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Dewatering Behaviour of Fine Oil Sands Tailings An Experimental Study

Yao, Yutian

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Dewatering Behaviour of Fine Oil Sands Tailings An Experimental Study



Dewatering Behaviour of Fine Oil Sands Tailings An Experimental Study

PROEFSCHRIFT

ter verkrijging van de graad van doctor aan de Technische Universiteit Delft, op gezag van de Rector Magnificus prof.ir. K.C.A.M. Luyben; voorzitter van het College voor Promoties, in het openbaar te verdedigen op maandag 28 november 2016 om 15:00 uur

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Yutian YAO

Master of Science in Geotechnical Engineering, Hohai University, China geboren te Nanjing, Jiangsu Province, China This dissertation has been approved by the

promotor: Prof. ir. A. F. van Tol copromotor: Dr. ir. L.A. van Paassen

Composition of the doctoral committee:

Rector Magnificus Prof. ir. A. F. van Tol, Dr. ir. L. A. van Paassen,

Independent members:

Prof. Dr. G. W. Wilson Prof. Dr. C. Jommi, Prof. Dr. ir. J. C. Winterwerp, Prof. Dr. J. Bruining, Dr. P. J. Vardon chairperson Delft University of Technology, promotor Delft University of Technology, copromotor

University of Alberta, Canada Delft University of Technology Delft University of Technology Delft University of Technology Delft University of Technology





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Author: Yutian YAO (姚宇阗)

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Author email: yaoyt@126.com

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This thesis is dedicated to my family

献给我的家人

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Summary

Oil sands tailings are a warm aqueous suspension of sand, silt, clay, residual bitumen and naphtha. The tailings are hydraulically transported and stored in tailing ponds where they segregate, with the sand settling from suspension forming beaches and the remaining tailings flowing to the middle of the pond. After several years of tailings disposal, three layers have developed in the pond, which are, from top to bottom, water, thin fine tailing and mature fine tailing (MFT). MFT is the major reason that the tailing ponds cannot be reclaimed. Due to low the high water content and low hydraulic conductivity, MFT consolidate very slowly in the ponds. Therefore, many technologies have been proposed remove the water from the tailings and increase the consistency so that the tailing pond can be reclaimed. but most of these dewatering technologies are rejected due to the limited technical or economic feasibility. In this PhD thesis, two potential fine tailings management technologies were described. These two technologies were: (1) sub-aerial drying of fine tailings deposited in thin lifts, and (2) use of prefabricated vertical drains (PVD) in enhancement of consolidation of fine tailings in the pond. In this PhD project, experiments were carried out to investigate geotechnical properties and dewatering behaviour of fine oil sands tailings related to the described technologies.

This research starts with a review of oil sands tailings and existing tailing management technologies followed by an analysis of important engineering properties of the tailings related to the proposed dewatering techniques. Laboratory experiments were then performed to evaluate different aspects of the two proposed technologies. The experiments were generally divided into two groups. The first group consists of a variety of material characterization tests and the second group includes small scale dewatering tests which were carried out to simulate the core dewatering process of each dewatering technology.

Classification tests were performed on samples of fine oil sands tailings obtained from Muskeg River Mine which is located near Fort McMurray in Alberta, Canada to determine the physical and index properties. The results obtained were compared to the experimental data reported in the literature for the same type of tailings and of other types of mine tailings and organic dredged sludge. This comparison showed that the observed settling behaviour for the tailings was similar to other sludge types with comparable particle size distribution and plastic limit.

Flocculation tests were carried out to investigate the flocculation behaviour of MFT with the use of a high molecular weight polymer and determine the optimum dewatering performance and the optimum flocculation conditions. The mixing procedure of MFT and polymers was evaluated using a small scale stirred tank. By varying the operational parameters such as the geometry of the mixing set-up, mixing speed, mixing duration, polymer dosage and solids concentration in the MFT, effects of these factors on the flocculation results were evaluated and discussed. Based on these experiments an optimum dosage (i.e. 1 g/kg) and mixing procedure were defined.

Sedimentation and self-weight consolidation behaviour of fluid fine tailings was investigated through column settling tests. Hydraulic conductivity of the MFT suspensions at different initial void ratio and the boundary conditions were determined. The one-dimensional compression behaviour of the tailings at lower void ratios was investigated by through standard oedometer tests. It was concluded that the MFT sludge had similar settling and consolidation characteristics as other types of dredged sludge and that treatment of MFT using polymer greatly increased the settling velocity and the consolidation rate of the material, but resulted in a larger volume after settling and consolidation.

A series of tests was performed on small homogenous tailing samples to study three different aspects of desiccation behaviour of the tailings. Shrinkage and swelling tests were performed to assess the soil shrinkage characteristic curves and study the rewetting and swelling behaviour. Matric and total suctions were measured on the tailings samples at various water contents to construct the soil water retention curves. Desiccation cracking tests were conducted on thin (1 cm) tailing samples to investigate the crack initiation and propagation (e.g. cracking water content, crack pattern). The tailing samples were subjected to multiple wetting and drying cycles to assess the hysteresis effect. The results demonstrated that the polymer treated MFT had different desiccation behaviour compared to the non-flocculated MFT.

For the application of using vertical (wick) drains it was considered that when vertical drains are installed in a fine tailings pond, there might be a higher risk of clogging of wick drains compared to applying the PVD in a soil. Pressure filtration column tests were therefore performed to evaluate the clogging potential of PVD filter jackets and drainage behaviour of the system. Filterability of various tailing samples was assessed and compared through an experimentally determined parameter - the specific resistance to filtration (SRF). It was concluded that the filter jackets were not clogged by fines and bitumen at the evaluated stress and hydraulic conditions, and the drainage behaviour of the tailing-geotextile system was fully determined by the permeability of the filter cake which formed adjacent to the filter.

In order to demonstrate the drying potential of fine oil sands tailings, bench-scale box drying tests were performed under different drying conditions. The results suggested that three conditions should be met for drying to be efficient: (1) the surface pooling must be removed effectively; (2) availability of a favorable evaporation condition, and (3) the tailing should be deposited in thin layers. Laboratory column drying tests were performed to further investigate the drying behaviour. It was found that the evaporation rate measured from each tailing column was influenced by relative humidity and flowing velocity of air, tailing surface area and may to some extent be affected by surface bitumen and salinity of pore water. CT scanning analysis provided insight in the interior changes of the tailing during the drying process. It was concluded that deposition of a second layer did not cause significant swelling of the underlying tailings.

Finally, a one-dimensional drying model was used to simulate the consolidation and evaporation behaviour of fluid fine tailings. The model contains various features of drying, including overburden and evaporation driven pore pressure changes and changes due to swelling and shrinkage cycles. The model was validated using the material properties defined in the characterization tests and comparing the simulation results with the available experimental data from the laboratory column drying tests and field atmospheric fines drying tests. The comparison suggested that the model can well predict the key aspects of drying behaviour such as settlement and void ratio distributions.

Samenvatting

'Oil Sand Tailings' zijn een restproduct van oliewinning uit olie houdende zanden die door middel van dagbouw worden gewonnen. De olie is aanwezig als zeer viskeuze bitumen, die door verhitting met stoom van het zand wordt gescheiden. Het restproduct van dit scheidingsproces is een warme waterige suspensie van zand, silt en klei en restanten bitumen en nafta. Deze suspensie wordt hydraulisch verpompt en gestort in slibdepots. Tijdens het storten worden de grove van de fijne deeltjes gescheiden door een verschil in bezinksnelheid. Het grove zand vormt zandtaluds, de zogenaamde 'Beaches', terwijl de fijne deeltjes langer in suspensie blijven en naar het midden van het depot stromen. Uiteindelijk bezinken ook de fijne deeltjes. Vaak worden flocculanten toegevoegd aan de suspensie waardoor de deeltjes samenklonteren en sneller bezinken. De bezonken deeltjes vormen een sliblaag die in twee lagen kan worden onderverdeeld. Bovenop de 'Fine Tailings' (FT), dat de kleinste deeltjes bevat en onderop 'Mature Fine Tailings' (MFT), dat iets grovere deeltjes bevat en onder zijn eigen gewicht enigszins is ingeklonken, maar nog steeds een zeer hoog vochtgehalte heeft. MFT consolideert heel langzaam in de depots, waardoor bij een continue en eventueel toenemende olieproductie het waterverbruik toeneemt en de slibdepots steeds groter moeten worden en lange tijd niet toegankelijk zijn en het daarom moeilijk is om het landschap weer zijn oorspronkelijke of in een maatschappelijk acceptabele staat te herstellen. Daarom wordt er veel onderzoek gedaan naar methoden om het slib sneller te ontwateren, waarmee het water kan worden teruggewonnen en het slib verstevigd. Veel ontwateringstechnieken zijn voorgesteld maar verworpen vanwege beperkte technische of economische haalbaarheid. In dit onderzoek zijn twee mogelijke technologieën bestudeerd: (1) ontwatering door verdamping aan de lucht, waarbij het slib in dunne lagen worden opgebracht en (2) het gebruik van 'Prefabricated Vertical Drains' (PVD), oftewel versnelde ontwatering via verticaal geplaatste kunststof drainage filters die verticaal in het depot worden geplaatst. Verschillende aspecten, die de haalbaarheid van deze technieken beïnvloeden zijn voornamelijk experimenteel onderzocht.

Allereerst is een overzicht gemaakt van de bestaande ontwateringstechnieken gevolgd door een analyse van de relevante eigenschappen van de verschillende soorten slib. Een uitgebreide reeks laboratoriumproeven is uitgevoerd, die in twee groepen zijn onder te verdelen: Ten eerste testen om de verschillende materialen te karakteriseren. En ten tweede kleinschalige ontwateringsproeven die werden uitgevoerd om een beter begrip te krijgen van de het ontwateringsproces en van de twee genoemde ontwateringstechnieken. De bevindingen van het experimenteel onderzoek zijn uiteindelijk verwerkt in een numeriek model dat gebruikt is om de ontwatering door verdamping van het water uit het slib dat in dunnen lagen wordt opgebracht te simuleren.

Verschillende soorten slib zijn geanalyseerd, welke zijn verkregen uit de Muskeg River Mine, nabij Fort McMurray in Alberta, Canada. De resultaten van de karakterisatie experimenten zijn vergeleken met gegevens uit de literatuur van vergelijkbare slib uit de oliezand productie en verschillende andere typen gebaggerd slib. Deze vergelijking toonde aan dat het geobserveerde sedimentatiegedrag van de tailings niet afweek van andere typen slib met vergelijkbare korrelgrootte verdeling en plasticiteitsgrens.

Tijdens de behandeling van MFT worden flocculanten toegevoegd om de flocculatie en sedimentatie van de fijne deeltjes te bevorderen. Experimenten zijn uitgevoerd om het flocculatiegedrag van MFT te onderzoeken. De operationele parameters van het flocculatieproces zoals de geometrie van het meng vat, de mengsnelheid, duur van het mengen, polymeerdosering en droge stof gehalte van de MFT zijn gevarieerd, waarmee de optimale condities voor flocculatie en ontwatering zijn bepaald.

Het sedimentatie- en consolidatiegedrag van het slib zijn onderzocht in kolom testen, waarbij het initiële water gehalte en de randvoorwaarden zijn gevarieerd. Uit deze testen zijn correlaties bepaald tussen het poriëngetal en de samendrukbaarheid en water doorlatendheid van het slib, welke noodzakelijk zijn voor de numerieke simulatie van het ontwateringsproces. Eendimensionale samendrukkingsproeven zijn uitgevoerd m.b.v. een oedometer om de samendrukbaarheid en water doorlatendheid te bepalen bij relatief kleine poriëngetallen. Uit de resultaten bleek dat sedimentatie en consolidatie gedrag van MFT vergelijkbaar is met andere typen slib. Het gebruik van flocculanten versnelde zoals verwacht de sedimentatie en consolidatie van het slib, maar resulteerde wel in een groter slibvolume.

Een serie proeven is uitgevoerd om drie specifieke materiaaleigenschappen te bepalen die het uitdrogingsproces beïnvloeden. In verschillende lab opstellingen is de uitdroging van het slib bestudeerd, waarbij de veranderingen in het volume, water gehalte en capillaire zuigspanning in het slib is gemeten. Op basis van deze testen zijn de krimp- en waterretentie karakteristieke curves bepaald, die nodig zijn voor de numerieke simulatie van het uitdrogingsproces. Scheurvorming tijdens het uitdrogen is bestudeerd voor een dunne laag slib van circa 1 cm, waarbij het water gehalte waarbij scheurvorming begint en ontwikkeling van de scheuren in de verschillende soorten slib zijn gemeten. Testen waarbij nat-droog cycli zijn uitgevoerd laten zien dat zowel het krimp- als het waterretentie gedrag hysterese vertoont. Vergelijking van MFT met en zonder flocculant liet zien dat de toevoeging van flocculanten naast het sedimentatie- en consolidatiegedrag ook de krimp- en waterretentie karakteristieke curves van MFT beïnvloedt.

Bij toepassing van verticale drains in slibdepots kunnen de kunststof filters verstopt raken waardoor de drainage efficiëntie van de drains afneemt. Filtratie testen zijn uitgevoerd onder verschillende hydraulische randvoorwaarden, waarbij de doorlatendheidreductie in de tijd is gemeten. Na afloop is de specifieke doorlatendheid van het kunststof filter gemeten. De resultaten van de filtratie testen voor de verschillende materialen zijn met elkaar vergeleken via een empirisch bepaalde filtratie weerstand parameter, Specific Resistance to Filtration (SRF). De testresultaten toonden aan dat de kunststof filters niet verstopt raakten door de fijne deeltjes of de bitumen, maar dat de doorlatendheidsreductie kon worden toegeschreven aan consolidatie van de sliblaag (filtercake) die zich tegen de filter aan bevindt

Uitdrogingstesten zijn uitgevoerd in bakken en kolommen van verschillend formaat, waarbij het initiële vochtgehalte, de laagdikte en atmosferische condities zijn gevarieerd. De resultaten tonen aan dat het droogproces sterk verbetert wanneer (1) het water dat uittreedt aan de oppervlakte actief wordt verwijderd; (2) weer- en klimaatcondities (wind, temperatuur en relatieve luchtvochtigheid gunstig zijn (3) het slib in dunne lagen wordt aangebracht. Droog kolomtesten werden in het laboratorium uitgevoerd om het droog gedrag verder te onderzoeken. De kolomtesten bevestigden de invloed van relatieve luchtvochtigheid, windsnelheid, oppervlak en hoogte van de uitdrogende slibmassa op het uitdrogingsproces en in mindere mate de aanwezigheid van bitumen en zoutgehalte van het poriewater. Een aantal kolommen zijn tijdens het uitdrogingsproces op regelmatige tijdsintervallen in een CT scanner geplaatst. De CT analyse kon gebruikt worden om de interne verdeling van het watergehalte te bepalen. Tevens werd vastgesteld dat bij het aanbrengen van een tweede laag slib de hoeveelheid zwel van de onderliggende sliblaag niet significant was.

Tenslotte is een eendimensionaal numeriek model gebruikt om het verticaal watertransport en de vervorming als gevolg van bovenbelasting of uitdroging onder variërende atmosferische condities te voorspellen. Gebruikmakend van de materiaaleigenschappen die in het laboratorium zijn bepaald is het model gevalideerd door de simulatieresultaten te vergelijken met de bovengenoemde kolomstudies en beschikbare monitoringsdata uit het veld. Resultaten van deze validatie tonen aan dat het model de belangrijkste aspecten van het drooggedrag, zoals de vervorming en de verdeling van het vochtgehalte over de laag goed kan voorspellen.

List of Abbreviations

AE	Actual evaporation
AEV	Air entry value
AFD	Atmospheric fines drying
ASTM	American society for testing and materials
BT	Beached tailing
BAW	Tailings beached sub-aerially
BBW	Tailings beached sub-aqueously
CHWE	Clark hot water extraction
COT	Cyclone overflow tailings
CST	Capillary Suction Time
СТ	Computed tomography
CUT	Cyclone underflow tailings
DDA	dedicated disposal area
DUT	Delft University of Technology
EPL	End Pit Lakes
FFT	Fluid fine tailings
FFW	Fines water ratio
FMFT	Flocculated MFT
ILTT	In-line thickened tailing
LL	Liquid limit
MFT	Mature fine tailing
NST	Non-segregating tailings
NWR	Net water release
OSCT	Oil sands composite tailings
OST	Oil sands tailings
PBT	Pitched-blade turbine
PE	Potential evaporation
PI	Plasticity index
PL	Plastic limit
PSD	Particle size distribution
PVD	Prefabricated vertical drains
RH	Relative humidity
SEM	Scanning electron microscope
SFR	Sand to fine ratio
SL	Shrinkage limit
SRF	Specific resistance to filtration
SSCC	Soil shrinkage characteristic curve
SWRC	Soil water retention curve
TFT	Thin fine tailings
TLD	Thin lift drying
TSRU	Tailings solvent recovery unit
TT	Thickened tailings
TTQ	Totalized torque
USCS	Unified soil classification system

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Introduction

1.1. Statement of problem

Tailings are materials left over after the process of separating the valuable fraction from the uneconomic fraction of an ore. Oil sands tailings are produced when bitumen is extracted from oil sands ore using the Clark hot water extraction (CHWE) method. Oil sands is a type of unconventional petroleum resource and over 95 % of oil sands ores are located in Canada. Traditionally, the warm aqueous tailings produced from extraction process is hydraulically transported and stored in an engineered dam and dyke system referred to as the tailing pond. Upon arrival at the pond, the tailing stream segregates, with the sand dropping out of suspension forming beaches on the bottom and most of clay and residue bitumen are carried in the run-off slurry which flows over the already formed beaches into the middle of the pond. After many years of settling, three layers are developed in the pond. The top layer is water which is recycled. The bottom layer of is a clay suspension called mature fine tailings (MFT). Between the water and the MFT lies a transition zone of water and settling particles.

As higher oil prices and new technologies enable profitable extraction and processing, the Canadian oil sands industry developed rapidly in recent decades and a considerable amount of tailings has been produced. As of the end of 2009, the tailing ponds in the mineable region of Alberta covered more than 130 square kilo, which is similar to the size of the City of Vancouver (Government of Alberta 2010). Some tailings ponds have the maximum depth over 50m (Guo, 2009). These tailing ponds generated environmental and engineering problems summarized as follows. First, the tailings ponds are toxic to living organisms as they contain naphthenic acids, polycyclic aromatic hydrocarbons (PAHs), BTEX compounds (benzene, toluene, ethylbenzene and xylene), heavy metals, salts and residual bitumen (WWF report, 2010). Second, the tailings ponds leak into rivers and groundwater, which poses a threat to communities downstream. Third, oil sands tailings ponds emit methane, a potent greenhouse gas that contributes to increasing Canada's carbon emissions. Fourth, the containment dikes keep raising in order to meet the growing requirement of ponds' capacity, which poses the risk of foundation and slope instabilities which have occurred in the past (ICOLD-UNEP 2001). For the above reasons, oil sands companies must manage the tailings produced and reclaim the disturbed lands as well as the tailings ponds. Despite companies' assurances that disturbed lands will be reclaimed to viable ecosystems, after nearly fifty years of mining, only 0.2% of land has been certified as reclaimed by the government of Alberta and no tailing pond has yet been reclaimed up to date (Grant et al, 2008). The amount of MFT

continues to grow at a high rate as the production of 1 barrel of bitumen will result in 1.5 barrel of MFT (WWF, 2010).

MFT is the major reason that the tailing ponds cannot be reclaimed. Due to a very low hydraulic conductivity and a high thixotropic strength, MFT consolidates very slowly in the ponds (Jeeravipoolvarn, 2010). Without any engineering means, water removal and consolidation could be achieved over a period of 30 to 50 years (Wells, 2011). Therefore, oil sands producers are adopting technologies to treat MFT. The objective in treating tailings is to remove water and strengthen the material so that a trafficable load-bearing surface can be produced within a reasonable time-frame for subsequence reclamation (BGC, 2010). A number of tailing treatment technologies have been proposed and tested by different companies but they have been rejected due to the lack of technical or economic feasibility (BGC, 2010). In 2009, Energy Resources Conservation Board (ERCB) released Directive 074 (D074), a stricter regulation to hold oil sands producers accountable for the tailings produced. According to D074, tailing deposits that have been created must have a minimum undrained shear strength of 5 kPa within one year and 10 kPa within five years (D074 was withdrawn in March 2015 and currently there is no replacement). In order to comply with D074, oil sands producers have to search for alternative or improved technologies to treat fluid fine tailings. The research is now focusing on schemes which use more than one technology and combine them into a disposal package, and re-evaluation of some technologies that previously have been evaluated as being too expansive as they might be viable under today's socioeconomic conditions.

This thesis presents a research project sponsored by Shell Canada. This project investigates laboratory properties and dewatering behaviour of fine oil sands tailings using the selected dewatering technologies as listed here:

- Self-weight consolidation and atmospheric drying of fluid fine tailings, deposited in thin lifts on the drying area
- Use of Prefabricated Vertical Drains (PVD) in enhancement of consolidation of oil sands fine tailings in the pond

These two technologies have been described and evaluated in this research because they have been successfully applied in the Netherlands in disposal of dredged sludge and soft clay layers in a deltaic area, both of which may share similar engineering properties with fine oil sands tailings. It is considered that the knowledge and experience gained in the past can help better understand the behaviour of fine oil sands tailings and implement the technologies more efficiently. In the oil sands industry, the PVD technology has been field tested by Suncor in dewatering oil sands consolidated tailing (a mix of MFT and sand with chemical additives) in the ponds and some success was gained. However, this technology has not yet been used to dispose fine oil sands tailings. Although some laboratory and field fines drying evaluations have been carried out by different companies, most of the previous research did not cover detailed behaviour of the tailings.

In this project, the selected technologies are proposed for different fine tailings including the MFT dredged from tailing ponds, the hydro-cyclone classified fine tailing product (i.e. the thickened tailings, TT) and the polymer treated (flocculated) MFT. Various laboratory tests have been performed on the samples of these materials to develop their engineering properties and dewatering behaviour.

1.2. Objectives and scope of research

The main objectives of the research in this thesis are: (1) determine physical and engineering properties of fine oil sands tailings; (2) identify effects of polymer treatment on properties of MFT; (3) investigate dewatering behaviour of fine oil sands tailings related to vertical wick drains and thin lift drying technology; and (4) implementation of a numerical model to simulate the drying process of tailing. The content of research is divided into three main categories which are: materials characterization, physical modeling and numerical modeling. The specific objectives of each component are presented in the research plan in Chapter 2.

This research utilised two types of oil sands fine tailings – Material Fine Tailings (MFT) and Thickened Tailings (TT) - obtained from Shell Albian Sands Muskeg River Mine which is located 75 km north of Fort McMurray, Alberta, Canada. In order to classify and identify the tailings, laboratory classification tests were performed on tailing samples according to ASTM standard method unless noted otherwise. Although the pore water chemistry properties (i.e. ion concentration, conductivity and pH) affect the geotechnical properties of the fine tailings, interplays between the parameters are complex and not well understood and thus they were not considered in this work. Flocculation of MFT was achieved using a laboratory scale mechanical mixing system. The flocculant used to treat MFT was limited to one of the Shell's best performance polymers which has been used in pilot in-line flocculation program. Investigations of engineering behaviour of tailings were limited to important aspects that are closely related to the selected dewatering technologies. This behaviour was investigated by conducting various characterization tests in laboratory conditions. To achieve it, some simple and standard experiments such as column settling tests, oedometer tests and filter paper suction measurements were carried out. In order to evaluate the technical feasibility of the selected dewatering technologies, the key dewatering processes of the technologies were modelled through bench-scale dewatering tests. Due to the complexity of the tailings and the technical requirements, some special methods were developed according to previous experience and related literature. A one-dimensional numerical model was implemented to simulate the laboratory column drying tests and the field scale tests. The governing equations of the numerical model were based upon water flow, with the consolidation, drying behaviour due to evaporation and suctions incorporated. The material properties of the polymer treated MFT used in the simulations are limited to the optimum flocculation condition.

1.3. Organization of the thesis

This thesis is organized into 10 chapters. A brief introduction to each chapter is given as followings.

Chapter 2 begins with an introduction to the Canadian oil sands and the oil sands tailings industry, followed by a review of existing tailing management technologies and the technologies proposed in this study. Knowledge gaps and research needs in this study were then analyzed and finally the detailed research plan was proposed.

Chapter 3 presents the classification tests performed on MFT and TT samples to obtain their geotechnical index properties. These properties were compared with those of different tailing samples reported in the open literature.
Chapter 4 describes flocculation experiments on MFT using a laboratory scale mixing device developed for this research. Main factors such as effects of mixing tools, mixing intensity (energy), solids concentration and polymer dosage on flocculation outcomes were assessed. The optimum operational parameters for flocculation were determined.

Chapter 5 presents the results of settling column tests and oedometer tests performed on fine tailings samples in slurry state and soil-like sate, respectively. The sedimentation and self-weight consolidation phenomena of the tailings sludge at different void ratios were observed in glass cylinders. Hydraulic conductivity of high water content tailing slurry and bound void ratio between hindered sedimentation and consolidation are determined. Oedometer tests were carried out to determine stress – strain relationship of fine tailings at lower void ratio, the consolidation parameters were determined and compared.

Chapter 6 investigates three primary aspects of soil behaviour during desiccation – shrinkage (swelling) property, soil water retention characteristic and cracking behabiour. Shrinkage (swelling) curves and soil water retention curves of the tailings were assessed utilising different experimental procedures. Evaporation and cracking behaviour of a thin tailing layer was then investigated. Effects of drying-wetting cycles and polymer treatment on above behaviors were also discussed.

Chapter 7 presents clogging and filtration tests conducted on geotextile filter jackets of PVD with fine tailings sludge. The tailings sludge was allowed to consolidate in a PVC column under air or water pressure which was applied to simulate the stress circumstance at certain depth in the tailing pond. The clogging potential of geotextile filter jacket was evaluated and filterability of various tailings were compared.

Chapter 8 presents small scale air drying tests on different fine tailings. One group of box drying tests and two groups of column drying tests were carried out chronologically. Settling and desiccation behaviour of the tailings under different environmental conditions were investigated. Factors affecting the efficiency and results of dewatering were then discussed.

In Chapter 9, a numerical model is described and operated using a user interface to simulate the laboratory column drying tests described in Chapter 8 and the field pilot thin-lift drying tests conducted by Shell using the real climatic data. The calculation results were compared to the monitored parameters.

In Chapter 10, a summary of the conclusions developed throughout the thesis and recommendations for future research are given.

\sum

Background and Research Plan

2.1. Introduction

Compared to the tailings and waste produced from conventional mines (i.e. coal, copper, gold etc.), tailings produced from mining of oil sands ore are less well known to geotechnical engineers. To help readers get a better understanding of the research topic, an extensive background of oil sands tailings is presented in this chapter. The content provided in Section 2.2 includes a review of oil sands ore and bitumen extraction process, types of oil sands tailings and general properties, and oil sands tailings management technologies. In Section 2.3, a plan for this research is proposed. The sub-section 2.3.1 firstly presents an assessment of research needs and knowledge gaps based on the author's background knowledge and the available of published literature. In the sub-section 2.3.2, schemes of work that will be carried out and the detailed plans for each work are presented.

2.2. Background

2.2.1. Overview of oil sands industry

2.2.1.1. Introduction to oil sands

Oil sands as an unconventional petroleum reserves are found in about 70 countries around the world, but the largest and primary oil sands reserves are located in eight countries in, alphabetically: Albania, Canada, Madagascar, Romania, Russia, Trinidad, the USA and Venezuela. Over 95% of the known accumulations of oil sands in the world are located in Canada, specifically in three areas in Alberta province: Athabasca, Peace River and Cold Lake (Figure 2.1). These deposits contain in-place reserves of approximately 275 billion cubic meters of mineable and in-situ crude bitumen with 28 billion cubic metres as initial established reserves (ERCB, 2009). Amongst the three deposits, the Athabasca deposit is the largest deposit containing an initial volume of crude bitumen of about 223 billion cubic metres. By 2013 there were nine oil sands mining projects in the Athabasca oil sands deposit: Suncor Energy Inc. (Suncor), Syncrude Canada Limited (Syncrude)'s Mildred Lake and Aurora North, Shell Canada Limited (Shell)'s Muskeg River and Jackpine, Canadian Natural Resources Limited (CNRL), Horizon, Imperial Oil Resources Ventures Limited (Imperial),

Kearl Oil Sands Project (KOSP), Total E&P Canada Ltd., Joslyn North Mine and Fort Hills Energy Corporation (FHEC). In 2011 alone they produced over 52 million cubic metres of bitumen (ERCB, 2013).



Figure 2.1 Three oil sands deposits areas in Alberta

Oil sands deposits are loose sands or partially consolidated sandstones containing a natural mixture of sand, clay, and water, saturated with a dense and viscous form of petroleum technically referred to as bitumen (Figure 2.2). The bitumen content in oil sands ranges from 0 to 19% by total mass, averaging at 12%. The water content varies between 3% and 6% by total mass and increases as bitumen content decreases (BGC, 2010). The major clay components in oil sands are kaolinite (40~70%), illite (28~45%) and traces of montmorillonite (Chalaturnyk et al. 2002).



Figure 2.2 Oil sand ore (http://www.awarmerworld.com)

2.2.1.2. Bitumen extraction at surface-mined projects

In the Athabasca deposit, there is about 20.7 billion cubic metres of crude bitumen that has less than 65 metres overburden which makes it suitable for surface mining technologies (Kasperski, 2001). For the rest of Alberta's crude bitumen area, in-situ methods are required (EUB, 2004). The bitumen extraction processes employed by various oil producers are fundamentally the same, which is called the Clark hot water extraction (CHWE) process developed in the 1920s by Dr. Karl Clark collaborating with the Alberta Research Council. The whole extraction process can be summarized as follows. First, the overburden material (mainly clays) is removed. Oil sands are then mined using draglines and bucket wheels or truck and shovel methods and transported from the pit to the extraction plant by truck or a large network of conveyors. At the extraction plant, oil sands are crushed and sent to large tumblers where they are digested and conditioned with a mixture of hot water (50-80 °C), sodium hydroxide (NaOH), and steam. Heat and agitation are used to overcome the forces that hold oil sands lumps together. Sodium hydroxide is used to assist in maintaining the pH of the solution between 8.0 and 8.5 in order to separate the bitumen from the mineral solids. After the ablation of the oil sands lumps, the bitumen is separated from the sand grains and form bitumen droplets within the slurry. Air is sparged into the system to reduce the density of the bitumen phase by causing the oil to spread over the gas bubbles, which allows for future gravity separation of the phases. Next, the slurry is discharged to vibrating screens and washed with water to remove undigested oil sand lumps. The remaining slurry is diluted and fed to large gravity separation vessels, known as primary separation cells (PSC). The coarse solids settle fast to the bottom and they are withdrawn as a concentrated suspension which is called primary tailings. The smaller suspended solids and the poorly aerated bitumen droplets are all drawn off in a slurry from the middle of the vessel, which are called middlings.

Because Since the middlings stream has economic value, producers employ various technologies to capture as much as possible bitumen from the middlings. At Suncor, the middlings stream is directly processed in conventional flotation cells where more air is added to facilitate improved separation between bitumen and water. At Syncrude, the tailings and middlings streams from the primary separation vessels are combined and further processed in large deep cone vessels where additional bitumen is recovered. At Shell Albian Sands, the middlings stream is introduced to the primary flotation cells to recover additional bitumen. In these flotation cells, air is injected directly into the mixture and further shear is applied to improve separation. The tailings stream from the primary separation vessel is combined with the tailings stream from the primary flotation cells and is introduced to the secondary flotation cells to recover any residual bitumen. The primary and secondary froths are combined and are de-aerated in towers by allowing the aerated bitumen to cascade over a series of cones, flowing counter-currently to an upward flow of steam. The de-aerated froth is then processed in a froth treatment plant to remove solids and water prior to the upgrading process (Cabrera, 2008). Figure 2.3 shows the schematic of Muskeg River Mine Extraction Pilot Plant employed by Shell Albian Sands.



Figure 2.3 Schematic of Albian Sands Muskeg River Mine Extraction Pilot Plant (Masliyah, 2007)

2.2.2. Overview of oil sands tailings

2.2.2.1. Classification of tailings

In the surface-mining projects, 1.0 m^3 of the in-place oil sands will produce 3.3 m^3 of the tailings stream, if the solids content of the tailings stream is 40%; or 1.9 m^3 tailings stream, if the solids content is 60% (Jeeravipoolvarn, 2005). Tailings coming directly from extraction plant are a warm aqueous suspension of sand, silt, clay, residual bitumen and naphtha, at a pH between 8 and 9 and are called whole tailings (WT). The traditional tailing disposal method is to discharge WT into tailing ponds. In the ponds, WT segregates with the coarse particles (sand) settling out rapidly to form beaches, producing the so-called beached tailings (BT). The BT can be further subdivided into "BAW", referring to tailings beached sub-aerially, and "BBW", referring to tailings beached sub-aqueously. Most of fine particles are carried in the run-off slurry which flows over the already formed beach into the middle of the ponds where they settle by gravity. Over time, three layers are developed in the tailing ponds, as shown in Figure 2.4. The top layer (about 1 to 3 m thick) is clear water which is recycled to the extraction process. Under the water is the immature fine tailings or thin fine tailings (TFT) -- a transition zone of water and settling particles which is about 1 to 2 m thick. Below TFT a layer of silts and clays, fine sands, bitumen and water is formed and it is regarded as the mature fine tailings (MFT). Generally, the depths of the MFT vary from 15 to 20 m, not including the higher sand content material at the bottom and the pond (Guo, 2009). MFT has a solids content of about 30%. Further increases of the solids content of MFT appears to be very slow.



