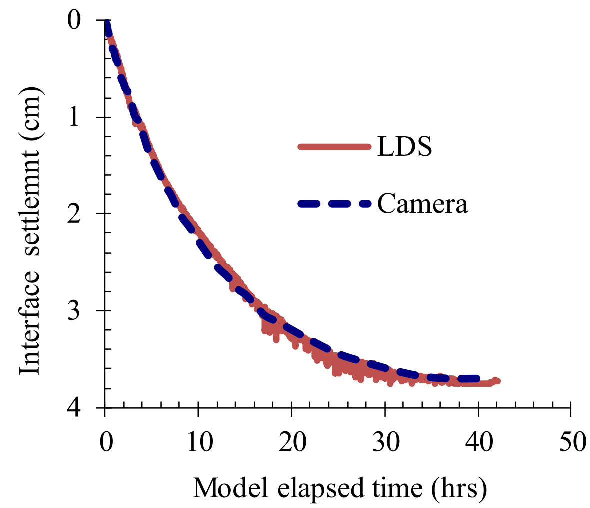

Figure 47. Interface settlement monitored using in-flight camera and LDS- CT0012 test

15. CENTRIFUGE RESULTS VERSUS NUMERICAL MODEL PREDICTION

The suitability of large strain numerical models in predicting changes in the volume behavior of tailings is examined in this section by comparing these results with centrifuge test results extrapolated to prototypes. Input parameters for numerical models were derived from the LSCT apparatus (except for material AL-15, which was derived from a centrifuge test). The FSConsol slurry consolidation program was used for the numerical modelling prediction. FSConsol is a one-dimensional slurry consolidation program based on the finite strain consolidation theory of Gibson et al. (1967) and developed by GWP Geo Software Inc. In addition to the consolidation parameters, the initial height, initial void ratio, specific gravity and duration of consolidation analysis were given as inputs for the numerical model, and "Tank-type Analysis" was used. Tank-type analysis is suitable for comparisons involving centrifuge results as it is intended to simulate a problem in which a container is filled instantaneously. The laboratory

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compressibility and the permeability data were inserted in the program in the form of power equations (Equations 7 and 8). Table 7 summarizes the constants A, B, C and D in Equations 7 and 8 for the materials used in this study. The interface settlement and the elapsed times of the centrifuge results were extrapolated to the prototype by using a theoretical time-scaling relation between the model and the prototype given in Table 2 (model interface settlement scaled by the number of accelerations and the elapsed time by the square of the number of accelerations used in the centrifuge).

$$e = A\sigma'^{B} \qquad [7]$$

$$k = Ce^{D} \qquad [8]$$

where e is void ratio, σ' is effective stress, k is the hydraulic conductivity, and parameters A, B, C and D are laboratory-determined parameters. Parameters B and D are unitless, whereas parameter C is the same as the unit of hydraulic conductivity, and parameter is one over the stress unit.

Table 7. Large strain consolidation input parameters

Material	Parameters			
	A (1/pa)	B	C (m/s)	D
Kaolinite	13.503	-0.210	1.7-E09	4.011
TT-50	5.294	-0.190	2.0E-09	3.556
FSMT	1.698	-0.111	9.3E-08	4.150
AL-15*	17.991	-0.255	6.0E-10	3.351
AL-7.5	10.726	-0.190	3.0E-11	3.559
TT-60	10.236	-0.237	1.5E-08	3.701

* Derived from centrifuge

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Figures 48 to 53 compare numerical model predictions and centrifuge test results. The marked points represent the centrifuge results and the solid lines represent the results from the numerical model using LSCT consolidation parameters (centrifuge parameters for AL-15). The ultimate settlements of the numerical model are comparable but the settlement rates are slower than the measured centrifuge results. The numerical method and the centrifuge tests do not consider the time-dependent effects, and thus the differences in settlement rates may not be related to time-dependent effects. The centrifuge result is not affected by the segregation of particles, as non-segregating materials were selected for the test program. Moreover, the void-ratio profile at the end of the centrifuge does not indicate the sorting of particles based on particle size. Images taken during the tests and observations made at the end of the tests do not indicate the formation of internal dewatering pathways (structures). The reasons for this discrepancy are somewhat uncertain, but the strain-rate effect is not considered in the numerical model and the hydraulic gradient used in the laboratory may result in lower hydraulic conductivity. Generally, the permeability from the centrifuge tests was found to be higher than the LSCT permeability, as shown in permeability plots from Figures 27 to 37. The centrifuge results were extrapolated using theoretical time relation between the model and prototype, but the modelling of the model results in this study indicates that the time-scaling relation between the model and the prototype may differ from the theoretical value at certain stages of consolidation.

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In order to fit the centrifuge results, a series of numerical analyses were run with different sets of large strain consolidation parameters. The numerical model prediction and centrifuge results were found to be close when using the measured compressibility data and were also higher than the measured permeability data of the LSCT. The permeability was found to increase by less than one order of magnitude. The dotted line in Figures 48 to 53 shows the numerical model prediction used in LSCT compressibility data and permeability data to fit the centrifuge results.

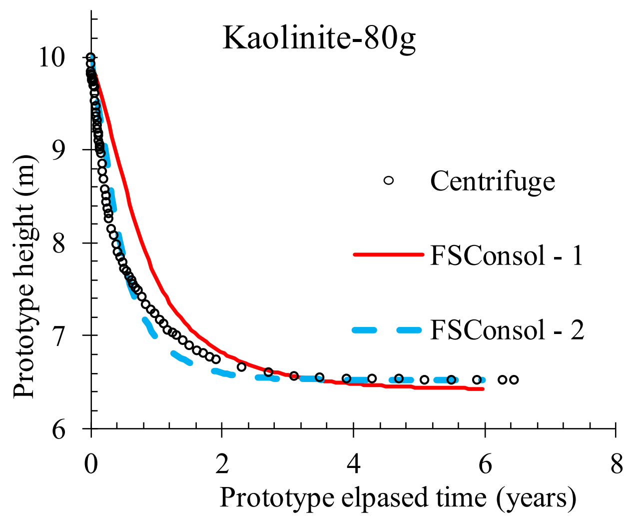

Figure 48. Comparison of centrifuge results and FSConsol prediction – Kaolinite-80g

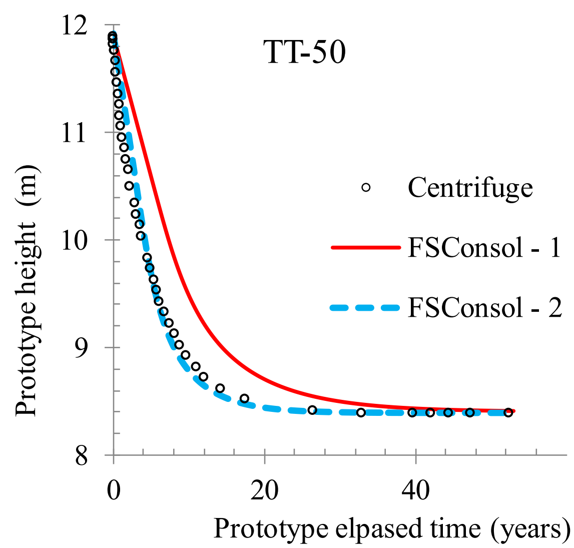

Figure 49. Comparison of centrifuge results and FSConsol prediction – TT-50

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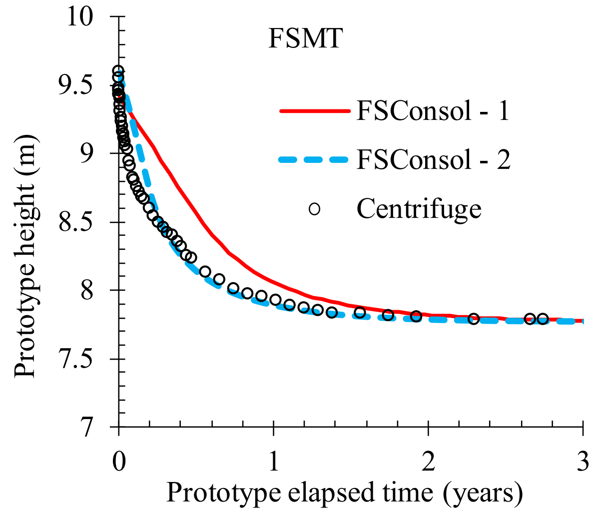

Figure 50. Comparison of centrifuge results and FSConsol prediction - FSMT

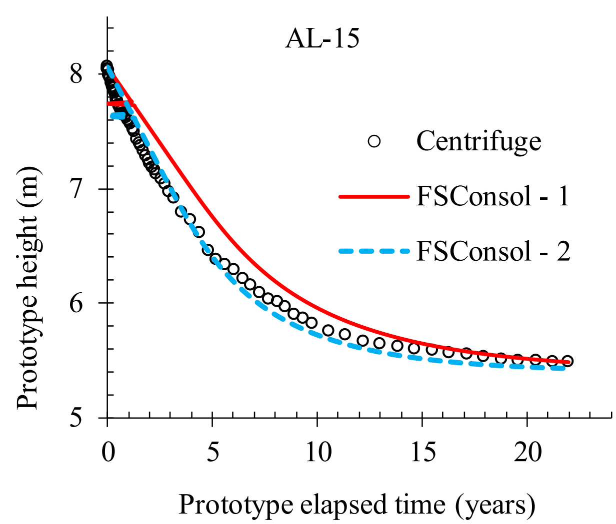

Figure 51. Comparison of centrifuge results and FSConsol prediction – AL-15

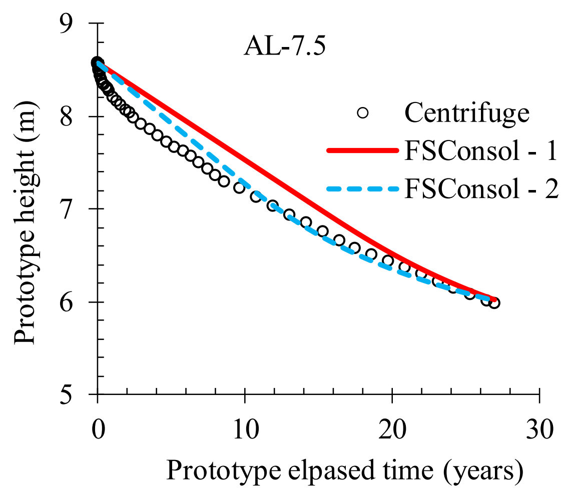

Figure 52. Comparison of centrifuge results and FSConsol prediction – AL-7.5

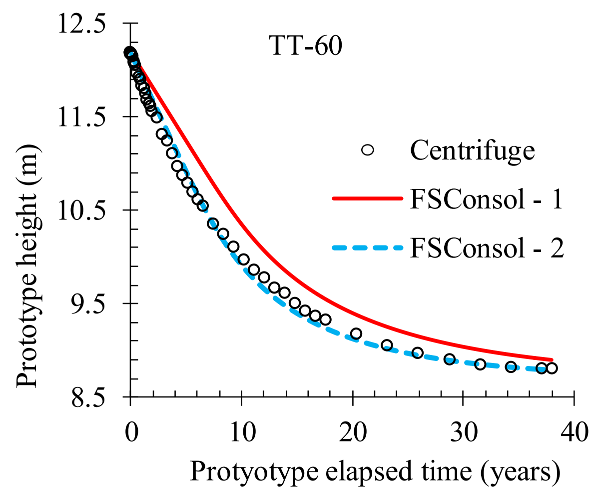

Figure 53. Comparison of centrifuge results and FSConsol prediction – TT-60

16. CONCLUSION

A number of centrifuge tests were conducted using oil sand tailings and kaolinite for modelling verification as well as for evaluating instrument applications for use during centrifuge testing, driving consolidation parameters from in-flight

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measurements of pore pressure and solids content profiles, and studying the long-term consolidation behaviour of oil sand tailings in centrifuge while comparing these results with large strain consolidation numerical model predictions. The centrifuge tests were conducted at different initial compositions and heights, at an acceleration of 40 to 100g. All centrifuge tests were conducted at GeoREF, except for one, conducted at the C-CORE centrifuge facility. Large strain consolidation parameters were also determined using the LSCT apparatus and were used as an input for numerical models and compared with centrifuge-derived consolidation parameters. The following conclusions can be drawn from the tests and analyses of the test results.

- The centrifuge tests conducted at two centrifuge facilities (C-CORE and GeoREF) on the same materials and initial conditions and accelerations gave similar results, indicating that the centrifuge test is repeatable between the two facilities.
- The modelling procedure was verified by running the model tests on kaolinite slurry and two centrifuge tests on thickened oil sand tailings of the same initial void ratio and prototype height, but at different fine-sand ratios, showing that the settlements from the thickened tailings are close. Moreover, the compressibility curves from the modelling of model at the ends of the tests are the same. The tests proved that the deformation scaling relation between the model and the prototype is equal to theoretical scaling laws. The time-scaling relation seems dependent on the degree of consolidation, but the average value is close to theoretical value.

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- The effect of centrifuge radius definition on the rate and magnitude of settlement is insignificant. Also, the use of constant acceleration or varying the acceleration based on the change in thickness of the model as the consolidation progresses has a minor effect. That these effects are minimal may be due to the fact that the height of the model/centrifuge radius used in the testing program is below the height recommended for the maximum height-to-radius ratio for centrifuge modelling (<20%).
- TDR can be used to measure the solids content profile monitoring of soft soils during centrifuge flight. TDR readings are not influenced by the high gravity of the centrifuge, and probe calibration is not influenced by the installation of a probe through a Plexiglas cylinder.
- Solids content and pore pressure monitoring provide deeper insight into the mechanics of tailings consolidation and can be used to determine consolidation parameters from data collected during the test flight.
- Pore pressure started dissipating immediately after loading, indicating that consolidation type of settlement governs changes in the volume behaviour of tailings or kaolinite in centrifuge.
- LDS can be used for monitoring of interface settlement of soft soil. It requires less space and has higher resolution than in-flight cameras. The use of LDS may increase the possibility of running multiple models in a single centrifuge flight.
- The strain rate in the centrifuge is higher than conventional consolidation tests. The strain rate is not constant during the centrifuge test, is high at the

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initial stage of consolidation, and decreases as the consolidation progresses. The compressibility of oil sand tailings and kaolinite appear to depend on the rate of strain. Compressibility measurements obtained during the centrifuge flights are higher than those derived from the LSCT apparatus. Centrifuge compressibility tends to come to closer to the LSCT results as the consolidation progresses and the strain rate decreases. Compressibility at the end of the centrifuge flight is similar to that of LSCT results.

- Hydraulic conductivity-void ratio relationships derived from centrifuge are found to be above that of LSCT results.
- Although FSConsol settlement predictions are generally lower than those for centrifuge at given prototype elapsed times, ultimate settlement predictions agree with centrifuge results. Furthermore, numerical modelling predictions agree with centrifuge results when measured compressibility and higher-than-measured permeability are used. Hydraulic conductivity was increased by less than one order of magnitude to achieve an acceptable match.
- Centrifuge replicates important stresses that govern consolidation, enabling self-weight consolidation to be modelled in a shorter time. Because the centrifuge testing method separates time-dependent and gravity-dependent factors, it is important to study gravity-dependent factors on the consolidation of tailings. Moreover, because time-dependent effects such as thixotropic and creep are not properly model in a

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centrifuge, the model results may not represent actual prototypes where the effect of time-dependent processes have a significant influence on changes in the volume behaviour of tailings. The effect of chemical and biological processes along with environmental effects such as seasonal drying, freezing and thawing need to be considered in modelling and interpreting model results to the actual prototype, as do the sequence and layer of deposition and tailings in homogeneity. The effect of strain also needs to be considered in laboratory and prototype-scale consolidation.