Figure 2.4 Cross-section of an Oil Sands Tailings Basin (FTFC, 1995)

As illustrated in Figure 2.3, WT can be classified purposely to separate fines and sands by hydro-cyclones. The overflow of hydro-cyclone is called cyclone overflow tailings (COT) while the underflow is cyclone underflow tailings (CUT). The COT is a high fines content stream that can be stored in a pond or further treated to recover more bitumen and/or water. Thickened tailing (TT) is a tailing product which is produced by thickening the COT in a thickener with flocculant additions. After treatment water is released quickly from tailings and the released water has very small solids contents (<1%), making it suitable for recycling as make-up water for extraction. In-line thickened tailing (ILTT) is a rather new tailing product, which is produced by conditioning the COT via an in-line thickening process. By using a multi-stage flocculation and coagulation mixing process, the size of flocs, hydraulic conductivity and shear strength of tailings are increased, and the dewaterability is greatly improved (Jeeravipoolvarn, 2010). The CUT, mostly sands, can be used to construct containment dykes or produce tailing products. Consolidated tailings (CT) is one tailing product, which is produced by combining CUT and MFT with an additive of gypsum. Similar to CT, non-segregated tailing (NST) is mixture of CUT and TT with chemical additives.

2.2.2.2. Characterization of oil sands tailings

The ternary diagram developed by Scott & Cymerman (1984) is commonly used to characterize oil sands tailings from the geotechnical point of view. A typical construction layout of the ternary diagram is shown in Figure 2.5(a). In this diagram, the vertical apex, the left corner and the right corner represents 100% water, 100% sand and 100% fines, respectively. The solid particles in tailings are classified into fines (grain size smaller than 44 µm) and sands (grain size larger than 44 µm). If the mass of sand, fines, water and bitumen in a tailing is defined as *s*, *f*, *w* and *b* respectively, then the total mass T = s+f+w+b, the sand content S = s / T, the fines content F = f / T, the water content W = w/T, and the solids content = (s+f+b)/T = 1-W. It should be pointed out that the water content used in the ternary diagram is not the gravimetric water content as used in geotechnical engineering. The sand to fine ratio (SFR) is an important tailing characterization index which is defined as s / f. The ternary diagram can be expressed in another type as shown in Figure 2.5 (b). The alternate axes of ternary diagram are: solids content, geotechnical fines content (f / (f+s)), and fineswater ratio (FFW = f / (f+w)).



Figure 2.5 Typical layout of the ternary diagram (a) and ternary diagram with alternate axes (b) (Sobkowicz & Morgenstern, 2009)

Azam and Scott (2005) utilised the ternary diagram to show boundaries between different types of geotechnical behaviour as the solid content and fines content of the tailing material is varied. The boundaries are shown in Figure 2.6 and explanations are given as follows:

• Sedimentation (A) vs. Consolidation (B)

This boundary differentiates between sedimentation region (above the line A/B) and consolidation area (below the line A/B). Sedimentation refers to the settling of a

spatial network of soil particles without measurable effective stresses whereas consolidation commences when the solid grains are in contact thereby transmitting effective stresses.

• Segregating (C) vs. Non-segregating (D)

Segregation occurs because of a low shear strength in the soil matrix which is caused by low initial density and low attractive forces between particlesAbove this boundary the coarse particles settle through the tailings slurry and therefore segregate while below the boundary no appreciable differential settling of the coarse particles takes place. Tailings can be rendered non-segregating by increasing the solids content to below the boundary. According to the graph, fine tailings do not segregate even at low solids contents of 20% to 30%.

• Pumpable (E) vs. Non-pumpable (F)

This pumpable – non-pumpable boundary depends on both rheological characteristics of material and economics of disposal system. It is seen that the boundary lies around the 50% fines-water ratio line for mixtures with a fines content over 50%. For coarser materials, the boundary sharply drops to the matrix boundary.

• Liquid (G) vs. Solid (H)

This liquid – solid boundary is defined by plotting equal undrained shear strengths, which closely approximate the liquid limit (2.5 kPa) for slurry mixes (Azam and Scott, 2005). This boundary is highly sensitive to grain size distribution and physico-chemistry. The determination of this boundary provides a tailings management alternative in which the material achieves enough strength to be capped with a soil cover.

• Saturated (J) vs. Unsaturated (K)

The boundary pertains to the shrinkage limit for fines contents falling in the fines matrix whereas in the sand matrix, it denotes the minimum void ratio of the sand.

• Fines-dominated matrix (L) vs. Sand-dominated matrix (M)

The boundary distinguishes between a sand matrix (below the line) and a fines matrix (above the line). A sand matrix is one in which the coarse grains barely touch one another, that is, the sand void ratio is at a maximum and the fines are present in the pore space between the sand grains (Azam and Scott, 2005). In a fines – dominated matrix, the sand grains are suspended in the fines matrix.

Sobkowicz & Morgenstern (2009) added a liquefaction boundary to the ternary plot as Zone N. They proposed that sand tailings plotting on or above zone N are potentially liquefiable whereas those below Zone N are not. It should be pointed out that the boundaries shown on Figure 2.6 are not accurate for the tailings from any particular oil sands mine. This plot gives a general indication of tailings behaviour and should only be used for illustrative purposes.

Sobkowicz & Morgenstern (2009) also presented general areas of various oil sands tailings on the ternary diagram, as shown in Figure 2.7. It is seen that a mass percentage of

50-70% solids in WT are characterized as fines (< 44 μ m). After classification by hydrocyclone, the COT contain about 80 - 90% fines. After a flocculation and thickening process, fines content of the resulted tailing material (TT) drops significantly. Among all the tailings, MFT have the highest fines content, which is over 90% according to the plot. It was found that all fluid fine tailings (e.g., MFT, TT, COT etc.) are above the boundary between "pumpable" and "non-pumpable". It indicates that the fluid fine tailings can be delivered via pipelines. In addition, all tailings are well above the liquid vs. solid boundary, indicating that additional stages of dewatering are required to render these tailings suitable for reclamation.



Figure 2.6 Zones of different geotechnical behaviour of tailings (Sobkowicz & Morgenstern. 2009)



Figure 2.7 Illustration of areas of various oil sands tailings and tailings products on the ternary diagram (Sobkowicz & Morgenstern. 2009)

Suthaker and Scott (1996) determined that hydraulic conductivity of oil sands tailings was a power law function of fines void ratio. Since the fines void ratio is a function of fines-water ratio (FFW), general ranges of hydraulic conductivity of fines and sand mixtures can be illustrated on the ternary plot, as shown in Figure 2.8 which was presented by Sobkowicz and Morgenstern (2009). This plot shows that the initial state of fluid fine tailings have a hydraulic conductivity in a general range between 10^{-6} and 10^{-7} m/s, and the hydraulic conductivity drops to 10^{-9} to 10^{-10} m/s after the water content decreases from 70% to 30%.



Figure 2.8 Hydraulic conductivity of Fines/Sand Mixtures (Sobkowicz & Morgenstern, 2009)

While a convenient and useful characterization tool, one weaknesses of the ternary diagram is that it does not explicitly show clay content (< 2 μ m %) which may govern the behaviour of fine tailings due to the electro-chemical activity of clay.

2.2.3. Oil sands tailings management technologies

2.2.3.1. Existing technologies

In 2010, BGC Engineering Inc. published an in-depth review of up to 34 existing oil sands fine tailing treatment technologies. These technologies were divided into 5 groups. In this section, some important technologies are briefly introduced based on BGC's report. Some additional information is provided from the available literature at the time of writing.

2.2.3.1.1. Physical/mechanical processes

Physical/mechanical processes involve the use of different technologies to separate water from solids. Filtration is a traditional method for solid-liquid separation which can take place either by pressure or vacuum force. In practice, drums, horizontally or vertically stacked plates and horizontal belts are the most common filtration plant configurations. Filtration has been piloted in dewatering whole oil sands tailings since mid-1990s but many of the

experiments were unsuccessful, because the thick porous filter cakes formed by faster settling coarse particles was blinded by slower settling fines, which effectively shut off filtration. Centrifuge technology applies up to thousands of times the gravity force to extract fluid from material. Centrifuge technology was evaluated in the past, but the cost was unacceptable at that time. Recently, Suncor and Syncrude (2009) jointly evaluated available centrifuges and tested a small 5 tonne per hour centrifuge as a method to process MFT. The underflow from the centrifuge process was deposited as a paste comprising primarily fines with a content of 55% to 60% solids to in-pit beaching areas where material could be reclaimed in place (Suncor, 2009). The main drawbacks of centrifuge technologies are still high upfront capital and operating costs and challenges in transporting centrifuged cake. Electrokinetic dewatering involves the application of a direct current (DC) electric field to a clay slurry. The electrical field causes migration of negatively charged clay particles to the positive (anode) electrode, resulting in accelerated sedimentation. This technology has been investigated in the laboratory only by some researchers (e.g. Flintoff and Plitt 1976, FTFC 1995, Guo 2012). The main problems limiting the large scale application of electrokinetic dewatering include high energy costs, difficulty in removing supernatant liquid and corrosion of the electrodes. Prefabricated vertical drains (PVD) technology is a commonly used engineering method to enhance consolidation of soft soils. Detailed information about this technology will be presented in next section. PVD have been applied by Suncor in dewatering oil sands CT pond and the preliminary results seemed to be positive. However, viability of applying PVD in dewatering fine tailings materials is not proven.

2.2.3.1.2. Natural dewatering process

Natural dewatering processes involve making use of environmental or geophysical processes to dewater tailings. The mostly discussed natural processes in engineering are sedimentation/consolidation, natural drying and freezing/thawing. Sedimentation and consolidation uses the gravity force to separate the suspended solids from the tailings stream. As a mature technology, it has been used for more than 40 years in the oil sands industry. In a pond, tailings are allowed to dewater passively and the water released is recycled to the extraction process. Evaporative drying technology consists of depositing fluid tailings in thin lifts and allowing the lifts to desiccate by sun and wind induced evaporation. This technology has been accepted as the most cost-effective means of disposal of fine grained material. Subaerial drying and the variants are being evaluated by different oil sand companies for potential implementation in commercial scale. Freeze and thaw consists of depositing fine tailings in multiple thin layers which are allowed to freeze in winter and then the frozen mass is allowed to thaw the following summer. In winter, formation of a three dimensional reticulate ice network produces a negative pressure which drives the water in the tailings towards the forming ice. The moving mass of water would create a network of fractures throughout the layers that would be used as draining channels while thawing. Laboratory investigations (Dawson and Sego, 1993, Johnson et al. 1993, Proskin, 1998) demonstrated that a considerable amount of water is released when thin layers (5 cm to 15 cm) of MFT are subjected to free-thaw cycles. Sego (1992) determined that the effect of freeze-thaw dewatering can be enhanced via chemical amendment and altering drainage conditions. This technology is currently being evaluated by different company for commercial implementation.

2.2.3.1.3. Chemical / biological treatment

Chemical/biological amendments involves changing the properties of the tailings to remove water. The chemical treatment improves the dewaterability of fine tailings and thereby increases the operational efficiency of existing dewatering technologies. Research demonstrated that when tailings are mixed with appropriate coagulants or flocculants, the time of sedimentation is significantly reduced, and a relatively high solid content and strength can be achieved (Jeeravipoolvarn 2010, Yuan and Lahaie 2009). Existing technologies using chemical treatment include production of thickened tailings and in-line thickened tailings from cyclone overflow tailings, coagulation and flocculation of whole tailings, and in-situ treatment of the fine tailing stream. Biological treatment is studied to treat oil sands tailings, in which bacterial actions, such as inoculation and enhancement, are used to densify high fine content tailings (Fedorak et al. 2003, Guo 2009). The research is still at the preliminary stage with limited knowledge obtained.

2.2.3.1.4. Mixture technology

Mixture technologies involve mixing tailings with a variety of available soil materials and waste products to increase density of tailings. One typical technology is the composite tailings (CT) process which involves mixing of MFT and coarse sand with additive of coagulant (typically gypsum) to form a rapid consolidating soft deposit. The CT process was developed at the University of Alberta (Caughill et al. 1993). In 1995, Suncor was the first company to apply the CT process on a commercial basis, in its Pond 5, and it has continued to apply the technology (Suncor 2009). Syncrude conducted a non-segregating tailings field demonstration in 1995, followed by the CT prototype in 1997-1998. A commercial CT plant has been in operation at the Syncrude Mildred Lake site since 2000. CT remains the primary tailings management technique for existing and future plans for several operators. Besides the CT technology, other mixture technologies have also been studied. These technologies involve mixing MFT with clear water overburden (water capping), mixing MFT with reclamation material, mixing MFT/CT with coke and mixing TT with sand.

2.2.3.1.5. Permanent storage

Permanent storage technologies acknowledge the complexity and cost associated with tailings treatment and instead opts to store tailings in their original form. In a wet landscape scenario, MFT is stored in a mined pit and capped with a layer of water to form an artificial lake referred to as End Pit Lakes (EPL). In the lake, MFT will become denser over time and the released water adds to the thickness of the water cap. In the far-future, it is expected that the EPL will evolve into natural ecosystems which support healthy communities of aquatic plants, animals and fish. At the moment, the pit lake technology is not proven.

2.2.3.2. Technologies described in this research

2.2.3.2.1. Thin-lift drying techniques

Thin-lift (sub-aerial) drying technology utilizes natural evaporation to dry the slurrylike low permeability material that is deposited in thin layers, it is regarded as one of the most cost-effective dewatering method for fine grained materials. In the Netherlands, sub-aerial drying, known as mud farming, has been used for decades in disposal of the sludge dredged from Rotterdam harbor. The dredged sludge is deposited in a confined area where the sediments are allowed to settle by self-weight. As the stagnant water runs away, the sediment is desiccated by sun and wind induced evaporation. After a complex process, so called ripening, the sludge is converted to a soil. Implementation of the technology includes several steps. First, contaminant dikes are constructed around the low polder to create a confined disposal area. The disposal area is then subdivided into a number of smaller units by constructing drainage channels. Next, the sludge is deposited to the drying units in a thickness of 1.0 to 1.5 m. Excess water entering the drying unit with the dredged sludge is discharged via the channels and the evacuation boxes (drop inlet sluices) which are connected by steel pipes through the bund of the area. Evaporation of soil can be greatly encouraged by making ditches (furrowing) on the drying surface. Two types of devices were used in history, as shown in Figure 2.9. The Amphirol is used in the first stage and the disc wheel is used in the later stage. After furrowing, water coming from precipitation and consolidation is collected in the formed ditch networks and run off immediately, which boosts the dewatering process. By furrowing, the ripening period of sludge can be effectively extended from 3 months to 10 months per year under Dutch climatic conditions (RPW, 1984). Once a layer of sludge is desiccated, another layer is deposited on top of it. A soil deposit is built by repeating this process. The ripened soil was used to raise the dykes of the disposal site. The rest of ripened soils were used to maintain parks in the city but it stopped at the end of the 1980s when ripened soils appeared to be contaminated. The largest advantage of the sub-aerial drying technique over other technologies is a low application cost. In addition, the resulted surface after the disposal is trafficable with modest equipment and suitable for subsequent reclamation.



Figure 2.9 Tools used for making ditches on the drying surface: Amphirol (a) and Disc wheel (b) (DUT, 2010)

As a cost-effective engineering method in disposal of fine grained soils, it is believed that natural drying of oil sands fine tails was proposed and tested in the past, though the work is not widely acknowledged due to lack of open literature. However, it was not until recently that thin-lift drying technology has been implemented in a commercial scale. One possible reason is that the promotion of natural drying technology was heavily limited by the poor engineering behaviour of MFT. As technology progresses, in particular with the development of new polymer flocculants which can significantly enhance the dewaterability of MFT, an improved air drying technology has been proposed and field tested by different companies. This "new" technology is essentially a combination of several existing technologies including chemical treatment, sedimentation and consolidation, natural drying with improved management. In general, application of the technology in the field involves several steps described as follows. First, MFT is dredged from tailing pond and pumped via pipelines to the disposal area. Polymer solutions are then injected into the tailing stream and mixed and conditioned in-line. Second, the flocculated tailings are deposited in a thin lift on a gently sloped surface where they settle and consolidate by self-weight. Water released from the tailings flows along the slope to a lower point where it is collected for recycling. Third, the tailing sediments are subjected to atmospheric conditions and desiccated by wind and sun induced evaporation. Once a layer of tailings is desiccated to the required degree, a new layer is placed above it. By repeating above processes, a clay deposit can be built.

By 2009, Suncor has conducted several small-scale and large-scale pilot tests to evaluate methods to undertake MFT drying (Suncor, 2009). Suncor utilised different chemical additives to treat MFT and the results indicated that use of the polymers effectively increased the release of free water, decreased the drying time, and increased the allowable lift thickness and strength. In late 2012, Shell started field pilot tests to demonstrate the atmospheric fines drying (AFD) techniques in dewatering polymer treated MFT. At the time of writing, some primary results of field tests have been provided by Shell and are mentioned in this thesis. The field AFD tests were not developed to achieve specific properties of the polymer treated tailings upon drying and rewetting processes. Therefore, laboratory tests were performed in this research aiming at covering these knowledge gaps.

2.2.3.2.2. Prefabricated vertical drains (PVD) technology

Prefabricated vertical drains (PVD) also known as wick drains are a cost-effective ground treatment technology used to enhance the consolidation of soft soil and increase the soil stability. A common PVD consists of a plastic strip drainage channels wrapped in a filter fabric. The principal of the installation of the vertical drainage is based on the insertion of a hollow, steel mandrel with a drain inside. The mandrel is moved up and down through a system of cylinders and winches. The drain extension at the bottom of the mandrel is connected to an anchor plate which closes off the opening so that no soil can enter. The mandrel takes the drain to the desired depth and it is then withdrawn and the resistance created by the anchor plate upon retraction ensures that the drain remains in place. The drain is cut after the mandrel has reached the surface, and a new anchor plate is connected to the bottom of the next drain. Above process is shown in Figure 2.10.

PVD have been used for decades in the Netherlands in land reclamation and ground improvement projects. The western part of the Netherlands has vast areas of very soft and compressible subsoils with an average thickness of about 15 m. These soils (clay, silt and peat) must be dewatered and strengthened to make them suitable for construction. Surcharging loads are applied on the soil layers, excess pore pressures are then formed and dissipated slowly as the consolidation of soil progresses. Besides of soil permeability, duration of consolidation is also influenced by pore water travel distance. With properly-designed vertical drainage systems, pore water will flow laterally to the closest drain rather than vertically to the underlying or overlying drainage layer and therefore the drainage distance is significantly reduced. Research shows that when installing the PVD at a practical distance of 1.5 m the consolidation time of the soft layers in the deltaic areas reduces greatly by a factor of about 10. (Internal report of TU Delft, 2010).

The idea of applying vertical drains in dewatering oil sands tailings was proposed quite early (i.e., Liu & McKenna, 1998), but it is only recent that the technology has been implemented at a field scale. Wells & Caldwell (2009) reported field tests applying wick drains in Suncor's Pond 5, the first production-scale composite tailing (CT) pond located in the north of Fort McMurray. Dewatering trials with PVD were conducted at the southwest corner of the pond. The tailings materials in the pond had values of SFR between 0.4 and 3

and a solids content between 34% and 70%. The measured in-situ shear strengths of tailings increased with the depth below the pond surface from 0.1 to 2 kPa. After a coke cap was put on the surface of pond, wick drains in different length were installed into the tailings pond at the distance varying from 0.6 to 6 m. The results showed that the PVD were functioning in assisting the consolidation of the soft, high fines content oil sands CT.



Figure 2.10 Primary steps of installing a PVD: (i) Equipment position and anchor plate installation, (ii) Mandrel driving; (iii) Mandrel extraction and (iv) PVD cutting

2.3. Research plan

2.3.1. Research needs and knowledge gaps

2.3.1.1. General

Before a research plan is proposed, it is necessary to identify the research needs and knowledge gaps which include an assessment of what is important, what is missing and what research is required to be undertaken. The plan for current research can be proposed in three steps. Firstly, the researcher needs to establish a basic understanding of the oil sands fine tailings and the technologies studied in this research. Secondly, it needs to decide what tailing behaviour should be developed and how to develop them. Thirdly, it is required to consider what factors or conditions must be satisfied for implementations of the dewatering technologies to be successful and efficient and how to investigate the tailing behaviour with respect to variations of these factors or conditions. In this section, some specific engineering behaviour is proposed and explained in Section 2.3.1.2. These aspects are considered important for establishing a better understanding of the tailings behaviour and are necessary to be investigated in this research. Section 2.3.1.3 presents an assessment of critical conditions desired for successful implementation of the technologies and the research needs to be done to evaluate the feasibility of the technologies. The information provided in this section is based on available literature and the authors' opinions.

2.3.1.2. Important engineering behaviour

2.3.1.2.1. Sedimentation and consolidation behaviour

Sedimentation and consolidation are the two primary phenomena during the settling of a high water content clay slurry. In the thin lift drying technique, the settling rate of solids particles in a tailing slurry decides the amount of water that can be released within a given period. The higher the settling rate is, the more water is released from tailings, and a shorter period is required to dry the sediment if the released water is drained effectively. Consolidation of the deposited tailing layer is caused by self-weight and overburden, it occurs following the sedimentation and, in principle, lasts throughout the whole deposition process. The consolidation behaviour is mainly controlled by compressibility and permeability. To predict the dewatering behaviour, it is necessary to understand the sedimentation and consolidation behaviour and determine the settling parameters.

Major needs and knowledge gaps in investigation of sedimentation and consolidation behaviour are to:

- Analyse sedimentation and consolidation phenomena together
- Improve the understanding of the fluid to solid transition
- Understand the effect of flocculation on sedimentation and consolidation behaviour

2.3.1.2.2. Flocculation behaviour

The properties of MFT can be amended by flocculation with the use of flocculant. Flocculation is a physical process by which the colloidal-sized particles are agglomerated into significantly larger aggregates or flocs that settle more quickly than individual particles. Flocculation of MFT has been implemented as a pre-treatment step in thin-lift drying technique and other dewatering technologies. Effectiveness of flocculation can influence the whole dewatering process in an application. Undesirable flocculation can severely hamper the dewatering of the flocculated MFT with no or little improvement in the settling rate. For an effectively flocculated MFT, the sedimentation process occurs during the placement and for a short period immediately after, and considerable amount of tailing water is released and then drained. Fasking et al. (2012) conducted laboratory drying tests on the polymer treated oil sands solvent recovery unit (TSRU) tailings and found that a little over 50% of total water loss was gained from the sedimentation process.

In the Canadian oil sands tailings industry, synthetic polymers have been commonly used to treat MFT due to higher intrinsic flocculating power than other types of flocculant. According to literature, the flocculation and dewatering behaviour depends on a number of factors including soil properties (i.e. solids content, particle size, particle surface property, solution chemistry and temperature etc.), polymer dosage, and mixing conditions. In order to achieve the maximum dewaterability after flocculation, it is necessary to operate flocculation in the optimum condition. In author's point of view, the following knowledge gaps need to be filled in order to understand the flocculation behaviour:

- Develop a procedure used for laboratory flocculation purpose
- Understand the role of mixing in flocculation and dewatering behaviour
- The optimum operational conditions for efficient flocculation
- Difference between laboratory engineering properties of flocculated MFT

2.3.1.2.3. Desiccation behaviour

Desiccation is a process of drying and cracking. Desiccation of the deposited tailing material starts after excess surface water is evaporated or drained. By natural evaporation induced by wind and sun, pore water is lost in a gaseous phase from the tailing surface to the atmosphere. Properties of desiccating soil such as shear strength and permeability are controlled by suction which is function of water content. Soil shrinkage and desiccation cracking are the main phenomena observed during the desiccation period. Therefore, in the author's opinion, desiccation behaviour of the deposited fine tailings can be studied in three basic aspects which are shrinkage properties, water retention characteristics and cracking behaviour. Although other factors may also affect the desiccation results and thus are not considered in this research.

The shrinkage property of a soil describes how volume changes with water content and it is usually characterized by determining the shrinkage characteristic curve. When no crack occurs, shrinkage of a thin lift tailing deposit upon drying is considered onedimensional and it causes surface subsidence of the deposited tailings. The magnitude of shrinkage depends on clay minerals and soil microstructure. At the beginning, the deposited material is completely saturated until air enters the pores at a lower water content. As drying progresses, the unsaturated zone develops in the soil. Hydraulic and mechanical properties of the soil are related to the amount of water in the voids, which in turn depend upon suction. The water retention behaviour describes relationship between suction and water content. This behaviour is characterized by soil water retention curve (SWRC). With the SWRC, it is possible to predict permeability and shear strength of unsaturated soils (Fredlund et al., 1978, 1994). The soil water retention curve and the shrinkage curve can be used as input parameters for numerical modelling of desiccation behaviour. Shrinkage cracks occur in the desiccating layer when the increasing tensile stress exceeds the tensile strength of the soil. Desiccation is greatly encouraged by the presence of cracks because the overall permeability of the layer is increased by several magnitudes (Albrecht and Benson, 2001; Boynton and Daniel, 1985). Propagation of cracks divides the tailing layer into individual soil columns with a desiccated crust on the top.

In thin lift drying technology, desiccation is the dominant mechanism of water removal and investigation of desiccation behaviour is at the heart of identifying the dewatering behaviour of fine tailings. Research needs and knowledge gaps in this research are considered as:

- Analysis of different aspects together to establish a complete understanding of the dewatering behaviour
- Understand the effects of rewetting and drying-rewetting cycles on tailings drying
- Identify the difference between MFT and flocculated MFT in terms of dewatering behaviour

2.3.1.2.4. Gas production

Since the 1990's, generation of biological gas (e.g. carbon dioxide and methane) has been observed in Sycrude Mildred Lake Settling Basin (Holowenko et al. 2000). Biological gas is found to be caused by mathanogen - a microorganism in the oil sands tailing deposits. The role of gas generation in the management of tailing ponds is controversial. Some researchers (e.g. Fedorak et al. 2003; Guo 2009) proposed that fine tailings management can benefit from gas production as enhanced methanogenesis significantly accelerated densification and improved the rheological properties of MFT. In fine tailing deposits, it was observed that large cracks and fractures occurred during intense microbial activity. The densified MFT became more aggregated and some large fractures formed favourable drainage paths for water drainage and gas bubble migration (Guo, 2009). On the other hand, there is a concern that gas production can hamper the settling of tailing sludge. Wichman et al. (2000) developed a self-weight consolidation computer program to simulate the consolidation of gassy mud (dredged sludge). The simulation and laboratory tests all demonstrated that production of gas exerts a retarding effect on the self-weight consolidation, and the final settlement achieved is less than that of the non-gas case. They explained that due to the presence of gas bubbles, the self-weight per unit volume is less and the drainage lengths were increased.

2.3.1.3. Considerations of application of dewatering technologies

2.3.1.3.1. PVD technology

When PVDs are utilised in sludge material, there is a higher risk of clogging of wick drains compared to application of PVD in a normal soil. The position of particles in a soil is rather stable and water is transported from the soil to the drains. In a tailing pond where PVD are installed, water flows from sludge to drains due to the difference of hydraulic potential between the outside and the inside of the drain. Particles in the sludge may flow with tailing water and may clog the drains if too many particles enter the drains. Field tests of PVD applied in the oil sand CT pond indicated that the PVDs functioned well without serious clogging (Wells, 2009). It is considered that the sand in CT formed bridge and arch networks outside the filter jacket of PVD, which effectively retained the oncoming particles. In fine oil sands tailings, however, the suspended particles are rather uniform in size. Due to lack of well-graded coarse particles, the bridge and arch networks are not likely to form and thereby the fine particles may clog the openings of the filter jackets. Since most bitumen in tailing sludge is attached to fines, the filter jacket could be blinded by viscous bitumen. Besides of clogging of wick drains, flow behaviour of the system can be affected by other factors. For example, as water is discharged from the tailing, solid-like material starts to form around the drains and hence the permeability of the material begins to impact the flow behaviour.

In order to evaluate the technical feasibility of PVD technique in dewatering fluid fine tailings, the first step is to investigate the clogging potential of the PVD in fluid fine tailings and the flow behavior of the tailing – wick drain system.

2.3.1.3.2. Thin-lift drying technology

Based on Dutch experience on mud farming of dredged sludge, critical conditions desired for successful and efficient implementation of thin-lift drying in dewatering fluid fine tailings are considered as: (1) the tailing materials must exhibit considerable settlement and strength gain upon air drying, (2) availability of favourable climatic conditions in the drying area (e.g., high potential evaporation and high precipitation deficit), and (3) proper cell design (e.g., degree of slope, length and width) and management (e.g., tailing distribution, application rate, lift thickness, release water control).

The first condition can be checked by developing specific engineering behaviour of the tailings and drying. Laboratory and field tests are required to be carried out to investigate

the drying potential of tailings under different conditions (e.g., temperature, air circulation, humidity, thickness of lift).

2.3.2. Plan for the thesis

2.3.2.1. Overview

In Section 2.3.1, important engineering behaviour of fine oil sands tailings and knowledge gaps that needed to be filled were proposed. The research will therefore be carried out by considering these factors. The methods employed in this research include a literature study, laboratory investigation and numerical modelling. Literature study involves a comprehensive review of the available literatures related to the research topics. Facts of oil sands tailings have been introduced in Chapter 1 and the first part of this chapter. Theory of tailings behaviour and results of previous work are presented in each chapter after this one. Laboratory experiments performed in this research are divided into two groups. The first group consists of a variety of material characterization tests. These tests include, according to the organization of the chapters, index testing (Chapter 3), flocculation behaviour tests (Chapter 4), sedimentation and consolidation tests (Chapter 5), and desiccation behaviour tests (Chapter 6). In the second group, small scale model tests are carried out to identify the dewatering behaviour of fine oil sands tailings. Column filtration tests and air drying tests are carried out under controlled conditions, and the result are presented in Chapter 7 and Chapter 8 respectively. The numerical study includes model implementation and verification and the details are presented in Chapter 9. Figure 2.11 shows an overview of the research plan for this thesis. Specific plans for each component of research are given in the subsequent sections.



Figure 2.11 Scheme of work to be carried out in this research

2.3.2.2. Material classification tests

Objectives

- Determine the baseline characteristics of the fine oil sands tailings used in this research
- Classify the tailings based on the index properties
- Compare the measurements with the literature data for the same type of tailings and different clay slurries

Descriptions

As the first part of the experimental research, this chapter aims to establish a basic understanding of the tailing materials. Laboratory classification tests will be performed to classify the fine oil sands tailings materials as received. The tests to be performed include measurements of water content, bulk density and bitumen content, specific gravity, particle size distribution and Atterberg limits.

2.3.2.3. Flocculation behaviour tests

Objectives

- Develop a single-use mixing set-up for the flocculation purpose
- Assess the factors affecting the flocculation of MFT
- Determine the optimum flocculation conditions

Descriptions

The purpose of this research is to investigate the flocculation behaviour of MFT. To achieve this, flocculation tests will be performed using a single-use mixing set-up which is developed for this research. A series of flocculation tests will be conducted by varying the set-up configuration, mixing variables, polymer dosage and solid concentration of tailings. Dewatering results of the polymer treated MFT will be compared to determine the best design of the set-up and the optimum flocculation condition.

2.3.2.4. Sedimentation and consolidation behaviour tests

Objectives

- Investigate the sedimentation and consolidation behaviour of fluid fine oil sands tailings and develop an understanding of the fluid to solid transition
- Measure the hydraulic conductivity of fluid fine tailings at high void ratios
- Determine the stress-strain relationships and consolidation parameters of the tailings samples
- Compare the compressibility characteristics of different tailings materials
- Identify the effect of flocculation on the sedimentation and consolidation behaviour

Descriptions

Column settling tests and oedometer tests will be carried out to investigate the sedimentation and sedimentation and consolidation behaviour of fine tailings. The tailing slurries are prepared at various water contents which are significantly higher than the initial value. By measuring the initial constant settling velocity, the initial hydraulic conductivity of the tailing slurry can be calculated using the empirical formula. Changes of settling velocity with void ratios will be used to determine the soil formation void ratio which distinguishes hindered sedimentation and self-weight consolidation phase. Oedometer tests are performed to characterize the stress-strain behaviour of saturated fine tailing samples under vertical surcharge pressures. The expected results include the presentation of the effective stress-void ratio relationship and the consolidation parameters. The obtained data will be compared to the reported data and the effects of flocculation on the settling and consolidation will be identified.

2.3.2.5. Desiccation behaviour tests

Objectives

- Determine the shrinkage curves and water retention curves for the fine tailings and combine them to determine the correct desiccation parameters
- Investigate the rewetting (swelling) behaviour of the tailings
- Investigate the evaporation and cracking behaviour of a thin tailing layer
- Identify the difference between the MFT and flocculated MFT in desiccation

Descriptions

This part investigates three specific properties of oil sands fine tailings – shrinkage property, water retention behaviour and cracking behaviour. These three aspects are actually interrelated and all of them influence the desiccation behaviour of a deposited tailing. Three independent tests will be performed. The shrinkage and swelling tests are carried out to assess the shrinkage curve of a small tailing sample from very soft to completely dry state and the rewetting swelling behaviour of the tailings. Determination of water retention curves involves continuous measurement of soil suction at different water content. The filter paper method and the WP4C device are employed to cover the wide suction range of fine tailings. Cracking tests will be conducted on a thin tailing layer (approximately 1 cm). Images are taken on the sample surface at different time to trace the evolution of crack networks. The cracked tailing samples are subjected to multiple wetting - drying (W-D) cycles to see if W-D processes will affect the crack networks.

2.3.2.6. Clogging and filtration tests

Objectives

- Evaluate the clogging potential of PVD filter jacket in the fluid fine tailings
- Investigate the flow behaviour of the sludge-geotextile system
- Compare the filterability of different tailings and identify the effect of flocculation

Descriptions

In this part, the clogging potential of the PVD filter jackets with fluid fine tailings and the flow characteristic of the system will be evaluated by performing column filtration tests. Both water pressure and air pressure are applied to induce filtration. The magnitude of applied pressure is to set to simulate the net pressure differential between outside and inside of the PVD at a certain depth in the pond. The amount of discharged water will be monitored throughout the tests. The filterability of MFT, TT and flocculated MFT will be compared through the experimentally determined specific resistance to filtration (SRF) value.