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CHAPTER 6. BEHAVIOUR OF OIL SANDS FINES-SAND MIXTURE TAILINGS

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CHAPTER 6. BEHAVIOUR OF OIL SANDS FINES-SAND MIXTURE TAILINGS

ABSTRACT

The settling, shear strength, and index properties of oil sands fines-sand mixture tailings (FSMT) for a wide range of solids and fines content are investigated. Results indicate that the liquid limit of FSMT obeys a linear mixture law. The fines-water ratio (FWR) governs the permeability of composite tailings (CT) and CT with comparable geotechnical behaviour can be produced from the same initial FWR mixtures. A phosphogypsum (PG) dosage > 900 mg/kg does not further improve the dewatering behaviour of CT. The undrained shear strength of FSMT at the liquid limit is approximately 2.4 kPa, but is dependent on fines content at the plastic limit.

1. INTRODUCTION

Oil sands bitumen extraction processing in northern Alberta produces high water content extraction tailings composed of sand, silt, clay, and a small amount of unrecovered bitumen. The extraction process involves surface mining and the use of hot water, steam, and caustic soda (NaOH) to liberate bitumen from oil sands ore (Fine Tailings Fundamentals Consortium [FTFC], 1995; Chalaturnyk, Scott, & Özüm, 2002). Albian Sands Energy Inc. uses sodium citrate instead of caustic soda to aid in liberating the bitumen. Conventionally, the extraction tailings are discharged into tailings ponds where the coarse particles segregate and form beaches/dikes, whereas the fines tailings flow to tailings ponds as a thin slurry (5–

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8% solids). The fines tailings settle to 20% solids content in a few months and to 30% solids content in a few years. Upon reaching 30% solids content, the fines tailings are called mature fines tailings (MFT) and the water release rate becomes very slow, taking close to 100 years for self-weight consolidation (FTFC, 1995).

The slow dewatering behaviour of MFT initiated the innovation of different processes and technologies to improve the water release characteristics of tailings (BGC Engineering Inc., 2010). As both fines and sand are by-products of the bitumen extraction process, tailings management that involves blending fine and coarse tailings and disposing of the mixture may have economical and engineering advantages when compared to disposing of and treating the fines tailings separately. Different fines-sand mixture tailings (FSMT) disposal options, such as composite/consolidated tailings (CT), thickened tailings, nonsegregating tailings, and MFT-sand-overburden mixtures have been considered for treating oil sands tailings (Sobkowicz & Morgenstern, 2009; BGC Engineering Inc., 2010).

Despite the fact that both fine and coarse tailings are produced and their mixtures are components of existing tailings disposal strategies, fundamental studies on the geotechnical behaviour of FSMT are limited, especially with regard to proportioning the fines and sand to change the behaviour of the mixture. It is important to examine the fundamental behaviour of FSMT at various sand-fines ratios (SFRs) because the efficiency of the tailings treatment method and the strength, dewatering, and flow behaviour of the resulting product are a function of the relative proportion of fines and coarse particles.

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The focus of this study is to investigate the fundamental behaviour of oil sands FSMT at various SFRs to aid in the planning and disposal of FSMT. The relative proportion of fines to sand and the effect of residual bitumen on the geotechnical behaviour of FSMT, the material parameters that control the settling and strength behaviour of the FSMT, and the effects of coagulant/flocculent addition on the settling behaviour of the FSMT are addressed by conducting vane shear, settling column (standpipe), and index tests on combined tailings at various fines and solids contents.

2. METHODS

2.1. Description of materials

Fines and coarse tailings from Albian Sands Energy Inc. are used in the study. The Albian fines tailings are MFT taken from the Albian Muskeg River mine tailings pond from depths of 7.5 m (Albian_7.5) and 15 m (Albian_15). The coarse tailings are Albian beach sand - the coarse portion of extraction tailings that segregated while the tailings were discharged into large tailings containment. Table 1 summarizes the characteristics of the tailings. Fines content is defined as the mass of solids passing the No. 325 (0.045 mm) sieve relative to the total mass of solids. This definition of fines is consistent with oil sand industry use, though materials passing the No. 200 (0.075 mm) or the No. 230 (0.063 mm) sieve are commonly classified as fines in soil mechanics. Clay is defined as the solids fraction containing particles finer than 2 μm. The residual bitumen in the tailings

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is considered a solid and the bitumen content is defined as the mass of bitumen over the total mass of solids.

Table 1. Characteristics of tailings

Material	Bitumen (%)	Fines <45 μm (%)	Fines <75 μm (%)	Clay (%)	Clay Fines Ratio (%)
Albian_15	7.0	91	96	38	42
Albian_7.5	1.0	99	99	57	58
Beach Sand	0.0	5	11	0	0

3. LIQUID AND PLASTIC LIMITS OF FSMT

The Atterberg limit tests are the most widely used tests in geotechnical engineering practice for soil classification, as well as for correlation and prediction of various soil properties (Wroth & Wood, 1978; Sivapullaiah & Sridharan, 1985). The swelling, shrinkage, compressibility, permeability, and shear strength properties of a soil can be related to its Atterberg limits (Sivapullaiah & Sridharan, 1985). For example, Carrier III and Beckman (1984) and Morris (2003) used index properties to normalize and describe the compressibility and permeability of high water content materials over a wide range of void ratios. Correlation of Atterberg limits with remolded strength provides a lower bound for in situ strength, with the remolded compression index providing a lower bound for compressibility (Skempton & Northey, 1952). Soil parameters derived from index tests can be used in preliminary design when it is very difficult and expensive to extract undisturbed samples and/or to conduct laboratory or field tests (Wroth & Wood, 1978).

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Even though the Atterberg limits have an important application, the tests are underused within the oil sands industry (Sobkowicz & Morgenstern, 2009), only a few test results are available, and efforts to correlate with the consolidation, permeability, and strength characteristics of tailings are limited. The objectives of the liquid and plastic limit tests in this study are to experimentally define the liquid limit–fines content and plastic limit–fines content relationships of oil sands FSMT and to examine the effect of the residual bitumen on these relationships. Defining the relationships can broaden the use of Atterberg limits for correlation and prediction of oil sands tailings engineering properties at different SFRs. Once the index properties of the tailings at different SFRs are known and correlated with strength parameters, the task of predicting the strength of tailings at the disposal facility, the surcharge load, and the degree of consolidation required to attain a desired strength can be greatly simplified (Wissa, Fuleihan, & Ingra, 1983).

The liquid and plastic limits of Albian_7.5-sand and Albian_15-sand mixtures were examined at a fines content of 20–99%. The FSMT with the desired solids and fines content were prepared by mixing beach sand with Albian_7.5 or Albian_15. It was necessary to decrease the water content of Albian_7.5 and Albian_15 to close to their liquid limit before mixing with the sand. The water content of the MFT was decreased by self-weight consolidation and incremental loading sample preparation. The sample preparation procedure was time consuming due to the slow dewatering behaviour of the MFT, but offered the advantage of maintaining the appropriate fines content, pore-fluid chemistry, and

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bitumen content of the MFT. The concentration of soluble salt, the percentage of fines, and the bitumen content affect the liquid and plastic limits (Scott, Dusseault, & Carrier III, 1985); hence, it was important to preserve these during sample preparation. The Atterberg limit test on the FSMT was conducted according to the American Society for Testing and Materials (ASTM; D4318-10) testing procedures (ASTM, 2010). Previous studies on fines tailings (Suthaker & Scott, 1997; Miller, Scott, & Sego, 2011) and FSMT (Sorta, Sego, & Wilson, 2012) indicate that oil sands tailings are thixotropic materials. Thus, the Atterberg limit tests were performed immediately after mixing to minimize the effect of thixotropy on the measured values.

The results of the liquid limit, plastic limit, and plastic index of the FSMT are presented in Figures 1 and 2. Figure 1a shows the liquid limit–clay content relationship of the FSMT and the results indicate that the liquid limit of the FSMT is governed by the linear law of mixture; that is, the ratio of liquid limit to clay content is constant. For natural soils without any residual bitumen, the liquid limit is a linear function of clay content (Skempton & Northey, 1952; Trask & Close, 1957; Seed, Woodward, & Lundgren, 1964b; Pandian, Nagaraj, & Raju, 1995; Polidori, 2007). Like natural soils, oil sands FSMT follow a linear mixture law, despite the presence of residual bitumen and its variation with clay content in the samples. The slope of the liquid limit–clay content relationship for natural soils varies from 0.67 to 4.86; the minimum value is for kaolinite mineral and the higher value for montmorillonite clay (Polidori, 2007). The slope of the liquid limit–clay content relationship of the FSMT is within and close to the lower range

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of natural soils, indicating that the clay mineral in the MFT is kaolinite. As with the clay content, the liquid limit has a linear relationship with the fines content (Figure 2a). This is because the clay-fines ratios of the FSMT are constant; however, the slope of the liquid limit–fines content relationship of Albian_7.5-sand FSMT is different from Albian_15-sand FSMT because the clay-fines ratio of Albian_7.5 is different from that of Albian_15 (Table 1).

The plastic limit test results of the FSMT are presented in Figures 1b and 2b. The linear relationship between the plastic limit and clay content is weaker than the linear relationship between the liquid limit and clay content (Figure 2). This is consistent with the literature in that the plastic limit is not a simple linear function of clay contents (Fukue, Okusa, & Nakamura, 1986; Polidori, 2007). Due to the frictional resistance between non-clay particles, the plastic limit is independent of clay content and increases slightly with increasing sand content when the clay content of the mixture is low (Fukue et al., 1986).

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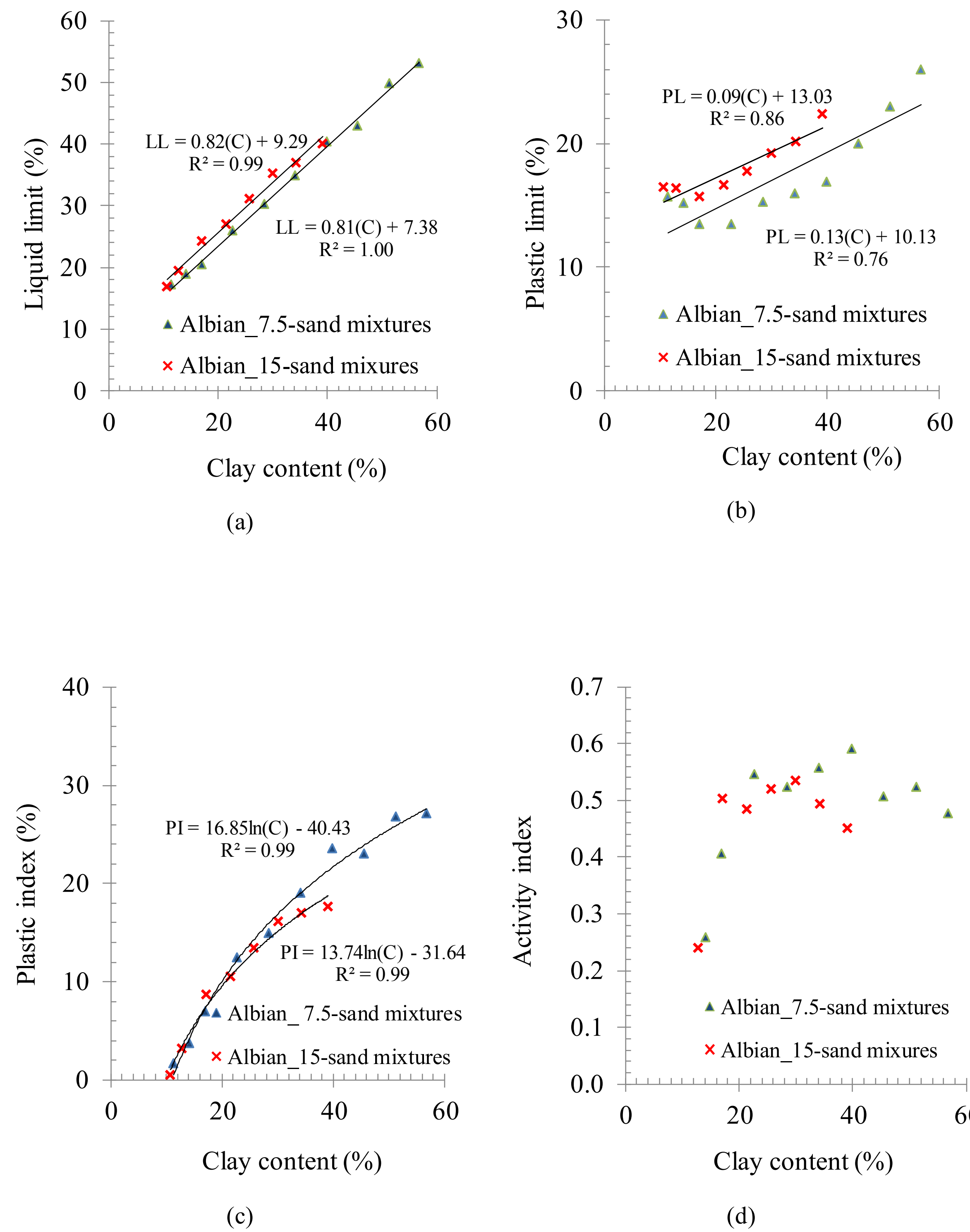

Figure 1. a) Liquid limit; b) plastic limit; c) plastic index; and d) activity index of Albian_7.5-sand mixtures and Albian_15-sand mixtures as function of clay content

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The plastic index–clay content relationships of the FSMT are shown in Figure 1c and the results indicate that the plastic index–clay content relationship cannot simply be described by a linear function. Skempton and Northey (1952) and Seed, Woodward, and Lundgren (1964a), however, indicate that the plastic index of natural soils is a linear function of clay content. Upon further investigation, Seed et al. (1964b) showed that the plastic index–clay content is better described by a bilinear relationship: a line that passes through the origin for clay content > 40% and another line for clay content < 40% that intercepts the clay axis. The results from the present study show that the plastic index of the FSMT can be described using the bilinear relationship but is best described by the logarithmic function of clay content (Figure 1c). For clay content < 10%, it appears that the FSMT are nonplastic (Figure 1c); this is consistent with the literature, except for mixtures containing montmorillonite clay, in which clay-sand mixtures are nonplastic when clay content is < 10% (Trask & Close, 1957; Seed et al., 1964b).

The plasticity of the FSMT is below the 'U' line of the plasticity chart, indicating that the index properties of oil sands FSMT are within the ranges of natural soil plasticity (Figure 2d). For clay content < 20%, the FSMT behave as low-plasticity silt (Figure 2d). For clay content > 20%, the relationship between the liquid limit and clay content of the FSMT is above the "A" line of the plasticity chart, indicating that the addition of the sand results in the mixture behaving as a low-plasticity clay or low-plasticity clayey soil.

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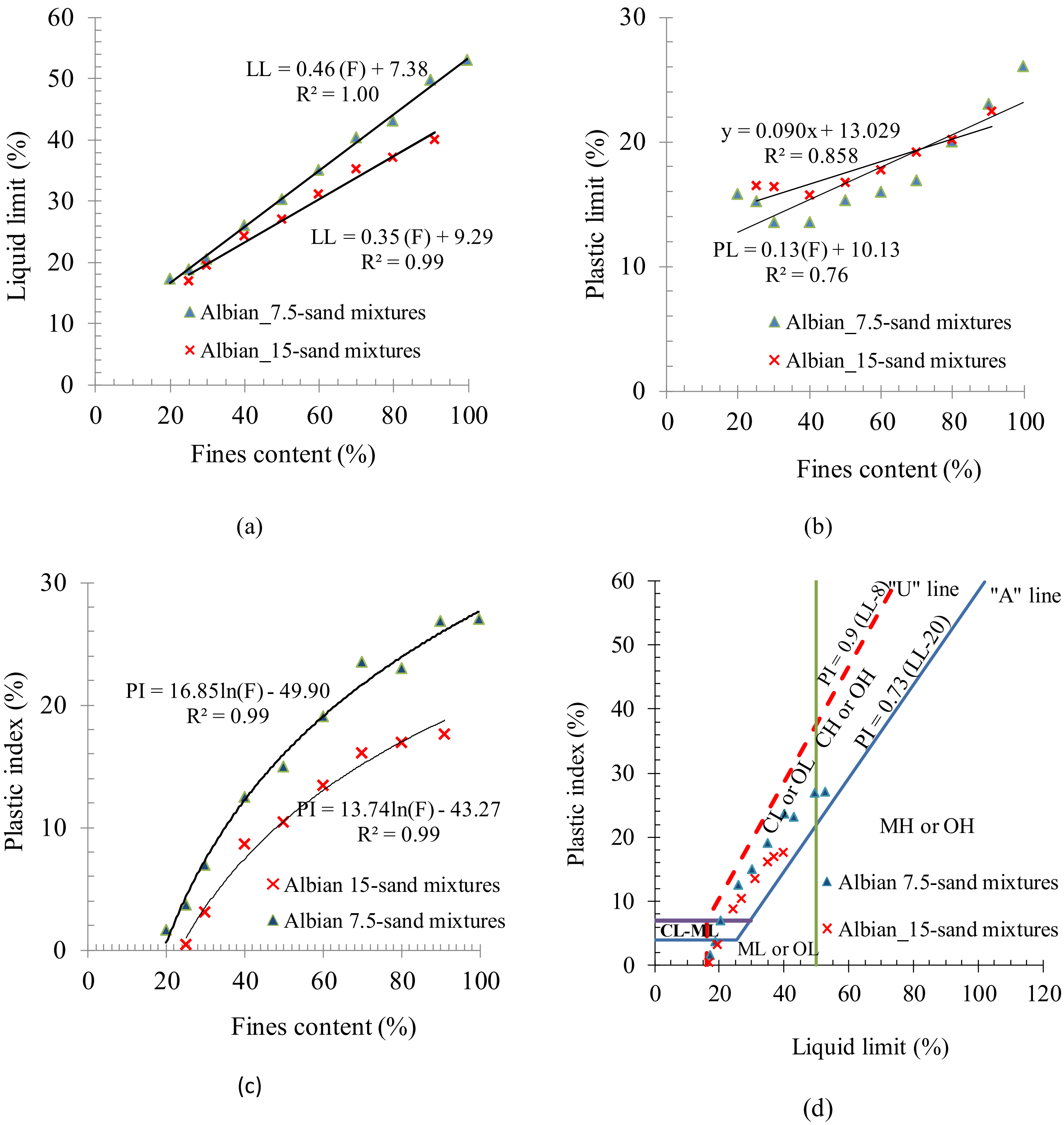

Figure 2. Liquid limit, plastic limit, plastic index, and activity index of Albian_7.5-sand mixtures and Albian_15-sand mixtures as a function of the percentage of fines in the mixture: a) liquid limit; b) plastic limit; c) plastic index; and d) Albian_7.5-sand mixture and Albian_15-sand mixture on a plasticity chart. Abbreviations: CL = lean clay; OL =organic clay; CL-ML = silty clay; CH = fat clay; OH = organic silt; MH = elastic silt; and ML = silt

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The plasticity of soils can be related to their compressibility, as indicated by Skempton (1944). The reduction of fines tailings plasticity with the addition of sand implies that the compressibility of fines tailings can be reduced by mixing it with sand. The activity index of the FSMT (the slope of the plastic index versus the clay-sized fraction; therefore, it is unitless) varies from 0.04 to 0.58 (Figure 1d). For clay content > 20%, the activity index of the FSMT is approximately 0.55, but for clay content < 20% it depends on the percentage of clay in the mixture (Figure 1d).

The activity index of the FSMT indicates that the clay fraction of the mixtures is kaolinite, which is in line with the previous knowledge that the clay fraction of MFT is mainly kaolinite (FTFC, 1995). The low activity index of the clay minerals (< 0.75) suggests that the FSMT are less reactive to large volume changes on wetting or drying and are also less susceptible to chemical changes.

4. SEDIMENTATION AND SELF-WEIGHT CONSOLIDATION OF FSMT

The storage capacity of the disposal area, the rate of clear water production, and the long- and short-term storage capacity of tailings impoundments depend on the settling behaviour of tailings. The suitability of alternative processes for tailings disposal and land reclamation options are mainly a function of the rate and magnitude of consolidation (FTFC, 1995; Eckert, Masliyah, Gray, & Fedorak, 1996). The initial composition and behaviour of fines (Imai, 1980), the relative proportion of fines and sand (Boutin, Kacprzak, & Thiep, 2011), and the type and

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amount of chemical additives (Caughill, Morgenstern, & Scott, 1993) are important variables that control the settling behaviour of tailings.

In this study, the settling behaviour of CT with a wide range of initial composition and phosphogypsum (PG) dosages are studied using settling column (standpipe) tests. The study focused on CT because CT represent one of the primary FSMT disposal methods in the oil sands industry. The CT are a chemically amended, nonsegregating mixture of MFT and sand (Matthews, Shaw, Mackinnon, & Cuddy, 2002). The chemical addition is intended to coagulate the fines, thereby improving the dewatering and segregation behaviours of CT (Matthews et al., 2002). The relatively high water release rate of CT allows faster reclamation, reducing freshwater intake from rivers for extracting bitumen from oil sand ores. Field depositions of CT are made via thin layers and the sedimentation and self-weight consolidation are essentially one dimensional, due to the large width of the disposal area relative to its depth (Boratynec, 2003). The settling column test replicates the sedimentation and initial self-weight consolidation of a layer of CT deposited in a disposal pit prior to the deposition of subsequent layers.

In the development of CT technology and thereafter, research has been conducted to characterize CT (Caughill et al., 1993; Matthews et al., 2002). Most of the research either focused on selecting the amount and type of chemical additive that would make the mixtures nonsegregating or studied the dewatering behaviour of CT at a particular SFR (Caughill et al., 1993). In this study, the objectives are to investigate the effect of the SFR on settling rate and amount, identify material parameters that control the dewatering behaviour of CT, describe various

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characteristics of CT prepared over a wide range of solids and fines content, and examine the possibility of producing “alternative CT” by varying the initial solids and fines content and/or by varying the amount of chemical addition. Here, alternative CT is defined as CT of a different initial composition that results in the same geotechnical characteristics, both during the progress and at the end of sedimentation and self-weight consolidation.

Fines-sand mixture tailings can be produced by combining the cyclone underflow tailings and MFT or by combining extraction tailings and MFT. The possible composition of FSMT by combining cyclone underflow tailings and MFT can be represented by points along line A on a ternary diagram (Figure 3). The possible compositions of FSMT by combining extraction tailings with MFT are bound by lines B and C in Figure 3. The possible compositions of FSMT by combining thickened tailings and cyclone underflow tailings are represented by points along line D. Line E represents the composition of FSMT by combining MFT with beach sand. Points along lines A–E indicate that FSMT can be produced with a wide variety of solids and fines contents. In addition to the FSMT represented by lines A–E, increasing the solids content of the coarse and/or the fine tailings before mixing results in various FSMT compositions. Considering the options for making FSMT, one of the objectives of the settling column tests is to examine the possibility of producing CT of different initial compositions that would settle at the same rate and yield the same geotechnical performance CT at the end of self-weight consolidation.

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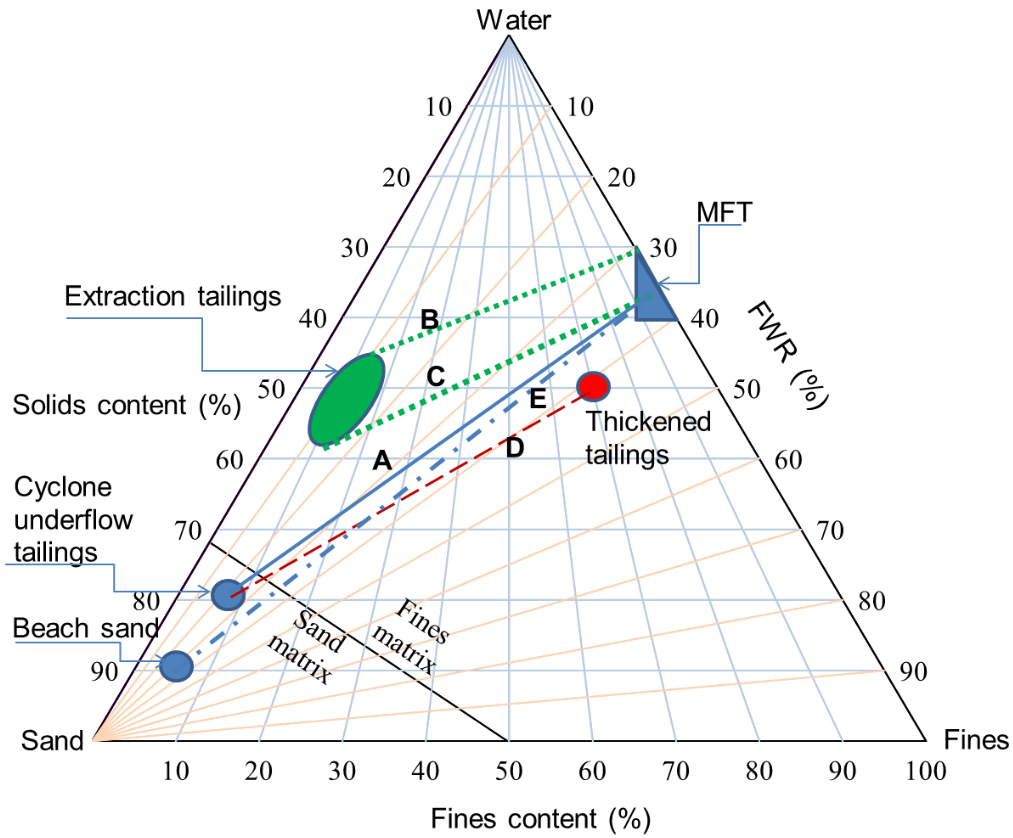

Figure 3. Ternary diagram showing the possible compositions of FSMT

The sedimentation/consolidation, segregating/nonsegregating, and liquid/solid boundaries of oil sands tailings are roughly parallel to the constant of fines-water ratio (FWR) lines of 15, 30, and 68%, respectively (Sobkowicz & Morgenstern, 2009). As these boundaries are closely parallel with the constant FWR, this study focused on examining the behaviour of CT at the same initial FWR, on the assumption that CT prepared at the same initial FWR may produce alternative CT. Thus, CT have been created by varying the solids and fines content while keeping the same initial FWR. The FWR is defined as the ratio of the mass of fines to the mass of fines plus the mass of water. Equation 1 describes the relationship of FWR to the fines and solids content of a mixture.

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$$FWR = \frac{f}{f + (\frac{1}{s} - 1)} \quad (1)$$

where f is the fines content and sis the solids content.

In evaluating the possibility of producing alternative CT, CT prepared at FWRs of 24.7, 26.6, 29.0, and 32.9% were used in the investigation, covering solids contents of 45–71% and fines contents of 17–40%. At each FWR, six to seven CT were prepared at fines contents of 17, 20, 23.6, 25, 30, 35, and 40%; the solids content varied depending on the fines content and the initial FWR.

A series of settling column tests was also conducted at different PG dosages to examine the possibility of producing alternative CT, not only by varying the initial composition of CT, but also by varying the amount of chemical addition. The CT of 24.6% FWR, fines contents of 20, 25, 30, 35, and 40%, and PG dosages of 248–5059 mg/kg (mass of PG/mass of CT) were used for this investigation.

The materials used for making the CT were Albian_15 and beach sand. The CT with desired solids and fines content were prepared by first mixing Albian_15 and beach sand for approximately 3 min; pond water and dissolved PG were then poured into the mixture and the sample was mixed for an additional 5 min. A double-head auger mixer was used and the entire mixture was suspended during mixing. After mixing, the CT were immediately poured into 1 L graduated

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cylinders in a manner that minimized particle segregation. The CT in excess of the settling column tests were used for checking the solids and fines content.

The settling behaviours of the CT were studied by monitoring settlement of the water-suspension interface. The interface settlement was monitored every 30 s for the first 2–3 h, then every hour to the end of the self-weight consolidation. Steel tape attached on the sidewall of the settling column and time-lapse photography was used for monitoring the interface settlements. To evaluate the segregation characteristics of the CT, at the end of self-weight consolidation the sediments were sliced and the solid content profiles were determined by drying the subsamples in an oven at 105°C. A total of 70 settling column tests were conducted.

Figure 4a–d show the interface settlement (water-suspension interface) for CT prepared at initial FWRs of 24.7, 26.6, 29, and 32.9%, respectively. At each FWR, six to seven time-settlement plots are presented for CT prepared at fines contents of 17, 20, 23.6, 25, 30, 35, and 40%. The amount of PG per mass of fines was kept constant in all samples. The settling rate of CT in Figure 4a–d indicates that samples having a lower initial FWR had higher dewatering rates than samples with higher FWRs. The CT made at the same initial FWR have the same initial settling rates, irrespective of the difference in the initial solids and fines content.