2.3.2.7. Air drying tests

Objectives

- Investigate the deposition and desiccation behaviour of fluid fine oil sands tailings in controlled conditions
- Identify how desiccation evolves in a deposited tailing layer
- Identify the influence of placement of the additional lift on properties of the existing lift
- Provide experimental data for validation of the numerical model

Descriptions

The purpose of bench-scale air drying tests is to demonstrate the feasibility of air drying in strengthening oil sands fine tailings. According to the size of tailing samples, two types of experiments – box drying tests and column drying tests – are distinguished. In the box drying tests, the tailings sludge is contained in a series of uncovered glass containers (30 cm by 30 cm in cross-section) and placed in different environment for drying. To shorten the desiccation duration, excess surface water is removed manually. Water content and shear strength is measured at different time on the surface soil layer. As a primary research, box drying tests are expected to show the settling and strength gain behaviour of the tailings. Following the box tests, small scale column drying tests are carried out with improved measurements. To perform the tests, the tailing sludge is filled into PVC cylinders which are placed in climate controlled environment. Air pump is used to create continuous air circulation above the tailing. The height and total mass of the samples will be monitored. The samples will be scanned with CT technology at different time of drying. After the test is completed, the soil column will be analysed.

2.3.2.8. Numerical modelling

Objectives

- Implement a one-dimensional numerical model which is developed to simulate desiccation behaviour of fine tailings
- Verify the model and test the simulation tool by comparing the simulation results with the measurements from laboratory and field drying tests

Descriptions

A one-dimensional numerical model, initially reported by Kim et al. (1992), has been implemented in Matlab program by van der Meulen (2012) and Nijssen (2013) to simulate the desiccation of fine oil sands tailings. Vardon et al. (2014) improved the program and developed a simulation tool based on Matlab interface so that the model can be operated more easily. In this part, the simulation tool will be operated to model the laboratory column drying tests using the developed material properties and Shell Atmospheric fines drying (AFD) field tests using the real climate data. The results will be compared with the laboratory measurements and the primary field tests results.

2.4. Summary

This chapter presents an extensive background of oil sands tailings. According to the information presented, the following facts about oil sands tailings can be summarized: (1) oil sands tailings are produced when bitumen is extracted from oil sands ore using the Clack hot water extraction method. (2) Oil sands tailings are an aqueous suspension of sand, silt, clay and residual bitumen which segregates upon deposition in the pond with the sand dropping out of the suspension. (3) In Alberta oil sands engineering, various tailing products are produced and these tailings vary significantly in properties. (4) Fine oil sands tailings are high fines content, large water content and low permeability slurries. (5) Different tailing management technologies have been proposed in disposal of fluid fine tailings, however, no unique and acceptable technology has been found. (6) PVD technology and thin-lift air drying technique are proposed and evaluated in this research.

The research plan is then proposed by considering the research needs and the assessed knowledge gaps. According to the plan, laboratory experimental research is the major method. Different experiments will be carried out to develop various tailings behaviour and evaluate the feasibility of the proposed dewatering technologies. A numerical study will be carried out to simulate the laboratory and field drying tests.

3

Classification Tests

3.1. Introduction

In geotechnical engineering, index properties are usually determined for a soil by performing simple tests. These tests are called classification tests since it is assumed that the soils with similar engineering properties can be classified based on the index properties. The main index properties include specific gravity, particle size and Atterberg limits.

An experimental research was performed on the fine tailings as received. The objective was to provide a primary impression of the materials described in this thesis. Through these tests, physical and index properties of the TT and the MFT were determined. Results obtained were compared with the experimental data reported in the open literature for the same tailings to see whether they are significantly different. The results were also compared to those of different slurry materials in the engineering to determine the similarities and differences. This chapter begins with an introduction of the material and sample preparation, followed by detailed descriptions of the experiments that were performed. Results of the classification tests are then presented, analysed and compared. A summary of this part of study is then given.

3.2. Classification tests

3.2.1. Overview

A total of seven barrels (180L each) of tailings, four barrels of TT and three barrels of MFT, were shipped from Canada to the geo-engineering laboratory of Delft University in two batches in 2010 and 2012 respectively. The attached documents show that the TT were produced from the winter batch in 2009 and the MFT were obtained in the autumn of 2011. After arrival, the materials in the barrels have settled resulting a layer of clear water on the top. To prepare samples for the tests, the barrels were agitated using a top-entered mixer to rehomogenize the slurry (Figure 3.1). Mixing was operated at a speed of about 300 rpm for a duration ranging from 30 minutes to 1 hour to ensure all of the clay clumps formed due to consolidation were dissolved. After mixing, the tailings sludge was poured into some 20 L buckets, and each bucket was assigned a number. The homogenous tailing sludge has a sticky texture with a strong odour of petroleum. The sludge colour is slightly different between the

two types of tailings, the TT show a colour of dark brown while the MFT is dark grey. After mixing, some bitumen was floating on the surface of the sludge and some bitumen was lost to the container wall. The classification tests described in this chapter were carried out 1-2 days after the moment that the tailings were transferred from barrels to buckets using representative samples taken from different buckets. Classification tests were performed in two rounds for TT to see whether there is significant difference in material properties. After taking the samples for the first test series, the buckets were kept air tight and stored in a cool environment at 10°C. Two years later, the buckets were thoroughly mixed and samples were taken for the second round of tests.



Figure 3.1 Mixing of tailing slurry in a barrel

3.2.2. Methods

3.2.2.1. Solids content

Solids content or solids concentration of a soil refers to the mass of solids over the total mass of soil and is given as following equation:

$$C_s = \frac{M_s}{M_T} \times 100$$
[3.1]

where M_S is the mass of solids in soil, M_T is the total mass of the sample. Soils content is conveniently used for the fluid tailings with high water content. In geotechnical engineering, gravimetric water content (w) of a soil is defined as a ratio of the mass of water to the mass of solids (Eq.[3.2]).

$$w = \frac{M_w}{M_s} \times 100$$
[3.2]

where M_w is the mass of water contained in the sample. In the oil sands industry in particular in the ternary plot, water content is expressed as a percentage of the total mass as given in equation [3.3]:

$$C_w = \frac{M_w}{M_T} \times 100$$
[3.3]

where C_w is water content used in the ternary diagram. C_w is equal to the difference between 100 and the solid content (Eq. [3.4]).

$$C_w = 100 - C_s$$
 [3.4]

In laboratory, the solid content or water content of a soil is usually determined by oven drying the soil to constant weight by assuming that the moisture is completely removed. In this research, solids content of the tailings sludge was determined according to the ASTM Standard Test Methods for Laboratory Determination of Water (Moisture) Content of Soil and Rock by Mass (D2216-10). The tailing sample (about 100 g) was dried in the oven at a temperature of 105 °C for 24 hours. Since the boiling point of bitumen is far higher than the drying temperature, oven-drying will not change the mass of bitumen. In this research, bitumen is treated as solid phase because it is at least 10^6 times as viscous as water, and it cannot be considered a mobile phase with respect to the fluid being expelled (Scott et al.1985).

3.2.2.2. Bitumen content

In the oil sands industry, bitumen content of oil sands tailings is defined as the mass of bitumen over the total mass of the tailing. The most common method of measuring bitumen content is Dean Stark method which uses toluene to separate water and bitumen from the solids in a soil. In current research, due to unavailability of necessary apparatus used in Dean Stark bitumen extraction, an alternative method was developed to measure the bitumen content. The principle of the method is to make use of the fact that bitumen is dissolved in some solvents which are less dense than water so that the dissolved bitumen floats up to the top and is decanted. A blue solvent obtained from petroleum laboratory was used in the test. The procedure is described as follows:

- About 100 ml tailing sludge was oven dried to constant weight.
- The dry soil clod was crushed with mortar and pestle into fine particles. All the particles were transferred to a beaker and about 50 ml blue solvent was added. The solids were allowed to soak with solvent overnight.
- Sufficient demineralised water was added to the beaker and the materials were mixed at a high speed for several minutes. The mixture was then allowed to stand for several hours until three clear layers were formed in the beaker. These layers are, from the top to the bottom, bitumen solvent, clear water and clay.
- The layer of bitumen solvent was carefully decanted and the remaining clay was oven dried and then weighed. The decrease in the mass of dry solids is considered due to bitumen that has been separated and removed.

Although this methodWhile a simply and fast method, it is not recommended for critical use as it needs more examination on the reliability and accuracy.

3.2.2.3. Total density

The total density (or bulk density) of a soil is the ratio of the total mass to its total volume. Due to the fluid state of the tailing sludge, the total density was simply determined by measuring the weight and volume of the tailings contained in a graduate cylinder. To increase the measurement accuracy, filling of tailings sludge into the cylinder was completed in several times and each time after filling the weight and the volume were measured. The measured volumes are plotted against the weights and a linear equation was used to fit the relationship. The slope of the fitted line was used as the mean total density.



Figure 3.2 Quantachrome Ultrapycnometer 1000 used for specific gravity measurement

3.2.2.4. Specific gravity of solids

The specific gravity of a soil is defined as the ratio of the mass of a volume of soil particles to the mass of equal volume of water at a specific temperature. In this research, specific gravity was measured by Quantachrome Ultrapycnometer 1000, which is an automatic gas pycnometer (Figure 3.2). Gas pycnometer is a device used for measuring the density, or more accurately, the volume of solids by employing the method of gas displacement and the volume - pressure relationship which is known as Boyle's Law. The oven-dried tailing sample (including bitumen) was crushed into fine particles. About 60 g particles were filled in the sample cup which was then inserted into the gas pycnometer. After the lid of sample chamber was screwed, the measurement started automatically and after several minutes the first reading was displayed on the screen. For each sample, up to 10 density readings were obtained and the average value was used.

3.2.2.5. Atterberg limits

The Atterberg Limits are used to describe the consistency of fine-grained soils. The states used are solid, semi-solid, plastic and liquid and are separated by specific water contents, namely, the shrinkage limit (SL), plastic limit (PL) and liquid limit (LL). These limits provide information which is used for soil classification and identification. In this research, the liquid limits of oil sands tailing samples were determined using the Casagrande

Cup device. To perform the tests, the original tailing sludge was air dried to lower the moisture content to the practical range for the liquid limit measurement. The liquid limit and plastic limit were then determined according to the ASTM Standard Test Methods for Liquid Limit, Plastic Limit and Plasticity Index of Soils (D4318-10). The shrinkage limit is usually determined by the Mercury method (ASTM D427-10). Due to the health safety concerns, this method is no longer considered acceptable in most countries. In this characterization exercise, the alternative method described by ASTM Standard Test Method for Shrinkage Factors of Soils by the Wax Method (D4943) was employed.

3.2.2.6. Particle size distribution

Conventionally, determination of particle size distribution (PSD) of a soil is achieved by sieve analysis and/or hydrometer analysis. Due to small particle size, the hydrometer and wet sieving method is used to analyse PSD of fine tailings. A standard procedure is described in ASTM Standard Test Method for Particle-Size Analysis of Soils (D422). However, the standard procedure is found not suitable for the oil sands fine tailings which contain very high fines content. Jeeravipoolvarn et.al. (2008) proposed some modifications based on the standard method. The modifications involve three aspects which are described as follows. First, the bitumen is not removed from the tailings before the PSD analysis. When the sample is dried for bitumen removal using Dean Stark method, the asphaltenes tend to cement some fines together and the results underestimate the amount of clay size material in tailing. Second, the soil sample is not oven-dried. Oven-drying the sample as suggested by ASTM standard will result in a dry lump of soil which needs to be pulverized by some grinding or dispersion processes. These processes will exert a considerable influence on the particle size distribution. Third, dispersing agent is not used in hydrometer analysis. In ASTM D422, sodium hexametaphosphate solution is used to disperse clay particles to ensure that they are far enough apart and the assumptions in Stokes law are satisfied. In the Clark Hot Water Extraction method, addition of sodium hydroxide has exerted a dispersing effect on the tailings particles. Therefore, it is not necessary to use the dispersing agent in the tests. These modifications were considered in this research and the following procedure was applied:

- A volume of tailing sample with a dry mass about 25 g was prepared from homogenous tailings sludge.
- The tailing sample was filled into a dispersion cup. The slurry was then mixed at the rate of 800 rpm for a period of 3 minutes.
- Any bitumen floating on the top of the suspension was skimmed. The tailings was then allowed to stand for 6 to 12 hours and bitumen was skimmed one more time.
- Soil-water slurry was transferred from the dispersion cup into the glass sedimentation cylinder. Some process water was added into the slurry until the volume was 1000 ml.
- The cylinder was turned upside down and back for a period of 1 minute using the rubber stopper in the open end. The cylinder was then placed in the water bath maintained at 20°C. The hydrometer (type 151H) was inserted into the cylinder and the timer was started.
- Hydrometer readings were taken at total elapsed times of 0.25, 0.5, 1 and 2 minutes without removing the hydrometer from the cylinder.
- The hydrometer was removed after the 2 minutes reading. Content in the cylinder was remixed and test was restarted but no reading was taken until 2 minutes.
- A series of hydrometer readings were taken at total elapsed time at 2, 4, 8, 15, 30, 60, 120, 240, 480 and 1440 minutes.

- After the last reading was taken, a standard test method for wet sieve analysis was performed with a range of sieve sizes from 2 mm to 0.044 mm.
- All soil including that washed through the 0.044 mm sieve was collected. Soil was dried to obtain the dry mass used in the hydrometer test.

3.3. Results

3.3.1. Index properties

The complete set of the results of the classification tests are presented in Appendix A. For the same type of tailings contained in different barrels, the measured physical and index properties were generally identical. A summary of the obtained property parameters is provided in Table 3.1.

Property index	MET	TT	TT
rioperty index	1011, 1	(round 1)	(round 2)
Average solid content (%)	32	35	35
Average water content (%)	213	185	185
Average specific gravity, G_s	2.3	2.3	2.3
Average void ratio, e	4.9	4.3	4.3
Average total density (g/cm^3)	1.21	1.23	1.23
Bitumen content (%)	1-2	1-2	0.9
Liquid limit (%)	48 - 61	48 - 52	52 - 55
Plastic limit (%)	26 - 29	20 - 21	23 - 24
Shrinkage limit (%)	14 - 18	10 - 13	12
Plasticity index	22 - 33	28 - 31	29 - 31
Fines content (< 44 µm %)	90 - 93	64 - 70	70-80
Clay content (< 2 μ m %)	45 - 50	10 - 18	14-22
Average D_{10} (µm)	-	0.7	_
Average D_{30} (µm)	0.8	6	4
Average D_{50} (µm)	2.2	21	13
Average D_{60} (µm)	4.8	30	21
Average (SFR)	0.09	0.05	0.09

Table 3.1 Properties of the MFT and TT samples used in this research

According to the data provided, the fine oil sands tailings samples had similar initial solids content and bulk density values, with the mean value being 32% and 1.21 g/ml for TT and 35% and 1.23g/ml for MFT, respectively. The TT and MFT samples contained very small amount of bitumen which was 1 to 2% of the total mass. However, this value is considered to some extent underestimated the real bitumen content in the tailings since the bitumen sticking to the container wall during mixing was not reckoned. The average specific gravity of the solids (minerals + bitumen) was 2.3 for both TT and MFT. It is considered that the presence of low specific gravity ($G_s = 1.03$) bitumen in the tailings resulted in the specific gravity value which is lower than the typical range (e.g., 2.6 to 2.9) for sedimentary clays (Das, 2013). In terms of particle size distributions, as high as 90% of total solids in the MFT were finer than 44 µm which is referred to as fines and a percentage of 45-50 % was smaller than 2 µm which is defined as clay. The TT samples were classified as having 64% to 70% fines and 10% to 18%

clay. Unlike MFT, TT is a flocculated fine tailing material (see Section 2.2.2.1). With help of chemical additives, fine particles conglomerate to form flocs in the slurry, and this could be the reason why the TT had lower fines content compared to the MFT. In terms of the Atterberg limits, the TT had smaller values than the MFT. Above property parameters indicate that the TT was more permeable and less compressible than the MFT. In this research, classification tests were performed in two rounds on the TT using the samples taken from the same buckets. Comparing the results of two rounds of classification tests, it is found that the average bitumen content of the tailings decreased while the fines content and the Atterberg limits increased. Decrease of bitumen content was due to loss of some bitumen to the container wall during the mixing process before the second round of tests. Increase of the fines content of the tailings was caused by decomposition of flocs in the TT due to mixing. In Unified Soil Classification System (USCS), the liquid limit and the plasticity index (PI) are used to classify the fine grained soils with 50% or more solids passing the No.200 sieve (0.075mm). Figure 3.3 provides a plasticity chart showing the classifications of the tailings used in the tests. According to the chart, the TT and MFT used in this work can be classified as either CL (clay of low plasticity) when the liquid limit is smaller than 50% or CH (clay of high plasticity) when the LL is larger than 50%.



Figure 3.3 Classifications of the fine oil sands tailings used in this work

3.3.2. Comparison of results

3.3.2.1. Comparison of TT

Over the past few years, several large-scale thickened tailings evaluations have been conducted by different companies. However, much of the work is not easily accessible to the public and very limited number of papers regarding the characteristics of TT have been published. Table 3.2 compares the properties of the TT studied in this work with those of two TT and one in-line thickened tailing (ILTT) reported in the open literature. It is seen that the average fines content of the TT was obviously higher than that of the other two TT samples while the clay content did not vary significantly. In terms of the Atterberg limits, the obtained LL, PL and PI values were all larger than that of the reported. Jeeravipoolvarn et al. (2008) measured the Atterberg limits of the fine portion (<44 μ m) of the TT and showed that the determined Atterberg limits as well as the PI were significantly larger than the corresponding

values obtained for the whole TT. It suggests that the particle size distributions, in particular the silt and clay content, greatly influence the properties of the soils. In this work, the solid particles of the tailings had an average specific gravity (G_s) of 2.3, which was smaller than that of the TT from literature. Since bitumen was not removed from the tailings, the specific gravity of solids decreased as the bitumen content of the tailing sample increased due to the low specific gravity of bitumen. In a fine oil sands tailing sample, majority of bitumen is attached to or trapped within the fines. Therefore, the higher fines content of a tailing, the larger amount of bitumen is likely to be bounded and thus the lower specific gravity of solids is measured. This is the reason why the G_s of the fine portion of TT was obviously smaller than the value of the total solids in Jeeravipoolvarn's research.

Duonoutry Indox	Current	Innocent-Bemard,	Jeeravipoolvarn	Jeeravipoolvarn,
Property mdex	study	(2013)	(2008)	ILTT (2010)
Solid content (%)	35	52	39	_
Bitumen content (%)	2	0.33	1.8	-
Specific gravity, G _s	2.3	2.55	$2.44(2.28)^{*}$	2.46
Void ratio, e	5	2.2	-	-
Liquid limit (%)	50	31	35 (57)	66
Plastic limit (%)	22	11	16 (27)	23
Plasticity index	28	20	19 (30)	43
Fines content	71	52	54 (100)	55
Clay content	14	14-25	22 (39)	4
SFR ₄₄	0.44	0.9	0.85	0.82
USCS classification	CL/CH	CL	CL	CH

Table 3.2 Comparisons of laboratory properties between the TT used in this study and
the TT (or ILTT) materials reported in literature

* Property parameters in the brackets are measured on the fine portion (<44µm) of the tailing

The comparison shows that the TT tested in current research have quite different properties to the TT reported by Innocent-Bemard and Jeeravipoolvarn which are similar to each other. Some factors are considered accountable for the differences. First, TT is a chemically treated material, and properties of TT may vary with the different chemical additives and the thickening process utilised by different producers. Second, mixing process exerts a shear effect on the tailing, which may change the size of flocs and thus vary the index properties. The TT samples used in this work were shipped from Canada by sea. After a few months of transportation, the particles (flocs) settled and in laboratory they were remixed before the tests were performed. Therefore, mixing applied in sample preparation may cause breakage of flocs and form smaller flocs and microflocs. This could be the explanation why the fines content of the TT in this work was larger than that of the other two TT which were tested locally without experiencing long transportation and intensive mixing. Third, in the case that the TT samples are taken from the TT pond, samples taken from different part of the pond may have significantly different properties. Jeeravipoolvarn (2010) reported that the tailing materials obtained from the inlet station of a pond have 50% higher fines content than the samples taken at the outlet station.

ILTT is a similar tailing product to TT which is also produced from cyclone overflow tailings (COT). Unlike TT which is treated and conditioned in a thickener, ILTT is obtained via a multi-stage flocculation and coagulation mixing processes (Jeeravipoolvarn, 2010). Comparing the data of the TT and the ILTT presented by Jeeravipoolvarn, it shows that the

ILTT is more compressible (higher LL and PI) than the TT. The TT and ILTT have identical fines content but the ILTT have much lower clay content. The difference may be attributed to varieties in the flocculation and mixing process and the flocs properties.

3.3.2.2. Comparison of MFT

Properties of the MFT obtained in this research are compared to those of different MFT reported in the literature, as shown in Table 3.3. Comparing the data presented, it is found that there is no significant difference in terms of properties between the MFT in this work and the other MFT presented in the literature and all the property parameters for the MFT listed in the table are in the similar ranges. Note that the MFT presented by Suthaka (1995) with the maximum bitumen content (6%) had the minimum of specific gravity value. This is in accordance with previous findings. The MFT samples compared here were obtained from different mines at different time from 1990s till recently. The results indicate that the characteristics of MFT in Alberta are generally consistent and stable, though more data are required to confirm it.

			it i escui en		
Property index	This	Jeeravipoolvarn	Gholami	Suthaka	Rima
Floperty muex	work	(2005)	(2014)	(1995)	(2013)
Solid content (%)	32	30	36	30	29
Bitumen content (%)	1.3	3	_	6	—
Specific gravity, G _s	2.3	2.28	2.2	2.1	2.36
Total density (kg/m ³)	1210	1280	_	—	_
Liquid limit (%)	55	44-53	45	47	55
Plastic limit (%)	28	21	19	20	25
Plasticity index	27	23-32	26	27	30
Fines (< 44µm %)	91	93	93	92	92
Clay (< 2 μ m %)	48	48	46	55	53
USČŠ	СН	CL	CL	CL	CH

 Table 3.3 Comparisons of laboratory properties between the MFT used in this study and some MFT used in different research

3.3.2.3. Comparison to different mine tailings

Tailings produced from different mining process are generally in the state of a slurry that is delivered and deposited hydraulically in the disposal area. In this research, oil sands fine tailings are compared with other mine tailings to determine the similarities and varieties between them. In Table 3.4, the basic properties of the TT and MFT in this research are compared with those of four different mine tailings reported by Qiu & Sego (2001). These tailings include copper mine tailings, gold mine tailings, coal wash plant tailings and oil sands consolidated tailings (CT), which represent a wide range of wastes from different types of mines. The data show that the various tailings have a wide range of the property parameters. The gold mine tailings have the largest specific gravity value at 3.17 while the coal wash plant tailings and the tailings. Based on the grain size distributions, the gold mine tailings and the coal wash tailings can be classified as "fine tailings" because majority (> 60%) of solid particles are smaller than 74 μ m. Despite of very high fines content, the clay content of gold mine tailings is very low, which is only one quarter of that of coal wash tailings. Copper

mine tailings and oil sands CT are both characterized as sandy soils, as more than 70% of total solids are larger than 74 µm. Among these tailings, MFT have the largest fines content and in particular clay content, which is far higher than any other tailings listed. It implies that MFT may have more complex characteristics due to electro-chemical activity of clay. Compared with the four different mine tailings, the TT tested in current work is to some extent similar to the coal wash tailing in terms of particle size distributions. However, its liquid limit and plasticity index values are both larger than that of the coal wash tailings. Qiu & Sego did not present the LL and PI data for the other tailings except the SL. Comparing the SL, the TT and MFT in this work had lower values than the other tailings, which is ascribed to varieties in particle size and clay minerals. Clayey soils have much lower permeability and higher plasticity compared to sandy soils. By comparing the basic properties of various tailings, it is seen that permeabilities of fine oil sands tailings are lower than that of the tailings resulted from various mining process, and disposal of fine oil sands tailings could be more difficult.

Property index	Copper	Gold	Coal	СТ	TT	MFT
Specific gravity	2.75	3.17	1.94	2.60	2.29	2.3
LL (%)	_	_	40	_	50	55
PI (%)	—	_	16	_	27	28
SL (%)	24.4	21.6	21.1	25.2	12	16
Clay (< $2\mu m$)	1.3	5.3	22.5	8.9	14	48
Sand (> 60µm)	74.5	33.3	40	77	29	9
Fines ($<74\mu m$) [*]	31.3	81.3	66.4	21.2	71	91
D ₁₀ (µm)	16.28	5	1.31	2.7	0.7	_
D ₃₀ (µm)	72.25	19	4.13	11.2	6	0.8
D_{50} (µm)	120.6	44.8	29.2	182	21	2.2
D_{60} (µm)	153.5	54	60	204	30	4.8
USCS	SM	ML	CL	SM	CL/CH	CH

Table 3.4 Comparisons of oil sands fine tailings with different mine tailings and
dredging

* Fines refer to particle size $< 44 \mu m$ for fine oil sands tailings

3.3.2.4. Comparison to dredged sludge

As introduced in Chapter 2, sub-aerial drying technologies have been utilised for decades in the Netherlands in disposal of unpolluted sludge dredged from Rotterdam harbour and plenty of experience was gained in the past. In order to assess whether the Dutch experience can be promoted to manage oil sands fine tailings, it must compare the two materials. Comparison of basic properties is made between the fine tailings and the dredged sludge material presented by Limsiri (2008), as shown in Table 3.5. The unripened sludge material was obtained from ripening fields of Slufter, Rotterdam, a large disposal site for dredging sludge. The parameters show that the dredged sludge samples had larger bulk density and specific gravity values than the TT and MFT. The fines content of dredged sludge was similar to the TT if $63 \mu m$ is used as the size limit between fines and sand. The clay content of dredged sludge was larger than TT but smaller than MFT. The dredged sludge had high liquid limit and plasticity index which was even larger than that of the MFT. It is known that a large liquid limit indicates high compressibility and shrink/swell tendencies and a large plasticity index indicates low shear strength. The dredged sludge is classified as CH (clay of

high plasticity) in USCS, which is similar to fine oil sands tailings. The comparisons indicate that the dredged sludge and the oil sands fine tailings may share some similarities in general engineering properties such as high compressibility, low permeability and low shear strength. It is noted that the dredged sludge contained 7-11% organic matter, which was considerable compared to the bitumen content of the oil sands fine tailings. The organic matter may exert significant effect on the physical, chemical and biological properties of the material, and the residual bitumen may also influence the tailings behaviour. Therefore, they are the uncertain factors when comparing the engineering properties. After the treatment by mud farming, however, the ripened material can be used in the engineering such as construction of the embankment.

Properties index	Dredged sludge	Fine oil sands tailings		
Properties muex	(Limsiri, 2008)	TT	MFT	
Bulk density (g/cm ³)	1.3-1.4	1.2	1.2	
Organic content (%)	7-11	-	-	
Bitumen content (%)	-	1-2	1-2	
Specific gravity	2.54-2.62	2.29	2.3	
Liquid limit (%)	79-117	48-52	48-61	
Plastic limit (%)	30-42	20-21	26-29	
Shrinkage limit (%)	27-33	10-13	14-18	
Plasticity index (%)	47-75	28-31	22-33	
Sands (> $63\mu m$)	9-19	30-36	7-10	
Fines (< 63µm) **	81-91	64-70	90-93	
Clay (< 2μ m)	22-33	10-18	45-50	
USCS	СН	CH/CL	CH/CL	

 Table 3.5 Comparison between the dredging sludge and the fine oil sands tailings

* Fines refer to particle size $< 44 \mu m$ for oil sands fine tailings

3.4. Summary

Fine oil sands tailings (TT and MFT) samples obtained from Shell Muskeg River Mine were classified by performing laboratory classification tests. Comparing the results of two tailings, it can be found that the TT and the MFT had similar water content and bulk density in their initial state, and they had identical specific gravity of solids. Particle size analysis results showed that the TT had lower fines (< 44μ m) content and less clay size materials compared to the MFT. The Atterberg limits measurements showed that the TT was also lower in both the liquid limit and the plasticity index. According to the Unified Soil Classification System, the TT and MFT were both classified as either CH when LL > 50% or CL when LL < 50%. Unlike the MFT, the TT was a tailing product produced after chemical treatment, therefore, some property parameters such as particles size changed during handling.

Results of comparisons indicated that the MFT in current research were consistent with other MFT investigated by different researchers in terms of index property while the TT were a bit different from the reported. The index properties of TT and MFT were compared with four different mine tailings. The comparison showed the complexity of the tailings produced from different types of mine. Among these tailings, the MFT and TT had obviously higher ratio of silt and clay material compared to other tailings. Finally, the fine oil sands tailings were compared to the dredged sludge. Some similarities were identified from the two materials. The experimental work provided an insight into the materials investigated in this thesis.



Flocculation Behaviour Tests

4.1. Introduction

Properties of MFT can be amended by flocculation with the use of flocculants. Flocculants accelerate the dewatering behaviour of MFT by serving as binding agents for the solids and enhancing floc strength (Farinato and Dubin 1999; Gregory 1989; Moudgil and Somasudaran 1988, 1994). In the field of oil sands tailings, high-molecular-weight (e.g. $>10^6$ g/mol) polymers have been used in flocculation of MFT due to higher intrinsic flocculating powers compared to other types of flocculants and no salts are added to the recycled water. As a pre-treatment step in thin-lift drying and other dewatering technologies, the effectiveness of flocculation can influence the disposal result. According to literature, flocculation and dewatering outcomes depend not only on the polymer used but also on a number of factors (e.g., properties of MFT, polymer dosage, mixing conditions, temperature etc.). Once a polymer is selected, it is necessary to investigate the flocculation behaviour and determine the optimum flocculation conditions through experimental investigations.

In this research, a laboratory program was conducted to develop the flocculation behaviour of MFT based on a high molecular weight polymer (FLOPAM DPR 5285). This polymer has been regarded as one of the Shell's best performance flocculants used in the pilot in-line flocculation program. A stirred tank was constructed for the flocculation purpose. Effects of different factors such as impeller type, polymer dosage, solid concentration, mixing speed and mixing duration on flocculation were assessed through the results of tests. The flocculation results were evaluated by the settling velocity of the polymer treated MFT in column cylinders.

Since specific details regarding the polymer used was not made available to the author, a review of general knowledge about flocculation and high molecular weight polymer is presented in Section 4.2. Section 4.3 presents the experimental measurements and the flocculation and dewatering results. A summary of the observations and findings is then given in Section 4.4.
4.2. Theory of flocculation

4.2.1. Flocculation mechanism

In general, the mechanisms of flocculation by polymeric flocculants can be studied in two stages: (1) adsorption of polymer onto the particles and (2) the formation of aggregates. Ruehrwein and Ward (1952) first proposed the bridging mechanism of flocculation. They came up with a hypothesis that flocculation is adsorption of one end of a long chained, linear polymer molecule onto a colloidal particle and the other end onto a second particle, thus aggregating the two. According to this hypothesis, a high molecular weight polymer can adsorb on several particles at once and form a three-dimensional matrix (Figure 4.1). This mechanism was utilised in the early research to explain experimental results (i.e. La Mer & Smellie.,1962).



Figure 4.1 The hypothesis proposed by Ruehrwein and Ward (1952) that a high molecular weight polymer attaches several particles at once



Figure 4.2 The hypothesis proposed by La Mer and Healey (1963) that polymer attaches at several points leaving loops projecting which attach to other particles

The hypothesis proposed by Ruehrwein and Ward (1952) seems unlikely to happen in reality because it has been found that the polymer molecule is not linear and the ends will probably not be available for bonding. The bridging theory was refined by La Mer and Healey (1963). They proposed that the polymer adsorbed on the particle surface leaving long loops projecting into solution; adsorption of these loops onto a similar particle could form the bridges necessary for flocculation (Figure 4.2). Using this hypothesis, it is possible to postulate that the polymer molecules may completely adsorb on individual particles before bridge formation can occur. This is most likely to happen at high polymer concentrations and explains why flocculation is seen to decrease above a critical dosage. In such a situation, flocculation will be hindered by repulsion of the charges on the polymer molecules. This would seem to be the more feasible theory since it better explains the observed effects.

4.2.2. Application of flocculation in engineering

4.2.2.1. Flocculant preparation

Modern polymers are usually supplied with solid particles for the convenience of transportation and storage. Each particle is a hard packed tangle of long polymer chains similar to a ball of strings. In order to release the individual chains, particles must absorb water to uncoil by hydrating and activating their repulsive ionic groups. Once the polymer is wetted, a highly viscous gel is formed on the outer surface of each particle, which resists the passage of the free water necessary for wetting the polymer in the centre of the particle. Therefore, it is critical that the mixing device provides a good mixing of completely separated particles with the water. The concentration of polymer solution varies in different applications. In general, the concentration should not be too high, otherwise the solution will be too viscous and generate mixing problems. It also should not be too low to avoid adding too much water into the sludge.

4.2.2.2. Addition and mixing of flocculant

Addition and mixing of flocculant is critical to flocculation outcomes. The viscous polymer solution is sometimes difficult to be distributed homogeneously throughout the suspension. Polymer is very attractive to particle surfaces and becomes irreversibly attached, therefore uneven distribution of flocculant may result in overdosing in some polymer-rich areas, which wastes the flocculant. To avoid this, sufficient agitation must be generated but without producing excess shear that would destroy the flocs that are formed. For industrial large scale flocculation, in-line mixers are the dominant mixing tools due to their capacity for continuous operation at very low capital cost. For bench-scale applications and laboratory research, the stirred tank is commonly used due to simplicity and low operational cost.

4.2.2.3. Flocculation and dewatering

The flocculation process in a clay suspension can be divided into three principle steps (Hogg, 2000): (1) Destabilization of the suspended fine particles, (2) floc formation and growth, and (3) floc degradation. Fine clay suspensions (i.e, MFT) exhibit a significant degree of stability due to the electrical charge acquired by particles dispersed in aqueous media (Hogg, 2000). Destabilization is accomplished by eliminating or shielding the charges with help of flocculant, which allows particles to adhere to one another on contact. Flocs grow as a result of collisions between particles moving relative to each other based on the following

possible mechanisms: (1) Brownian motion arising from thermal energy in the suspending fluid; (2) velocity gradients in mechanically agitated suspensions; and (3) differential settling of individual particles or flocs (Elimelech et al. 2013; Gardner et al. 1998 and Gregory & Melia, 1989)). Floc strength is dependent upon the strength and number of individual interparticle bonds between the components of the aggregate (Parker et al., 1972; Bache et al., 1997). A floc breaks when the shear stress applied on its surface exceeds the bonding strength within the floc (Boller & Blaser, 1998). Although floc degradation is normally considered to be detrimental to dewatering, it can also play a positive role in the redistribution of particles and reagents as flocs develop and grow (Hogg, 2000). Settling of flocs generally involves three regimes (Fitch, 1962): (1) free settling in that individual flocs settle independently; (2) hindered settling, which is characterized by reduced and concentration - dependent settling rates; and (3) compression — flocs in permanent contact form a continuous network structure that has mechanical strength.

4.2.2.4. Evaluation of flocculation results

Effectiveness of flocculation in an application can be evaluated from the degree of improvement in the dewaterability of the slurry after treatment. The self-weight settling test is a common method to determine the settling rate of sludge. If flocculation is effective, there is a substantial increase in the settling rate of the treated MFT compared to the non-treated MFT. The effectiveness of flocculation can also be evaluated by performing the pressure filtration tests on the treated sludge using an experimentally determined parameter — specific resistance to filtration (SRF). SRF is a measure of the resistance of the formation cake to the flow of the filtrate. Higher SRF values indicate worse filterability.

4.2.3. Factors affecting flocculation

Many researchers (i.e., Kane et al., 1964; Miyanami et al. 1982; Henderson & Wheatley 1987; Gregory & Li, 1991; Brij et al., 1993; Pillai, 1997; Kotlyar et al., 1998; Demoz & Mikula, 2012; Sworska et al. 2000a, 2000b; Taasdemir, 2012) have demonstrated that behaviour of flocculation is influenced by a number of factors. Some important factors are summarised as follows.

4.2.3.1. Molecular weight of polymer

The molecular weight affects the effectiveness of a polymer. When a low molecular weight polymer is used, there is a tendency for each polymer molecule to adsorb on to a single particle. The degree of flocculation is then lessened by further polymer addition. With a polymer of the same type, but higher molecular weight, a greater amount of particles can be adsorbed and utilized by the flocs. Overall molecular weight is not the only criterion for effective flocculation, since two polymer products with the identical apparent molecular weight may have different molecular weight distributions.

4.2.3.2. Dosage of polymer

For a polymeric flocculant, there exists an optimum dosage in flocculation. The optimum dosage is the maximum amount of polymer that the solid can utilize for flocculation under the conditions of the experiment and is directly related to the amount of multiparticle

adsorption. When the amount of polymer added is higher than the optimum dosage, all the available adsorption sites on the particles are occupied and there are no free sites for bridging from other particles. When the polymer is applied below the optimum dosage, particles are not completely adsorbed by polymers, leading to insufficient flocculation and poor dewatering results. The optimum dosage cannot be easily predicted since they vary not only with ionic character and degree, but also with molecular weight.

4.2.3.3. Particle size of solids

Basically, flocculation is best observed for fine clay suspensions, typical less than 50 μ m. Aggregation of coarser particles produces smaller, more compact flocs compared to the voluminous flocs formed from finer particles. It is found that the optimum polymer/solid ratio is directly proportional to the surface area of the solid, therefore, a decrease in particle size means an increase in flocculant demand.

4.2.3.4. Mixing conditions

Mixing of polymer and clay slurry is crucial in a flocculation application and improper mixing can render even the best additives ineffective (Jarvis, 2005; Spicer, 1996). The general mixing conditions involve method of addition and mixing of polymer, mixing equipment, and other operational parameters. For a given mixing system, the flocculation result is greatly affected by the mixing parameters applied (e.g., mixing intensity and duration). Flocs will hardly grow if the mixing is too mild while too vigorous agitation may break the formed flocs into smaller flocs and deteriorate the dewatering results.

4.2.3.5. Temperature

Temperature plays a role in flocculation. A change in temperature will exert different effects on the flocculation results. The rate of diffusion of polymer and collision of particles increases with increasing temperature, but the adsorption step, which is exothermic, must be unfavourably affected by higher temperature. The linear extension of the polymer molecules may vary with temperatures, depending on the nature of the solvent-solute interactions. Thus, it is difficult to accurately predict the effect of temperature in a given system.

4.2.3.6. pH

There is evidence indicating that the pH affects the slurry properties and flocculation behaviour. Sworska et al. (2000) found that clay particles tend to coagulate at a low pH. In alkaline pH, clays form stable suspensions, the addition of the flocculant leads to the development of bimodal size distributions consisting of flocs and dispersed fine particles. The pH of pulp controls the degree of ionisation of the polymer, and therefore varies the amount of charge on the polymer chain, and hence determines the degree of extension of the molecule. This in turn affects the degree of bridging and flocculants can therefore only function over a certain pH range, depending on the type.

4.3. Experimental work

4.3.1. Construction of mixing system

4.3.1.1. The mixing set-up

Normally, design of a mixing system used for flocculation consists of understanding of process requirements, selection of mixing tools and estimation of energy consumption. In this research, the mixing set-up used for flocculation was designed according to the handbook of industrial mixing (Paul et al., 2004). A basic mechanical mixing device consists of mixer, impeller and tank. An over-head electric mixer with two speed ranges (60-500 rpm and 240-2000 rpm) and two different impellers available in laboratory were used as mixing tools. The purpose of using different impellers was to assess whether mixing tools can influence the flocculation outcomes. As shown in Figure 4.3, the impellers used in this work were, namely, pitched-blade turbine (PBT) (left) and flat paddle (right). The PBT has four pitched blades, the pitched angle of each blade was initially 30° and adjusted to 45° in the later stage tests. The paddle impeller has two vertical blades (30 mm by 25 mm in dimension) welded to the shaft. Two glass beakers, in different diameter of 88 and 128 mm respectively, were used as the mixing tank. One beaker was added four glued plexiglass baffles while the other one was not.



Figure 4.3 Impellers used in this study: pitched blade turbine (left), flat paddle (right)



Figure 4.4 Sketch of the mixing system (paddle impeller and baffled tank)

Figure 4.4 shows the sketch of the mixing set-up developed for flocculation. According to the theory of industrial mixing, the filling height of sludge was set equal to the diameter of tank (H = T) so that only one impeller is sufficient for mixing. The clearance between the base of the tank and the bottom of the impeller (c) was set to a quarter of H. The width of baffle (B) was 1/10 of the tank diameter (T) and the height of the baffle was 2 cm higher than the filling height of the fluid (H). The geometry parameters of the constructed mixing set-up are provided in Table 4.1.

	Q (1	a . a
	Set-up I	Set-up 2
Impeller types	PBT	Paddle
Impeller Diameter (D, mm)	45	60
Blade height (h, mm)	varying	25
Blade angle (°)	45	90
Clearance (c, mm)	22	22
Diameter of tank (T, mm)	88	88
Fluid height (H, mm)	88	88
H/T	1	1
D/T	0.51	0.68
c/H	0.25	0.25

Table 4.1 Geometries of the mixing set-ups constructed in thisresearch

4.3.1.2. Analysis of flow pattern

The delivery of viscous polymer into particles is heavily influenced by the flow created in the tank. The flow pattern varies in different mixing systems. Typically, flow in a tank is characterized as either axial or radial. Impellers are classified conveniently according to which flow dominates. In this work, the paddle impeller is a radial flow impeller, which discharges flow radially to the tank. The pitched blade turbine (PBT), although classified as an axial flow impeller, is sometimes referred to as a mixed flow impeller, due to the flow in both axial and radial directions. In a mixing vessel, the flow pattern is affected by geometry of the system such as the D/T value. It is reported that when the D/T is above 0.55, the PBT becomes radial flow impellers (Paul et al. 2004). When a clay suspension is agitated in a cylindrical tank, the swirling motion of the suspension around the tank occurs, which is caused by tangential velocities coming from the impeller. As the impeller rotates faster, a larger surface vortex occurs near the shaft (Figure 4.5). In that case, the flow is two dimensional and it is normally considered as an ineffective flow pattern for solids suspension mixing. To prevent the swirling flow, wall baffles are usually installed in the cylindrical vessel.



Figure 4.5 Flow pattern generated in a cylindrical vessel

According to the handbook, flow patterns created by the PBT and the paddle in a baffled cylindrical vessel are similar to the ones shown in Figure 4.6. In the baffled vessel, the bulk flow generated by rotating impeller impinges the baffles and changes direction. Axial flow is therefore generated in the tank, and the flow pattern is three dimensional which is assumed to be favourable for distribution of polymer throughout the whole suspension. The difference between the two impellers is that the paddle impeller produces two circulating loops while the PBT produces only one.



Figure 4.6 Flow pattern generated by PBT (left) and paddle impeller (right) in a cylindrical vessel equipped with wall baffles (modified from Paul et al.(2004))

4.3.2. Preparation of samples

4.3.2.1. MFT suspensions

To prepare samples for the flocculation tests, original MFT sludge was adjusted to different concentrations as "high" -32%, "medium" -21% and "low" -15%. In each flocculation test, approximately 500 ml homogenous tailing suspension was prepared. Table 4.2 provides the physical properties of the tailing samples.

Properties	High	Medium	Low
Solids content (%)	32	21	15
Water content (%)	213	376	567
Bulk density (g/ml)	1.20	1.12	1.08
Void ratio	4.9	8.6	13.0

 Table 4.2 Physical properties of the MFT samples used for flocculation

4.3.2.2. Polymer solutions

The polymer used in this research is one kind of high molecular weight polymer (FLOPAM DPR 5285). The dry polymers are while granules with a bulk density of 0.8 g/cm³. To avoid formation of a gel layer at the outside surface of a cluster of particles, the dry polymer granules were added slowly into the tank of water where local turbulence was already created. The mixture was agitated at a high revolutions per minute (i.e. around 600 rpm) for 30 minutes to ensure that the polymer surfaces are individually wetted and no clumps are formed. The rotation speed was then lowered to 300 rpm and the mixing was lasted for another 2 hours for the flocculant molecules to be completely hydrated and stretched. The polymer solutions were prepared at various concentrations from 0.2 to 1.2 % for rheological measurements. In order to limit the amount of water that is added into the tailings with polymer solutions, a higher concentration of polymer solution, 0.8 % by weight, was used in flocculating MFT. To minimise the aging effect that may exist in polymeric flocculants, the polymer solution was used within 2 days, otherwise was discarded. The dosage of polymer is dependent on the solids content of MFT and is expressed as kilograms or grams of dry polymer per ton or kilogram of MFT solids. A dosage (1g/kg) was suggested by Shell based on the results of pilot flocculation program. This potential optimum dosage will be examined in this research.

4.3.3. Measurements

4.3.3.1. Rheology

Measurement of rheological property for the materials to be mixed is necessary to understand the fluid's response to deformation and determine the optimum conditions for the efficient operation of mixing equipment. In this research, rheological properties of the MFT suspensions and the polymer solutions were determined using AR-G2 rotational rheometer (TA Instruments, New Castle, DE, USA). A minimum sample volume of 14 ml was filled into the rheometer cell to cover the rotor. The gap spacing between the rotor and stator was 1.0 mm and the measurement temperature was set to 23°C. The flow diagrams (shear stress vs. shear rate curves) were obtained for the samples with different concentrations. Through the flow curves, viscosity of the fluid can be determined.

4.3.3.2. Mixing energy (impeller torque)

Demoz and Mikula (2012) proposed that mixing energy dissipated into a sludge system can be used as one of underlying parameters determining the flocculation outcomedewaterability of the polymer treated MFT. In current investigation, mixing energy was measured and correlated with flocculation and dewatering outcome in each test to see if there exists optimum mixing energy input for a given system. In principle, power dissipated by a rotating impeller in a stirred mixing tank is calculated as:

$$P = N_P \rho N^3 D^5 \tag{4.1}$$

where P = power consumed by impeller (W); $\rho =$ density of fluid (kg/m³); N = rotation speed (1/s), D = impeller diameter (m), $N_p =$ impeller power number which is an indicator of how much power is needed to rotate a specific impeller in a certain liquid. In this work, impeller rotation speed was kept constant during flocculation and it was measured by a laser tachometer (Standard AT-6) with an accuracy of ± 0.1 rpm. Once the value of N_p is obtained, the mixing energy can be calculated. Impeller power number is essentially experimentally correlated result and only for some simple impellers it can be estimated from the geometry using the empirical correlation equations proposed by Kamei et al. (1995). In laboratory measurement, impeller torque is usually measured and multiplied by rotational speed to get the mixing power, see Equation [4.2]:

$$P = 2\pi N M$$
[4.2]

where M is the net impeller torque (N \cdot m). Impeller torque is a measure of the forces that cause an impeller to rotate in fluid. For a large scale mixer, impeller torque is usually detected by shaft torque sensor or other transducers. Due to the lack of suitable sensor for the mixer used in this work, an alternative inexpensive torque measurement device was developed. The working principle of the device is to measure the torque reaction instead of the torque itself by using Newton's third law that they are equal. As shown in Figure 4.7, the mixing tank with fluids is placed on an elliptical plate which rotates about the axis. Due to the fluid resistance and frictions between fluid and wall, the forces applied to fluid by the rotating impeller will make the plate to turn. In order to keep it static, an opposite moment must be applied to the plate, and the moment is by magnitude equal to the impeller torque. Therefore, the impeller torque can be obtained by measuring the applied moment which can be decomposed into a force and a lever-arm distance in the same plane. In this case, rotation of the plate was stopped by an object fixed on the base. A pressure transducer was attached to the object. The moment is thus determined from the cross product of the force detected by the pressure transducer and its lever-arm distance. The device was calibrated before the use and it had an accuracy of 1.42×10^{-4} N·m.



Figure 4.7 The impeller torque measurement device

4.3.3.3. Sedimentation of treated MFT sludge

In this research, flocculation results were evaluated by comparing the settling results of the treated MFT in glass cylinders. Flocculation is considered effective if the flocs settle rapidly in the cylinder with considerable amount of water released in a short time. As soon as the cause of agitation was removed, the MFT-polymer mixture was poured into a 500 ml cylinder for self-weight settling. The criteria used to evaluate the flocculation outcome is the total volume of water released after a settling period of 24h.

4.3.4. Procedure

The procedure used in one flocculation test is described as follows. Firstly, the homogenous MFT suspension was filled into the mixing tank to the required height and the tank was placed on the rotatable plate of the torque measuring device. Secondly, the predetermined volume of polymer solution was injected into the suspension using a syringe with extended mouth. The polymer was injected slowly and the mouth of the syringe was moved up and down in the tank to make the addition as uniform as possible in the suspension. Third, the impeller was lowered into the tailing to a fixed depth. The mixer was then switched on and the timer was started. The impeller torque values were recorded manually throughout mixing. Finally, after the required duration was met, the mixer was switched off and the impeller was taken out of the vessel. The flocculated tailings were transferred immediately to a cylinder and the surface of the sediment was recorded with time.

4.4. Results and discussions

4.4.1. Results of rheological measurements

4.4.1.1. Fine tailing suspensions

Figure 4.8 provides the rheograms obtained for MFT samples. It is seen that when extrapolate the data points through the shear stress axis all the intersections are above zero, which indicates the existence of yield stress in fine tailing slurry. Yield stress is the resistance of sludge solids to deformation until sufficient stress is applied to exceed the yield strength of the network structure. Clay network is formed as the result of net negative platelet charges and net positive edge charges that the anisotropic particles have. If the applied shear stress is smaller than the yield stress, this structure is strong enough to appear as elastic flow. If the applied shear stress exceeds the yield stress, the MFT suddenly transforms from elastic flow to viscous flow (Dobias 1993; Van Olphen 1977; Luckham and Ross 1999; Phelps et al. 1983). For all the MFT samples, after the yield point, the shear stress is linearly related to the shear rate, which indicates that the plastic viscosity of MFT suspension, calculated as the slope of flow curve, is constant during mixing. The flow behaviour can be described by Bingham model, as shown in Equation [4.3]:

$$\tau = \tau_0 + \eta \gamma \tag{4.3}$$

where τ is the shear stress (Pa); τ_0 is the yield shear stress (Pa); η is the Bingham plastic viscosity (Pa·s), and γ is the shear rate (1/s). The fitted parameters for MFT samples at various concentrations and the coefficients of determination (R^2) are given in Table 4.3.



Figure 4.8 Rheograms determined for samples of MFT suspensions with various solids content

Table 4.3	Fitting parameters	for the MFT	suspensions using	Bingham model

Solid content	τ_0 (Pa)	η (mPa·s)	R^2
9%	0.013	2.4	0.998
15%	0.059	3.0	0.998
21%	0.211	4.1	0.995
32%	1.339	8.0	0.994

The provided data shows that the yield stress and the Bingham plastic viscosity increase as the solids content rises. There is a generally exponential dependence of viscosity on solids content, which can be expressed in Equation [4.4].

$$\eta = 1.348 + 0.501 \times e^{(8.1 \times C_s)}$$
[4.4]

where C_S is solids content (%) and η is in unit of mPa·s; Demoz and Mikula (2012) measured the viscosity of MFT at different solids content in their research, the obtained viscosity vs. solid content relationship is:

$$\eta = 4.048 + 0.865 \times e^{(8.1 \times C_s)}$$
[4.5]

It is seen that the power law index in the fitted equation [4.4] and [4.5] are equal, which indicates a similarity in terms of rheology between the MFT materials used in two research. According to the results, viscosity of the original MFT sample (32% in solid content) was about 8 times of water. The rapid rise of viscosity with the increasing solids content implies that flocculation of higher solids content MFT requires significantly more mixing energy.

Figure 4.9 shows the shear rate vs. shear stress curves of the 32% solid content MFT in one up and down cycle. The term "up" refers to the process in which the shear rate increases with time while the term "down" refers to the opposite process. At the same shear rate, shear stresses measured during the "down" process are less than corresponding values in the "up" process. Similar phenomenon was reported by Zrobok et al. (1991), who carried out

seven consecutive shearing cycles on oil sands fine tailings. They also found that the level of shear stress decreased as the number of cycles increased. This phenomenon can be explained by breakdown of network structures in MFT due to shearing. The decrease in network strength results in higher shear rate for a given stress.



Figure 4.9 The up and down curves in one shearing cycle

4.4.1.2. Polymer solutions

Figure 4.10 provides the rheograms determined for the polymer solutions prepared at different concentrations. The data show that the polymer solution is a non-Newtonian fluid because the shear stress vs. shear rate relationship is not linear. It is found that the flow curves obtained for the polymer in this work are by shape similar to those reported by Demoz and Mikula (2012) for two high-molecule-weight polymers (see referenced paper). In particular, the shear stress vs. shear rate relationships at the concentration of 0.2% are almost the same. The shear rate vs. shear stress curves can be best fitted by Herschel-Bulkley model, given as follows:

$$\tau = \tau_0 + k\gamma^n \tag{4.6}$$

where τ is the shear stress (Pa); τ_0 is the yield shear stress (Pa); k is the consistency index, n is the power law index, and γ is the shear rate (1/s). Results show that the shear stress has more power law dependence on the shear rate with the increasing polymer concentration. The dynamic viscosity of the polymer solutions measured by rheometer is shown in Figure 4.11, which shows clear decreasing trend of viscosity with the increasing shear rate demonstrating that the polymer solution is a shear thinning fluid. Macosko (1994) demonstrated that for shear thinning fluids, it will return to its original rheological state once the shear is removed. The results show that the polymer solutions have at least 2 magnitudes higher viscosity than water.



Figure 4.10 Rheograms determined for the polymer solutions at different concentrations





4.4.2. Impeller torque (mixing energy) results

4.4.2.1. Mixing energy correlations

Mixing trials with impeller torque measurements were conducted on MFT suspensions using different mixing set-ups. The purpose was to test the sensitivity of the torque measuring device and verify Equation [4.1]. Figure 4.12 shows the impeller powers calculated from torque measurement for the PBT in MFT changing with the rotation speed and solids concentration. At the same mixing speed, operating impeller in a baffled tank consumed significantly more energy than in an unbaffled tank. It could be explained that the wall baffles break the bulk flow into small eddies which contain kinetic energy (Figure 4.13). When the eddies become so small that they can no longer sustain rotational motion, their kinetic energy is dissipated as heat. At a constant speed the torque of impeller detected in the baffled tank

was a bit fluctuating, which was unlike the situation in the unbaffled tank where the torque was rather stable. It indicates that the torque measuring device is sensitive to small changes of fluid's load applied to the impeller due to changes of flow directions. At the same speed, more energy was dissipated in a higher concentration MFT because of the larger density and viscosity.



Figure 4.12 Correlations of impeller power with rotation speed for PBT (left, D/T=0.51, C/H=0.25) and paddle impeller (right, D/T=0.68, C/H=0.25)



Figure 4.13 Effects of wall baffles in the vessel in changing flow direction

4.4.2.2. Impeller torque monitoring results

Figure 4.14 shows the impeller torque monitoring results detected for the paddle impeller used in six flocculation tests. In each test, 500 ml MFT in medium solid content (21%) was treated by polymer at dosage of 1g/kg and mixed in the unbaffled vessel at a specific speed. It is seen that the impeller torque detected in each test (except the one mixed at 100 rpm) undergoes a sudden increase followed by a sharp decrease which is illustrated in Figure 4.16. Changes of impeller torques are results of formation and degradation of flocs in the tailing slurry. Formation of an elastic floc network dramatically increases the overall viscosity of the slurry (Michaels and Bolger, 1962; Firth and Hunter, 1976; Murray &

Ormeci, 2008) and thus increases the load applied to the motor which is driving the impeller. In order to maintain the rotation speed, the impeller torque must increase accordingly. On the contrary, decrease of torque is caused by breakage of floc networks due to fluid shear and the peak on the torque response curve indicates the point where the network bonds rupture. Figure 4.15 shows a great dependence of the impeller torque on the applied mixing speed in each test. At a higher mixing speed, the change of impeller torque occurred earlier and the attained peak torque value was larger than the situation at a lower speed. It should be noted that there was no obvious change in the torque response curve determined at 100 rpm. It indicates that at a low shear rate, flocculation is incomplete and flocs can hardly grow. The torque response curves can provide information in predicting the progress and degree of flocculation. More torque response curves for the flocculation tests are provided in Appendix B.



Figure 4.14 Impeller torques monitored in the flocculation tests on 21% solid content MFT samples using the paddle and unbaffled vessel mixing set-up



Figure 4.15 Schematic drawing of change of impeller torque during flocculation

Figure 4.16 shows the impeller torques obtained from five flocculation tests with various polymer dosage being applied in each one. The mixing conditions used in the tests were identical (200 rpm and 3 min, the paddle-unbaffled tank) and this condition was proved

to create effective flocculation in each test. It is seen that the flocculation in the sample treated at the minimum dosage (0.5 g/kg) obviously lagged behind the other samples and the peak torque attained was the lowest $(5.3 \times 10^{-3} \text{ N} \cdot \text{m})$. When the dosage was increased to 0.75 g/kg and then 1 g/kg, the flocculation started earlier and the peak torque value was increased to $6.6 \times 10^{-3} \text{ N} \cdot \text{m}$ and $6.9 \times 10^{-3} \text{ N} \cdot \text{m}$, respectively. Since the other operational parameters in each tests were identical, the impeller torque was a measure of fluid consistency and floc strength. The results suggest that increasing the dose of polymer from 0.5 g/kg to the optimum dosage can effectively accelerate the flocculation and increase the floc strength.



Figure 4.16 Torque curves detected for PBT in 21% MFT treated with flocculant at different dosages and mixed at 200 rpm for 3 minutes



Figure 4.17 Totalized Torque (TTQ) for PBT and paddle used in 21% MFT treated with flocculant at different dosages

The Totalized torque (TTQ) is a parameter which is by value equal to the area under the torque-time curves over the torque application period. The TTQ is proportional to the total energy dissipation during mixing. Figure 4.17 shows the TTQ values calculated at different dosages for this test and another group of mixing tests using the PBT impeller (not provided). It can be seen that the TTQ values increase monotonically with the increasing dosage, which indicates that the increase of dosage above the optimum dosage will further increase the fluid's resistance due to high viscosity unabsorbed polymer. Therefore, overdosing in a flocculation application increases the mixing energy consumption and the associated operational cost.

4.4.3. Dewatering results as affected by different factors

4.4.3.1. Effect of mixing

Figure 4.18 presents the dewatering results (volume of water released after 24 hours) of thirty-five flocculation tests carried out in different mixing conditions. These tests were divided into five groups and each group was assigned a constant mixing speed in the range from 100 to 500 rpm. At each speed, the MFT and polymers were agitated for various time from 1 min to 10 min using the paddle impeller in the unbaffled vessel. It can be seen from the graph that the dewatering results depend greatly on the mixing speed, and to a less extent, on the mixing time. Firstly, look at the results obtained at the mixing speed of 100 rpm, the minimum water release obtained after a mixing time of 1 min was 50 ml. The water release value was increased to 120 ml by giving more time for adsorption of particles, but this value was still significantly lower than average water release values obtained in other groups at higher mixing speeds. The dewatering results and the monitored impeller torques demonstrate that flocculation was incomplete when mixing was too mild. In order to take full advantage of binding action of polymers, an initial rapid mixing is desired for homogenous distribution of the polymers among the particles so that a considerable amount of particles can be adsorbed. When the shear created is too mild, it is difficult to disperse the viscous polymer and leads to local overdosing in some polymers rich areas. Local overdosing actually wastes the flocculant while the whole tailing is still underdosed. Polymers adsorb strongly onto solid surface and this process is considered irreversible unless the shearing force exceeds the floc strength. Therefore, in case that the rapid mixing is not initially provided, the flocculation outcomes cannot be effectively enhanced by simply lengthening the period of mixing. According to the data, there was a huge leap in terms of dewatering results when the applied mixing speed was increased from 100 to 200 rpm. Among all the samples, the group at constant 200 rpm released the largest amount of water (233 ml on average). The peak dewaterability occurred at a mixing time of 3 min. In this sample, a total amount of 245 ml water was released from 500 ml treated sludge after 24 h, which indicates that a maximum ratio of 52% total water can be removed from the optimally flocculated MFT deposit one day after the placement. In this group, the water release values did not significantly reduce when mixing time was increased. Even after 10 min of mixing, the treated MFT still showed rapid dewatering, which was marginally worse than the optimum value. It implies that the mean size of flocs was not severely decreased during mixing. It can be explained that in the unbaffled cylindrical vessel, flocs and aggregates rotate with the whole slurry, and a dynamic equilibrium has been established between the shear stress and the floc strength during this process. Agitated at higher speeds (e.g. ≥400 rpm), dewaterability of the polymer treated MFT deteriorated significantly as the mixing time increased, indicating serious degradation of the flocs. When the slurry was subjected to prolonged mixing process, only small and compact flocs were formed, which led to mediocre dewatering results. In the extreme case of the over-mixed tailings (at 500 rpm and 10 min), the amount of released water (166 ml) was 32% less than the optimum but still 38% larger than the peak value (120 ml) obtained in the group of 100rpm.

Therefore, compared to overmixing a slurry, insufficient mixing is detrimental to flocculation result and should be prevented in the engineering.



Figure 4.18 Dewatering results for 21% solids content MFT treated with polymer at the dosage of 1g/kg and mixed by paddle in the un-baffled tank



Figure 4.19 Correlations of dewaterability with impeller torques for MFT-polymer mixtures mixed at 200 rpm

The dewatering results are correlated with the impeller torque results to see whether the peak torque value is accountable for the peak dewatering result. Figure 4.19 provides two examples of the correlations at the mixing speed of 200 rpm and 400 rpm, respectively. The graphs show that at each speed level, time required to reach the peak torque value is shorter than that to achieve the peak dewatering result. The results indicate that high attainable strength of flocs is not necessarily desirable for fast settling.

Demoz and Mikula (2012) proposed that the mixing energy input into the sludge system can be used as a controlling parameter for the dewaterability of treated MFT in condition that mixing is intense enough to disperse the polymer to create a homogeneous mixture and allow sufficient collisions for the flocs to grow (Demoz and Mikula, 2012). In the mode of Orthokinetic flocculation, growth of flocs is governed by velocity gradient, G, which is the root of mean energy dissipation rate per unit volume and is calculated in Equation [4.8] (van der Walt, 1998, Haarhoff and van der Walt, 2001) :

$$G = \sqrt{\frac{P}{\eta V}}$$
[4.7]

Velocity gradient (G) is indicative of mixing intensity (Reynolds and Richards, 1996). It has been established that mixing of added polymer, adsorption of polymer on particles, formation and breakage of flocs are all affected by applied shear, which is controlled by mixing intensity. The product of G and mixing time t is indicative of the mixing energy input into the sludge system. Note that G is the mean value over the agitation period, the integral of the dynamic torque versus time at constant impeller speed can give $G \times t$ more accurately, as shown in Equation [4.8] (Demoz and Mikula, 2012):



Figure 4.20 Dependence of dewatering results of flocculated MFT on G×t values

Figure 4.20 shows the relationships between the dewatering results and the calculated $G \times t$ values for above flocculation tests. In this test, the G×t value corresponding to the optimum mixing condition was 3.35×10^4 s⁻¹ s. It can be seen that the dewatering results in the

 $G \times t$ range from 2×10^4 to 7×10^4 s⁻¹ s are superior to those in the rest range. It indicates that there is an optimum operating envelop for effective flocculation in this application. When mixing is operated outside this envelop, the flocculation performance are poor.

In this research, mixing and flocculation tests were also performed using different impellers and vessels and MFT with higher (32%) and lower (15%) solid content. The peak dewatering results and the mixing variables are provided in Table 4.4. These results will be compared and discussed in the following sections.

MFT solid content (%)	Impeller type	Wall baffles	Impeller Speed (rpm)	Mixing time (min)	Max. water release after 24h (ml)
21	Paddle	No	200	3	245
21	PBT	No	600	6	240
21	Paddle	Yes	200	2	245
35	Paddle	No	400	6	140
35	Paddle	Yes	400	5	140
15	Paddle	No	100	1.5	309

 Table 4.4 Summary of the peak dewatering results and the mixing variables

4.4.3.2. Comparison of mixing tools in flocculation

In the flocculation tests, MFT-polymer mixing was proceeded using two different impellers cooperated with the cylindrical vessels. In order to find out which impeller is more suitable in the flocculation tests, the peak dewatering results and the optimum flocculation conditions determined for the two impellers are compared in this section (Table 4.5). In this research, the maximum flocculation result of the flocculated MFT produced using the PBT was 240 ml water released after 24 hours, this value was slightly less than the peak dewatering result (245 ml) obtained using the paddle impeller. It indicates that in proper mixing conditions both the paddle (radial flow impeller) and the PBT (axial flow impeller) can create the FMFT with promising dewatering results. In order to achieve the optimum flocculation result, the PBT had to rotate at 600 rpm which was two times as large as the speed of the paddle impeller. Although the maximum dewatering results obtained using the two impellers were similar, the initial settling rate (constant settling rate occurring at the beginning of settling, see Chapter 5) of the FMFT produced using the PBT was somewhat smaller. It is probably due to higher mixing velocity (larger G value) used with the PBT which produced smaller flocs. The calculated G×t values indicate that the total mixing energy consumed by the PBT was 3.3 times the energy consumed by the paddle under the optimum flocculation conditions. Above results demonstrate that the paddle impeller was more efficient than the PBT in the flocculation tests. The major differences between the paddle and the PBT are in the aspects such as impeller diameter (60 mm vs. 45 mm), number of blade (2 vs.4) and the blade angle (90° vs. 45°). It has been established that shear stress plays an important role in mixing and flocculation. Shear stress is a complex function of shear rate. The local shear rate in the flow is proportional to impeller rotation speed and it decreases rapidly with distance from the impeller blade tip (Paul et al. 2004). Perry and Green, 1997 proposed that the shear rate is typically 5-10 times higher around the impeller for a stable fluid. In this work, the ratio of impeller diameter to tank diameter (D/T) was 0.51 for the PBT and 0.68 for the paddle, indicating that there was larger gap between the PBT and the cylinder wall. Assuming that identical shear rates are created at the blade tips of both impellers at the same rotation speed, at a fixed point in the marginal zone of fluid the shear rate and density of turbulence in the PBT tank is lower than in the paddle tank because of larger distance from the impeller. Polymers in this zone may not be well mixed because the local shear rate is insufficient. In order to provide higher shear rate in this zone, the PBT must rotate at a higher speed.

Table 4.5	Comparison of the peak dewatering flocculation conditions created by the
	paddle and the PBT impeller in the unbaffled mixing vessel

Impeller	Speed (rpm)	Time (min)	G (s ⁻¹)	$G \times t$ (s ⁻¹ ·s)	Initial settling speed (m/s)	Max. water release (ml)
Paddle	200	3	186	33,488	1.2×10^{-3}	245
PBT	600	6	305	109,800	8.8×10 ⁻⁴	240

In this work, wall baffles were installed on the side walls of the cylindrical vessel by considering that they can prevent the swirling flow and produce axial flow in the tank, which were considered favorable in mixing MFT and polymer. Results in current study indicate that mixing in an unbaffled tank can create as good results as in the baffled tank. The effect of baffles on flocculation results can be illustrated in Figure 4.21. The maximum dewaterability produced in the baffled and unbaffled tank were exactly identical (245 ml in 24 hours). Only at the lower speed (150 rpm), results obtained in the baffled vessel were better than that obtained in the unbaffled. This superiority vanished after a mixing time of 10 minutes. Similar results were observed for the same material mixed using the PBT in the baffled and unbaffled tanks (the results are not presented). According to the results, roles of baffles in mixing and flocculation can be summarized as follows. When the applied mixing intensity is insufficient, mixing in a baffled tank produces better results than in an unbaffled tank. As the mixing speed increases, the advantages of using the baffled tank over the unbaffled tank reduce and finally vanish. At the high mixing speed, the baffles have negative effects on flocculation as higher turbulence destroys the flocs networks. It suggests that wall baffles are not necessary if adequate shear rate and turbulence is provided in the fluid.



Figure 4.21 Comparison between dewaterabilities of the polymer treated MFT which were agitated in baffled and unbaffled tanks

4.4.3.3. Verification of optimum polymer dosage

Prior to the flocculation tests, a polymer dosage (1g/kg) has been suggested and this dosage has been utilised in Shell's field in-line flocculation program. In current research, this dosage was verified. Figure 4.22 presents two groups of dewatering results for the FMFT which were treated at various dosages and mixed using the paddle and the PBT impeller. In each test, adequate mixing was provided to ensure that the polymer was well dispersed and homogenous mixture was produced. As shown in the graph, the peak dewatering results in each tests were obtained both at 1g/kg. It demonstrates that the suggested dosage is the optimum dosage for the polymer used in this research. When the polymer is dosed at this dosage, the resulted flocculated MFT may have the maximum dewaterability when proper mixing is provided.