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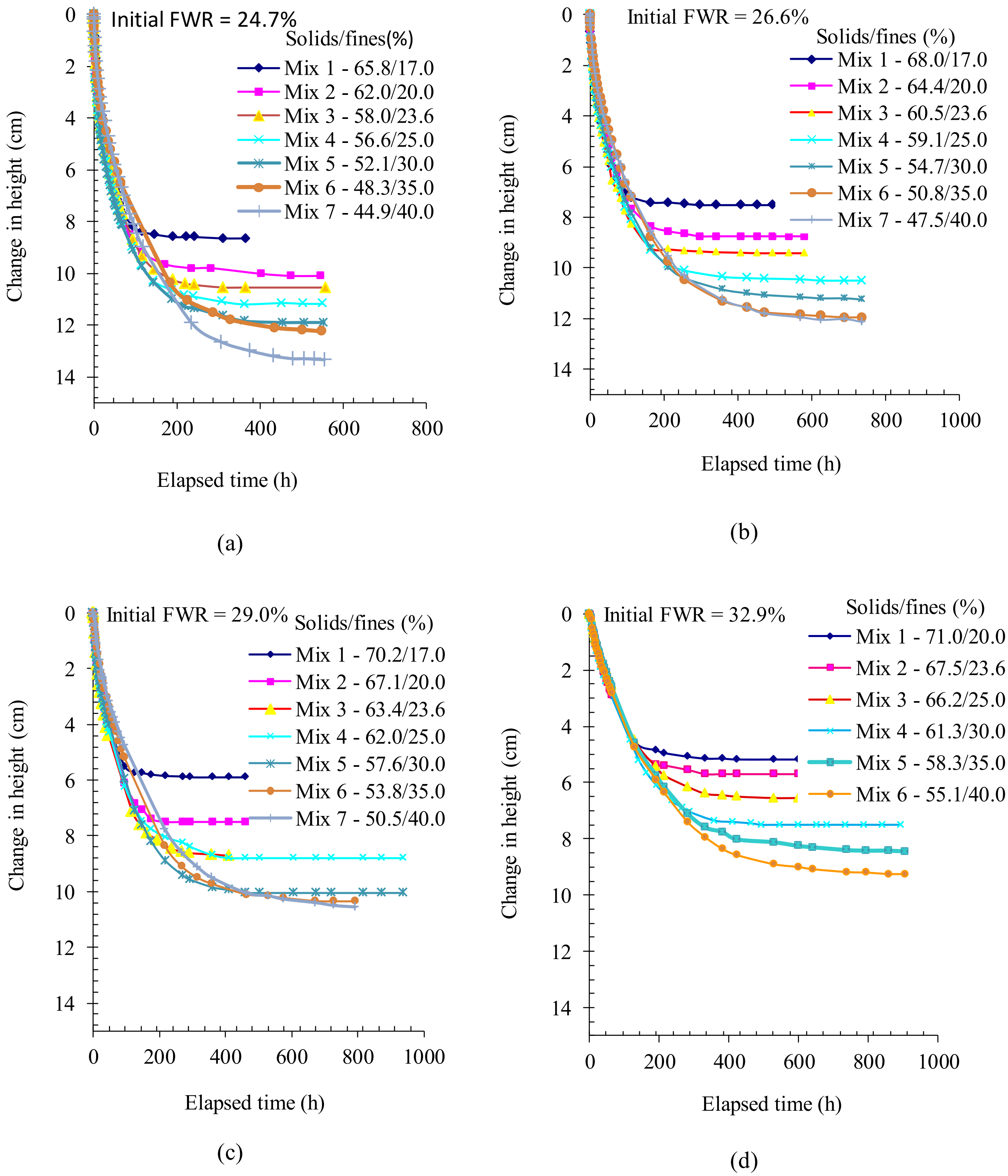

Figure 4. Interface settlement of CT prepared at the same initial FWR by varying the solids and fines content: a) initial FWR of 24.7%; b) initial FWR of 26.6%; c) initial FWR of 29.0%; and d) initial FWR of 32.9%.

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The initial settling rate can be related to the permeability of the material through the equation of Pane and Schiffman (1985), thus the permeability of CT is a function the initial FWR (Figure 5). For CT prepared at the same FWR, the time to reach the end of self-weight consolidation is a function of fines content in the mixture. High fines content CT (40% fines) are four to six times slower to reach self-weight consolidation than low fines content CT (≤ 20% fines).

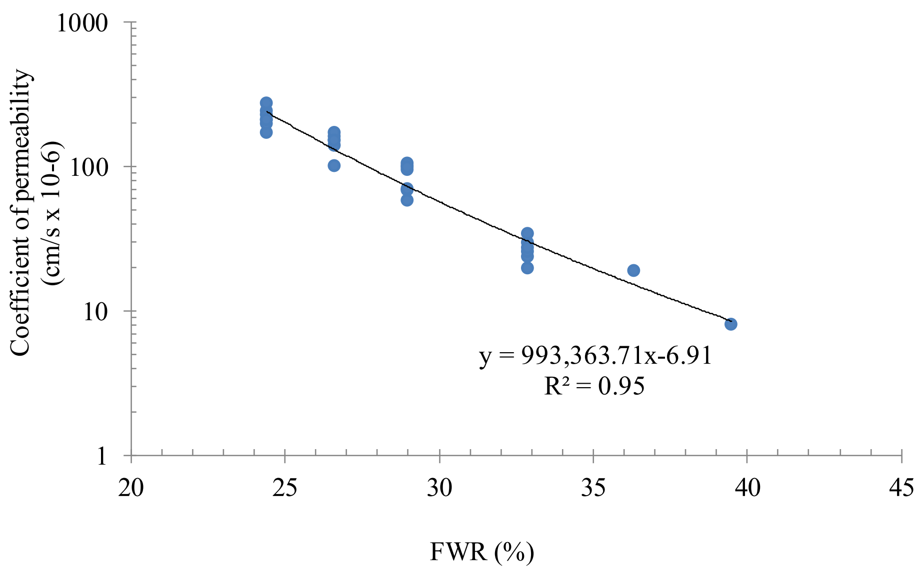

Figure 5. Permeability coefficient of CT as a function of FWR.

Figure 6 shows the average FWR as a function of elapsed time. The CT were prepared at the same initial FWRs of 24.7, 26.6, 29, and 32.9%. At the initial stage of settling, the changes in the FWR with time are the same but hey diverge slightly as settling progresses, resulting in different but comparable FWRs at the end of consolidation. The FWRs during settling and at the end of self-weight consolidation suggest that the geotechnical behaviours of CT of the same initial FWR are comparable.

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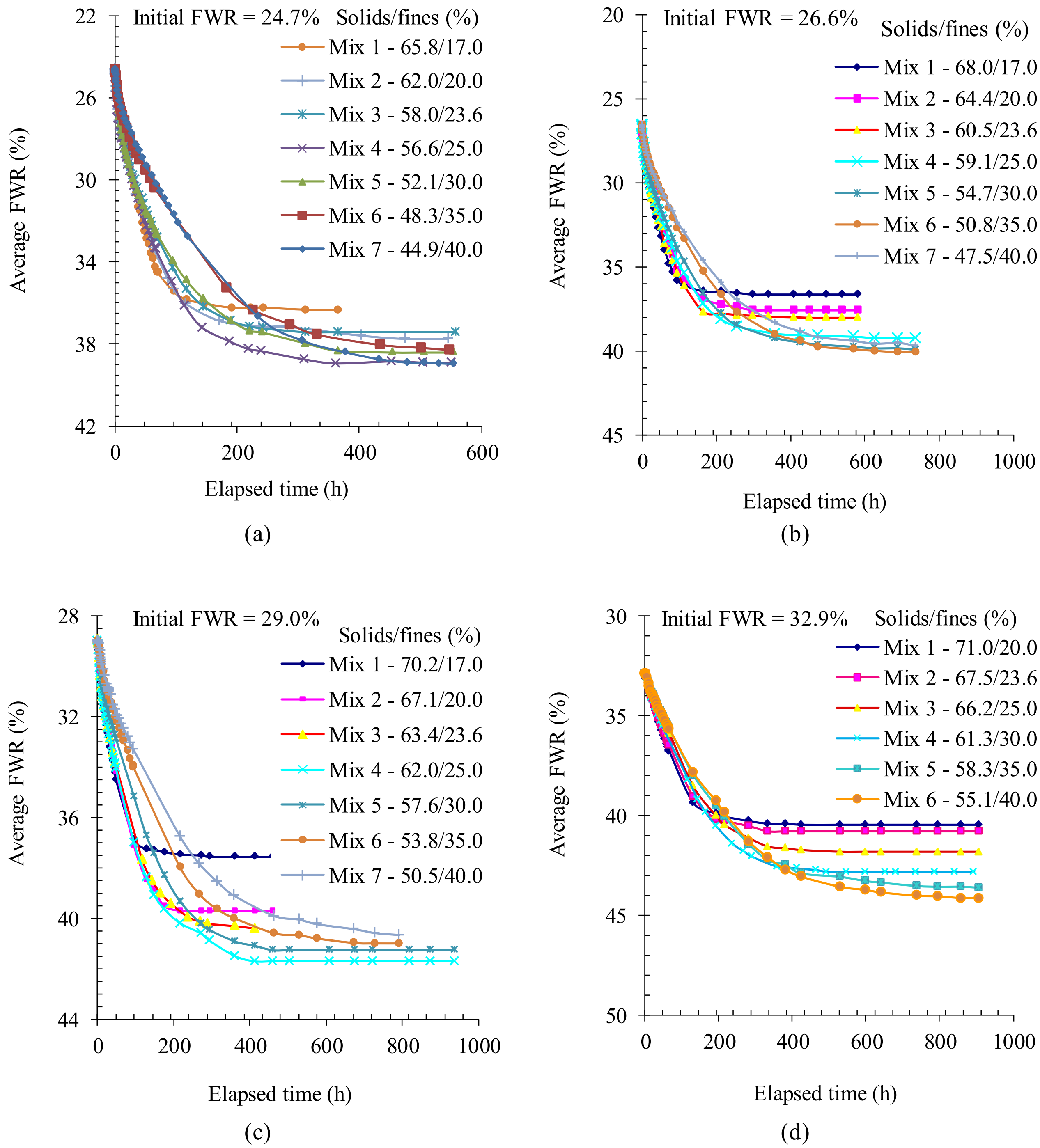

Figure 6. The FWR as a function of time for CT with different solids and fines content prepared at the same initial FWR: a) initial FWR of 24.7%; b) initial FWR of 26.6%; c) initial FWR of 29.0%; and d) initial FWR of 32.9%

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Figure 7 shows a typical time-settlement curve for CT prepared at the same initial FWR. The change in volume of CT can be divided into three general stages: flocculation (induction), settling, and consolidation. These stages are similar to the zone settling stages of clay slurry described by Imai (1980). During the flocculation stage, there is no observable change in volume. The development of flocs and the formation of flow channels between flocs occur during flocculation (Michaels & Bolger, 1962; Imai, 1980). Irrespective of the variation in the fines and solids content, CT having the same initial FWR have essentially the same length of induction period (Figure 7).

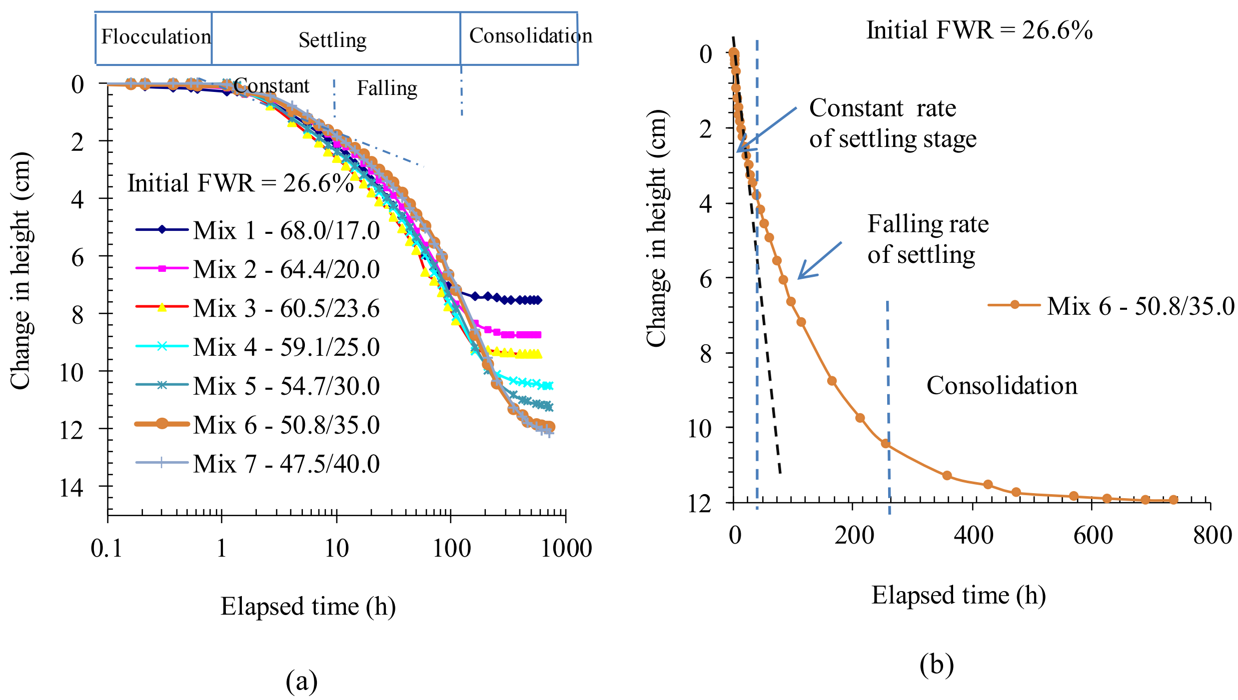

Figure 7. Stages in change in volume of CT: a) initial FWR of 26.6% CT; b) 50.8% solids and 35% fines CT

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The settling stage is where most of the volume change occurs in CT. Depending on the initial composition and the amount of PG added, the settling stage accounts for 85–90% of the total change in volume but takes < 50% of the combined time of sedimentation and self-weight consolidation. The settling of the CT can be divided into two stages: constant rate and falling rate. In the constant rate stage of settling, the slope of the time-settlement curve is nearly constant. The thickness of sediment deposited at the bottom of the cylinder is believed to be small and does not affect the settling behaviour of the CT during the constant rate stage of settling. The volume change mechanism during the constant rate stage can be described by hindered sedimentation: en-masse settling of coarse and fine particles together without the development of effective stress (Imai, 1980; Pane & Schiffman, 1985). The CT made with the same initial FWR have the same dewatering rate during the constant rate stage of settling. The falling rate stage of settling is characterized by a decrease in the slope of the time-settlement curves, which is believed to be due partly to the hindered sedimentation of the suspension and partly to the self-weight consolidation of the sediment deposited at the base of the cylinder. High fines content CT have a longer falling rate stage than those with low fines content (Figure 7).

The consolidation stage starts after the settling stage and is due to the self-weight consolidation of the sediment. Like the falling rate stage of settling, the consolidation stage is characterized by a decrease in the slope of the time-settlement curve; however, the slope of the time-settlement curve in the consolidation stage is much lower than that of the falling rate stage of settling.

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The change in volume during the consolidation stage is < 15% of the total volume change but accounts for > 50% of the total time for sedimentation and self-weight consolidation. Like the falling rate stage of settling, the consolidation stages of higher fines content CT are longer than those of lower fines content CT. The results in Figures 4–7 indicate that CT with comparable settling behaviour can be produced by keeping the same initial FWR and varying the solids and fines content of the CT. The time to complete self-weight consolidation depends, however, on the fines content of the mixture.

The interface settlement of CT made at the same initial solids and fines content but at different PG dosages is presented in Figures 8a–d. Figure 8a, for example, shows the interface settlement of CT with 62% solids and 20% fines content at PG dosages of 248–3,720 mg/kg. Figure 8e summarizes the initial settling rates of the CT prepared with different amounts of PG by plotting the average FWR at the end of the settling stage versus the amount of PG used. Figure 8f summarizes the time to reach 90% of settlement for CT prepared at the same solids (62%) and fines content (20%) as a function of the amount of PG added to the mixture. Figures 8g and h show the change in height (ΔH) normalized by the initial height (H_o) for CT prepared with different PG dosages during the induction and the initial stages of the settling.

The results in Figures 8a–f show that the length of the flocculation (induction) stage, the water release rate of the CT, and the time to reach the equilibrium FWR or the time for 90% settlement all depend on the initial composition of the sample

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and the amount of PG added. High fines content and/or low PG dosage CT have longer flocculation periods and lower settling rates than low fines content and/or high PG dosage CT. The addition of PG reduces the induction period and increases the settling rate; however, it appears that a PG dosage > 900 mg/kg does not further improve the dewatering rate of the CT, nor does it shorten the length of the induction period or the time to reach the equilibrium void ratio. The results in Figure 8 indicate that the ability to change the behaviour of CT or produce CT with similar geotechnical characteristics (alternative CT) by varying the amount of PG added is limited because the addition of > 900 mg/kg of PG does not change the dewatering behaviour of the CT.

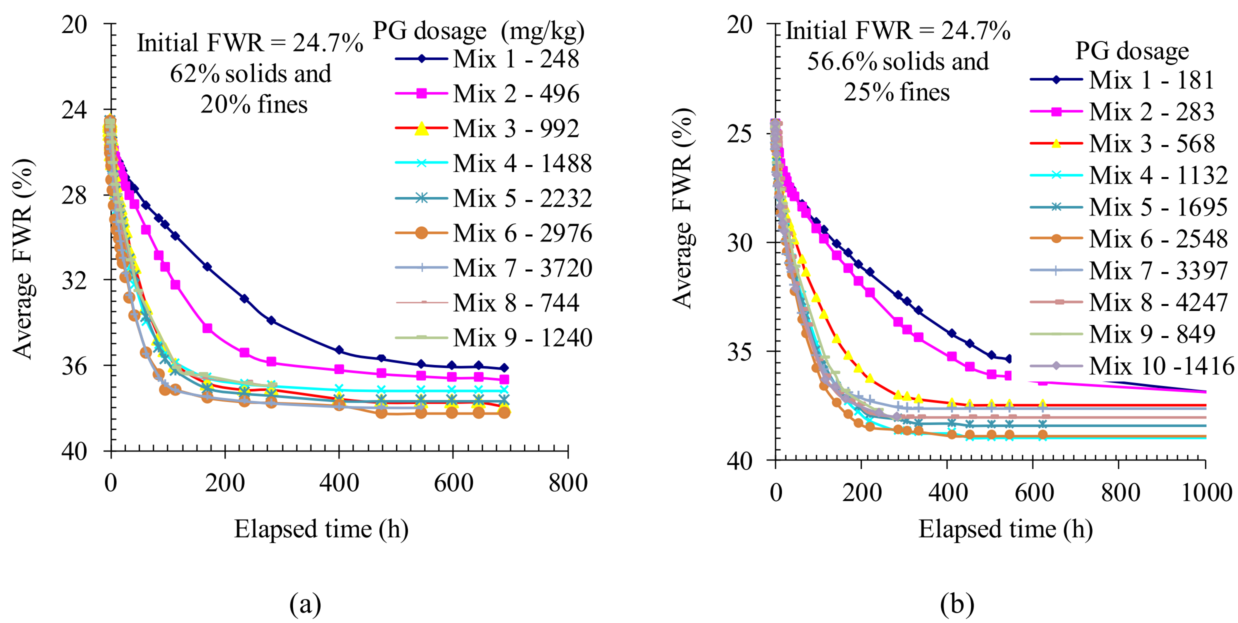

Figure 8. The settling characteristics of CT made with the same initial FWR of 24.7% and different amounts of PG a) time settlement, 62.0% solids, 20.0% fines; b) time settlement, 56.6% solids, 25% fines

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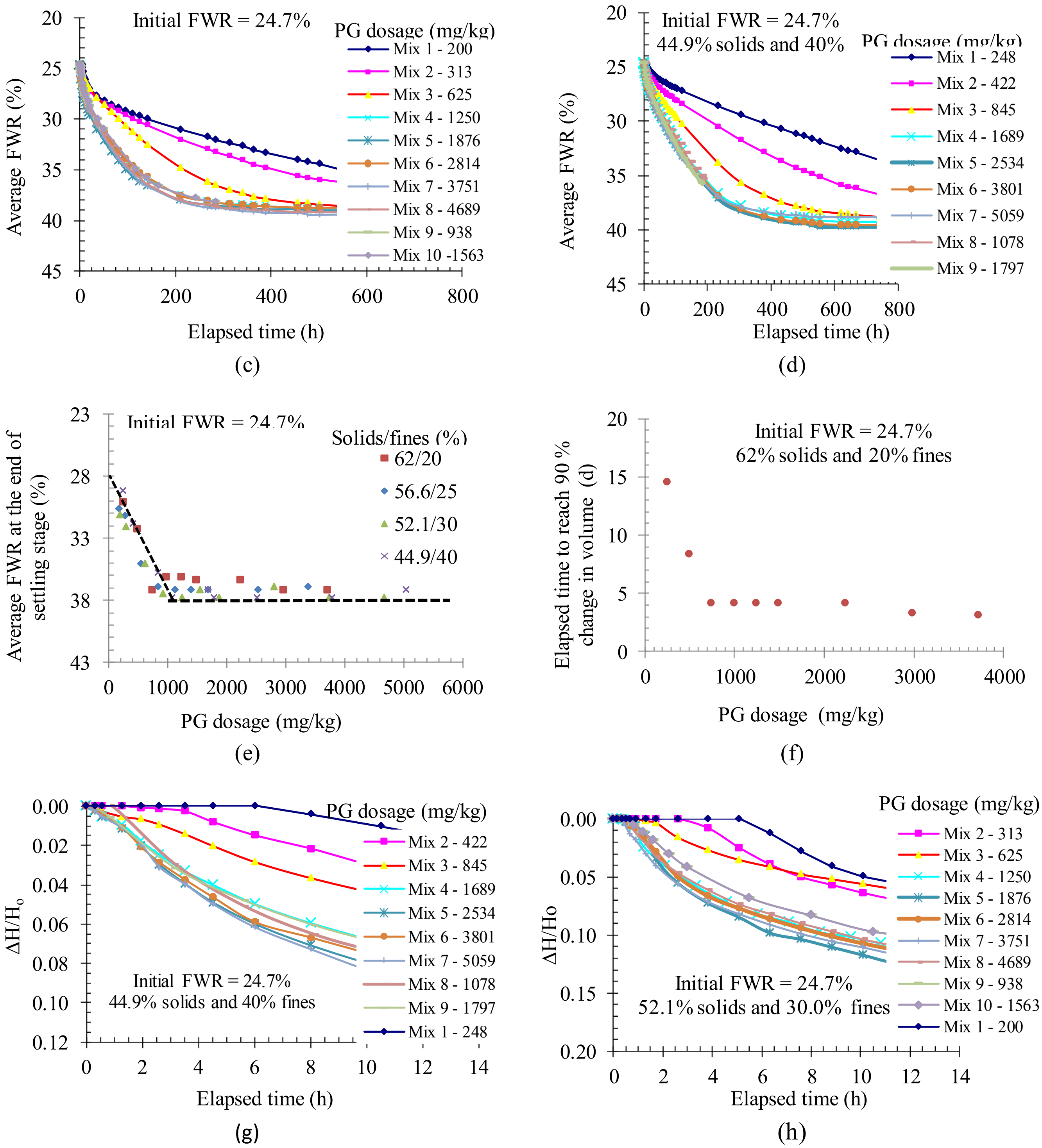

Figure 8. The settling characteristics of CT made with the same initial FWR of 24.7% and different amounts of PG: c) time settlement, 52.1% solids, 30% fines; d) time settlement, 44.9% solids; 40% fines; e) average FWR at the end of the settling stage; f) time to reach 90% settlement, 20% fines, 62.0% solids; g) induction and initial stage of settling, 44.9% solids, 40% fines; and h) induction and initial stage of settling, 52.1% solids, 30% fines.

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Figure 9 shows the change in height of CT prepared at the same initial solids content (62%) with a fines content of 20–40%. In Figure 9a, the mass of PG per mass of CT was kept constant, whereas in Figure 9b, the mass of PG per mass of fines was kept constant. Comparing the settling rates in Figures 9a and b indicates that the settling rate of high fines content CT is significantly slower than low fines content CT, but was improved by keeping the amount of PG per mass of fines constant. The results indicate the settling rate of CT with the same initial solids content depends on the fines content of the mixture, despite the use of a constant amount of PG in terms of total mass or in terms of fines mass. The results in Figure 9 imply that it might not be possible to produce alternative CT by keeping the initial solids content of the mixture the same while varying the PG dosage, and tailings treatment processes or technologies that modify the mixture composition while keeping the solids content constant may not produce CT with similar dewatering behaviour.

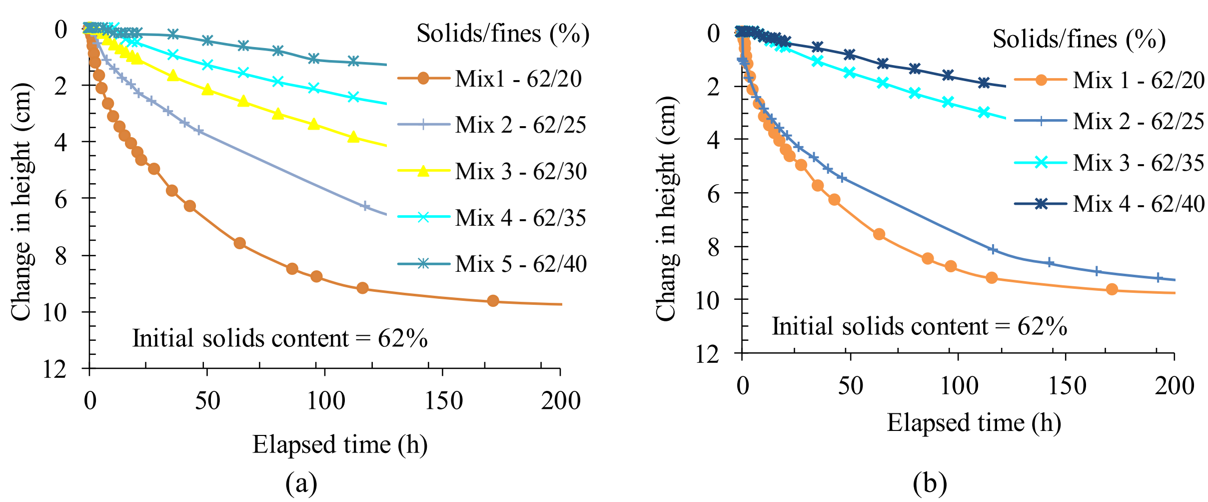

Figure 9. Interface settlement of CT prepared at the same initial solids content and different fines content: a) equal PG dosage per mass of CT; b) equal PG dosage per mass fines

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Figure 10 summarizes the different characteristics of CT after the end of sedimentation and self-weight consolidation. Figure 10a shows the ratio of the thickness of CT at the end of self-weight consolidation to the initial thickness of CT. Figure 10b shows the average equilibrium solids content and Figure 10c shows the ratio of the average equilibrium solids content to the initial solids content. Figure 10d compares the solids content and Figure 10e shows the FWR at the end of self-weight consolidation for CT made with the same initial FWR.

The results in Figure 10a indicate that the equilibrium sediment volume is 62–86% of the initial volume of CT. The change in volume due to the sedimentation and self-weight consolidation is thus approximately 14–38% of the initial volume, depending on the initial solids content of the samples and the initial FWR. The results in Figure 10a are a preliminary indicator of the volume of containment needed to temporarily store CT as a function of the volume of materials deposited. The results in Figure 10b suggest the final solids content of CT is controlled by their initial solids content, with a slight dependency on the initial FWR of the samples. The results in Figure 10c show that the average solids content of CT at the end of self-weight consolidation is 1.1–1.4 times the initial solids content.

The initial dewatering rate and the progress of consolidation are a function of the FWR, but the results in Figure 10d indicate that the equilibrium solids content is not a direct function of the initial FWR. For CT prepared at the same initial FWR, the results in Figure 10e indicate that the FWR at the end of the self-weight consolidation depends slightly on the SFR of the mixture, with $< 5\%$ difference between high and low SFR CT. The results in Figure 10a–e generally indicate that

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the magnitude of settlement depends more on the amount of solids than the texture of the samples.

Figure 10f shows typical solids content profiles of CT at the end of self-weight consolidation. The solids content of the sediments increases with depth, with no distinct stepped density profile at the bottom of the sediment, indicating that the CT used in the study are nonsegregating. The segregation boundary of PG-treated CT is close to a FWR of 18% (FTFC, 1995). The CT used in this study have a FWR≥ 24.7%; thus, the mixtures were expected to settle as non-segregating mixtures.

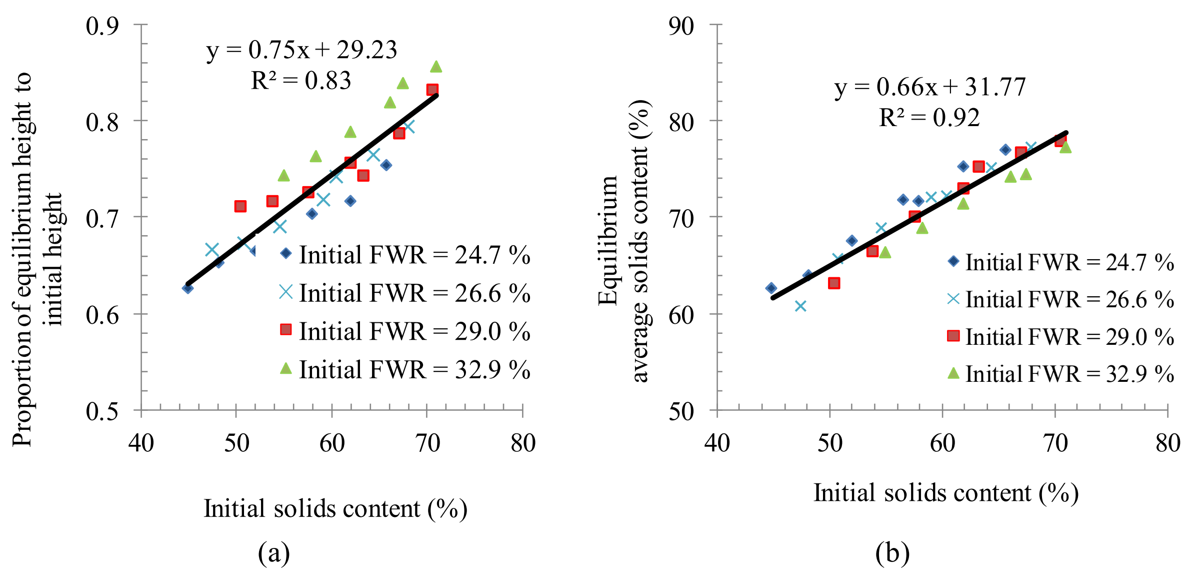

Figure 10. Characteristics of CT at the end of sedimentation and self-weight consolidation