Figure 4.22 Effects of polymer dosages on the dewatering results for 500 ml 21% MFT mixed in the unbaffled tank

4.4.3.4. Effect of solids concentration on flocculation

In order to investigate the effect of solid content of MFT on the flocculation, constant volumes (500 ml) of MFT in high (32%), medium (21%) and low (15%) concentrations were flocculated at the fixed polymer dosage (1g/kg) and the peak dewatering results and the optimum flocculation conditions are compared. Since dry polymer must be dissolved in water before it can be used, addition of the polymer solution into MFT exerts a dilution effect on the tailings. At a given dosage, the amount of water added with polymer solution into MFT varies with the tailing concentration. To eliminate this effect, the flocculation outcomes are presented as the Net Water Release (NWR), which is calculated as follows:

$$NWR = \frac{W_R - W_A}{W_0} \times 100\%$$
 [4.9]

where W_0 is the initial mass of water in the MFT, W_R is the mass of water released, and W_A is the mass of water added with the flocculant solution into MFT. In current investigation, the optimum flocculation result determined for the high concentration MFT was 140 ml released after 24 hours. For the low concentration MFT, the peak dewatering result was 309 ml. These results were all obtained using the paddle impeller and unbaffled vessel system. The calculated NWR values for the optimally treated MFT are shown in Table 4.6. The subscript 24 indicates 24 hours after the flocculation. The data show that the lower solid content MFT released more water after flocculation, whereas less mixing energy was consumed. It has been determined that viscosity of MFT increases exponentially with the increasing solid content, added that the amount of polymer added to the tailing is proportional to the solid content of MFT. Therefore, mixing polymer with high solid content tailings is sometimes difficult and flocculation might be incomplete if mixing is not adequate. It seems that using a lower concentration tailing is easier to create homogenous mixture, which is necessary for rapid dewatering. According to the NWR data, it is estimated that 1 m³ MFT in solid content of 32% would release 0.231 m³ water (excluding water in polymer solution) in 24 hours after the treatment. In order to lower the solid content from 32% to 21%, about 0.629 m³ water must be added to 1 m³ MFT. The resulted suspension would release about 0.753 m³ water in 24 hours and the net water release is 0.124 m^3 , which is less than the water released by the high concentration FMFT. If the 15% solid content MFT is flocculated, the net water release is only 0.073 m³. Therefore, flocculation using low solid content MFT does not help release more water from the tailings. In Table 4.4, the NWR of the optimally treated MFT are compared with the NWR values for the non-treated MFT obtained from the column settling tests (will be presented in Chapter 5). It shows that the 32% MFT benefited the most from the improvement of dewaterability, with the measured NWR being increased by 1116% after the flocculation. For the 21% and 15% MFT, the NWR were increased by 466% and 36%, respectively. Above observations demonstrate that using the high concentration MFT (32% solid content) for flocculation can obtain the highest dewatering potential despite of larger cost in polymer and mixing energy.

Solid	Original MFT		Polyr	ner trea	ted MFT	
content	NWR ₂₄ *	Speed	Time	G	G×t	NWR ₂₄
(%)	(%)	(rpm)	(min)	(s^{-1})	$(s^{-1} \cdot s)$	(%)
15	47.8	100	1.5	124	11,160	65.2
21	9.2	200	3	186	33,488	52.1
32	2.5	400	6	461	165,960	30.4

Table 4.6 Peak dewatering results and the optimum flocculation conditions for
constant volume of polymer treated MFT in various concentrations

* Data are obtained from 250ml column settling tests, as provided in Chapter 5

It was observed that after the original MFT were flocculated, the treated tailings have high yield strength. This material is considered a problem for transportation via pump line. Therefore, it is suggested that in practice the original MFT (containing 30-40% solids) be prepared at a lower concentration before being flocculated to ensure the pumpability and the possibility of placement in thin layers. The degree of dilution of MFT should be determined to balance the dewatering efficiency and the pumpability.

4.5. Summary

In this chapter, research was carried out to investigate the flocculation behaviour of MFT and determine the peak dewatering results and the optimum flocculation conditions. Rheological properties of MFT suspensions and polymer solutions were explored firstly, and

important rheological parameters were assessed through the determined flow curves. A laboratory flocculation program was then performed using the laboratory scale mixing setups. The mixing set-ups were constructed using two different impellers in conjunction with cylindrical vessels with or without wall baffles. Impeller torques and mixing energies were monitored using an inexpensive set-up developed in this work. Flocculation tests were carried out by varying the factors including mixing tools, mixing variables (rotation speed, mixing duration), polymer dosage and solids concentration. Effects of these factors on flocculation results were discussed. The observations and conclusions obtained in this research are summarized as follows:

- The rheologies of the MFT suspensions were well fitted by Bingham model. The Bingham viscosity of the MFT suspensions increased exponentially with increasing concentration. The rheologies of the polymer solutions were well described by the Herschel-Bulkley equation of state. The viscosities of the polymer solutions were at least two orders higher than that of water.
- The mixing energy dissipated by a rotating impeller in fluid was obtained by measuring the impeller torque. The impeller torque response curves monitored in the flocculation tests provided information on the changes of consistency of mixtures caused by flocculation. There was no correspondence between the peak impeller torque value and the maximum dewaterability of the FMFT. The high strength of floc networks was not desirable for fast settling.
- The flocculation tests reveal that mixing is at the heart of MFT flocculation and dewaterability. Dispersion of added polymer, adsorption of particles, growth and breakage of flocs are all affected by the shear rate (and shear stress) which is controlled by mixing velocity. In order to produce a well-flocculated and readily dewatering MFT, sufficient mixing intensity is required to disperse the polymers and create homogenous treated mixture. However, prolonged high intensity mixing may break the flocs into small flocs and microflocs which produce mediocre dewatering results. For a MFT-polymer mixture mixed in a specific mixing system, dependence of flocculation outcomes on the $G \times t$ values was demonstrated and shown as an optimum range of $G \times t$ which was accountable for fast dewatering results.
- Polymer dosage affected the flocculation and dewatering outcomes. When the polymer is overdosed, the excess flocculant increases the overall viscosity of slurry which was detrimental to the settling of flocs. The optimum dosage for the polymer adopted in this research was determined to be 1g/kg.
- Both the radial flow impeller and the axial flow impeller can be used in flocculation of MFT in laboratory. Due to a larger D/T ratio, the paddle impeller was more efficient than the PBT in the flocculation tests. When adequate mixing intensity was provided, it is not necessary to install wall baffles on the cylindrical mixing vessel.
- The solids content of MFT used in flocculation decided the difficulty of MFT-polymer mixing and the dewatering efficiency. Lowering the solid content of the original MFT did not increase the water release but it was necessary to assure acceptable pumpability of the treated MFT.

5

Column Settling Tests and Oedometer Tests

5.1. Introduction

In practice, upon deposition a dilute soil slurry undergoes a settling process which consists two primary stages – sedimentation and consolidation. In thin lift drying technology, the sedimentation and self-weight consolidation rate of the deposited tailing material (treated or non-treated) plays an essential role in the dewatering efficiency. Therefore, it is of great practical importance to determine the settling behaviour of the tailing slurries. After sedimentation is completed, the tailing deposit consolidates under self-weight and overburden. The consolidation behaviour of fine oil sands tailings is affected by several factors including compressibility, hydraulic conductivity, thixotropy, creep and gas production (Suthaker,1995; Jeeravipoolvarn, 2005). Compressibility is the most discussed property because it constitutes the response of the material to the applied pressure.

In this research, sedimentation and consolidation behaviour of fine oil sands tailings was investigated by performing column settling tests and standard oedometer tests. In the column settling tests, the settling velocities of different solids concentration MFT were determined. The results were used to assess the initial permeability and the boundary void ratio between sedimentation and consolidation. The standard oedometer tests were performed on the compacted tailings samples to determine their void ratio – effective stress relationships at lower void ratios. The effects of polymer treatment on the settling behaviour of MFT was identified by comparing the results between MFT and polymer treated MFT.

This chapter is organized into five sections. Section 5.2 presents a literature review of general theory of sedimentation and consolidation followed by an introduction to actual settling process of oil sands tailings and factors affecting the consolidation behaviour. Compressibility and hydraulic conductivity data of MFT obtained from open literature are then presented. In Section 5.3, procedures of the experiments are introduced. Results obtained from the tests are presented and discussed in Section 5.4. Finally, a summary of observations and conclusions is given in Section 5.5.

5.2. Literature review

5.2.1. Sedimentation and consolidation

The formation of soil typically goes through two stages which are sedimentation and consolidation. The sedimentation velocity of clay suspensions represents a statistical average of all solids velocity which is governed by the combined action of gravitational force, Brownian force, interparticle electrical force, Van der Waals force, and Stokesian viscous force (Russel et al., 1989). In a geotechnical process, sedimentation takes place when a dilute slurry is allowed to settle freely under gravity. Particulate settling (or Stokian settling) may start at this time. In this mode of settling, the particle settling velocity can be calculated using the theoretical formula presented by Stokes

$$V_s = \frac{2r^2g(\rho_s - \rho_f)}{9\eta}$$
[5.1]

where V_s is particle settling velocity, r is a Stokes radius of particle, g is gravitational acceleration, ρ_s is solids particle density, ρ_f is fluid density and η is fluid viscosity. According to equation [5.1], larger particles (i.e., sand) settle faster than smaller particles (i.e., silt and clay) in a slurry. As a result, particle segregation or particle sorting occurs when there is significant difference in the particle size in a slurry. Li and Williams (1995) stated that if the slurry is less than or equal to solid concentration of 35%, the self-weight consolidation starts at the base and proceeds upward. Imai (1981) described the sedimentation to consolidation process as consisting of three stages which are flocculation, (zone) sedimentation and consolidation, as shown in Figure 5.1. In the first stage, no settling takes place but the flocculation yields flocs. Flocculation is the agglomeration of destabilized particles into microflocs and after into bulky floccules (flocs) due to attractions between negative face charges and positive edge charges. In the second stage, the whole system of flocs fall and the concentration of the floc system increases with time and a layer of supernatant water appears on the top. This stage is known as hindered sedimentation. The boundary between the settling zone and the sediment is the birth place of new sediment. As the thickness of the sediment grows, the settling zone becomes thinner and finally vanishes. In this stage, the sludge-water interface typically settles linearly with time, which has led to a believe that the settling velocity is a unique function of solid concentration (Holdich and Butt, 1997). The boundary between sedimentation stage and consolidation stage is not well understood. Studies (i.e., Tan et al., 1990; Been, 1980; Been and Sills, 1981) suggest that there may be a transition zone between sedimentation and consolidation where effective stresses are partially developed.

Been and Sills (1981) proposed one numerical model for self-weight consolidation (see the referenced paper) based on laboratory sedimentation and self-weight consolidation tests. It was found that self-weight consolidation model by Been and Sills (1981) closely predicted the surface settlement during sedimentation and consolidation stages (Bo, 2001). Figure 5.2 shows the isochrones of void ratio and excess pore pressure of the settling material worked out using the model.



Figure 5.1 The general characteristics of settling of clay-water mixture (modified from Imai, 1981)



Figure 5.2 Isochrones of void ratio (left) and excess pore pressure (right) when $z_0 = 1.5$ z_1 worked out using the self-weight consolidation model proposed by Been and Sills (1981) (after Been and Sills, 1981)

5.2.2. Settling of oil sands tailings in the pond

Jeeravipoolvarn (2005) described the settling process of oil sands tailings in a tailing pond as the following:

"In a tailings pond, after the whole tailing slurry is pumped into it, the slurry travels on the top of the coarse grained beach, into a clear water zone and finally stops in a sedimentation region. During this traveling, the slurry separates into a sand density current and thin fine particle current. The thin fine particle slurry which has a bulk density around 1.05g/ml and a solid content around 8 % travels down the beach into a sedimentation zone until it reaches a zone of similar density. Sedimentation is occurring in this region by the solid particles falling through the water, during which there is no stress transfer between particles except for collision of the particles. For this type of a material, both Stokian and hindered settling can be observed. During this process some of the free bitumen separates from the slurry and forms a layer of bitumen on the top of the fine tails. This is because the bitumen remains in the slurry. It takes about 2 years after the solids content of the slurry reaches about 15 to 20%, the slurry begins to form a matrix such that stress can be transferred within the solid particles. After this solids content, any increase in density arises from the process of self-weight consolidation. This process is controlled by the hydraulic conductivity and compressibility of the matrix, and is induced by the buoyant weight of the particles. The slurry at this point is known as MFT."

Consolidation of MFT by gravity is extremely slow, which would be difficult to detect over a short period of time. It has been estimated that a layer of MFT that is 5 meters thick with an initial total density of 1264 kg/m³ would consolidate under its own weight to a final height of 2.7 meters, but it would take over 100 years to reach that state with an initial settlement rate of 6.5 cm per year (Znidarčić et al. 2011). In real tailing ponds, the settling process could be even slower or the consolidation process might not even be triggered without additional input (Wells, 2011).

5.2.3. Compressibility and permeability of MFT

Compressibility and permeability are the most discussed geotechnical properties that affect the consolidation behaviour of soils. Compressibility and permeability are usually presented in two constitutive relationships (void ratio versus effective stress and hydraulic conductivity versus void ratio). These two relationships are used to solve the governing equation in finite strain consolidation modelling. Compressibility and permeability characteristics of MFT have been reported since 1980s. Figure 5.3 shows some compressibility data obtained from open literature. The compression curves (i.e., Suthaker (1995), Proskin (1999)) indicate that compressibility of the fine tailings is controlled by the initial void ratio of the sample. Imai (1981) suggested that the void ratio where the effective stresses start to exist is dependent on the initial void ratio and therefore countless compression curves may exist under very low effective stresses. Bo et al. (2003) pointed out that for a ultra-soft soil the final void ratios under the same applied stresses are about the same, regardless of the initial condition. It was also suggested that the transition point from an ultrasoft soil into a Terzaghi soil was approximately at an effective stress of 10 kPa where the compressibility was independent of initial void ratio. Comparing compressibility of the MFT presented, it is seen that there is a wide spread of the compression curves under low effective stresses. At higher stresses (i.e. >10 kPa), these curves approach to each other despite of various initial conditions. It indicates that MFT produced in Canadian oil sands industry are quite similar in terms of compressibility. Unlike young or newly deposited soils, MFT show apparent pre-consolidation pressures, which is ascribed to thixotropy of MFT (Jeeravipoolvarn, 2010). The void ratio - effective stress relationships of the fine oil sands tailings can be best described by power function (Equation [5.2]) or extended power function (Equation [5.3]).

$$e = A\sigma'^B \tag{5.2}$$

$$e = A(\sigma' + E)^B$$
[5.3]

where e is void ratio, σ' is effective stress (kPa), and A, B and E are fitting parameters. Table 5.1 provides some fitted formulas for the MFT reported in literature. It is noted that the power function is used exclusively in the seepage induced consolidation tests. For the different MFT at different initial void ratios, the fitted parameters are not significantly varied.



Figure 5.3 Compression curves (void ratio vs. effective stress) for different samples of MFT reported in literature

Author (year)	e_0	Measurement method	Fitted function
Pollock (1988)	5.1	Slurry consolidometer	$e = 3.38 \times \sigma'^{-0.309}$
Proskin (1998)	5.4	Slurry consolidometer	$e = 2.71 \times \sigma'^{-0.278}$
Znidarčić (2011)	4.6	Seepage induced test	$e = 3.27 \times (\sigma' + 0.074)^{-0.195}$
Gan (2011)	4.9	Slurry consolidometer	$e = 3.12 \times \sigma'^{-0.208}$
Estepho (2014)	5.2	Seepage induced test	$e = 3.00 \times (\sigma' + 0.035)^{-0.177}$

Table 5.1 Some fitted functions for the compressibility data of MFT

Figure 5.4 shows a series of hydraulic conductivity data for different samples of MFT reported in the available literature. Unlike the compressibility behaviour of the fine tailings, hydraulic conductivity-void ratio behaviour is not influenced by the initial void ratio, which means that the hydraulic conductivity has a one-to-one correspondence with the void ratio (Suthaker,1996). The results show that the hydraulic conductivity values are dependent on the hydraulic gradient used in the tests. According to the data, the hydraulic conductivity-void

ratio behaviour assessed for different samples of MFT can be described by power function as follows:

$$k = Ce^{D}$$

$$[5.4]$$

where k = coefficient of hydraulic conductivity (m/s), C and D are fitting parameters.



Figure 5.4 Hydraulic conductivities of MFT reported from literature (modified from Jeeravipoolvarn, 2005)

Figure 5.5 provides the best-fitted hydraulic conductivity-void ratio curves for different MFT samples reported in the available literature. Look at these curves, it is interesting to find that the hydraulic conductivity values determined in the early research are larger than those obtained in the later research when compared at the same void ratio. In addition, as shown in Table 5.2, the power low index of the best-fitted function is between 3.85 and 5.26 for the MFT in the early work (1980s and 1990s) while it is between 2.84 and 3.55 in the later research (2000s and 2010s). Since the hydraulic conductivity is controlled by the fines content (Suthaker,1995), it seems that the fines content of MFT is time dependent but it needs more evidence to verify this. From the data presented by Miller (2004) in Figure 5.5, it is seen that the hydraulic conductivity - void ratio behaviour of the MFT obtained from Syncrude and Suncor Project are almost identical. It indicates that the MFT have rather consistent properties.



Figure 5.5 Fitted hydraulic conductivity – void ratio curves for different samples of MFT

Authors	Year	Value of C	Value of D
Bromwell	1983	10×10 ⁻¹¹	4.20
Yong	1983	1.0×10^{-11}	5.26
Pollock	1988	7.4×10^{-11}	3.85
Suthaker	1996	6.2×10^{-11}	4.47
Proskin	1998	4.7×10^{-11}	4.38
Miller	2004	8.0×10^{-11}	2.84
Miller	2004	9.0×10^{-11}	2.89
Znidarčić	2011	2.5×10^{-11}	3.39
Estepho	2014	1.4×10^{-11}	3.55

Table 5.2 The fitted parameters for the permeability functions of MFT

5.2.4. Other factors affecting consolidation behaviour

Creep behaviour is another property of the MFT that relates to consolidation. Creep is defined as the time dependent volumetric strains and/or shear strains that develop at a rate controlled by the viscous resistance of the soil structure (Mitchell,1993). Secondary consolidation following primary consolidation is a specific case of creep. Laboratory investigations suggest that oil sand fine tailings have large creep index compared to other clayey soils (Suthaker and Scott, 1995). The 10 metre standpipe tests conducted at University of Alberta showed that creep was occurring in the settling standpipes and 30% of the total settlement at the end of 10 years was attributed to creep (Jeeravipoolvarn, 2010).

Thixotropy is defined as an isothermal, reversible, time-dependent process occurring under conditions of constant composition and volume whereby the material stiffens while at rest and is softened or liquefied by remolding (Mitchell, 1993). The thixotropic phenomenon takes place in the majority of clay-water systems. MFT is in nature thixotropic and thixotropic gain in strength can explain some phenomena of MFT such as the slow settling rate and the pre-consolidation behaviour at very low effective stress. When MFT is allowed to remain undisturbed it forms a moderate gel of thixotropic strength, causing an increased effective stress without lowering the void ratio (Jeeravipoolvarn, 2010).

Dusseault and Scott (1983) proposed that the residual bitumen may have the effect of reducing the effective relative density of the solids column and hence affect the consolidation behaviour of tailings in the pond. It was also suggested that the viscous bitumen can reduce the permeability of the system by blocking pore throats. The permeability was reduced by two magnitudes in bitumen-rich sludge (Scott and Dusseault. 1982). Suthaker (1995) postulated it that blocking of pore throats by residual bitumen may occur at high hydraulic gradients and suggested that the laboratory hydraulic conductivity test must be performed at the field hydraulic gradient to obtain representative values.

5.3. Experimental work

5.3.1. Column settling tests

In this research, column settling tests were carried out on fluid fine tailings to investigate their sedimentation and self-weight consolidation behaviour. Samples for the settling tests were prepared using the tailings stored in the plastic buckets after complete agitation. The original MFT was diluted by tailing water to form clay suspensions with various initial solid content. The purpose of preparing higher water content of the slurry was to create hindered sedimentation condition. In each settling test, the clay suspension prepared at the required water content was poured into a graduated cylinder, which was then closed by a stopper. The cylinder was inverted 20 times before the cylinder as allowed to stand in the climate controlled environment where the air temperature was maintained at 23 ± 1 °C. During the test, height of the sharp interface formed between supernatant water and sludge was recorded with time. The column tests were performed on MFT, TT and FMFT.



Figure 5.6 Duplicate settling tests on 10% and 14% solid content MFT

Reproducibility of the column settling tests was checked. As shown in Figure 5.6, the duplicate tests performed on MFT at various solid content of 10% and 14% following the above-mentioned procedure had very good reproducibility.

5.3.2. Standard oedometer tests

Oedometer tests (one-dimensional compression tests) were performed to determine the compressibility characteristic of the fine tailing samples under the stresses from 1 to 10^2 kPa. This range is appropriate because it is operative in the majority of tailings management facilities (Qiu and Sego, 2001). The tailings samples (MFT, TT and polymer treated MFT) were prepared at lower water content (i.e., slightly below the liquid limit). To achieve it, the fluid tailing was subjected to consolidation by self-weight and small loading pressure to remove excess water. Degrees of saturation of the prepared samples were checked before the tests. Compression tests were performed using two oedometer devices, namely, the simple one and the modified one (Figure 5.7). The simple apparatus uses a steel ring in diameter of 64mm and height of 20mm to contain the specimen. Vertical loads were applied directly on the loading cap which was placed on top of the sample. The minimum load that must be applied to the specimen was the self-weight of the displacement gauge and the loading cap, which was in total about 500g. Therefore, the minimum effective stress created in the specimen was about 1.5kPa. To ensure good accuracy of measurement, the applied surcharge pressure was limited below 200kPa. Unlike the simple oedometer device, the modified oedometer has a beam system with an adjustable counterbalance, therefore the net pressure applied on the specimen can be relatively small (i.e. <1kPa). The deformation of the specimen was detected by a displacement transducer and the data was logged by a data acquisition software. Compared with the simple oedometer device, compression tests using the modified oedometer can provide wider range of soil compressibility. In order to adapt to large strain consolidation of the sample, a taller steel ring (50 mm) was manufactured to accommodate the sample. After the ring was mounted above the bottom plate, the net height of the sample was 44 mm, which was twice the height of the sample used in the standard oedometer.



Figure 5.7 Two oedometer devices used in this work, the simple oedometer (left) and the modified oedometer (right)

5.4. Results and discussions

5.4.1. Column settling tests results

5.4.1.1. Settling results for the MFT samples

In this research, a total of 10 hindered sedimentation tests were performed on the MFT suspensions with initial void ratio varying from 11 to 119 (solid content from 1.9 to 17.5%). By assuming complete saturation and using unity for the specific gravity of water, void ratio of homogenous tailing slurry can be calculated from its gravimetric water content using the following equation:

$$e = G_s w ag{5.5}$$

where G_s is specific gravity of solids, w is gravimetric water content. The 500 ml graduated cylinder was used in this group of tests. The cylinder had an inner diameter of 49 mm and a fluid filling height of 36 cm.



Figure 5.8 Settling curves of MFT at various initial void ratios in 500 ml graduate cylinders

Figure 5.8 shows the interface settlement curves determined from the settling tests. It can be seen that the settling curves for lower initial void ratios samples lie above those with higher void ratios. According to the figures, the settling process of MFT suspensions can be divided into three stages. The first stage is regarded as the flocculation stage, which is characterized by a small interface settling velocity. The duration of the flocculation stage decreased with increasing initial void ratio, and it was hard to recognize at high void ratios (e.g. e > 99). After the flocculation stage, the mud-water interface settled at high and constant velocity, this stage is recognized as hindered settling or zone settling. In this case, hindered

settling conditions were achieved for the MFT suspensions at the initial void ratios between 11 and 119. At higher void ratios, interface between sludge and water was blurred and undefined. In the last stage, the settling velocity decreased sharply as flocs deposited on the bottom. It was observed that some bitumen migrated with flow to the surface of supernatant water in the hindered settling stage. Some floating bitumen then dropped to the surface of sediment bed. It was believed that most of bitumen were still bonded by clay particles.

Been (1980) and Pane and Schiffman (1997) proposed that the hydraulic conductivity of a homogenous high water content clay suspension can be inferred from hindered sedimentation tests. The initial constant settling velocity is used to calculate the hydraulic conductivity of a clay suspension corresponding to the initial void ratio through the following equation:

$$k = \frac{V_{si}(1+e_0)}{\Gamma}$$
[5.6]

where V_{si} is the initial settling velocity of the sludge – water interface, e_0 is the initial void ratio, and the non-dimensional constant Γ is given by

$$\Gamma = \frac{(\gamma_s - \gamma_w)}{\gamma_w}$$
[5.7]

where γ_s and γ_w are unit weight of solids and water, respectively. Equation [5.6] is valid only when there is suspension of the initial porosity at the sediment - water interface, that is, as long as the surface settling velocity is constant. Tan et al. (1990) proposed that a non-linear part of the settlement curve can also be used to obtain hydraulic conductivity via Kynch theory. In order to perform this analysis, the surface solids concentration must be determined. Based on Kynch theory, Tan et al. (1990) proposed an expression to calculate solids concentration, given in Equation [5.8].

$$\left(x + t\frac{dx}{dt}\right)_P = \frac{M}{\eta}$$
[5.8]

where x is height of water-sludge interface; t is time; M is total mass of solids, η is concentration and subscript P indicates a point on a settlement curve. For high water content suspension, the settling characteristics are normally expressed in terms of void ratio. Therefore, void ratio at point P is given as follows:

$$e = \frac{(1+e_0)(h+v_{sp}t)}{h_0} - 1$$
[5.9]

where *h* is height at point P; v_{sp} is a tangential velocity at an interest point and h_0 is initial height of suspension. The hydraulic conductivity during a nonlinear part of the settlement curve can be calculated from equation [5.6]. The use of equations [5.6] is widely accepted when a clay suspension is undergoing hindered sedimentation but it is believed that during consolidation this method is not valid.
Test	e_0	C_{s} (%)	h_z (cm)	h_s (cm)	e_s	v _{si} (m/s)	k_{si} (m/s)
M1	11	17.5	2.20	-	-	1.22×10^{-6}	1.11×10 ⁻⁵
M2	15	13.4	1.64	18.5	10.3	8.92×10^{-6}	1.09×10^{-4}
M3	19	10.9	1.31	17.5	12.3	1.02×10^{-5}	1.56×10^{-4}
M4	23	9.2	1.09	16	13.7	1.16×10^{-5}	2.13×10^{-4}
M5	31	6.9	0.82	13	14.9	1.77×10^{-5}	4.33×10 ⁻⁴
M6	39	5.6	0.65	12.5	18.1	2.17×10^{-5}	6.65×10^{-4}
M7	59	3.8	0.43	11	24.3	2.58×10^{-5}	1.19×10^{-3}
M8	79	2.8	0.33	9	26.6	3.04×10 ⁻⁵	1.87×10^{-3}
M9	99	2.3	0.26	7.5	27.8	3.56×10 ⁻⁵	2.73×10 ⁻³
M10	119	1.9	0.22	6.5	29.0	4.66×10^{-5}	4.30×10 ⁻³

 Table 5.3 Summary of 500 ml column settling tests for MFT

In this test, the initial settling velocities were determined from the linear parts of the settling curves and the corresponding hydraulic conductivities were calculated. The estimated parameters for the whole set of settling tests are shown in Table 5.3. It is seen that when the initial void ratio of the MFT suspension is increased from 11 to 119, magnitude of the measured hydraulic conductivity is increased by 2 orders, which indicates that the relationship between k and e is highly non-linear for fluid fine tailings. The results are compared with the experimental data of Specwhite kaolin presented by Pane and Schiffman (1997). In their research, the kaolin with a clay fraction of 75% was flocculated by Sodium chlorite into a "card-pack" form with a predominant face-to-face orientation. The liquid limit and plastic limit of Speswhite kaolin was 53% and 32%, respectively. Kaolinite is the major clay component in oil sands tailings, added that NaOH used in Clark Hot Water Extraction process exerts the flocculation effect on the particles, this may explain why the MFT slurry and the Speswhite kaolin slurry are in the similar range of permeability as illustrated in Figure 5.9.



Figure 5.9 Comparison between the MFT and the Speswhite kaolin slurry presented by Pane and Schiffman (1997) in terms of permeability at high void ratios

Figure 5.10 shows the settling curve for sample M6 ($e_0 = 39$), it can be seen that the sedimentation region and the consolidation region are separated by soil formation line (0A) which is characterized by a constant value of the void ratio e_m , herein denoted as soil-formation void ratio. In this test, at the settling time t = 150 min and the thickness of the sediment $h_s = 12$ cm, the soil formation line intersects the upper interface of the sludge and at this point the settling velocity abruptly decreases, indicating that sedimentation stage is completed. In Table 5.3, h_z refers to the material height (the total thickness of the solid manner) of the sample; e_s is the average void ratio in the sediment at time t_s and it can be inferred through equation [5.10] by considering that h_z for each test is constant:

$$h_z = \frac{h_0}{1+e_0} = \frac{h_s}{1+e_s} = \text{constant}$$
 [5.10]

It is noted that the estimated e_s increases with the decreasing h_z , indicating that some consolidation occurs below the soil formation line during the sedimentation stage (Pane and Schiffman,1997).



Figure 5.10 The sedimentation curve of MFT obtained from test M6 in 500 ml cylinder

Another group of settling tests were performed using 250 ml cylinders on the MFT suspensions at initial solids content of 32, 21, 18, 15, 12% (void ratios of 4.7, 8.7, 11, 13 and 17, respectively). Compared to the previous group of tests, the 250ml cylinders were allowed to stand for much longer period up to 800 days to determine the long term consolidation behaviour of the fluid fine tailings. Figure 5.11 shows the settling curves obtained during the first 24 hours. It can be seen that the exhibited settling behaviour could be divided into two types, designated as type I for lower initial void ratios (i.e., sample C1, C2 and C3) and type II for higher initial void ratios (i.e., sample C4 and C5). Tailings in type I have significantly smaller initial settling velocity values compared to those in type II, and the settling velocity decreases gradually with time. It can be explained that at lower void ratios the clay particles are likely to form a floc structure and the low settling velocity is caused by consolidation of the structure. This type of settling is called consolidation settling in order to distinguish it from hindered or zone settling (type II). Initial permeability values of the suspensions in 250 ml cylinders were determined from the settling curves, which are presented in Table 5.4. It is

noted that sample M1 and C3 have identical initial void ratio but they have different initial settling velocities, the v_{si} value of sample M1 in 500 ml cylinder is larger than that of sample C1 in 250 ml cylinder. It is thought that settling of slurry in a smaller diameter cylinder suffered more from side wall resistance compared to in a larger cylinder. The hydraulic conductivity values corresponding to different void ratios of the suspensions were also assessed from the non-linear parts of the settling curves up to 90% total settlement. Shown in Figure 5.11, the obtained permeability results are combined with those of 500 ml settling tests to build a wider range of hydraulic conductivity – void ratio relationship for the fine tailing suspensions.



Figure 5.11 Settling curves for the MFT suspensions in 250 ml cylinders during the first 24 h



Figure 5.12 Coefficient of hydraulic conductivity measured for MFT suspensions

The critical void ratio between the sedimentation (settling) zone and consolidation (settling) zone is the maximum void ratio when consolidation begins (Imai 1980) and it should be the soil formation void ratio (e_m) . Different methods have been proposed to determine the soil formation void ratio of clay suspensions. Pane and Schiffman (1997) obtained e_m for Speswhite kaolin and phosphatic clay through an inversion process of the coupled sedimentation and consolidation theory by adjusting the parameters to optimise the fit between measured and predicted settlements. Another method is to regard e_m as the void ratio of top slurry, where the value of effective stress keeps zero during the process of sedimentation (Carrier et al. 1983; Liu, 1990). However, disturbance of the soil sample is unavoidable when sampling from the top of the slurry layer. Xu. et al. (2012) proposed that the e_m can be determined from variations of initial surface settling velocities (v_{si}) with initial void ratio. This method was adopted in current study to infer soil formation void ratio of the fluid fine tailings. Shown in Figure 5.13, values of v_{si} decrease abruptly with the decreasing void ratio at a value between 10 and 11, this value is designed as the soil formation void ratio of the fine tailing slurry. Soil formation void ratio may be used as a fundamental material property of a given clay-water mixture for a given set of chemical and environmental conditions (Pane and Schiffman, 1997). Based on Been and Sills' (1981) results, the void ratio (e_m) when the effective stress is firstly measured is usually around 9 and 10. Carrier (1983) suggested that in most practical applications, soil formation void ratio is about 7 times the void ratio at the liquid limit (e_L) . Xu et al. (2012) performed experiments on four different dredged slurry (fine clay) and showed that e_m was about 8.6 times e_L . In current research, e_m of MFT is about 8.5 times of e_L , which is in accordance with Xu's findings.



Figure 5.13 Relationship between initial surface settling velocity and void ratio

Figure 5.14 provides the complete settling curves for the MFT samples in 250 ml cylinders in a semi-logarithmic (h - log t) graph. As noted by Imai (1981), excess pore water pressure is dissipating during self-weight consolidation and this process is completed when the settling curve tends to be horizontal in the h - log t plot. According to the figure, it is seen that consolidation is considered completed for Sample C5, C4, and C3 at the end of 800 days. Sample C2 can also be regarded as completion of consolidation as the settling curve is almost horizontal. Sample C1, the original MFT, was still consolidating and the height of the

sediment was 16.3 cm by the end of the test. When the settlement curve of sample C1 is extrapolated along the time axis to the magnitude of 1×10^4 days (about 27.4 years), the height of the sediment at that time is estimated to be about 15.6 cm and this value is used as h_m for Sample C1. After the self-weight consolidation is completed, the average void ratio of the sediment is denoted as e_c , which can be calculated from h_c using Equation [5.10]. Table 5.4 shows that h_z and h_c both increase while e_c decreases with the decreasing e_0 .