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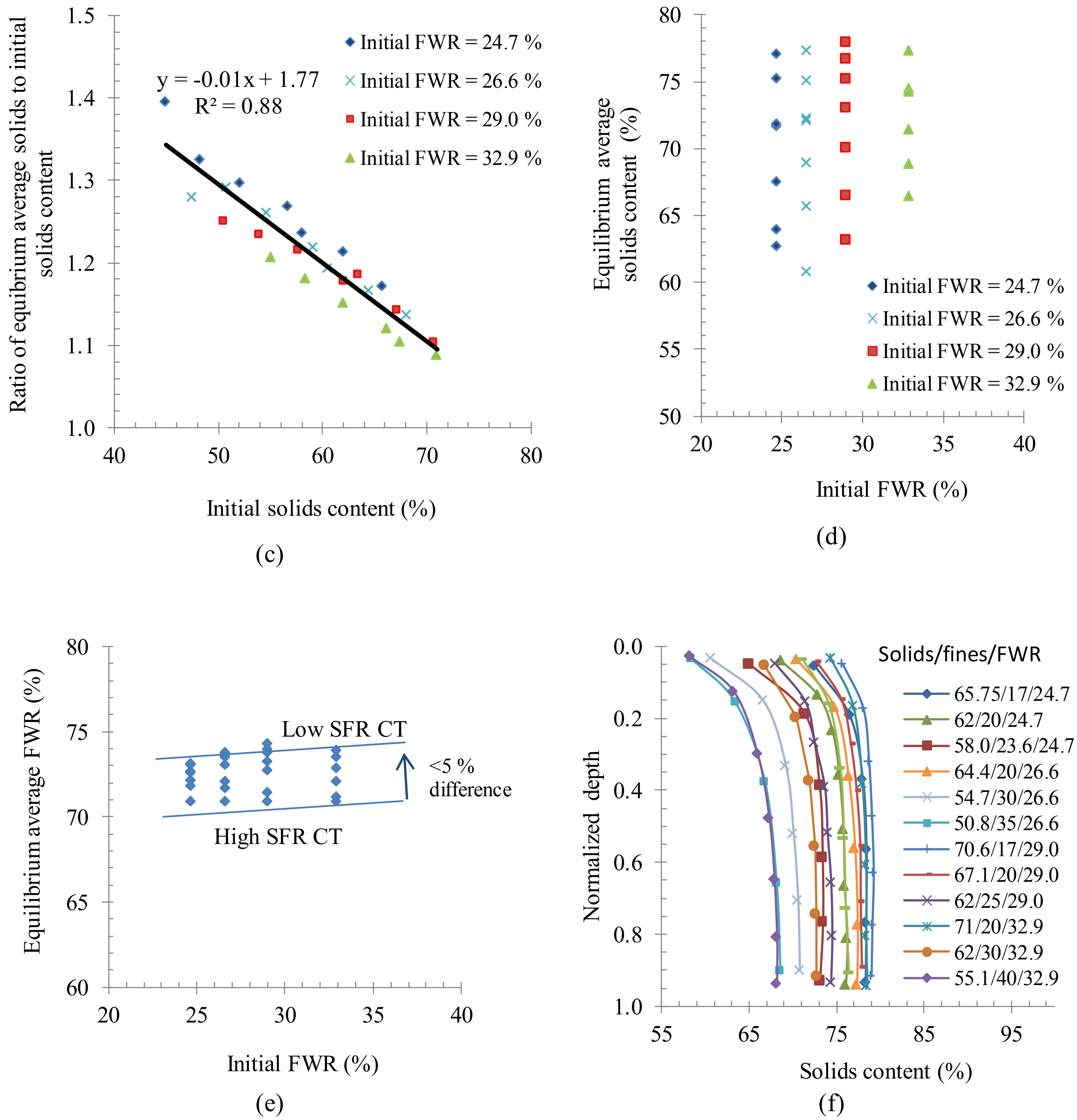

Figure 10. Characteristics of CT at the end of sedimentation and self-weight consolidation: a) ratio of equilibrium thickness to initial height; b) average solids content at the end of sedimentation and self-weight consolidation; c) ratio of average equilibrium solids content to initial solids content; d) equilibrium average solids content; e) equilibrium FWR; and f) typical solids content profiles at the end of sedimentation and self-weight consolidation

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Figure 11a shows the true strain (ln(1 + ΔH/Ho)) and engineering strain (ΔH/Ho) of CT with 44.9% and 65.8% initial solids content. The initial thickness represented by Ho and ΔH is the change in thickness. At the initial stage of settling, the true strains and the engineering strains are almost equal because the deformation is small. As the change in volume increases with time, the difference between the two strains increases.

Figure 11b summarizes the relative error between the engineering strain and the true strain at the end of self-weight consolidation for CT with various initial compositions. The results in Figure 11indicate that the magnitude of strain is a function of the initial solids content of the samples; low solids content CT have higher strain than high solids content CT. The relative error between the engineering strain and the true strain is a function of the solids content and increases with a decrease in solids content, as shown in Figure 11b. The relative error is < 8% if the initial solids content of the CT is > 70%, but if the initial solids content is < 45%, the relative error is 20% or more. The comparison of the two types of strain can indicate at what solids content the infinitesimal strain-consolidation theory can reasonably predict a change in volume behaviour for FSMT.

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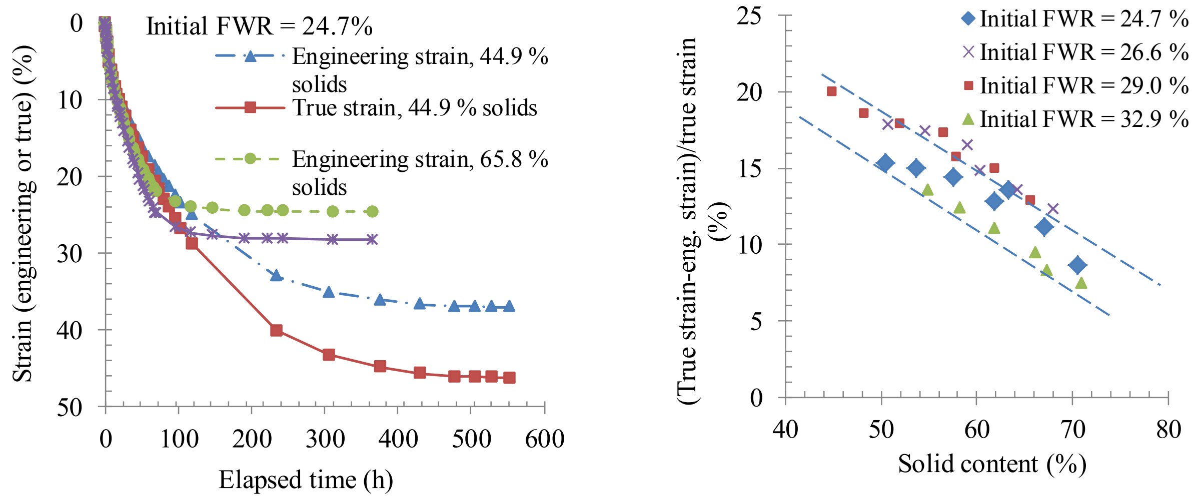

(a) (b)

Figure 11. a) True and engineering strains of CT with 44.9 and 65.8% initial solids content and b) relative error of the engineering strain at the end of sedimentation and self-weight consolidation for CT prepared at different initial solid contents

Figure 12a compares the mass of solids stored in the CT, measured as the mass of solids / (volume of CT excluding the volume of released water), immediately after deposition and after the end of self-weight consolidation. Figure 12b compares the mass of fines stored in the CT, measured as the mass of fines / (volume of CT excluding the volume of released water). The CT were prepared with the same initial FWR of 24.7%. The mass of solids stored in the CT increased due to self-weight consolidation and is a function of the fines content of the samples (Figure 12a). The CT with 17% fines store 1.5 times more solids than the CT with 40% fines, indicating that low fines CT store more solids than high fines CT. In terms of fines storage, high fines content CT increase the storage efficiency of fines; CT with 40% fines store 1.6 times more fines than CT with 17% fines. The results in Figure 12 indicate that CT prepared with the same initial FWR differ in their solids and fines storage capacities.

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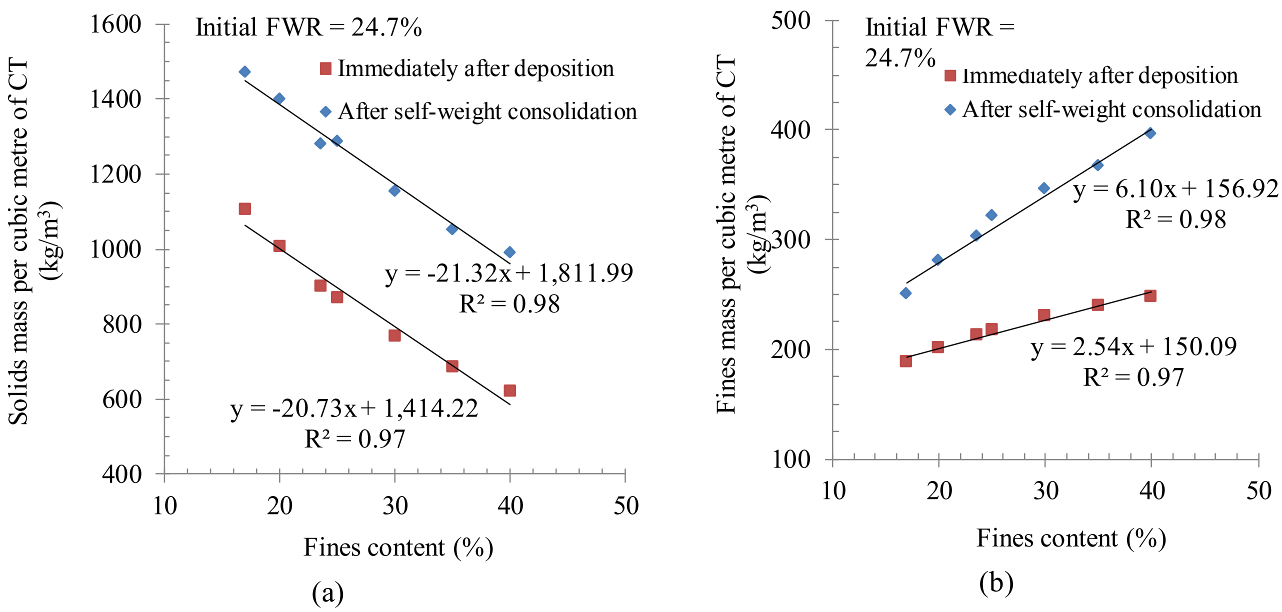

Figure 12. Solids and fines storage capacity of CT prepared at the same initial FWR of 24.7%.

5. UNDRAINED SHEAR STRENGTH OF FSMT

The bearing capacities of tailings and the selection of surcharge loads and loading procedures depend on the shear strength of the tailings. The remolded shear strengths of tailings at various solids and fines contents are of interest when selecting pump type and pump capacity. The shear strength of the FSMT over a wide range of solids and fines contents is important in evaluating the performance and suitability of disposal options.

In this study, the undrained shear strength of FSMT at different solids and fines contents is examined to evaluate the material parameters that best control the shear strength of oil sands FSMT; study the effect of water and fines content on the shear strength of the FSMT; and define the undrained shear strength at the liquid and plastic limits. FSMT at fines contents of 99, 90, 80, 70, 60, 40, 30, 25,

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and 20% were used in the investigation. The FSMT were prepared by mixing Albian_7.5 and beach sand at various SFRs. The undrained shear strengths of the FSMT were measured using a Wykeham-Farrance laboratory vane shear apparatus. The tests were conducted by first preparing the samples at water contents close to the plastic limit and then adding pond water, thoroughly mixing the samples, and measuring the shear strength and its corresponding water content. The shear tests were conducted immediately following sample preparation to minimize the effect of thixotropy on the strength of the mixtures. For each mixture prepared at a given fines content, six to nine shear strength measurements were made at different water contents to define the shear strength–water content relationship of the mixtures.

The vane shear test results are summarized by plotting the undrained shear strength as a function of water content. As can be seen in Figure 13a, the undrained shear strengths of the FSMT are a linear function of water content and depend on the percentage of fines in the mixture. The results indicate that the undrained shear strength of the FSMT can be increased through enrichment of fines and/or by increasing the solids content. The slopes of the undrained shear strength–water content relationship of soil are functions of clay type and the sensitivity of soil strength to changes in water content (Trask & Close, 1957). Because the mineral types of the FSMT are the same, the difference in the slope of undrained shear strength–water content relationship indicates the sensitivity of the tailings mixtures to changes in water content. The slopes of low fines FSMT samples are steeper than slopes for high fines FSMT samples (Figure 13a),

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indicating that low fines FSMT are more sensitive to changes in water content than high fines FSMT.

The undrained shear strength corresponding to the liquid limit (Su_{LL}) was calculated from the water content– undrained shear strength relationships of FSMT. The results indicate that the shear strength at the liquid limit varies from 1.6 to 3 kPa. The average undrained shear strength of the FSMT at the liquid limit is approximately 2.4 kPa, with a standard deviation of 0.4 kPa. The result is consistent with the literature, which indicates shear strength of natural soils at the liquid limit is 1.7–3 kPa (Youssef, El Ramli, & El Demery, 1965). The shear strength of soils depends on the type and boundary condition of shear tests used but is the same order of magnitude at the liquid limit irrespective of the soil composition and test types.

Figure 13b shows the shear strength of the FSMT versus the normalized water content. The water contents of the SMT are normalized to their liquid limit (w_{LL}). Despite some scatter in the data, the shear strengths of the FSMT converge such that the strength can be described by one equation or line. The strength-normalized water content relationship of the FSMT does not show a trend of being above or below the mean value depending on the percentage of fines in the mixture. The results in Figure 13b indicate that the liquid limit can be used to normalize and generalize the strength of FSMT with different SFRs. According to Pandian et al. (1995), soils have the same order of consolidation and possess the same shear resistance at the liquid limit; hence, the water content at the liquid

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limit can be regarded as a reference state and a generalized parameter. Figure 13c shows the undrained shear strength–liquidity index relationship of the FSMT. The liquidity index is defined as the water content minus the plastic limit divided by the plastic index. Except for low fines content mixtures (30, 25, and 20% fines), the undrained shear strength of FSMT with different SFRs can be described using the liquidity index. Low fines content mixtures deviate from the undrained shear strength–liquidity index relationship of high and medium fines content FSMT, perhaps because the liquidity index is a function of plastic limit and the plastic limit at low fines content is not a simple function of fines content (Figure 2b).

The shear strength of the FSMT corresponding to the plastic limit (Su_{PL}) is derived from the water content–undrained shear strength relationship and is dependent on fines content (Figure 13a). The ratio of the shear strength at the plastic limit to the shear strength at the liquid limit appears to be a linear function of fines content (Figure 13d). By extrapolating the Skempton and Northey (1952) liquidity index–undrained shear strength test results for clay soils, Wroth and Wood (1978) suggested the ratio of undrained shear strength at the liquid limit to that at the plastic limit is 100. Belviso, Ciampoli, Cotecchia, and Federico (1985); Sharma and Bora (2003); and Kyambadde and Stone (2012) also suggested the ratio of the undrained shear strength at the plastic limit to the undrained shear strength at the liquid limit is close to 100, but the results of the current study indicate that this ratio varies with the fines content of the mixture.