Figure 5.14 Settling curves of MFT determined from settling tests in 250 ml cylinders in semi-logarithmic scale

Test ID	e_0	$C_s(\%)$	h_z (cm)	$h_c(\mathrm{cm})$	e_c	k_{si} (m/s)
C1	4.9	32	2.20	15.6	2.67	2.77×10 ⁻⁷
C2	8.7	21	1.64	10.4	2.96	2.34×10^{-6}
C3	11	18	1.31	8.9	3.18	3.75×10 ⁻⁶
C4	13	15	1.09	8.2	3.48	6.15×10^{-5}
C5	17	12	0.82	6.3	3.52	1.03×10^{-4}

Table 5.4 Summary of the settling tests in 250 ml cylinders for MFT

In a clay suspension, floc, the fragile structure formed by charged particles, is the basic element for sedimentation. The flocs have some strength to resist external forces, though this strength is small. The maximum normal pressure that a floc can resist is regarded as the yield force (stress) of the floc, denoted as P_s (after Xu et al., 2012). The flocs may break when external forces applied on the flocs exceed P_s . In this group of tests, self-weight of the sediment keeps increasing with the accumulation of settled flocs and therefore the created effective stresses increase with time with the dissipation of excess pore pressure. At the beginning of consolidation, the initial skeleton that is formed is compressed under self-weight. As long as the effective stresses transmitted among the flocs are smaller than P_s , the flocs are not broken. Decrease in volume of sediment is mainly caused by compression of voids among

the flocs. When consolidation continues, with the maximum effective stress exceeding P_s , flocs on the base of the cylinder are broken firstly. At this time, decrease of void ratio of the tailing is caused by compression of voids among the pores and the internal voids within the flocs. This process may continue until all the flocs break (Xu et al. 2012).



Figure 5.15 Relationship between e_c and e₀ for the MFT suspensions used in this work and four dredged clay slurry determined by Xu et al. (2012)

For a given volume of suspension, a lower initial void ratio indicates a higher solids concentration and larger self-weight of the sediment. Therefore, the effective stress created by self-weight is also larger. When the initial void ratio decreases below a critical value that the maximal effective stress created is sufficient to break the flocs, compression of internal voids of the flocs will result in a lower void ratio of the sediment compared to the situation that the flocs are not broken. Therefore, it is assumed that there is a break in the relationship between e_c and e_{0} , at which the maximal effective stress is equal to the yield stress of floc. This assumption was proposed and verified by Xu et al. (2012) through the self-weight consolidation tests performed on four different dredged sludge. In current work, the relationship between e_c and e_0 is compared with the dredged sludges reported by Xu et al, as shown in Figure 5.15. Since the height of sediment was relatively small and the void ratio changed little with the height, e_c at the break point, denoted as e_p is regarded as the boundary void ratio of sediment when the maximal effective stress is equal to P_s . Results of the dredged sludge showed that e_p was linearly proportional to e_L and the coefficient was 2.86. For the MFT in current research, e_p was about 2.93 times e_L , which is also similar to that presented by Xu et al. At an equilibrium state, effective stress is the difference between total stress and pore pressure. The maximal effective stress in the sediment is found at the base. Therefore, P_s can be calculated using the following equation:

$$P_s = (\gamma_{sat} - \gamma_w)h_s = \gamma' h_s$$
[5.11]

where γ_{sat} is the average saturated unit weight of the sediment, γ' is the average unit weight of submerged soil and h_s is the height of the sediment when consolidation is completed. In this case, P_s is calculated to be 0.23 kPa for the MFT suspensions. This value is also close to those

of the dredged sludge, which are between 0.17 and 0.26 kPa (Xu et al. 2012). It suggests that MFT share some similarities with the dredged clay slurry in settling behaviour.

Based on the results provided above, it is assumed that the settling process of fine tailing suspension can be described using the void ratio vs. effective stress relationship as presented in Figure 5.16. The initial void ratio decides which type of settling the suspension will experience. When the tailing slurry is deposited at a void ratio larger than soil formation void ratio e_m , it will undergo two primary settling stages, chronologically, zone settling stage and consolidation stage. The consolidation settling stage can be subdivided into two stages. When the effective stress is lower than the yield stress of floc (P_s), the floc is not broken and decrease in void ratio of tailing is caused by compression of voids among the flocs. This stage can be regarded as the transition stage which is described by Pane (1985). When the effective stress exceeds P_s , the floc structures start to collapse and compress. At higher effective stresses, the soil behaviour can be explained by Terzaghi's principle.



Figure 5.16 Possible void ratio and effective stress relationship during settling of clay suspension (Xu et al. 2012)

An experimental evidence of above assumption is given in Figure 5.17, in which the compressibility data of oil sands cyclone overflow tailings reported by Jeeravipoolvarn (2010) is presented. It can be seen that the e-log *P* curve of the COT changed abruptly at the void ratio of about 4 (solids content of about 36%). This value is regarded as e_p of the COT and it is quite close to the corresponding value of the MFT in this work. Scanning Electron Microscopy (SEM) images provided in Jeeravipoolvarn's work showed that the clay particles in COT formed a mild edge to face flocculated and dispersed structure at a void ratio about 5. This structure is known as card-house like structure and it can be found in other fine tailings at void ratios higher than 5 (Tang, 1997). The card-house structure was not present at void ratios below 3, indicating that the card-house structure collapsed at a close range of void ratios between 3 and 5. According to the figure, the vertical effective stress (P_s) required to break the card house structure was about 0.5 kPa for the COT. Jeeravipoolvarn also reported a similar characteristic for the in-line thickened tailings (ILTT), but the flocs in the ILTT were a bit different from those in the COT due to various chemical additives.



Figure 5.17 Compressibility data of cyclone overflow tailings and possible structural changes during compression (modified from Jeeravipoolvarn 2010)

5.4.1.2. Settling results of the polymer treated MFT

The effectiveness of polymer in accelerating the settling velocity of MFT has been demonstrated in Chapter 4 in this thesis. It has been established that mixing has a substantial effect on the settling behaviour of polymer treated MFT as the shear rate and shear stress determine the shape and dimension of the flocs. Figure 5.18 shows the settling results of three FMFT samples produced under different mixing conditions. These samples represent three typical flocculation results as affected by mixing: optimal mixing, insufficient mixing and over-mixing. According to the figures, the FMFT produced at the optimal mixing parameters (200 rpm, 3 min) had the largest initial settling velocity. The over-mixed (500 rpm, 6 min) FMFT had the second largest settling velocity, followed by the sample which was insufficiently mixed (100 rpm, 3 min). The determined permeabilities of the slurries are compared to those of the non-flocculated MFT, as shown in Figure 5.19. According to the data, hydraulic conductivities of the MFT (21% solids content) were increased by 4 magnitudes after the treatment at the optimum condition. The optimally flocculated MFT was 2 magnitudes more permeable than the over-mixed sample as well as the insufficiently mixed sample. These results again demonstrate the important role of mixing in the properties of FMFT.



Figure 5.18 Settling curves of flocculated MFT samples produced under the different mixing conditions



Figure 5.19 Calculated permeabilities of the flocculated MFT samples produced under different mixing conditions

For the optimally treated sample shown in Figure 5.18, about 90% of total settlement was achieved within 30 min and the whole settling process was completed in 24 hours. The final thickness of the sediment layer (h_c) was 13.1 cm, which is about half of the initial height. The obtained settling parameters are compared with those of the non-treated MFT, as shown in Table 5.5. The time at completion of consolidation of the soil is denoted as t_c , which can be determined by applying Imai's method (1981) shown in Figure 5.20. The data indicate that after flocculation the consolidation time (t_c) of fine tailings reduces from about 7200 h to 13 h. The average void ratio of the sediment (e_c) for the polymer treated tailing was 35% larger than that of the non-flocculated MFT but their maximum effective stresses were almost identical. It

indicates that the FMFT has lower bulk density than the MFT at the same effective stress. This behaviour should be taken into consideration in the engineering practice.

Table 5.5 Comparison of self-weight consolidation properties between the non-treatedMFT and the optimally flocculated MFT

	Cs (%)	t_c (h)	e_c	e_c/e_0	γsat (kN/m ³)	σ'_{max} (kPa)
MFT	21	7200	3.0	0.34	13.0	0.329
FMFT	20	13	4.2	0.46	12.3	0.324



Figure 5.20 Method of determination of t_c (time when self-weight consolidation completes) proposed by Imai (1981)

5.4.1.3. Settling results for the TT samples

Thickened tailings (TT) are a concentrated stream of fine solids produced from cyclone overflow tailings (COT) after a series of flocculation and thickening processes. Due to addition of chemicals, flocs and aggregates are formed in the slurry and water is released rapidly from these tailings after the conditioning. It is known that flocs are sensitive to shearing forces applied in the slurry. Properties of flocs such as shape and dimension affect the settling characteristics of the tailing slurry. The TT materials used in this research were obtained from shipped in closed barrels from Canada to the Netherlands. During the transportation, settling occurred and the settled flocs formed floc networks with certain yield strength. Prior to laboratory testing, the TT was intensively mixed to re-homogenize the material, which inevitably exerted a shearing effect on the flocs. Therefore, the settling characteristics of sheared TT may be different from non-sheared tailings.



Figure 5.21 Settling curves for the TT samples at various initial solids content, settling curves during the first 600 min are presented on the top right corner

Figure 5.21 shows the settling curves of the TT samples measured from a series settling tests in 1000 ml cylinders (34 cm high and 6 cm in diameter). The original TT slurry was mixed at 300 rpm for about 20 min in the tailing bucket before samples were prepared. The settling curves in the beginning period (< 600 min) are provided on the top-right corner of Figure 5.20. It shows that when the initial void ratio decreases from 11.3 to 8.6, the setting type transfers from zone settling to consolidation settling. According to the data, Sample T3 had an initial settling velocity of 1.4×10^{-6} m/s. Using this value, the calculated hydraulic conductivity of the slurry was 1.35×10^{-5} m/s. This value is in the same magnitude as that of MFT at the same void ratio.



Figure 5.22 Comparison of settling results between the TT and the MFT samples at the same initial solid content

Figure 5.22 compares the settling results for the TT and MFT obtained in this work. Since the tests were performed in different cylinders, values of e_t/e_0 (ratio between the average void ratio of the sediment at time *t* and the initial void ratio) are used for comparison. The average void ratios of the sediment in TT were smaller than the corresponding values in MFT at the same time, which indicates that the TT samples settled a bit faster than the MFT samples.



Figure 5.23 Effect of mixing on the settling velocity of TT samples

Figure 5.23 compares the initial interface settling velocity of Sample T1 and Sample T0 (both at solid content of 32%) obtained from the preliminary research. Sample T0 was prepared directly from the tailing in the barrel after the virgin agitation in laboratory. Sample T1 was intensively mixed sample. The results show that Sample T0 settled faster than Sample T1, with the initial settling velocity being one magnitude higher than the other. Jeeravipoolvarn (2010) performed column settling tests on oil sands ILTT and showed that permeabilities of non-sheared ILTT were about 2 orders higher than that of sheared ILTT at high void ratios. He also determined the effect of mixing intensity on permeability of sheared ILTT. After a fixed mixing duration of 24 minutes, for example, the tailing mixed at 300 rpm was about two times more permeable than the sample mixed at 1080 rpm.

In this research, the TT samples showed higher magnitude and settling rates and permeabilities compared to the MFT at the same initial condition, but the difference was relatively small. It is considered that the mixing processes during sample preparation affected the particle size distribution in TT, which influenced the dewaterability of the material.

5.4.2. Oedometer tests results

5.4.2.1. Experimental data

Figure 5.24 presents the representative compression curves (e-logP curve) determined for the MFT samples using the simple oedometer device. It is seen that the compressibility behaviour for the two duplicate MFT samples were almost identical with slight difference at

lower effective stresses, which is due to various initial void ratio of the samples. Plotted in the semi-logarithmic graph, the measured void ratio – effective stress relationships for the MFT are generally linear, this is in accordance with the classic Terzaghi consolidation theory for a normally consolidated soil. The tests results are compared to the data shown in Figure 5.2 for different samples of MFT obtained from literature. It is found that the e-log P curves obtained in this research are in the same range to the data reported from literature, and particularly close to those presented by Pollock (1998) and Proskin (1999) in the range of effective stresses above 10 kPa (Figure 5.25). The slight differences can be found in the lower range of effective stress, which is due to different initial conditions of the tailing samples.



Figure 5.24 Compressibility of the MFT measured from oedometer tests



Figure 5.25 Compressibility comparison of the MFT used in current study and the MFT reported by Pollock (1988) and Proskin et al. (1999)

Figure 5.26 shows the compression results for two TT samples. It seems that Sample TT-2 was in an over-consolidated state compared to Sample TT-1 which was normally consolidated. The over-consolidated state of TT-2 may be due to different compaction degree of the sample resulted from the sampling process. Similar to the MFT samples, the normally consolidated TT sample also shows a linear $e - \log P$ relationship in the given range of effective stress.



Figure 5.26 Compressibility of the FMFT determined from oedometer tests

Figure 5.27 shows the compressibility data of two polymer treated MFT samples which were produced under the optimal mixing condition (200 rpm, 3 min) and the overmixed condition (500 rpm, 5 min), respectively. Using the modified oedometer, the minimum stress applied to the sample can be extended to as low as 0.45 kPa. The determined compression curves can be fitted by the following functions:

FMFT-1: $e = 3.195 \times \sigma'^{-0.202}$ $0.45 < \sigma' < 146$, $R^2 = 0.998$ FMFT-2: $e = 2.833 \times \sigma'^{-0.189}$ $0.48 < \sigma' < 251$, $R^2 = 0.996$

The results show that the optimally treated MFT (FMFT-1) had larger compression compared to the over-mixed sample (FMFT-2) over the same effective stress. The optimally mixed sample initially had larger flocs and pores, and hence larger initial void ratio. As the surcharge pressure increased, the flocs in the sample were broken, forming smaller flocs and micro flocs. According to the data, compressibility of the optimally mixed FMFT and the over mixed FMFT might be similar at high effective stresses. A similar phenomenon was observed by Jeeravipoolvarn (2010) in a comparison between non-sheared ILTT and sheared ILTT (Figure 5.28). It shows that the $e - \log P$ curves of non-sheared ILTT and shear ILTT tend to converge at the effective stress about 500 kPa.



Figure 5.27 Compressibility data for the FMFT samples produced at different mixing conditions



Figure 5.28 Comparison of compressibility data of ILTT (sheared and non-sheared) and COT (modified from Jeeravipoolvarn, 2010)

5.4.2.2. Comparison of MFT, TT and flocculated MFT in this work

In Figure 5.29, compressibilities of different tailings (MFT, TT and the flocculated MFT) studied in this research are compared. It can be seen that the compression data of the flocculated MFT lay above that of the non-flocculated MFT. It suggests that at the same void ratio the FMFT can sustain larger effective stress compared to the MFT. This suggests that the tailing was strengthened after the flocculation. Table 5.6 compares the consolidation parameters determined from the tests results between the two tailings. It can be seen that the flocculated tailing had larger deformation than the non-flocculated MFT over the same

effective stresses. It is considered that deformation of the FMFT was resulted from compression of both the voids among the flocs and within the floc structures. In addition, the FMFT consolidated faster than the MFT as it was more permeable. The different compression behaviour was caused by the different soil structures. It would be expected that the compressibility of the FMFT will be similar to the MFT if all the floc structures vanish. According to the figure, the compression curves of the MFT and the FMFT tend to converge at very high effective stress. Figure 5.29 also shows that the sheared TT and the MFT have similar compressibility characteristics.



Figure 5.29 Comparison of compressibility of the tailings determined from oedometer tests

Tailinga	Stress	Void	C	C_{v}	m_{v}	k_s
rannigs	(kPa)	ratio	C_c	(m ² /year)	(m^2/MN)	(m/s)
MFT	2.3-159.2	1.63-2.37	0.36-0.42	0.05-0.28	0.81-29.92	4.5×10^{-10} -7.2×10 ⁻¹¹
FMFT	0.48-160.0	1.06-3.33	0.63-1.65	0.13-0.52	1.46-249.04	$7.2 \times 10^{-8} - 1.4 \times 10^{-10}$

5.4.2.3. Comparison to samples obtained from Shell field tests

Field atmospheric fines drying (AFD) tests have been carried out by Shell since late 2012. In the field tests, MFT was treated via in-line flocculation process before the deposition. Consolidation properties of the deposited material were measured using field tests samples. Figure 5.30 compares compressibility of the polymer treated MFT obtained from the field tests (Shell, personal communication, 2014) and the FMFT prepared in this research. The e-log P curve of the field test sample was determined by seepage induced consolidation test, which provided a wider measurement range compared to the data obtained in this work. The results show that the field test sample and the laboratory sample are not significantly different in terms of compressibility.



Figure 5.30 Comparison of compressibility between the FMFT obtained in this research and the FMFT from field tests (Shell, personal communication, 2014)

5.4.2.4. Comparison to different type of tailings

In Figure 5.30, compressibility data of fine oil sands tailings (e.g., MFT, COT, ILTT and FMFT) are compared to those of different mine tailings presented by Qiu and Sego (2001). The void ratio – effective stress curves indicate that the fine oil sands tailings are more compressible with significantly larger void ratios at lower effective stresses compared to other mine tailings. Among the provided fine tailings, the e-logP curves of the chemically amended tailings (FMFT, ILTT) lay above those of non-treated tailings (MFT, COT). In terms of compressibility, MFT is generally similar to COT and FMFT is similar to ILTT. Table 5.7 compares the consolidation parameters for the MFT in current work and different mine tailings. It is summarized that compared to fine tailings coarse tailings (i.e., copper tailing, gold and CT) have lower compression index (C_c) while larger coefficient of consolidation (C_v) and saturated permeability (k_s). MFT has the least C_v and k_s values compared to other mine tailings, which implies that dewatering of MFT by consolidation is more difficult. The various consolidation properties of the tailings are the results of different material properties (see Table 3.4 in Chapter 3).

Table 5.7 Comparison of consolidation parameters for different tailings

Tailings	C_c	C_v (m ² /year)	$m_v \text{ (m}^2/\text{MN)}$	k_s (m/s)
MFT	0.357 to 0.420	0.05 to 0.28	0.81 to 29.92	4.5×10^{-10} to 7.2×10^{-11}
Copper	0.056 to 0.094	22.32 to 104.23	0.63 to 19.76	4.5×10^{-7} to 9.8×10^{-7}
Gold	0.083 to 0.156	13.58 to 80.07	0.29 to 162.50	2.7×10^{-7} to 6.7×10^{-7}
Coal	0.370 to 0.396	1.48 to 17.26	1.08 to 188.20	4.0×10^{-9} to 1.1×10^{-7}
CT	0.271 to 0.319	0.310 to 8.46	0.61 to379.90	2.2×10^{-9} to 6.3×10^{-9}



Figure 5.31 Comparison of compressibility of different mine tailings reported from literature (after Qiu and Sego (2001), Jeeravipoolvarn (2010))

5.4.2.5. Comparison of hydraulic conductivity of oil sands fine tailings

In this research, hydraulic conductivity values of fluid fine tailings at high void ratios were obtained from hindered sedimentation tests. This method is not valid for tailing during consolidation. In geotechnical engineering, permeability of the soil-like fine grained materials can be measured by performing various permeability tests (e.g., large strain consolidation test, seepage induced consolidation test). These tests were not carried out in current research due to unavailability of sophisticated instrumentation. However, permeability of MFT have been studied by different researchers (see Figure 5.4), which provides reference in terms of magnitude of hydraulic conductivity for the MFT in this work as it was found that properties of different samples of MFT were not significantly different. Hydraulic conductivity of the polymer treated MFT obtained from field AFD tests was determined associated with compressibility using seepage induced consolidation tests. The results (by personal communication) are shown in Figure 5.32 and compared with those of COT and ILTT provided by Jeeravipoolvarn (2010) and MFT reported by Estepho (2014). It appears that the overall magnitudes of hydraulic conductivity of different fine tailings are in the order of: FMFT > ILTT > COT > MFT. FMFT and ILTT are both chemical treated materials. The fact that FMFT is more permeable than ILTT suggests that treatment of MFT by polymer is as good as or even more effective than ILTT technology in improving the dewaterability of the fine tailings. No permeability data has been found for TT from open literature, but it is expected that the magnitude of permeability of TT is larger than COT but lower or close to ILTT. It is noted that hydraulic conductivities of various tailings vary significantly at high void ratios but the varieties are greatly reduced with decreasing void ratios. It implies that enhancement of dewaterability of fine tailings by chemical treatment is more effective in the sedimentation stage than in the consolidation stage.



Figure 5.32 Comparison of hydraulic conductivity between MFT, FMFT, ILTT and COT (after Jeeravipoolvarn (2010), Estepho (2014) and Shell personal communication (2014))

5.5. Summary

In this research, sedimentation and self-weight consolidation behaviour of fluid fine tailings were investigated through settling tests performed in a series of glass cylinders. By monitoring the surface settling velocity and settlement, hydraulic conductivity values for the MFT suspensions at initial void ratios and the boundary void ratio between sedimentation and self-weight consolidation were determined. The compression behaviour of fine tailings at lower void ratios were determined by performing oedometer tests. The compressibility data for different types of tailings were compared to those obtained from literature. The main results and findings obtained in the current research are summarized as follows:

- The settlement of high water content tailings slurries undergoes different stages including hindered sedimentation and consolidation. The column tests showed that the transition of hindered settling stage to consolidation settling stage occurred at a void ratio between 10 and 11 for MFT suspensions, this value was about 8.5 times the void ratio at the liquid limit. During sedimentation, clay particles formed floc structures with the maximum yield strength being estimated to be 0.23 kPa.
- The constant settling velocity occurring at the beginning of hindered sedimentation can be used to determine the initial permeability of the tailing slurry. Results showed that hydraulic conductivity of the MFT suspension decreased from the magnitude of 10⁻³ to 10⁻⁵ m/s as void ratio decreased from 119 to 11. The hydraulic conductivity versus void ratio relationships are highly non-linear at high void ratios.
- Comparison of settling velocities between the intensively mixed TT and the relatively less sheared TT sample indicates that mixing has a substantial effect on the properties of flocs and therefore influences the settling behaviour. In this work, the intensively

sheared TT samples exhibited similar settling and consolidation characteristics to MFT.

- Use of polymer in treatment of MFT significantly increased the settling rates and permeability of the material. At higher void ratios (i.e., e >13), initial settling velocity and hydraulic conductivity values of the flocculated MFT were 3 to 4 magnitudes of the non-flocculated MFT. At lower void ratios (i.e., e<2), based on the results of oedometer tests, FMFT was at least 1 magnitude more permeable than MFT. FMFT was more compressible than MFT in the same range of effective stress. Compressibility of FMFT was affected by the floc structure formed by flocculation. Shearing plays a role in floc structure and hence influences the compressibility of the tailings. It is assumed that the compressibility of MFT, non-sheared FMFT and sheared FMFT may become similar after the flocs are broken.
- The FMFT samples prepared in laboratory using small scale mixing device had similar compressibility characteristics to the field test FMFT samples produced via in-line flocculation process using the same flocculant and dosage.
- Compared to other different mine tailings (i.e., copper tailings, gold tailing, oil sands CT), fine oil sands tailings have significantly lower coefficient of consolidation and permeability values. It indicates that dewatering of fluid fine tailings by consolidation is more challenging than other mine tailings and chemical amendment is necessary.

6

Shrinkage Curve, Water Retention Curve and Cracking Tests

6.1. Introduction

In the thin-lift drying technique, after the supernatant water runs off or evaporates, desiccation of the deposited tailing lifts starts resulting in surface subsidence, strength gain and desiccation cracking, which are the main phenomenon observed during the whole desiccation process. Understanding the desiccation behaviour of the tailing materials and the factors affecting it can contribute to the achievement of the overall goal of the technology. As stated in Chapter 2, three aspects of desiccation behaviour (i.e. shrinkage properties, water retention behaviour and cracking behaviour) are considered important for the understanding of the desiccation process and the observed phenomenon. These aspects were investigated in this thesis by performing three independent tests using small homogenous tailing samples prepared from tailing slurry. Methods and observations of these experiments are described together in this chapter because they are correlated with other and should be analysed together. These investigations also considered the rewetting effect on the related soil behaviour, which was rarely studied in previous research.

In this chapter, a review of knowledge and theory related to the specific behaviour and previous work on oil sands tailings is presented in Section 6.2. Next, methods and procedures of the different experiments performed are described in Section 6.3. Laboratory results and observations are presented in Section 6.4 associated with some analysis. Finally, a summary of the findings and conclusions is given in Section 6.5.

Section 6.4.1 was published.

Yao, Y., van Tol, A. F., van Paassen, L. A., & Vardon, P. J., 2014. Shrinkage and swelling properties of flocculated mature fine tailings. In proceedings of the 4th International Oil Sands Tailings Conference, Lake Louise, Canada, 7-10, December 2014. University of Alberta: 27-35.

6.2. Literature review

6.2.1. Soil shrinkage/swelling behaviour

6.2.1.1. Shrinkage curve

Soil shrinkage is defined as the specific volume change of soil relative to its water content (Haines, 1923; Stirk, 1954). It can be measured in most soils with more than 10% clay content (Boivin et al., 2006). These volume changes depend on the amount and type of clay minerals and are characterized by their magnitude and geometry (Braudeau and Bruand, 1993; Boivin et al., 2004, 2009). The shrinkage property of a soil is usually presented as soil shrinkage characteristics curve (SSCC), which is represented as either the specific volume versus gravimetric water content or void ratio versus water content relationship. Generally, when a clay slurry or non-structured soil dries out, these shrinkage stages can be distinguished (Haines, 1923; Stirk, 1954; Bronswijk, 1991), as shown in Figure 6.1: (1) normal shrinkage (A to B); (2) residual shrinkage (B to C) and (3) zero shrinkage (C to D). The normal shrinkage stage is characterized by an equal decrease in water volume to bulk soil volume, with the intra-aggregate pores still being fully saturated. For a non-structured clay paste, the SSCC in the normal shrinkage stage is a straight line and this line coincides with the line representing 100% saturation degree. At the end of normal shrinkage stage, air enters the soil at a point that is referred to as the general air entry value (AEV) point. In the residue stage, the curve deviates from the 100% saturation line and the slope of the curve is decreasing. Air enters the intra-aggregate pores and a further decrease in water upon drying exceeds the volume change of bulk soil. In the last stage, the particles have reached their densest configuration, and the volume of the aggregates remains unaltered as the water volume further decreases. Bruand and Prost (1987) demonstrated that during this stage, reorganisation of clay particles occur, leading to the formation of microscopic cracks. Since both phenomena have a compensating effect, the aggregate volume remains unaltered.



Figure 6.1 Shrinkage characteristic curve for an initially slurried clay (modified from Fredlund et al, 2002)

For a specific soil, the pattern of the shrinkage curve (i.e. minimum void ratio, air entry point, slope of curve) depends on particle size distribution and stress history (Fredlund

et al, 2002). The shrinkage curve can be used to infer the plastic limit and the shrinkage limit of a soil. Fredlund et al (2002) proposed that the air entry water content is close to the plastic limit and the water content at the intersection between the saturation line and the horizontal asymptote of the curve when water content tends towards zero is considered as the real shrinkage limit. It should be pointed out that the general air entry value and the minimum void ratio is affected by the effective stress.

6.2.1.2. Rewetting swelling behaviour

When a desiccated soil is rewetted, it absorbs water and swells. Many research has been undertaken on the physical phenomenon behind the swelling behaviour of clayey soils. Madsen & Muller-Vonmoos (1989) gave an overview of swelling behaviour focusing on the mechanism of suction. Gens & Alonso (1992) extended the research by developing a description of the mechanical behaviour of expensive clays. Peng & Horn (2007) provided experimental data for some organic and inorganic soils during cyclic drying and rewetting processes and proposed that hysteresis existed in soil volume changes as a function of water content during shrinkage and swelling. Figure 6.2 shows a typical void ratio - water content plot for a clay during a full drying and rewetting cycle presented by Fredlund & Houston (2013). It is seen that at the same water content, values of void ratio on the rewetting curve are larger than those on the preceding drying curve, this phenomenon is regarded as hysteresis. The swelling curve has three phases with a lower degree of saturation for the clay compared to the shrinkage curve. The swelling curve finally reaches a plateau and meets the 100 % saturation line. Tripathy et al. (2002) also obtained similar drying and wetting curves for compacted expensive soils and they found that the swelling and shrinkage path was reversible once the specimen reached an equilibrium condition after about four swell-shrink cycles.



Figure 6.2 A drying and rewetting cycle for a clayey soil (Fredlund & Houston, 2013)

6.2.1.3. Determination of shrinkage curve

In principle, determination of shrinkage curve of a soil requires simultaneous measurement of the pore volume and the volume of water in a known volume of soil over the whole range of water contents, from saturation until oven dryness. Practically, total mass and

bulk volume of a soil clod are measured at different time during drying and the parameters used to build shrinkage curve are calculated using the constitutive relationships (Cornelis et al. 2006). For soil samples in regular shape, the bulk volume can be calculated from the dimensions of the sample which can be measured using different tools such as caliper, retractometer and laser sensors (Berndt and Coughlan, 1976; Braudeau, 1987; Braudeau and Boivin, 1995; Braudeau et al., 1999). For an irregular shaped soil, the bulk volume is usually measured by submerging the soil clod into a fluid, and the volume is obtained by measuring the weight or volume of a fluid displaced by the soil. In the past, different submergible fluids were used in soil volume measurement, such as kerosene or petroleum (McIntyre and Stirk, 1954), toluene (Sibley and Williams, 1989) and mercury (ASTM, 2005). Water can also be used once the soil sample is coated by paraffin before submerging (Johnston and Hill, 1944; Lauritzen, 1948). However, the coating must be removed after the measurement to allow drying of soil, which may be a difficulty when a soil is about to desiccated.

Tariq and Durnford (1993) developed a simple means called the balloon method. Figure 6.3 shows the configuration of Tariq and Durnford balloon test. The saturated soil specimen is filled in a rubber balloon which is closed by a stopper with an air inlet and outlet. To allow drying, both valves are kept open and air flow is injected to the balloon through the inlet that is connected to an air pump. Total mass and volume of the balloon and the soil within it are measured frequently during drying. To determine the volume, the air outlet is closed and a small vacuum is applied through the inlet to ensure a perfect fitting of the balloon and the soil. The balloon is then lowered into a beaker of water placed on a balance, and the volume is determined by measuring the mass of water replaced by the balloon. Cornelis et al. (2006) compared different methods in measuring the SSCC of clay and concluded that the balloon method provided well reproducible results and it is a good alternative for the paraffin-coated method if one wants to describe the SSCC at the scale of the soil matrix without cracks (Cornelis et al., 2006).



Figure 6.3 Set-up for Tariq and Durnford balloon shrinkage test (Cornelis et al., 2006)

6.2.3. Soil water retention characteristics

6.2.3.1. Soil Suction

When dried clays are in contact with fresh water they may attract water and this attraction is caused by soil suction. Soil suction is the free energy of the soil water which is equivalent to the energy required to remove a unit weight of water from the soil. This suction is also known as total suction and it comprises of two main components: matric suction and osmotic suction.

Matric suction is associated with the capillary phenomenon resulting from surface tension. Above the ground water table, the soil is unsaturated and water moves upward in the soil through adhesion to the sides of the pores and is held there by surface tension forces and this process is called capillary rise. At the interface between the water and air, the contractile skin (Fredlund & Rahardjo, 1993), imbalanced intermolecular forces result in a pressure difference of $u_a - u_w$, where u_a and u_w refer to pore air pressure and pore water pressure, respectively. This pressure difference is known as matric suction. In order to achieve mechanical equilibrium, surface tension is mobilized at the air-water boundary forcing the contractile skin to behave as an elastic sheet or membrane in forming a meniscus with radius of curvature (Fredlund & Rahardjo, 1993). The matric suction depends on the size of the pores which decreases with decreasing particle size. Since the pore air pressure is considered to be atmospheric, and takes a value of 0, the matric suction is a negative pressure.

The pore water in a soil normally contains dissolved salts and therefore it has lower vapour pressure compared to pure water (Fredlund & Rahardjo, 1993). Osmotic suction is generated by the osmotic repulsion mechanism, arising from dissolved salts in the pore water. Osmotic suction can be explained by considering a scenario where pure water is placed in contact with a solution through a semi-permeable membrane that allows water to move through it while preventing the solution to moving through. The double layer surrounding clay particles acts as such a semi-permeable membrane. The concentration of solutes creates the potential for water to flow through the semi-permeable membrane to the solution. The pressure on the solution required equalize the flow of water from the solution to the pure water is equal to the osmotic pressure of the solution. Osmotic suction can be a significant portion of the total soil suction.

6.2.3.2. Soil water retention curve

The soil water retention curve (SWRC) or soil water characteristic curve (SWCC) defines the relationship between gravimetric water content (or volumetric water content, degree of saturation) and soil suction. This curve plays a central role in understanding of unsaturated soil behavior. The shape of water retention curves can be characterized by several models, the two well-known models are Van Genuchten model and Fredlund and Xing model. The general equation of Van Genuchten model (1980) is given as follows:

$$\theta = WCR + \frac{WCS - WCR}{(1 + (\alpha_{WRC} \cdot \varphi)^{n_{WRC}})^{m_{WRC}}}$$
[6.1]

where, θ is the volumetric water ratio, φ is soil suction. *WCR* is the residual (volumetric) water content, *WCS* is the water content at full saturation and α_{WRC} , n_{WRC} and m_{WRC} are fitting parameters, where m_{WRC} is defined as $m_{WRC} = 1 - 1/n_{WRC}$. The general equation proposed by Fredlund and Xing (1994) to the experimental results of the SWRC is given as follows:

$$\theta = C(\varphi) \left[\frac{\theta_{S}}{\left(\ln[e + \left(\frac{\varphi}{a}\right)^{n} \right)} \right]$$
[6.2]

and
$$C(\varphi) = 1 - \frac{\ln(1 + \frac{\varphi}{C_r})}{\ln(1 + \frac{1000000}{C_r})}$$

where a is approximately the air-entry value in kPa; e = natural number (2.718); n =parameter that controls the slope at the inflection point in the SWRC; m = parameter that is related to the residual water content; θ = volumetric water content; θ_s = saturated volumetric water content. The full range SWRC can be divided into three stages, namely, the boundary effect stage, the transition stage and the residual zone of desaturation. In the boundary effect stage, all of the pores are filled with water and the contact between water menisci and soil particles is continuous. However, the pore water is in tension and suction is present due to the action of capillary forces (Vanapalli, et al., 2004). As suction increases, the resistance offered by the capillary tension prevents the flow of water out of the soil up to a point where it is big enough to overcome the capillary forces, the air entry value (AEV), where air enters the largest pores in the soil and the soils begins to desaturate. In the transition stage, water content decreases with increasing suction and water menisci area in contact with soil particles is not continuous and reduces as air phase becomes more continuous. In the residual zone, the water phase is discontinuous and the air phase is continuous. There is very little water-soil particle contact and water leaving the soil occurs in vapour phase (Fredlund & Rahardjo, 1993). A completely dry soil attains a suction of 10^6 kPa.

The SWRC of a given soil is affected by several parameters such as initial water content, initial void ratio and stress state, and each of these parameters has a different effect on the SWRC. Initial water content (or solid content) of the soil plays an important role. For the same soil but with different initial water content values, SWRCs vary at lower matric suction values but they tend to converge at higher matric suction values (Heidarian, 2012). A lower void ratio (denser soil) also has higher air entry value. Kawai et al. (2000) found an exponential relationship between initial void ratio and the AEV for a moderately plastic silty clay soil. A high AEV is also correlated to a higher residual water content. Ng and Pang (2000) investigated the effect of the 1-D consolidation pressure on the SWRC using a completely decomposed volcanic soil from Hong Kong. The results showed that specimens with a higher stress (load) have lower reduction rate of the volumetric water content and higher AEV (Ng and Pang, 2000).

6.2.3.3. Hysteresis

The water retention curve exhibits hysteresis displayed as variations in suction for the same water content depending upon the history of soil wetting and drying. As is shown in Figure 6.4, suction values on the adsorption (drying) curve are smaller than that of the desorption (drying) curve when compared at the same water content. The end point of the

adsorption curve may differ from the starting point of the desorption curve, which is due to air entrapment in the soil.



Figure 6.4 A typical soil water retention curve for a clayey soil (Fredlund and Xing, 1994)

As shown in Figure 6.5, when the soil is rewetted from the residual water content or drained from the saturated state, the main wetting or drying curves are followed, respectively (Šimůnek et al., 1999). When a wetting or drying process is reversed while following the main hysteresis curve, the retention curve follows a primary hysteresis curve. Secondary and higher-order scanning curves are a result of additional reversals (Jaynes, 1992; Kool and Parker, 1987; Šimůnek et al., 1999).



Water content

Figure 6.5 Idealised hysteretic soil-water characteristic curves showing main, primary, and secondary wetting and drying curves (Modified from Šimůnek et al., 1999)

According to the literature, the hysteresis effect can be attributed to several causes (Hillel, 1980; O'Kane et al. 2004): (1) geometric nonuniformity of individual pores (which are generally irregularly shaped voids interconnected by smaller passages), resulting from the

so called "Ink Bottle" effect. Hillel (1980) explains the ink bottle effect as follows. Consider the hypothetical pore shown in Fig. 6.6 which consists of a relatively wide void of radius R, bounded by narrow channels of radius r. Drainage of the irregular pores is governed by the smaller pore radius r, and wetting is dependent on the larger radius R (Figure 6.7), (2) different spatial connectivity of pores during drying or wetting process, (3) variation in liquidsolid contact angle, the contact angle is greater in an advancing meniscus than in the case of a receding one and hence the radius of curvature is greater. Therefore, at given water content the soil will tend to exhibit greater suction in desorption than in sorption. and (4) air entrapment. which further decreases the water content of newly wetted soil. (5) swelling, shrinking, or aging phenomena, which result in differential changes of soil structure, depending on the wetting and drying history of the sample.



Figure 6.6 Ink-bottle effect determines equilibrium height of water in a variable-width pore: (a) in capillary drainage (desorption) and (b) in capillary rise (sorption) (Hillel, 1980)

6.2.3.4. Soil suction measurement

Determination of SWRC requires to determine soil suction of a soil at different water content. Many methods have been developed for the measurement of soil suction and these techniques can be divided into two main categories, namely, the direct method which is used for matric suction measurement and the indirect method which is used for all the suction components (Hu et al., 2010). The direct measurement method requires a separation between water and air phase by means of a ceramic disk or a ceramic cup. The maximum value of matric suction that can be measured is limited by the air entry value of the ceramic disk or the ceramic cup used. The indirect matric suction measurement is performed by equilibrating the porous sensor with the matric suction in the soil. Therefore, the water content of the porous sensor represents the magnitude of matric suction. For the indirect total suction measurement, it requires determination of other parameters such as dew point (e.g. in the psychrometer), relative humidity and temperature (e.g. in the relative humidity sensor and the chilled-mirror hygrometer technique) and water content (e.g. in the non-contact filter paper technique). Table 6.1 compares conventional suction measurement techniques in terms of the measurement range and equilibrium time. It can be seen that only the filter paper method and the chilled-mirror hygrometer are capable of measuring very high suction, which is desired for fine tailing measurements.

Filter paper method (FPM) has been extensively used as a routine method for suction measurement in numerous research (e.g., McKeen 1980; Chandler & Gutierez 1986; Greacen

et al. 1989; Chandler et al. 1992; Ridley 1993; Marinho 1995; Houston et al., 1994; Bulut et al., 2000, 2001, Leong et al., 2002 etc.). In the FPM, the filter paper comes to equilibrium with the soil sample either through vapour if total suction is measured or liquid flow which is for matric suction measurement. At equilibrium, the filter paper will have the same suction value as the soil. After equilibrium is established, the gravimetric water content of the filter paper disc is measured and the filter paper water content is converted to suction using a predetermined calibration curve for the type of filter paper. This is the basic approach suggested by ASTM standard test method for measurement of soil potential (suction) using filter paper (D5298). The ASTM D5298 employs one single calibration curve to infer both total and matric suction measurements. However, Houston et al. (1994) pointed out that due to the marked hysteresis on wetting and drying processes of the filter paper the wetting curve and the drying curve don't match and they should be determined separately. Basically, the wetting calibration curve is established by vapour equilibrium technique using salt solutions (e.g. Gardner, 1937; Fawcett and Collis-George, 1967; Chandler and Gutierez, 1986; Houston et al., 1994; and Leong et al., 2002). The drying curve for the filter paper is commonly established using a pressure plate apparatus (e.g., Al-Khafaf & Hanks 1974; Hamblin 1981; Greacen et al. 1987,1989). Although a number of filter papers are available on the market, only Whatman No. 42 and Schleicher & Schuell No.589-WH are commonly adopted. Compared to other suction measurement techniques, the major disadvantage of filter paper is the long equilibrium time.

Type Suction Technique		Technique	Suction range	Equilibrium time
Direct Matric measurement suction		Axis-translation technique Tensiometer Suction probe	0-1500 kPa 0-1500 kPa 0-1500 kPa	hours hours hours
Indirect	Matric suction	Contact filter paper method Electrical conductivity sensor Thermal conductivity sensor	very wide 50-1500 kPa 0-1500 kPa	7-14 days 6-50 hours hours-days
measurement	Total suction	Non-contact filter paper Psychrometer technique Chilled-mirror hygrometer	very wide 100-10 ⁴ kPa 150-10 ⁶ kPa	7-14 days 1 hour 10 minutes

Table 6.1	Summary of	existing suction	measurement methods	(modified a	after Hu, 2010
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Chilled-mirror hygrometer is a fast and accurate suction measurement method which was first introduced to measure relative humidity of food products and pharmaceuticals. Now it has been applied in geotechnical engineering to measure total suction of soils (Albrecht et al., 2003; Schanz et al., 2004). A chilled-mirror hygrometer employs the chilled mirror dew point technique to determine relative humidity under isothermal conditions in a sealed container. Measurement of total suction is based on equilibrating the liquid phase of the water in a soil sample with the vapour phase of the water in the air space above the sample in a sealed chamber. The mirror is chilled using a thermoelectric cooler until dew just begins to form. Water vapour from the soil specimen is allowed to condense on the mirror. A photoelectric cell is used to detect the exact point at which condensation first appears on the mirror. The temperature of specimen, which is considered to be equal to the temperature of vapour space, is measured via an infrared thermocouple. The relative humidity of the specimen is computed from the measured dew point and temperature. A small fan is also employed to circulate the air in the sensing chamber and speed up vapour equilibrium. Leong

et al. (2003) reported that the technique could be used to quantify total suction as low as about 150 kPa. The value is considered small in the case of low total suction measurement where much larger error can be expected. The chilled mirror hygrometer has distinct advantages over other water vapour sensing technologies. For example, a chilled mirror hygrometer provides one of the few truly direct physical measurements of humidity.

6.2.4. Evaporation and cracking

6.2.4.1. Evaporation from soil

Soil evaporation is the process by which water is lost from the soil to the atmosphere through a change of the state of water from a liquid to gaseous phase (Lai and Shukha, 2004). Evaporation is the driving force of soil desiccation and plays critical role in the development of tensile stress which controls the initiation of cracks. In theory, three conditions are necessary if evaporation from a given body is to persist (Hillel, 1980): (1) there must be a continual supply of energy to meet the latent heat requirement, (2) the vapour pressure in the atmosphere over the evaporating body must remain lower than the vapour pressure at the surface of that body and the vapour must be transported away and (3) there must be a continual supply of water from or through the interior of the soil to the site of evaporation.

Potential evaporation (PE) and actual evaporation (AE) are mostly discussed concepts in the engineering. PE is defined as the maximum rate of evaporation from a pure water surface under given climatic conditions while AE is the amount of water which is actually evaporated from a soil and it is a fraction of the PE. Under a given climatic condition, the AE of a initially saturated soil changes with time, water content and soil suction, and it can be generally divided into three stages: (1) the constant-rate stage, (2) the falling-rate stage and (3) low-rate stage. The constant-rate stage represents the period when soil water is not limiting the evaporation rate. In this stage, the actual evaporation rate is constant if the energy supply and atmospheric conditions are in a steady state. The falling-rate stage represents the period when the actual evaporation rate is jointly controlled by the availability of soil water, energy supply, and atmospheric conditions. As the soil desaturates, the larger pores are emptied out and then the smaller ones which are held under high suctions. Due to the decrease in the radius of the pore and the presence of high suction, the relative humidity of the soil decreases and this translates into a decline of the vapour pressure gradient, the driving force for evaporation. As a result, the evaporation rate decreases gradually in this stage. The low-rate stage represents the period when the evaporation rate is controlled completely by soil physical characteristics (e.g. unsaturated hydraulic conductivity, suction). In this stage, the soil surface is dried and there is no longer any flow of water to the surface in the form of liquid but vapour which migrates through vapour diffusion to the surface.

6.2.4.2. Cracking

It is commonly considered that desiccating clayey soils crack when the tensile stress developed in the soil exceeds the tensile strength of the soil (Corte and Higashi,1960). Tensile stresses are induced by suction and will develop when soil shrinkage is restrained in some way. The restraints can be external (e.g. rough layer interfaces) or internal (e.g. sections of soil undergoing non-uniform drying, heterogeneity in water content or density, etc.). Figure 6.7 shows how a desiccation crack forms on an initially saturated clay layer. As shown in the figure, the soil fabric and stress–strain states are not affected by desiccation at the beginning of drying (Fig. 6.7(a)). After the water – air interface reaches the soil surface, a water – air meniscus starts to form between clay particles (Fig. 6.7(b)), and capillary suction is developed in the upper layer of soil. As drying continues, the curvature of capillary meniscus enlarges and is accompanied by an increase in capillary suction and effective stress between clay particles. As a result, the clay layer consolidates and shrinks. From the particle-level, each particle on the layer surface suffers a tensile force, which is induced by the developed capillary suction from the surrounding particles, and a tensile stress field is established in the upper layer (Figure 6.7(c)) (Tang et al. 2011). Crack initiates once the increasing tensile stress exceeds the tensile strength of clay layer (Figure 6.7(d)).



Figure 6.7 Schematic drawing of soil crack initiation process (modified from Tang et al., 2011)

In practice, the cracking behaviour of a soil is very complex as it is affected by many factors such as soil properties, boundary and ambient conditions, initial water content, thickness of soil layer, pore fluid chemistry, temperature and others factors (Tang et al. 2011). Fracture toughness, tensile strength, hydraulic conductivity and susceptibility to cracking are all related to soil properties such as dry density, clay mineral and wilting point (Djalal, 2014). Greater plasticity of clay increases shrinkage (and swelling) potential which in turn encourages shrinkage cracking (Inci, 2008). When the thickness of a soil layer decreases, the cracking water content reduces and the average crack length and crack intensity increase (Liu et al. 2008). The initial water content plays an important role in cracking phenomenon. Nahlawi and Kodikara (2006) found that compacted clay produced slightly higher mean cell area than slurry clay did at a particular soil thickness. Konrad and Ayad (1997) reported that the Saint Alban clay yielded primary cracks with spacings in the range of 20-24 cm at an initial water content 103% whereas the nearby weathered clay produced cracks with the spacings in the range of 10-12 cm at 50% initial water content (Konrad and Ayad, 1997).

The desiccation crack patterns which occur in the field can be divided into two broad categories, namely, orthogonal patterns and non-orthogonal patterns (Kodikara et al., 2000, 2006). In orthogonal patterns, cracks usually occur sequentially. Primary cracks firstly occur and propagate, dividing the clay surface into large blocks. The blocks tend to be subdivided by subsequent drying. In non-orthogonal cracking patterns, the cracks do not meet at right angles. One pattern of this category is hexagonal patterns in which cracks meet at angles of 120°. The non-orthogonal cracks appear to originate simultaneously and connect up to form a blocky pattern. However, during subsequent drying, cracking and opening of the cracks can occur over larger blocks encompassing a number of smaller blocks. This secondary and tertiary cracking behaviour can be considered to be a bifurcation from the primary cracking pattern (Bažant and Cedolin, 1991). Tang et al. (2011) found that the geometric characteristics of crack pattern were influenced by the multiple wetting-drying (W-D) cycles.

6.2.5. Existing work on fine oil sands tailings

Owolagba & Azam (2013) determined the shrinkage curve and water retention curve for the centrifuged MFT. The shrinkage curve was measured using the Wax Method described in ASTM standard D4943-08. The obtained data showed a "J" shaped curve in a progressive drying pattern (from e = 1.5 to e = 0.46). The SWRC was measured on the MFT cake of 60 % solids content in initial condition. A pressure plate was used to measure suctions from 30 kPa to 530 kPa and a cellulose membrane was used for 500 kPa, 3000 kPa and 6000 kPa suction, respectively. The suctions at low water content were measured using the dew point potentiometer (WP4-T).

Fredlund et al. (2011) also determined the shrinkage curve of MFT by measuring the dimension of the specimen contained in a brass ring using digital micrometer. In their research, the SWRCs were measured for the samples of MFT that had 0.1 and 0.8 in SFR, respectively. The independently measured shrinkage curves were combined with the gravimetric water content SWRCs to calculate all the volume-mass properties. According to their results, the correct air-entry value for the 0.8 SFR tailings was 100 kPa while it was 1000 kPa for the 0.1 SFR tailings. The 0.8 SFR tailings had a residual suction about 3000 kPa and the 0.1 SFR tailings had a residual suction about 15000 kPa.

Although some literature reported the shrinkage curve and the SWRC of the MFT material, the rewetting path for the shrinkage curve and the SWRC was rarely reported. There is limited literature which provides the shrinkage curve for the polymer treated MFT and TT. In addition, no published paper has been found on swelling behaviour and cyclic drying and wetting behaviour of fine oil sands tailings at the time of writing.

Innocent-Bernard (2013) performed drying tests on 5 cm and 10 cm thick oil sands TT samples and measured the suction at the cracks and crack area. However, the research did not show how the desiccation cracks initiated and propagated and what was the effect of drying and rewetting on the crack networks.

6.3. Experimental work

6.3.1. Materials

The remoulded fine oil sands tailings samples (e.g. MFT and TT) were used for the shrinkage/swelling and the cracking tests presented in this chapter. The samples were prepared by lowering water content of sludge to a practical range so that they can be handled more easily. The tailing sludge (MFT and TT) was dried by air at 20°C in the climate room. Air drying was stopped once the material attained the consistency similar to yoghurt. The clay paste then was thoroughly blended on a glass board to remove the entrapped gas bubbles. Representative samples were taken from the clay paste to determine the properties and the degree of saturation. The polymer treated MFT was prepared by following the procedure described in Chapter 4. The treated tailings were allowed to settle by self-weight and the supernatant water was removed. The sediment was transferred into a glass cup where it was dried by air to remove excess water. Different samples were prepared for different tests, the details of the samples are introduced in the subsequent sections.

6.3.2. Experimental methods

6.3.2.1. Shrinkage curve tests

The balloon method was used in this research to assess the shrinkage curves of tailing samples due to the simplicity and reliability. For the convenience of filling procedure of the samples, the balloon was replaced by a cylindrical latex suit. Using the water placement method, the measured total volume of the sample involves the volume of the latex suit which should be subtracted to improve the accuracy. To determine the volume of the latex suit, the soil clod was replaced by an object with known volume before the measurement. To avoid formation of cracks on the desiccating clay sample, as suggested by referenced paper, a relatively small volume ($30 - 50 \text{ cm}^3$) of soil was used. The soil was dried by air flow at the constant rate of 200L/h. During drying, measurements of mass and volume were made every 1 to 2 hours. Finally, the soil clod was dried in the oven to obtain the dry weight which is used to back calculate the water content at each measurement. The void ratio of a sample was computed from the total density and water content using the following equation:

$$e = \frac{(1+w)\,G_S}{\rho_T} - 1 \tag{6.3}$$

where w = gravimetric water content (%), $G_s =$ specific gravity of solids, and $\rho_T =$ total density (g/cm³). The degree of saturation is calculated through the volume-mass relationship:

$$S = \frac{w \times G_S}{e}$$
[6.4]

6.3.2.2. Rewetting tests

Desiccated tailing samples used in the rewetting/swelling tests were prepared by drying the tailings to low water content values (normally below the plastic limit). Two distinct methods were then employed in rewetting the samples. The simple and common method is to soak the soil clod with water. During soaking, the soil clod absorbs water and its bulk volume increases with time till reaching an equilibrium state. To assess the swelling curve or the rewetting path of the existed shrinkage curve, mass and volume of the specimen were measured at different time during soaking. Prior to each measurement, free water on the soil surface was absorbed by filter paper. To measure the volume of the sample, the soil clod was hanged by a needle and thread before being lowered into a beaker of water, which was placed on the balance (Figure 6.8).

During wetting, the tailing samples were subjected to three different boundary conditions. In the first, the soil was allowed to swell freely. In the second, the soil was trimmed and fitted in a rigid steel ring during soaking, therefore only axial deformation was allowed (one-dimensional swelling). In the third, the specimen was wound around by an electrical tape, as shown in Figure 6.9. Since the plastic tape has some flexibility, the soil was considered to be partially constrained.

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Figure 6.8 Measurement of bulk volume by water displacement method

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Figure 6.9 Soil sample confined by an electrical tape

Another wetting method used in this research was to make use of vacuum suction. As shown in Figure 6.10, the tailing sample was placed in an oedometer ring (49 mm in diameter) between two pieces of porous stones. The stones were bounded by elastic bands to ensure a good contact to the sample. The sample was placed under water in a vessel. By applying the vacuum pressure (1 bar) to the vessel, the air in the pores of the tailing was discharged.

During the saturation, the height of the sample was measured at different time using a calliper, meanwhile, the sample with the ring was weighed. The test was finished when there was no change in the measured parameters.



Figure 6.10 The vacuum saturation system

The oedometer swelling test was aimed at determining the rate and magnitude of vertical swelling of a desiccated sample during wetting. The samples were prepared by air drying the tailing paste filled in oedometer rings to various water content between 2% and 20%. To perform the test, the specimen was placed in the oedometer cell under certain surcharge pressure. Similar to previous tests, the sample was placed in either free swell or laterally confined condition. Water was poured into the cell, and as soon as the water inundated the specimen the timer was started. The vertical deformation was measured by a digital gauge displacement transducer which was connected to computer, and the displacement was logged automatically with time.

6.3.2.3. Soil suction measurements

In this research, Schleicher & Schuell No.589-WH ash free filter paper (S&S-589) was adopted for suction measurement. The filter paper was calibrated using the salt solutions. The result was compared with the calibration curve determined by Bulut (2001) for the same filter paper. If a close agreement is obtained, the drying calibration curve provided by Bulut is used in this research to infer the soil matric suction by assuming that the filter papers in the same type have similar water retention characteristics. If the obtained calibration curve does not match the reported one for the same filter paper, alternative method will be employed to establish the drying calibration curve.

To calibrate the filter paper, a series of 150 ml NaCl solutions with various concentrations were filled in 300 ml glass jars. In each jar, two pieces of filter papers were placed 2 cm above the surface of salt solution and the jar was then closed and sealed. The glass jars were kept in an insulation box which was placed in climate controlled chamber at the temperature of 25 ± 0.2 °C. After an equilibrium time of two weeks, the water content of filter paper was measured by following the procedure described in ASTM D5298. To examine the reproducibility, two boxes of filter papers from the same batch were calibrated. The constructed wetting calibration curves are shown in Figure 6.11 and compared with the curve
provided by Bulut et al. (2001). It can be seen that the calibration curves established in this work are in good agreement with the reported one. Therefore, both the wetting and the drying calibration curves determined by Bulut, as shown in Figure 6.12, were used in this work to assess the tailing suctions.



Figure 6.11 Comparison between the measurements and the wetting calibration curve determined by Bulut (2001) for S&S 589 filter paper



Figure 6.12 Relationships between suctions and water content of filter paper (S&S 589) established by Bulut (2001)

In order to construct the water retention curve, suctions should be provided at different soil water content. Due to long equilibrium time for each measurement, multiple specimens with different water content were prepared and equilibrated with the filter papers simultaneously. For each tailing specimen, both the total suction and the matric suction were measured, which was achieved by placing the filter papers in the non-contact manner and the contact manner, respectively (Figure 6.13). After an equilibrium period of 14 days, water content of the filter papers and the soil specimens was measured individually to establish the water retention curves.



Figure 6.13 Soil suction measurement using filter paper method

The total suction of the tailing samples were also measured using the Decagon WP4C potentiameter (Figure 6.14). The WP4C is a suction measurement device developed based on the chilled mirror dew point technique. The measurement range of WP4C is from 0.1 MPa to 300 MPa with an accuracy of \pm 0.05 MPa (50 kPa). Since readings below 0.05 MPa have errors of 100% or more, 0.1 MPa is considered the practical limit for measurement. The WP4C potentiometer was calibrated with standard salt solution with specific motility and water potential. As suggested by the user manual, the 0.5 mol/kg potassium chloride (KCl) solution was used for calibration. To measure the soil suction, the tailing sample was filled in a sample cup (4 cm in diameter and 1 cm in depth) and set in the Lexan sample drawer. The drawer was closed and the chamber was sealed by turning the knob. The water potential reading was displayed on the screen after an equilibrium was established. In general, one measurement took several minutes up to one hour, depending on the water content of sample, therefore one single specimen was repeatedly used for multiple measurements. After one measurement was done, the sample was weighed and dried to a lower water content for the next measurement. In order to assess the wetting path of SWRC, several drops of water was added to the desiccated specimen. The sample cup was then closed for 1 hour to allow water to be absorbed, and the mass and suction were then measured.



Figure 6.14 Decagon Device WP4C dew point potential-meter

6.3.2.4. Cracking tests on thin tailings

Cracking tests were performed on a thin tailing layer (about 1 cm) to investigate the evaporation and cracking properties (e.g. cracking water content, crack pattern) of the tailing. A set-up was constructed, as shown in Figure 6.15. To prepare the sample, the tailing slurry or saturated clay paste was filled into a glass cup which is 98 mm in diameter and 12 mm in depth. The cup was placed on an electrical balance with connection to computer. The clay was dried by air flow created by an air pump (EHEM air pump 400, 4W). The air pump has 2 outlets, each one is controlled by a switch. When both switches are turned to the maximum, the pump can produce constant air flow at the rate of 400 L per hour. During drying, the total weight of the specimen was monitored. A digital camera was fixed on top of the specimen for image capturing. The tests were performed in the climate-controlled chamber where the temperature was maintained at $24 \pm 1^{\circ}$ C and the relative humidity was 50% $\pm 10^{\circ}$. Distilled water was filled in a sample cup to determine the potential evaporation rate (PE) in the laboratory conditions. Frequency of image capturing was increased after the crack initiated at the sample surface. After the test, thickness of the specimen was measured using a digital micrometer. The desiccated soil specimen was rewetted by adding sufficient water in the cup, and the tailing was allowed to stand overnight. The sample was also subjected to several drying and wetting cycles to identify if there is any change in crack pattern.



Figure 6.15 The set-up of cracking tests (I) and the plan view of the sample (II)

6.4. Results and discussions

6.4.1. Shrinkage and swelling tests

6.4.1.1. Shrinkage curves

Figure 6.16 provides the results of shrinkage tests performed on MFT using the Balloon Method. Figures show that the four duplicate tests have similar shrinkage curves, it indicates that the shrinkage tests using the balloon method have good reproducibility. It can be seen that the obtained shrinkage curves match well the theoretical shrinkage curve for a non-structured saturated clay, in which three shrinkage stages can be identified. According to the figures, the shrinkage curves start to deviate from the 100 % saturation line at around 30% water content. This point is considered as the general air entry point and it is close to the plastic limit of the soil. The shrinkage limit can be inferred from the shrinkage curve and it is about 18% for MFT. This value is close to the experimentally measured shrinkage limit (see Chapter 3). The minimum void ratio of MFT after drying was about 0.44.

The determined shrinkage curve is quite similar to that reported by Owolagba & Azam (2013) for MFT, as shown in Figure 6.17. The experimental data can be best-fitted by the equation proposed by Fredlund et al (2002) (Equation [9.8] in Chapter 9). The fitting parameters provided in Figure 6.16 for the two shrinkage curves are also similar.



Figure 6.16 Shrinkage results determined for MFT using the balloon method



Figure 6.17 Comparison of the measured shrinkage curve and the one presented by Owolagba & Azam (2013) with fitting parameters using the equation proposed by Fredlund et al. (2002)



Figure 6.18 Shrinkage curves of the FMFT produced at different dosage and mixing conditions

Figure 6.18 shows the shrinkage curves determined for three polymer treated MFT which were treated at various dosage and different mixing conditions. These shrinkage curves are compared to that of the non-flocculated MFT (the dashed curve) to identify the effect of flocculation on the shrinkage behaviour. It can be seen that the shrinkage curves have some deviations in the void ratio values in the residue and zero shrinkage stage. When the dosage of polymer increases from 0 (non-flocculated MFT) to 500 g/t and then 1000 g/t (the optimum), the shrinkage limit of the soil increases from 18% to 25% and 31%, respectively. Meanwhile, the minimum void ratio increases to 0.57 and 0.7, respectively. It also shows that being treated at the same dosage (1000 g/t), the over mixed FMFT has lower void ratio compared to

the optimally mixed FMFT after drying. These findings indicate that the flocculation conditions (i.e. dosage and mixing) influence the shrinkage curves of the flocculated tailings and this effect is limited in the final void ratio after the desiccation. Since there was no external pressure on the tailing sample, the differences in final void ratios were largely due to various soil structures formed after drying. Based on the provided data, it is estimated that the final volume of the optimally treated MFT might be 25% larger compared to the non-flocculated MFT. This behaviour should be well considered in the capacity design for the tailing disposal facility.

Figure 6.19 shows the shrinkage curves determined by Qiu and Sego (2001) on several different mine tailings. It is noted that when drying out, the finer coal wash tailing has obviously lower void ratio compared to the coarser tailings (e.g. copper tailing, gold tailing and CT, see Chapter 3). It indicates that when no external pressure is applied to the sample, the minimum void ratio of a soil attained by drying is related to its particle size distribution and the type of minerals.



Figure 6.19 Shrinkage data for different mine tailings (Qiu and Sego, 2001)

6.4.1.2. Results of swelling tests

The oedometer swelling tests were performed to determine the swelling potential of the tailing sample after being rewetted. Figure 6.20 shows the vertical deformation for a desiccated MFT confined in an oedometer ring (57.5 mm in radius) during soaking. The sample had a diameter of 57.5 mm, with initial thickness and water content being 19.2 mm and 11%, respectively. A small surcharge pressure (1 kPa) was applied on the soil to ensure a good contact between the soil and the upper plate. According to the figure, the swelling process can be divided into three stages, namely, primary swelling stage, secondary swelling and zero swelling. The primary stage is characterized by the highest swelling rate. In this stage, about 70% of total swelling was achieved in 2 days. The swelling rate decreased gradually in the secondary stage and in the last stage there was almost no swelling. The thickness of the sample was increased by 10.6% after a soaking time of 14 days.



Figure 6.20 Vertical swelling vs. time curve for the MFT specimen which was confined in steel ring

For a soil specimen, the magnitude of swelling can be expressed as swell potential, calculated as follows.

Swell potential =
$$\frac{\Delta e}{1+e_0} \times 100$$
 [6.5]

where Δe = increase in void ratio at the maximum swelling, e_0 = void ratio of sample before wetting. Table 6.2 provides the swell potentials obtained for four FMFT samples that were confined by steel rings. It is concluded that the swell potential was dependent on factors such as initial water content, thickness, and surcharge pressure. In general, a specimen had lower values in above parameters, it had a larger swell potential value. The results demonstrate that the fine tailing samples have a relatively low swell potential compared to typical expansive soils. This is largely due to the fact that the clay components in oil sands contain little montmorillonite (Chalaturnyk et al. 2002), which has the most dramatic shrink-swell capacity.

Sample ID	FMFT-1	FMFT-2	FMFT-3	FMFT-4
Surcharge (kPa)	1	1	1	20
Initial:				
Thickness (mm)	16.6	19	19	15.2
Water content (%)	20	6	20	1.7
Void ratio*	0.69	0.65	0.69	0.72
Saturation degree (%)**	57	21	58	5.3
Final:				
Thickness (mm)	20.6	22.9	23.0	15.8
Water content (%)	44	40	40	27
Void ratio*	1.18	0.91	1.03	0.82
Saturation degree (%)**	87	92	90	76
Swell potential	29	16	13	6

Table 6.2 Results of oedometer swelling tests for FMFT specimens

* Calculated using equation [6.3]

** Calculated using equation [6.4]

A similar swelling process was identified for the unconfined desiccated tailing. Since the sample was allowed to deform in both axial and radial direction, the specimen had a smaller magnitude of vertical swelling compared to the laterally confined sample. Figure 6.21 shows an unconfined FMFT sample after a soaking period of 2 weeks. It can be seen that the sample was cracked, with a major horizontal crack and some minor vertical cracks on the side. Not only on this sample, cracks were also found on other unconfined MFT and TT which were soaked for a relatively long period (e.g. 2 to 3 weeks). In the author's opinion, these cracks are likely to be generated by the microcracks formed in the initial drying process. In the later stage of drying, microcracks may occur due to reorganization of clay particles. As a result, some clay bonds are broken resulting in weak zones. Since the sample is not confined during soaking, some existing microcracks may re-open and develop in the weak zones. It was found that applying a sufficient confining pressure to the specimen effectively reduced the number of the cracks after soaking. For the laterally constrained samples, e.g. FMFT-1, FMFT-2 and FMFT-3 in Table 6.2, only some horizontal cracks were formed due to lack of sufficient confining pressure in the axial direction.



Figure 6.21 The FMFT specimen at the end of soaking showing cracks

According to the data provided in Table 6.2, none of the specimens attained 100% saturation after the soaking. The possible reasons are given as follows. First, the cracks on the soaked sample increase the bulk volume, leading to an overestimation of void ratio when Equation [6.2] is used to calculate the void ratio. Secondly, with the soaking method, some trapped air has not yet been discharged from the sample.

6.4.1.3. Shrinkage and swelling upon drying and wetting cycles

Figure 6.22 presents the rewetting curves of desiccated FMFT specimens. The specimens were prepared by air drying the clay to the lower water contents that are generally identical to each other. The samples were rewetted by two different methods. Sample 1 and 2 were rewetted by normal soaking method and Sample 3 was rewetted using a vacuum pressure saturation device. The samples were subjected to different confining conditions. For Sample 1, there was no constraint; Sample 2 was constrained by an electrical tape (Figure 6.9); and Sample 3 was confined in a steel ring sandwiched by two pieces of porous stones (Figure 6.10).



Figure 6.22 Rewetting curves for FMFT in different initial conditions

It can be seen from Figure 6.22 that all the rewetting curves differ from the initial shrinkage curve, indicating the existence of hysteresis between drying and wetting. The obtained rewetting curves consist of two parts: a curvilinear portion and a linear portion. The curvilinear portion had larger tangent slope than the shrinkage curve had in the same water content range. The linear portion was parallel to the shrinkage curve and also the 100% saturation line. Due to the slight difference in the initial water content, there was a small distance between Curve 1 and Curve 2, and the distance kept constant from the start till the linear portion. Fine cracks (about 0.1-0.2 mm width) occurred on Sample 1 in the range where the void ratio increased linearly with water content. These cracks developed quickly with the increasing water content and it was assumed that any further increase of total volume of the clod was due to the widening of the existing cracks. For Sample 2, the curve started to turn to the 100% saturation line at water content about 38%, it soon became linear and parallel to the saturation line. In this case, development of microcracks in the sample was to some extent supressed by the plastic tape which has some elasticity. Therefore, the swelling curve showed a shift towards the saturation line. Later some cracks were formed and enlarged on the sample due to lack of axial constraints. As a result, the bulk volume continued to increase until the soil collapsed. Curve 3 is obviously different from Curve 1 and 2, which shows an acceleration in approaching the saturation line with the increasing water content. Curve 3 tends to intersect with the saturation line at a water content 36%, which indicates that the soil is almost fully saturated. No visible crack was found on Sample 3 at the end of test, indicating that the opening of microcracks was effectively restrained. It was observed that in the vacuum saturation device, gas bubbles were continuously released from the soil, this was not observed in the normal soaking tests. The results demonstrate that by utilising vacuum pressure saturation device and confining the sample, a high saturation of soil closing to 100 % can be attained.