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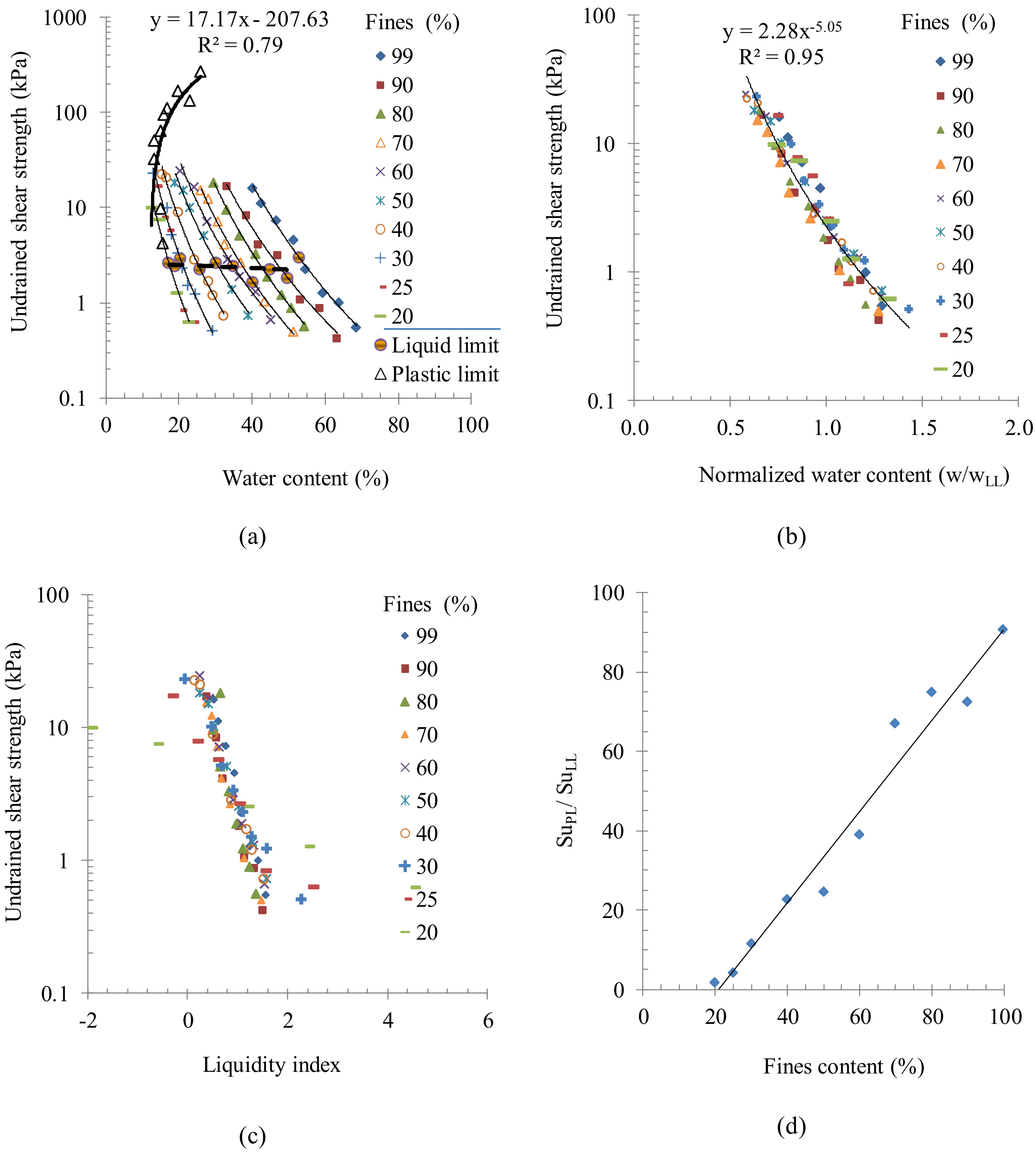

Figure 13. Undrained shear strength of Albian_7.5-sand mixture tailings: a) undrained shear strength as function of water content; b) undrained shear strength as function of water content normalized by the liquid limit; c) undrained shear strength as function of liquidity index; and d) the ratio of the undrained shear strength at the plastic limit to the undrained shear strength at the liquid limit

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6. CONCLUSIONS

In this study, the behaviour of oil sands FSMT was studied by preparing samples at various solids and fines contents. Liquid and plastic limits, settling column (standpipe), and vane shear tests were conducted at various solids and fines content. The objectives of the tests were to investigate the material properties that best describe the behaviour of the FSMT, to study the various geotechnical characteristics of FSMT, and to investigate the possibility of producing CT of different initial compositions that result in the same geotechnical behaviour. The following conclusions were drawn:

- The liquid limit at various solids and fines content provides experimental evidence that the liquid limit of oil sands FSMT is a linear function of fines/clay content. The presence of small percentages of residual bitumen in the fines and its variation with the SFR of the mixture does not affect the linear trend of liquid limit–fines/clay content relationship. The linear relationship implies that the sand functions as filler material that only displaces the fines matrix and that the liquid/solids boundaries of FSMT are parallel to the constant FWR line on the ternary diagram. The liquid limit–fines content relationship extends the importance of the liquid limit for correlation and normalization of FSMT over a wide range of SFRs.
- The plastic limit tests indicate that the plastic limit–fines/clay content relationship of FSMT cannot be described by a simple linear law of mixture. The FSMT with clay contents < 10% appear to be nonplastic. The plasticity of oil sands FSMT is within the range of natural soil

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plasticity. The activity indexes of the FSMT indicate that the clay fraction of the mixture is mainly kaolinite.

- The settling column test results indicate that the dewatering rate of FSMT is a function of the initial composition of the samples and the amount of PG added. The initial dewatering rates of CT are governed by the relative amounts of fines and water. The CT with a low FWR settle faster than those with a high FWR and the CT with the same FWR have the same initial dewatering rate. The addition of PG flocculates the solid particles, which improves the water flow rate and the segregation behaviour of the tailings. It appears, however, that beyond a PG dosage of 900 mg/kg, the addition of more PG does not further improve the settling rate or the permeability of the CT, nor does it reduce the length of the induction period or the time to reach the end of sedimentation and self-weight consolidation. The fact that the addition of > 900 mg/kg of PG does not change the behaviour of CT implies that there is a limited ability to change the behaviour of CT by adding more PG.
- The CT made with the same initial FWR result in comparable settling rates and FWRs at the end of the self-weight consolidation, but the time to reach the equilibrium FWR and the fines and solids storage capacity are a function of the percentage of fines in the sample. The behaviour of CT prepared with the same initial FWR result in comparable but not the same geotechnical behaviour CT, thus alternative CT cannot be produced by starting with the same initial FWR.

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- The shear strength of the FSMT at the liquid limit lies within 1.6–3 kPa, with a mean value of 2.4 kPa and standard deviation of 0.4 kPa. The shear strength at the liquid limit does not show an increasing or decreasing trend with respect to the fines content in the mixture. The shear strength of the FSMT at the plastic limit is highly dependent on the fines content. The ratio of the shear strength at the plastic limit to the shear strength at the liquid limit of the FSMT is a function of fines content, despite suggestions in the literature that this ratio is close to 100.
- The logarithm of the undrained shear strengths of fines-sand mixtures is a linear function of water content. The slope and intercept of the undrained shear strength– water content relationship of FSMT depend on the SFR. The undrained shear strength of the FSMT at a wide range of solids and fines contents can be best described and predicted by the water content normalized to the liquid limit. The liquidity index can also be used to describe the strength of FSMT with various SFRs, but the liquidity index works best for FSMT with clay contents > 20%.

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CHAPTER 7. SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

7.1. SUMMARY

Centrifuge has been used to model the sedimentation and self-weight consolidation behavior of slurries and soft soils. Concerns over the segregation that occurs during the application of high-gravity in centrifuge tests were recognized, but there appears to be no well-established guideline for selecting samples that do not segregate during centrifuge tests. One of the main advantages of using centrifuge testing techniques is the reduction in testing time as compared to conventional consolidation tests. However, reducing the testing time may marginalize time-dependent processes that can influence the settling behavior of thixotropic materials.

Concerns related to segregation during high-gravity application in centrifuge tests were studied in Chapter 3 by conducting a number of settling column and centrifuge tests over a wide range of solids and fines contents. The centrifuge tests were performed using the 5.5 m radius C-CORE beam centrifuge. In the same chapter, the shear strength of fines and fines-sand mixture tailings at a wide range of initial compositions was studied at different elapsed times (up to 189 days) to investigate the influence of time-dependent processes on modelling the settling behavior of slurry/soft soils using centrifuge. A waiting time for slurry/soft soils before subjecting them to high centrifugal acceleration was established for reducing the potential for segregation during centrifuge tests.

Deriving a material constitutive relation from centrifuge tests requires the monitoring of density and pore pressure profile during a centrifuge flight. Mini-pore pressure transducers have been used to measure the pore pressure profile during the centrifuge flight and the centrifuge technology had many years of experience in using these transducers. But the centrifuge technology has yet to develop a reliable in-flight solids content profile measuring probe for high water content material undergoing settling. Instrument modelling with solids content and pore pressure transducers helps in monitoring excess pore pressure dissipation and effective stress development, thus providing a better understanding of the change in volume behavior of the tailings. Moreover, the in-flight determination of the mechanical properties of soil widens the application of centrifuge modelling (Corte et al., 1991).

The lack of solids content profile measuring probes and the importance of measuring the mechanical properties of soil during the centrifuge flight initiated the examination of different solids content measuring technologies for the possibility of using the probes for in-flight solids content measurement. Gamma-ray, X-ray, total pressure, neutron probe, TDR, image analysis, sampling and electrical resistivity techniques were examined for potential applications in centrifuge in-flight solids content measurements. Measuring accuracy, probe mass and sizes, and operational difficulties limited most of the techniques for in-flight centrifuge solids content profile monitoring. The TDR method was considered for further investigation due to their light mass, small size, and ease of adaptation for centrifuge tests. Throughout the course of this study, it was observed that the oil sands industry lacks a cost-effective, fast, and real-time tailings water content measuring transducer for field and laboratory applications.

In addition to the potential application for centrifuge tests, the TDR can have important applications in the oil sands industry for both field and laboratory measurements. Thus, the TDR method was considered for detailed investigation, including the studying of influencing parameters and developing calibration equations. The dielectric constant-water content relationship, along with the effects of texture, residual bitumen, temperature, thixotropy, and the addition of solutes on TDR water content measurements were investigated in Chapter 4 using oil sand tailings of different compositions as well as Devon silt and kaolinite clay

The long-term self-weight consolidation behaviour of oil sands tailings and kaolinite slurries was studied in Chapter 5 using a centrifuge modelling technique. A centrifuge was used because of the slow dewatering behaviour of the tailings (which may require several months or even years to complete in conventional tests) and to create a prototype-effective stress regime in the model. The study in Chapter 5 also aimed to verify the centrifuge modelling application for high water content materials and to develop an in-flight instrument (solids content and position sensor) so that the performance of tailings-treated methods can be evaluated in the future using the geotechnical beam centrifuge. Additional objectives of the tests were to examine the possibility of deriving large strain consolidation parameters (void ratio-effective stress and hydraulic conductivity-void ratio relationships) from centrifuge tests based on data collected during the centrifuge flights.

The centrifuge tests presented in Chapter 5 were conducted at various initial compositions, heights, and gravity. Oil sands tailings and kaolinite clay were used in the tests. The initial solids content of the materials was chosen to be higher than the solids content of the materials on the centrifuge segregation boundary, based on results from Chapter 3. All of the centrifuge tests were conducted at the GeoREF centrifuge facility, except for one that was conducted at the C-CORE centrifuge facility. In-flight cameras and laser displacement sensors were used for interface settlement monitoring. Five miniature pore pressure transducers and one general purpose pore pressure transducer were utilized to measure pore pressure profiles during the centrifuge flight. Results from Chapter 4 indicate that the TDR probes can be used, with reasonable accuracy, for solids content measurements of oil sands tailings at wider ranges of solids content. Thus, the solids content profiles of the centrifuge models in Chapter 5 tests were monitored using TDR probes installed through the wall of a centrifuge consolidation cell at a spacing of 2 cm, starting from 1.6 cm above the base.

In Chapter 5, test repeatability and the centrifuge scaling law were verified through the testing program. The modelling of models testing technique utilizing kaolinite clay slurry was used to verify the similitude between different experiments and/or to verify the scaling relation between the model and the prototype. The effect of the effective radius definition on consolidation rates and magnitude was investigated by varying the effective radius from the center of rotation to depths of one-third, one-half, and to the bottom of the model.

Also in Chapter 5, large strain consolidation parameters of oil sands tailings and kaolinite slurry were determined from a centrifuge in a shorter time than was required for the large strain consolidation test (LSCT). Large strain consolidation parameters were also determined using an LSCT apparatus and were used as an input for numerical models and compared with centrifuge-derived consolidation parameters. The suitability of large strain numerical models in predicting changes in the volume behavior of tailings was examined by comparing these results with centrifuge test results extrapolated to prototypes. The FSConsol slurry consolidation program was used for the numerical modelling prediction.

Despite the fact that both fine and coarse tailings are produced and their mixtures are components of existing tailings disposal strategies, fundamental studies on the geotechnical behaviour of oil sands fines-sand mixture tailings (FSMT) are limited, especially with regard to proportioning the fines and sand to change the behaviour of the mixture. Tailings treatment performance, the strength, dewatering, and the flow behaviour of tailings are all functions of the relative proportion of fines and coarse particles.

In Chapter 6, the fundamental behaviour of oil sands fines-sand mixture tailings at various sand-fines ratios (SFR) was investigated. The relative proportion of fines to sand and the effect of residual bitumen on the geotechnical behaviour of FSMT, the material parameters that control the settling and strength behaviour of FSMT, and the effects of coagulant/flocculent additions on the settling behaviour of FSMT are addressed by conducting vane shear, settling column (standpipe), and index tests on FSMT at various fines and solids contents. The conclusions from the investigation from Chapters 3 to 6 are presented in the following section.

7.2. CONCLUSIONS

7.2.1. Effect of thixotropy and segregation on centrifuge modelling

From the investigation of the effect of segregation and thixotropy on the centrifuge modeling of oil sand tailings, the following conclusions can be made.

- The segregation boundaries of the materials from the centrifuge and settling column tests are a function of tailings composition and source. The segregation boundary of tailings with a higher clay-fines ratio lies above the boundary of tailings with a lower clay-fines ratio.
- The segregation boundary from the centrifuge tests is a function of the acceleration level used in the tests.
- The application of high-gravity in centrifuge testing enhances the segregation of tailings. The segregation boundary from the centrifuge tests shifts towards a higher solids content on the ternary diagram compared to the segregation boundary from settling tests. The area bounded by the centrifuge and settling column segregation boundary on the ternary diagram refers to tailings compositions that segregate as a result of applying high centrifugal force.
- Segregation related to high gravity applications would result in specimen behaviour in the centrifuge model being different from the prototype. It would also limit the composition of materials that can be used in centrifuge tests and the range of consolidation parameters that can be derived from the tests.

- The segregation boundary of fines-sand mixture tailings is influenced by the maximum size and the particle size distribution of the sand.
- Without the need for in-flight instrumentation and monitoring, multiple samples can be tested in a single centrifuge flight to evaluate the segregation behaviour of tailings. Solids content or fines content profiles after a few minutes of centrifuge runs can be used to characterize segregating and non-segregating materials.
- The evaluation of segregation based on the equations of Cardwell (1941) and Weiss (1967) under high acceleration fields is highly conservative. The Cardwell (1941) equation can be used for the characterization of the segregation of fines-sand mixture samples under Earth's gravity, whereas the Weiss (1967) formula is conservative in estimating the maximum size of sand that remains in suspension under Earth's gravity.
- The gain in the shear strength of tailings in one day varies from 5 to 150% of the strength immediately following mixing, with a general increasing trend following increases in the fines-void ratio. Allowing oil sands fines-sand mixture tailings to rest for one day before centrifuge tests reduces the potential of segregation in centrifuge testing.
- For the oil sands tailings used in the study, the strength gain that was due to time-dependent processes is greater than that due to changes in volume (decreases in water content). The significant contribution of strength gain with elapsed time due to a non-gravity time-dependent process may create

difficulties in extrapolating centrifuge modelling test results to the prototype.

7.2.2. Time domain reflectometry measurements of oil sands tailings water content: A study of influencing parameters

The investigations of TDR-influencing parameters for laboratory and field applications indicate that:

- TDR can be used to measure the water content of oil sands tailings over a wide range of solids content. Detectable measurable inflections are observed over all ranges of solids content (15 to 78%) and for all materials used in the study (oil sands tailings, Devon silt, and kaolinite).
- The dielectric constant-volumetric water content relationships of high water content materials differ markedly from the commonly used Topp calibration equation. Material-specific calibration is an important element for the use of TDR for solids content measurements. The use of calibrations that are derived for very high solids content and unsaturated materials would result in a significant underestimation of water content if applied to very high water content materials.
- The percentage of clay and bitumen in tailings affects TDR water content measurements. High clay and/or high bitumen materials tend to have a lower dielectric constant than high sand content oil sands tailings or non-bitumen materials (kaolinite and Devon silt).

- The TDR method is found to have good repeatability in measuring the water content of the tailings. The standard deviation for solids content measurements from repeated TDR measurements is less than 0.6%, but the standard deviation in TDR solids content measurements tends to increase to 1% when the solids content of the tailings is less than 25%.
- The solids content measurement of TDR depends only slightly on temperature. Depending on the solids content of the tailings, the dielectric constant of the tailings decreased at a rate of 0.03–0.1/°C with an increase in temperature. Low solids content tailings tended to depend more on temperature than high solids content tailings.
- Over a wide range of solids content, the additions of phosphogypsum up to 5000 mg/kg do not affect the TDR solids content measurements of tailings.
- The dielectric constant of the tailings at different ages is more or less constant, which indicates that the age of tailings does not affect the TDR water content measurements of tailings. Thus, TDR can be used for long-term monitoring of oil sands tailings water content without the need to correct for the age of the tailings.

7.2.4. Centrifugal modelling of oil sands tailings consolidation

The following conclusions can be made from the investigation of the repeatability of centrifuge tests, the verification of scaling laws, the modelling of oil sands tailings consolidation, the deriving of consolidation parameters, and the comparison of centrifuge result with numerical models.

- Centrifuge tests conducted at the C-CORE and GeoREF centrifuge facilities with the same material type, initial solids content, initial height, relative acceleration and consolidation cell indicate that the centrifuge test is repeatable.
- Centrifuge tests conducted on two types of thickened tailings that were started at the same initial void ratio and subjected to the same self-weight stress indicate that the centrifuge modelling procedure is acceptable and the theoretical deformation scaling relation between model and prototype is valid.
- The modelling of the model test conducted on kaolinite clay slurry indicates that the same prototype response can be found at the end of the consolidation, but the theoretical time-scaling exponent falls short of satisfying the scaling relation between the model and the prototype at certain stages of consolidation.
- Consolidation time estimates from the centrifuge tests are highly dependent on the time-scaling exponent. The effect of the effective radius definition on consolidation rate or magnitude is minor compared to that of the time-scaling exponent. Also, updating the effective radius during the consolidation progress does not significantly affect either the rate or the magnitude of consolidation.

- There is a rapid dissipation of pore pressure after applying the centrifugal acceleration along the model depth, suggesting that the settlement during centrifuge is a consolidation-type of settlement.
- The permeability of oils sands tailings and kaolinite slurry derived from centrifuge tests is generally higher than those derived from LSCT. The compressibility at the end of the centrifuge tests is similar to LSCT test results. However, compressibility during the test flights is above that of LSCT and may be associated with higher strain rates in centrifuge testing.
- Laser displacement sensors (LDS) can be used for interface settlement monitoring of tailings in centrifuge tests, with better resolution and less data processing time than an in-flight camera. The use of LDS may increase the possibility of running multiple samples in a single centrifuge test.
- The TDR technique was successfully applied for measuring the solids content of tailings during centrifuge flights. The TDR response is not affected by high gravity applications in centrifuge or by the probe installation through the wall of the consolidation cell. Calibration results arrived at before and after installation were found to be the same.
- The settlement rates of tailings or kaolinite from the numerical model prediction are slower than centrifuge results, but the ultimate settlement predictions are comparable to centrifuge results. The

numerical model prediction and centrifuge results are close when using the measured compressibility data, but still higher than the measured permeability data of LSCT.

7.2.5. Behaviour of oil sands fines-sand mixture tailings

The following conclusions can be drawn from the different types of tests conducted to evaluate the behaviour of oil sands fines-sand mixture tailings (FSMT).

- The liquid limit of FSMT is governed by the linear law of mixture. The plastic index of FSMT can best be described by the logarithmic function of clay content. FSMT are nonplastic for clay content of less than 10%.
- The index properties of oil sands FSMT are within the ranges of natural soil plasticity. FSMT behave as low-plasticity silt for clay content between 10 to 20%, and as low-plasticity clay or low-plasticity clayey soil for clay content 20% or more.
- The activity index of FSMT is approximately 0.55 for clay content greater than 20% but depends on the percentage of clay in the mixture for clay content less than 20%. The activity index indicates that the clay minerals in the oil sands FSMT are kaolinite, that they are less reactive to large volume changes on wetting or drying, and that they are also less susceptible to chemical changes.
- The permeability of consolidated tailings (CT) is a function the initial fines-water ratio (FWR). CT that have the same initial FWR essentially have the same length of induction period and the same initial dewatering

rate, but high fines content CT are four to six times slower to complete self-weight consolidation than low fines content CT.

- The change in volume of CT can be divided into three general stages: flocculation (induction), settling, and consolidation. The settling stage accounts for the majority (~85%) of the total change in volume but takes less than 50% of the combined time of sedimentation and self-weight consolidation.
- The addition of a phosphogypsum (PG) reduces the induction period and increases the settling rate of CT. However, it appears that a PG dosage higher than 900 mg/kg does not further improve the dewatering rate of the CT, nor does it shorten the length of the induction period or the time to reach the equilibrium void ratio.
- The solids content of FSMT at the end of sedimentation and self-weight consolidation is controlled by their initial solids content, with a slight dependency on the initial FWR of the samples.
- The storage capacity of CT prepared with the same initial FWR is different in that low fines CT store more solids than high fines CT, but high fines content CT increase the storage efficiency of fines.
- The undrained shear strengths of FSMT are a linear function of water content, but the slope depends on the percentage of fines in the mixture. Low fines content FSMT are more sensitive to changes in water content than high fines content FSMT.

- The average undrained shear strength of FSMT at the liquid limit is approximately 2.4 kPa, with a standard deviation of 0.4 kPa.
- Liquid limit can be used to normalize and generalize the strength of FSMT with different sand-fines ratios (SFR). Like liquid limit, liquidity index can be used for normalization, but only for FSMT greater than 20% clay.
- The ratio of shear strength at the plastic limit to shear strength at the liquid limit is a linear function of fines content, despite suggestions in the literature that this ratio is close to 100.

7.3. Research Contributions

The research presented in this thesis highlights the importance of segregation on centrifuge modelling of a high water content material and methods that could be used as a guide in selecting a non-segregating material for centrifuge tests. The influence of non-gravity time dependent factor such as thixotropy on centrifuge modelling or model results interpretation is presented.

The long term consolidation behaviour of oil sands tailings are studied using the centrifuge modelling technique by measuring interface settlement, density and pore pressure profile during the centrifuge flight that could open the door for the use of centrifuge for physical modelling of treated or untreated tailings consolidation including the study of effective stress development and excess pore pressure dissipation along the model height in a much shorter time than required in conventional self-weight consolidation tests. The research make a contribution on the application of centrifuge modelling techniques for a high water content material by checking the tests repeatability and verifying the scaling laws. The study presented the performance of numerical modelling predictions by comparing with physical modelling of oil sands tailings consolidation.

Time domain reflectometry (TDR) is applied for the first time for solids content profile measurement during the centrifuge flight. The study presented the importance TDR probe calibration especially for high water content material and presented the effect of temperature, age, solute and age of sample on TDR calibration over a wide range of material composition. The research contributes on in-flight sensors application/development for centrifuge modelling, such as the application of laser displacement sensor for monitoring the interface settlement of tailings and the development of light refraction based density profile measuring probes during the tests flight. The use of laser displacement sensor helps in running multiple samples in single centrifuge flight that would save both cost and time while investigating the behaviour of a slow dewatering material with a centrifuge.

The study presented the effect of strain rate on the behaviour of oil sands tailings that could potentially explain why there is a large change in volume under small change in effective stress in tailings ponds or why the estimation of settling rate based on laboratory derived parameters is different compared to the rates of settling in a prototype. The research presented a new approach for measuring the large strain consolidation parameter of tailings from the centrifuge tests based on data collected during the centrifuge flight. The research also make a contribution on identifying material parameters that controls the shear strength, permeability and plasticity of oil-sands fines as well as fines sand mixture tailings.

7.4. RECOMMENDATIONS FOR FUTURE RESEARCH

- The effect of strain rate on the compressibility of a material needs to be investigated further through a test program that includes centrifuge, constant rate of strain, and a large strain consolidation apparatus. If the testing program further confirms the strain rate effect on compressibility, a large strain consolidation numerical model needs to be developed that accounts for the compressibility dependency on the stain rate.
- A series of centrifuge tests that includes modelling of model tests on different materials is needed to further investigate the scaling relation between model and prototype and the repeatability of centrifuge tests.
- A centrifuge tests program may be designed to measure pore pressure within the model (along the center of the model) as well as at the side ports to investigate if there is radial drainage that would affect the centrifuge modelling results.
- Standpipe tests need to be conducted on different types of tailings to compare with centrifuge results. The initial solids content of the tailings should be greater than the solids content of the centrifuge segregation boundary. Alternatively, the centrifuge program may be designed to model existing standpipe test results. Some of the existing standpipe tests, however, were conducted at lower solids content than solids content on the

centrifuge segregation boundary. Centrifuge modelling of these standpipes using acceleration as low as 20g may result in the segregation of particles.

- Segregation related to high gravity applications should be extended to determine the minimum solids content of tailings that would able to support different thicknesses of surcharge loads without the sorting of particles or bearing capacity failure.
- The effect of thixotropy on consolidation rate and magnitude may be investigated by running centrifuge tests immediately after filling and after the induction period. The induction period depends on the material composition, drainage length and initial solids content, and may be engineered by increasing or decreasing the drainage length.
- The development of in-flight probes for centrifuge modelling may be extended to include in-flight water or soil sampling, in-flight shear strength measurements, and in-flight total stress measurements. The use of total stress probes at the bottom of the model may help in examining the effect of side friction on centrifuge results.

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Appendix

Appendix- Vertical Stress Distribution Error in Centrifuge modelling

(Reference: Taylor, 1995)

Vertical stress distribution in centrifuge model is non-linear due to centrifugal acceleration dependence on the radius of the centrifuge. The stress profile deviation from linear stress profile is an inherent error in vertical stress distribution. In calculating the centrifugal acceleration, centrifuge radius that minimizes the stress error in the model profile needs to be chosen. The following formulations demonstrate how to calculate the effective radius that minimize the over and under stress due to the curvilinear nature of the stress profile in the model and the maximum over and under stress.

- Vertical stress distribution in prototype

$$\sigma_p = H\rho\boldsymbol{g} \qquad \text{[A-1]}$$

Where H is the prototype depth at any location, ρ is density of material and ***g*** is Earth's gravitational acceleration

- Vertical stress in prototype (σ_p) and in model (σ_m)are equal for an effective radius (r_e)

$$\sigma_p = H\rho\boldsymbol{g} = \sigma_m = ha_m\rho = \omega^2 r_e h \qquad \text{[A-2]}$$

Where h is the model depth to any point, H is prototype depth to any point, ρ the density of material, g is earth gravitational acceleration and am is acceleration in model

- Actual vertical stress distribution in model can be found by integrating the stress from surface to the required depth in model

$$\sigma_m = \int_{r_s}^{r_s+h} \rho\omega^2 r dr = \rho\omega^2 (r_s h + \frac{h^2}{2}) \qquad \text{[A-3]}$$

Where h is the model depth to any point, r_s is the radius from center of rotation to the top surface of the model.

- Vertical stress distribution error at any point

$$\Delta\sigma = \rho\omega^2\left(r_s h + \frac{h^2}{2}\right) - \rho\omega^2 r_e h \qquad \text{[A-4]}$$

- Height of the model where vertical stress distribution error equals to zero can be found by equating Eq A-4 to zero

$$\Delta\sigma = 0 = \rho\omega^2\left(r_s h_i + \frac{h_i^2}{2}\right) - \rho\omega^2 r_e h_i; \quad \rho\omega^2 h_i\left(r_s + \frac{h_i}{2}\right) = \rho\omega^2 r_e h_i$$

$$\left(r_s + \frac{h_i}{2}\right) = r_e \qquad \text{[A-5]}$$

Where h_i is the height of model where the vertical stress distribution error is zero.

- Relative over stress distribution Error

$$\frac{\Delta\sigma}{\sigma_p} = \frac{\rho\omega^2\left(r_s h + \frac{h^2}{2}\right) - \rho\omega^2 r_e h}{\rho\omega^2 r_e h} = \frac{r_s h + \frac{h^2}{2} - r_e h}{r_e h} = \frac{r_s + \frac{h}{2} - r_e}{r_e} \qquad \text{[A-6]}$$

- **Maximum over stress occurs at the bottom of the model**

$$\frac{\Delta\sigma}{\sigma_p} = r_0 = \frac{r_s + \frac{h_m}{2} - (r_e)}{r_e} = \frac{\Delta\sigma}{\sigma_p} = \frac{r_s + \frac{h_m}{2} - (r_s + \frac{h_i}{2})}{R_e} = \frac{\boldsymbol{h_m - h_i}}{\boldsymbol{2r_e}} \qquad \textbf{[A-7]}$$

Where h_m is the model height

- Relative under stress distribution Error

$$\frac{\Delta\sigma}{\sigma_p} = \frac{\rho\omega^2 r_e h - \rho\omega^2\left(r_s h + \frac{h^2}{2}\right)}{\rho\omega^2 r_e h} = \frac{r_e h - (r_s h + \frac{h^2}{2})}{r_e h} = \frac{r_e - (r_s + \frac{h^2}{2})}{r_e} \qquad \text{[A-8]}$$

- **Maximum relative under stress distribution Error at model height of hi/2**

$$\frac{\Delta\sigma}{\sigma_p} = r_u = \frac{r_e - r_s + \frac{h}{2}}{r_e} = \frac{r_s + hi/2 - (r_s + \frac{hi/2}{2})}{r_e} = \frac{h_i}{4re} \qquad \text{[A-9]}$$

- Equating under and over stress ratio (Eq (A-7) and Eq. (A-9))

$$\frac{h_m - h_i}{2r_e} = \frac{h_i}{4re}$$

$$\boldsymbol{h_i = \frac{2}{3} h_m} \qquad \textbf{[A-10)}$$

- Maximum over or under stress ratio can be obtained by inserting Eq.[A-10] in[A-7] or [A-9]

$$r_u = r_o = \frac{h_m}{6r_e} \qquad \textbf{[A-11]}$$

- The effective radius (r_e) in terms of model height can be obtained by inserting Eq.[A-10] in[A-5]

$$\left(r_s + \frac{h_m}{3}\right) = r_e \qquad \textbf{[A-12]}$$

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