In order to evaluate the effect of initial water content on the rewetting swelling behaviour, the tailing samples were dried to various water content values before they were rewetted by soaking. Figure 6.23 shows the rewetting curves for a group of FMFT samples

with different initial water content. According to the figures, all the curves have a similar shape including the curvilinear and the linear portion. With the decrease of initial water content, the curvilinear part of the rewetting curve is lengthened. Unlike the other samples, the swelling curve of Sample 4 coincides with the initial shrinkage curve. Notice that only Sample 4 had a starting water content larger than the shrinkage limit, it indicates that once the initial drying does not extend below the shrinkage limit, the wetting path coincides with the previous drying path. Otherwise, the wetting path is above the drying path on the void ratio – water content plot.



Figure 6.23 Rewetting curves for FMFT with varying initial water content



Figure 6.24 Schematic drawing of shrinkage and swelling paths of a fine tailing clod during multiple wetting-drying cycles based on the tests results

After the soil was rewetted to a certain water content, the tailing was dried and two extra wetting and drying cycles were performed. Based on the tests results, a schematic presentation of the measured drying and rewetting paths is given in Figure 6.24. On this drawing, point A is the minimum water content that a saturated soil can attain by initial drying. When the soil specimen is rewetted from this point, the distance between the rewetting and drying paths is the largest. The linear portion in the path AD is parallel to the 100% saturation line. Once the second cycle starts from point D, the drying path will follow the saturation line 1 and finally arrive at point B which has the same void ratio as point A. The wetting path BE in the second cycle and the drying path EC in the third cycle is similar to the curve AD and DB, respectively. The slope of the linear portion of the rewetting path is always less than that of the drying path.



Figure 6.25 Swelling and shrinkage curves of FMFT during multiple cycles

Figure 6.25 shows the swelling and shrinkage paths for a single FMFT specimen during successive five wetting and drying cycles. It is seen that the effect of hysteresis was reduced with the increasing number of cycles. An equilibrium stage was established in the fourth wetting and drying cycle and the wetting path coincides with the drying path. This phenomenon is in accordance with that observed by Tripathy et al. (2002) who performed drying and wetting tests on compacted expensive clay in four full swell-shrink cycles.

6.4.2. Water Retention Characteristics of Tailings

6.4.2.1. Soil water retention curves

Figure 6.26 provides all the suction values measured for MFT samples in various water content. It is seen that in the range of suction from 0 to 1500 kPa, the total suction values determined by filter paper are larger than the matric suction values measured using the same method. The difference between total suction and matric suction at a given water content is regarded as osmotic suction. Osmotic suction is generated by the osmotic repulsion mechanism, arising from the presence of soluble salts in the pore water of tailing. At a given water content 30%, for example, the matric suction was about 200 kPa while the simultaneously measured total suction was 500 kPa with the osmotic suction being 300 kPa. The results show that osmotic suction is a major contributor to total suction, it suggests that

the pore water in MFT had high salinity. According to the pore water chemistry analysis for Suncor's tailing Pond 1A (Wells, 2011), the tailing water contains various dissolved salts with a pH value of 8.03. The salinity of pore water may lead to high osmotic suction in the MFT. Total suction and matric suction measured by filter paper were equivalent at high suction ranges (>1500 kPa) because the filter papers, no matter being placed in contact or non-contact manner, always come to equilibrium with soil through vapour rather than liquid flow and matric suction measured by the sandwiched filter paper is actually total suction. For low water content soils, it is usually assumed that matric suction is equal to total suction. Comparing the suction values measured by filter paper and the WP4C, it can be seen that they do not match at low suction values (<1000 kPa) but they are close in higher suction range. The WP4C device is known for its distinct advantage over other techniques in accurately measuring high suction. For suction walues lower than 150 kPa, however, the WP4C in the range above 1000 kPa was combined with the data determined by filter paper in the low range (<1000 kPa) to build the SWRC.



Figure 6.26 All the suction values measured for MFT

Figure 6.27 shows the SWRC for the tailings studied in this work. Looking at the MFT data, it can be seen that the highest water content was approximately 42% where the measured matric suction was about 30 kPa. Preparing tailing samples at higher water content is challenging in filter paper method because the tailing sample is too soft to stand by itself in a glass jar and the filter paper is completely soaked by tailing water. According to the SWRC determined for the flocculated MFT, flocculation of MFT resulted in some changes in water retention characteristic of the tailing. At the same water content, the MFT has obviously larger suction than the FMFT has. The cause for the variety between MFT and FMFT may be the difference in particle size distributions and soil structures. In this thesis, the TT samples showed obvious over-consolidated characteristic compared to MFT and FMFT. This may be attributed to a higher degree of compaction of the tailing resulted from sample preparation process.



Figure 6.27 Experimentally established SWRC for the fine oil sands tailings studied in this work

6.4.2.2. Interpretation of SWRC using shrinkage curves

From the SWRC shown in Figure 6.27, it is difficult to determine the air entry value (AEV) because in each curve there is no distinct curvature in the region of low suctions. Therefore, it is necessary to use the shrinkage data to properly interpret the SWRC. By using the basic volume - mass relationship, shrinkage curves of the fine tailings obtained in this research can be expressed in water content versus degree of saturation relationships, as shown in Figure 6.28.



Figure 6.28 Shrinkage curves of fine tailings expressed as degree of saturation vs water content plots (the best-fitted curves are derived from the equation proposed by Fredlund, 2002)

With these relationships, the previously presented SWRCs can be transformed to the degree saturation vs. suction relationships, as given in Figure 6.29. From these plots, distinct air entry value (AEV) of each tailing can be identified by the break in the curvature of the curve at the 100% degree of saturation. For the flocculated MFT, the AEV of SWRC was about 60 kPa, which was significantly smaller than those of MFT (700 kPa) and TT (800kPa). Fredlund and Houston (2013) used this method to assess the AEV of an oil sands tailings with 0.1 SFR, and a value of 1000 kPa was obtained. They stated that the values obtained were the correct AEV of the tailings. In this case, the fact that the AEV of MFT decreased dramatically from 700 kPa to 60 kPa after flocculation can be explained by the known fact that the FMFT had larger pores compared to the MFT and air enters the larger pores more easily. According to Figure 6.28, the TT had a slightly larger AEV than the MFT despite of a lower fines content it had. It is assumed that the TT sample had an initially higher compaction degree compared to the MFT.



Figure 6.29 SWRCs plotted as the degree of saturation versus suction plots

Use of shrinkage curves makes it possible to plot void ratio against suction. Figure 6.30 shows that suction increases sharply when void ratio decreases to the value corresponding to the shrinkage limit of the tailing. At the shrinkage limit of the tailings, the measured suction value (u_{SL}) is approximately 1000 kPa for the FMFT and about approximately 3000 kPa for both the MFT and the TT.

In this thesis, the SWRC used for numerical modelling was presented as volumetric water content versus matric suction. By using the shrinkage data, the volumetric water contents of the tailings can be calculated based on the instantaneous volume measurements. Figure 6.31 presents the plots of volumetric water content against soil suction for the fine tailings. These curves appear to be similar in the shape to the SWRC constructed using gravimetric water content.



Figure 6.30 Void ratio versus soil suction plots for fine oil sands tailings



Figure 6.31 Volumetric water content (based on instantaneous volume) versus suction for tailings

6.4.2.3. Comparison of SWRC to different tailings

In Figure 6.32, the SWRC of the MFT obtained in this work is compared to those reported by Fredlund et al. (2011) and Owolagba & Azam (2013) for different MFT samples. Comparing these curves, one can find some slight deviations in the lower suction range. However, these curves are similar at higher suction range (i.e.> 1000 kPa).



Figure 6.32 Comparison of SWRC between the MFT obtained in this research and the MFT reported from literature

Figure 6.33 compares the SWRC between the polymer treated MFT prepared in this study and the polymer treated MFT obtained from field in-line flocculation program undertaken by Shell (Shell, personal communication, 2014). These two tailings were produced utilising the same polymer and dosage but with different mixing processes (laboratory scale stirred tank vs. large scale in-line flocculation). The data shows a general agreement between the SWRC of the two FMFT materials. It indicates that the FMFT used in this work had similar soil water retention characteristics to the tailings used in the field tests.



Figure 6.33 Comparison of SWRC between the MFT in this work and the MFT obtained from Shell AFD field test (Shell, personal communication, 2014)



Figure 6.34 Comparison of SWRC between the TT in this work and the TT presented by Innocent-Bernard (2013)

There is limited literature which provides soil water retention curve of oil sands TT. Innocent-Bernard (2013) assessed the SWRC for the TT with significant lower fines content (0.43 in SFR) than current work. The SWRC of these two TT are compared in Figure 6.34. Ignoring the effect of various initial water content on the SWRC in the low suction range, it can be seen that the TT in current research has larger suction values than the TT studied by Innocent-Bernard at the water content below 30%. It demonstrates that the particle size distributions especially the content of fines and clay plays a critical role in the soil water retention behaviour.



Figure 6.35 Comparison of SWRC data between oil sands fine tailings and other mine tailings

Finally, the water retention characteristic data of fine oil sands tailings are compared with those of four different mine tailings given by Qiu and Sego (2001), as shown in Figure 6.35. It is apparent that the fine oil sands tailings (MFT, TT) in this work have significant

larger suction values than the other mine tailings have at the same water content. Among the listed four different mine tailings, coal wash tailing behaves as plastic cohesive soil and it exhibits larger matric suctions than the other tailings (i.e., copper tailing and oil sands CT) which are classified as sandy soils (see Chapter 3). The water retention characteristics are dependent on the pore size and thus particle size of the soil. The smaller the pores, the higher water rises in the soil and the greater the matric suction. Higher suction in fine tailings means that removing water from these tailings requires larger free energy. Table 6.3 compares the parameters of SWRC for various tailings. It can be seen that fine oil sands tailings also have much higher AEV than the other tailings.

	Property parameters	Copper	Gold	Coal	CT	TT	MFT
	Air entry value (kPa)	5	6	18	6	900	800
	Residual water content (%)	3.4	2.2	18	6.2	10	15
Water content (%)	50 40 30 20 10 0	-D-Drying 1 Wetting 1 End of 1st shrinkage	50 40 00 00 10 0	End of 1st wetting			Drying 1 Wetting 1 Drying 2 Wetting 2
	1000 1000 10000 Suction (kPa)	100000	10	00	1000 Suction (k)	10000 Pa)	100000
	(a) Cycle 1				(b) Cycle	2	
5	0	Drying 1	50				Drying 1
4	0 End of 2nd swelling	Drying 2	40	End of 3rd			- Drying 2
(04) II		-O-Drying 3 Wetting 3	ut (%)	swelling			- Drying 3 - Wetting 3
2			ater conten			→ →	- Drying 4 - Wetting 4
8			Ŵ				
1			10				
	100 1000 10000 10000 Suction (kPa)	100000	10	0	1000 Suction (k)	10000 Pa)	100000
	(C) Cycle 3				(d) Cycle	4	

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Figure 6.36 Suction vs. water content curves for flocculated MFT during four dryingwetting cycles

6.4.2.4. Suctions in drying and wetting cycles

Figure 6.36 shows the suction values determined using WP4C potential meter for a single FMFT sample during consecutive four drying and wetting cycles. Due to the limitation of WP4C in accurate measuring low suction, the low-end suction values provided are above 100 kPa. The FMFT specimen had an initial water content of 40% at which the suction was measured to be 220 kPa. In each cycle, the sample was desiccated by air till the residue water content with the suction exceeding 10000 kPa before it was rewetted by soaking with water. From these graphs, it can be seen that hysteresis exists in each cycle resulting in smaller suction values on the wetting path compared to that on the previous drying path. In one drying and wetting cycle, the wetting path terminated at a lower water content than the starting water content in this cycle due to hysteresis and limited measurement range. The subsequent cycle started at a lower water content than the previous cycle. The figures suggest that all the drying and wetting curves (scanning curves) fall into the envelop formed by main drying curve and the main wetting curve. Therefore, the suction of a deposited tailing is not solely dependent on the water content but is affected by drying-wetting history.

6.4.3. Results of evaporation and cracking tests

6.4.3.1. Evaporation behaviour

In order to determine the potential evaporation rate, a glass cup (91 mm in diameter and 12 mm high) was filled with de-minimalised water and placed at the same elevation as the tailing samples on an electrical scale. By continuous monitoring changes of total weight of the cup and water, the rate of evaporation from water surface can be measured. Results showed that the water evaporation rate at static air drying condition was generally constant in the climate controlled room (24 ± 0.5 °C, $40 \pm 10\%$ relative humidity). The average evaporation rate was 17.28 g/day which is equivalent to 2.7 mm/day. When the air pump was used to blow air over the surface of water, the evaporation rate was greatly increased compared to static air drying. It is because moving air has lower RH compared to static air and the rate of evaporation is inversely proportional to the vapour pressure of the gas that is in direct contact with the surface of water. Figure 6.37 shows the weight changes for the cup of water with air blowing on it at constant rate of 400 L/h. It can be seen that the rate of evaporation was not strictly constant but decreased gradually throughout drying. This is considered to be the result of the decrease in air velocity at the settling water surface with the increasing distance from the source of air flow. However, the evaporation rate during the initial period (e.g. 200 min) is rather constant with the average value being 14.03 mm/day. For convenience this value was assumed to be the rate of PE in the evaporation tests at the accelerated air drying condition.



Figure 6.37 Total weight of the glass cup and water during drying by air blown at 400 L/h above the surface

Figure 6.38 shows the monitored evaporation rates and the average water content of a thin (12 mm) flocculated MFT sample during drying at accelerated conditions. The sample was the optimally polymer-treated MFT with an initial water content of 85% (1.96 in void ratio). According to the graph, the three different stages of evaporation (see Section 6.2.4.1) are clearly identified. In the first stage (constant-rate stage), the monitored evaporation rate was generally stable and the average water content of the layer decreased linearly with time. This stage ended at about 600 min before the evaporation rate started to drop. In the second stage (falling-rate stage), the water content decreased gradually and the evaporation rate dropped at a relatively high speed. In the last stage (low-rate stage), there was no decrease in the water content and the evaporation rate became zero. It is noted that the evaporation rate started to decrease at the water content value of 30%, which is close to the plastic limit of the FMFT. The residual water content at zero evaporation was about 4%.



Figure 6.38 Water content and evaporation rate for a FMFT sample in accelerated air drying condition

Figure 6.39 shows the water content and evaporation rate for the 12 mm thick MFT sample at the same drying condition. The initial water content of the sample was 145% and the evaporation rate started to decrease at the average water content of 25%, this value is also close to the plastic limit. It indicates that the evaporation rate of the tailing decreases rapidly when the soil matrix starts to desaturate. According to the shrinkage curves, most of the volumetric shrinkage occurred in the constant evaporation rate stage. The obtained evaporation behaviour of the fine tailings is similar to that described by Wilson et al. (1997) and Tang et al. (2011) for thin layer of saturated clay.



Figure 6.39 Water content and evaporation rate versus time curves for a MFT specimens with accelerated drying

In above tests the MFT sample was dried at a higher initial water content compared to the FMFT sample. For the MFT, it took 400 min before the average water content of the sample decreased from 146% to 85%. The rate of evaporation from the tailing (AE) is divided by the rate of evaporation from water (AE), which yields the normalised evaporation rate, and the values for the MFT after 400 min are compared with the values of the FMFT, as shown in Figure 6.40. In principle, for a saturated soil, the actual evaporation is equal to the potential evaporation in the constant rate stage (Wilson et al. 1997). However, the figures show that the AE/PE ratios in the constant-rate stage were around 0.85 for both the MFT and FMFT. In the author's opinion, this deviation could be explained by two aspects. On the one hand, it may be due to the errors in the measurement of potential evaporation since the pure water surface dropped with time. On the other hand, the actual evaporation from the tailing may be affected by the bitumen film formed on the surface and the soluble salts in pore water of MFT. The salinity of tailing at the surface may supress evaporation by developing high osmotic suction. Figure 6.40 also shows that the evaporation rate of MFT dropped earlier and faster than that of the FMFT. This is because the MFT has been desiccated for 400 min before reaching the average water content of 85%, which was the initial water content of the FMFT. However, water content at the surface of the MFT was smaller than the average water content, and therefore the surface resistance (e.g. hydraulic conductivity, suction) exerted an earlier effect on the evaporation rates. It should be mentioned that some desiccation cracks, which will be shown in the next section, occurred at a relatively high water content and they developed rapidly afterwards. However, the cracking did not cause significant increase in the actual evaporation rate since the increase of surface area was small.



Figure 6.40 Normalised evaporation rate for the MFT and FMFT comparing at the same average water content

6.4.3.2. Cracking characteristics

Figure 6.41 illustrates how the desiccation cracks occur and propagate on the surface of a FMFT sample. According to the surface images, the whole cracking process can be generally divided into four steps described as follows:

- After a drying duration of 5h and 15 min, the average water content decreased to 52%, and four tiny pits formed on the specimen surface (Figure 6.41-1). These pits are surface defects which occurred independently due to local inhomogeneity of soil texture.
- As drying proceeded, the closest two pits (1 and 2) were connected, forming the first crack (Figure 6.41-2) on the sample. The crack propagated and a small branch was born (Figure 6.41-3). At the same time, on the other side of the sample, a new pit was formed and propagated as a tiny "Y" shaped crack (Figure 6.41-4). One end of the crack propagated toward the centre and intersected with the nearest existing pit (Figure 6.41-5) and therefore the second crack was formed. Associated with the first one, these two cracks are regarded as the primary cracks. These two cracks propagated and intersected with each other and finally reached the rim of specimen (Figure 6.41-6 to 6.41-8).
- Secondary cracks initialised at existing primary cracks and terminated when they joined other cracks or extended to the rim of specimen (Figure 6.41-9 to 6.41-13). The specimen surface was split into several large polygonal aggregates. The large aggregates were split again into smaller ones by the third-class cracks.
- As the water content of sample dropped below 30%, the geometry of the crack networks stabilized. No new cracks formed during the period when the water content decreased from 30% to 13%. This stage may consist of widening of existing cracks until the desiccation ceases (Figure 6.41-14 and 15). The average thickness of the desiccated soil was 6 mm measured at the residue water content of 4%.

In the first stage, when the water content decreases to a certain range, some pits or microcracks may occur in a random manner on the surface. These surface defects may be caused by intrinsic soil inhomogeneity factors. In an oil sands tailing, surface defects can occur near the bitumen spots due to different density and viscosity. Desiccation cracks normally initiate at the surface defects because shrinkage distortion and stress concentration occur around the surface anomalies (Weinberger, 1999; Zebat et al., 1997, Tang et al., 2011). Water content plays critical role in soil cracking. The cracking water content is defined as the critical water content of the specimen at the onset of crack initiation. In this test, the cracking water content for the thin FMFT sample was around 50%. According to the shrinkage curve, at the cracking water content the main soil matrix was still saturated. Other researchers (e.g. Peron et al., 2009; Rodriguez et al., 2007) also found that the average degree of saturation is almost 100% when the initial crack forms. The geometry of the crack networks is completely stabilised when the water content decreases to the shrinkage limit. Below this water content, water loss does not result in any volume change of soil. This can also be explained by the shrinkage curve of the sample. According to the images, the crack pattern of the flocculated MFT sample belongs to the category of orthogonal. It was observed that when a crack approached an existing crack, it changed direction to meet the existing cracks perpendicularly (i.e., Figure 6.41-9). This phenomenon can be explained by the maximum stress release criterion and crack propagation criterion (Lachenbruch, 1962; Morris et al., 1992). Generally, cracks tend to grow in the direction perpendicular to the local maximum tensile stress. The internal tensile stress has been released once the crack is initiated, so the direction of the maximum tensile stress must be parallel to the plane of the existing crack. Shown in Figure 6.41-2, the clay began to separate from the wall of a glass cup at the water content of 50%. The gap between clay and wall was enlarging with the progress of drying. When the water content reduced to 45%, the sample completely pulled away from the wall. The clay pad had a rather smooth rim with little clay particles adhering to the wall.





Figure 6.42 shows temporal evolution of the desiccation cracks on the MFT sample mentioned previously. Unlike the FMFT, the MFT suffered a significant effect of side wall adhesion. Clay adhering to the wall resulted in circumferential cracks, dividing the clay pad into two zones (Figure 6.42(b)). In the central zone, cracks initiated at an average water content around 44%. According to previous research, the soil matrix was still in full saturation. When the water content dropped to about 30%, the crack pattern was fixed. As shown in figure 6.42(d), one loop crack and six radial cracks were formed in the central zone. These cracks are regarded as the primary cracks to distinguish from the minor cracks that occurred later.



Figure 6.42 Initiation and propagation of cracks on a MFT specimen

Figure 6.42 indicated that the side wall adhesion plays an important role in cracking behaviour of the MFT sample. During drying MFT adhered to the wall of glass container even after the side walls were coated by Vaseline. After the clay clods were dried out, it was difficult to separate them from the glass wall. Gachet et al.(2003) proposed that the interface adhesion between glass and clay increased dramatically with decreasing degree of saturation of the soil. According to Fig. 6.41, there was almost no side wall adhesion effect on the FMFT and therefore the crack pattern was not affected by this boundary effect. In the author's opinion, the different response of the tailing to the side wall cohesion effect is largely due to the larger particle bonding strength in FMFT compared to MFT, which makes the soil sufficiently strong to resist the soil – glass interface adhesion. In addition, it was found that the FMFT specimen contained significantly less amount of bitumen than the MFT did because majority of bitumen was lost in the mixing and flocculation process. It is considered that bitumen adhered to the clay-glass interface, as shown in Figure 6.43, can also increase the side wall adhesion.



Figure 6.43 Presence of bitumen on the side wall of glass cup for the FMFT (left) and MFT (right)

In current research, the cracking tests were also performed on MFT and FMFT samples with different initial water content, thickness and desiccation rate. The results suggest that the cracking water content of the MFT in the static atmospheric condition (52%) is higher than the cracking water content (44%) for the same thickness MFT with air blowing (at 400L/h) over the surface. Kodikara and Nahlawi (2006) reported a similar phenomenon for a thin clay sample and explained that the tensile strength increases with increasing desiccation rate, which reduces the cracking water content. The tests also demonstrated that the cracking behaviour was affected by initial condition the sample. Figure 6.44 compares the cracks formed on three MFT specimens after drying. The specimen in Figure 6.44(a) had 30% lower initial water content than the other two specimen. The specimen in Figure 6.44(c) had a smaller initial thickness (6 mm) compared to the other two. The images show that the higher water content and the thinner clay sample had larger crack ratio (ratio between area of cracks and total surface area) and smaller mean cell area. Similar phenomenon has been discovered by many researchers in the past (e.g. Corte and Higashi, 1960; Kodikara and Nahlawi, 2006, Tang et al., 2011).



Figure 6.44 Crack patterns for MFT specimens with varying initial water content and thickness

6.4.3.3. Effect of drying and wetting cycles on cracks

The desiccated cracked samples were subjected to several consecutive wetting and drying cycles to see whether the crack pattern formed in the initial drying process will be affected by frequent and sharp changes of water content and suction. Figure 6.45 shows the crack patterns of the MFT sample after completion of each wetting and drying (W-D) cycle. The initial crack pattern shown in Figure 6.45 (a) was formed by the drying process illustrated in Figure 6.42. The desiccated tailing was soaked with water overnight to allow most cracks to close. It was then dried at the same condition as the initial drying process. Figure 6.45 (b) shows that after one W-D cycle some new cracks developed in the central zone of the specimen, these cracks are referred to as secondary cracks according to their width. After two W-D cycles, the secondary cracks intersected with existing primary cracks and split the large clods into smaller aggregates (Figure 6.45(c)). In the subsequent cycles, the mean area of the cells reduced with the growing number of cracks. It was observed that after four W-D cycles the soil structure collapsed losing a large amount to water upon soaking. Some cracks were filled by the exfoliated aggregates and therefore the crack pattern changed significantly compared to the initial one. Results indicate that W-D cycles significantly affect the crack pattern of the MFT specimen. With increasing of W-D cycles, the soil surface becomes more cracked, the cracking cells are smaller and more cracks are close together. This behaviour is consistent to the observations presented by other researchers for some thin layer clayey soils (e.g. Yong and Warkentin, 1975, Yesiller et al. 2000, Tang et al. 2011). Explanations for this phenomenon given by the referenced papers are summarized as follows. During the W-D cycles, volume shrinkage and cracking would result in irreversible fabric changes and decrease of specimen integrity and increase of weak zones in specimen (Yong and Warkentin, 1975). As a result, the specimen tensile strength is reduced, promoting specimen cracking at a higher cracking water content upon the subsequent drying. Yong and Warkentin (1975) stated that cracking will occur at the weakest locations of the soil structure. The broken bonds caused during the first drying cycle may become preferential zones of cracking (Tang et al. 2011). In addition, the multiple W-D cycles give rise to an increase in material heterogeneity. Due to the non-uniform distribution characteristics of aggregate sizes and inter-aggregate pore sizes, the tensile stresses developed during the subsequent drying cycles would also be nonuniform and can easily be concentrated at the defects with lower tensile strength. From the last image which was captured after five W-D cycles, it can be seen that the whole surface was split by cracks into many cells with similar area and the intersection points of the cracks generally formed "T" and "+" shapes.



Figure 6.45 Changes of crack pattern of the MFT during 5 wetting-drying cycles

Figure 6.46 shows the crack networks of a FMFT sample during multiple drying and wetting processes. Figure 6.46 (a) shows the cracked desiccated FMFT specimen. The sample was soaked with water for 6 hours and the crack pattern is shown in Figure 6.46 (b). It can be seen that after wetting the primary cracks were closed or significantly narrowed. The specimen was then desiccated and rewetted for another several cycles. Figure 6.46(c) shows the soil which had experienced two wetting-drying cycles. It shows that both the number and the length of existing cracks did not change after two consecutive W-D cycles except that some cracks were slightly widened. This may be due to the shift of clay aggregates during soaking. Observations demonstrate that the drying and wetting processes did not affect the crack pattern formed in the initial drying process.



Figure 6.46 Changes of cracks for a FMFT specimen during drying and wetting

The different cracking behaviour between MFT and FMFT is mostly due to the differences in soil structure and tensile strength of the tailings. The various behaviour indicates that the flocculated MFT have much more stronger particle bonds compared to the non-flocculated MFT. The soil structure in FMFT, consisting of flocs and aggregates, was much stronger than the soil structure in MFT in resisting significant changes of water content and suction as well as clay-glass interface cohesion.



Figure 6.47 The cracked polymer treated MFT in the field tests (Caldwell et al. 2014)

In current research, all the cracking tests were performed on a thin layer of tailing sample at a maximum thickness of 12 mm. These tests were aimed to explore some important aspects of the desiccation cracking process. The author admits that the current investigation has the limitations in the relevance to the cracking behaviour of the deposited tailing lift in the field tests. In Shell AFD field tests, for instance, the tailing materials were deposited at varying thickness from 40 to 100 cm for each lift (Shell, personal communication, 2014). The cracking behaviour (e.g. cracking water content, width and depth of cracks, area of cracking cells, crack pattern etc.) of the tailing lifts may be significantly different from that obtained in this work. Furthermore, the thin tailing samples used in current research were initially homogenous and smoothed flat before drying. In the field tests, however, the deposited tailings are not homogenous and flat due to the slope of the drying area. In the field tests, the in-line flocculation provided large pores among the flocs or aggregates, which formed surface drainage channels for excess water after the deposition. These channels are more likely to

become desiccation cracks. As a result, the cracking water content and the propagation of desiccation cracks may be different on the same tailing lift. In general, field tailings are more complex than the remoulded tailing samples used for experimental research. Cracking of field tailings is a 3D phenomenon and the patterns are usually composed of irregular polygonal shapes (Figure 6.47). Quantification of a 3D crack pattern is much more challenging than the 2D process described in this investigation.

6.5. Summary

This chapter presents laboratory investigations on three aspects of desiccation behaviour of fine oil sands tailings. In Section 6.3, shrinkage and swelling tests were performed using small homogenous tailings samples to assess the shrinkage curves and the rewetting swelling behaviour. In Section 6.4, matric and total suction measurements were undertaken on the tailings samples at different water content to construct the soil water retention curves. The shrinkage data presented in Section 6.3 are used to determine the air entry values (AEV) and the instantaneous volumetric SWRC which are important in understanding the soil water retention behaviour. Hysteresis in the SWRC was assessed by repeatedly drying and rewetting the tailing sample for several cycles. In Section 6.5, desiccation cracking tests were conducted on thin (approximately 1 cm) tailing layer. Different evaporation stages were identified from the measured evaporation rates. Differences in cracking behaviour between MFT and FMFT were discussed. Effect of multiple drying and rewetting processes on cracked soil sample was also evaluated.

The main findings and conclusions withdrawn from laboratory experiments are summarized as follows:

- The obtained shrinkage data (plot of void ratio and gravimetric water content) for fine oil sands tailings (TT, MFT and FMFT) shows a J-shaped curve in a progressive drying pattern. Three shrinkage stages can be identified and the shrinkage limit and plastic limit can be estimated from the shrinkage curve. The minimum void ratio attained by the tailing sample after complete drying is about 0.43 for MFT and varying between 0.55 and 0.7 for polymer treated MFT samples depending on polymer dosage and mixing parameters. According to the shrinkage curves, FMFT have higher plastic limit and shrinkage limit values than MFT. The shrinkage curves obtained for the MFT in this study are similar to those of some MFT samples reported in literature.
- Similar to the drying process, once a desiccated tailing sample is rewetted, the swelling process also consists of three stages and the maximum swelling rate occurs in the first stage. Swelling potentials of tailing samples are influenced by parameters such as initial water content, thickness and confining pressure. In general, if a tailing has lower value in the above parameters, it will have larger swelling potential. Using the conventional soaking method, the maximum axial strain of a laterally confined desiccated tailing sample ($w_0 = 11\%$, diameter to thickness ratio is 3) is 10 %. It demonstrates that the fine oil sands tailings has relatively low swell potential compared to typical expensive soils.
- The observations suggest that the rewetted tailing sample has lower cohesion and strength compared to the sample before soaking. When there was no sufficient confinement on the sample, cracking occurred on the sample after several weeks

soaking. These cracks may originate from microcracks formed during the initial drying process. Due to cracking and low permeability, the desiccated tailing sample did not attain 100% saturation after full swelling. By using vacuum pressure saturation device and applying sufficient confining pressure on the sample, a high degree of saturation closing to 100% was obtained.

- If the initial drying process for a tailing slurry does not extend beyond the shrinkage limit of the material, when the soil is rewetted the wetting path coincides with the previous drying path. When a desiccated tailing is rewetted, hysteresis occurs in the swelling path resulting in a higher void ratio than the corresponding value on the previous shrinkage path at the same water content. For a FMFT sample, the effect of hysteresis between shrinkage and swelling process vanished after the soil experienced four consecutive wetting-drying cycles.
- In this research, soil water retention curves (SWRC) were constructed by combining the measurement data obtained from filter paper tests and those from dew point potentiometer (WP4C). The independently measured shrinkage curve should be used to interpret the measured SWRC to obtain the correct air entry values and the SWRC based on volumetric water content. The determined AEVs for the MFT, TT and FMFT samples were 700 kPa, 800 kPa and 60 kPa, respectively.
- The SWRC determined for the MFT samples used in this research is similar to those of different samples of MFT reported in the literature. The SWRC assessed for the optimally flocculated MFT samples prepared in this work was compared with that of the polymer treated MFT obtained from field tests and generally good agreement was identified. The differences in SWRC between MFT and FMFT and other different mine tailings arise from various soil properties such as particle size and pore size distributions. Compared to different mine tailings in the engineering (e.g. gold, coal, copper tailings), fine oil sands tailings have significant larger suction values, indicating that removal of water from the fine tailings requires higher free energy.
- Due to changes of surface resistance (e.g. permeability, suction), evaporation of water from a thin tailing layer surface was divided into three stages: constant-rate, falling-rate and low-rate. At the same drying condition, the rate of evaporation measured from the tailing surface was lower than that from a water surface. This phenomenon is considered related to salinity of pore water or the residual bitumen in the tailing. Results showed that most of deformation and cracks occurred during the constant-rate stage. Desiccation cracks initiated at the sample surface when the clay matrix was still fully saturated. The crack pattern stabilised when the average water content dropped below the shrinkage limit.
- The observed cracking phenomenon for a thin MFT sample was similar to a normal saturated thin clay layer during drying. A Higher desiccation rate resulted in a lower cracking water content. The higher water content and smaller thickness of the sample created smaller mean cell area. In the multiple wetting and drying cycle tests, wetting provided some healing to the cracks that developed in the first cycle for both MFT and FMFT. However, these cracks remained as weak zones, and with the subsequent cycles these cracks re-opened and cracking progressed easily.

- Desiccation cracks observed on the thin (approximately 1 cm) tailings samples (MFT and FMFT) belong to the category of orthogonal. Crack patterns formed on MFT and FMFT samples are quite different. The MFT samples suffered from side wall cohesion, some clay particles adhered to the side wall of the container, which influenced the crack pattern. There was almost no side wall adhesion for the FMFT. With increasing of W-D cycles, the MFT sample surface became more cracked, the cracking cells were smaller and more cracks were close together. For a cracked FMFT, there was almost no change in the existing crack pattern after several wetting and drying cycles.
- The different cracking behaviour between MFT and FMFT is considered due to the different soil structure formed between the two tailings. The FMFT have much stronger particle bonds compared to the MFT.

Filtration Column Tests

7.1. Introduction

In Chapter 2, use of Prefabricated Vertical Drains (PVD) has been mentioned as one potential engineering means to accelerate the consolidation of oil sands tailings. When PVD are installed in the tailing pond after capping, migration of fine particles during the drainage and consolidation might present a potential risk of clogging of the filter jackets, and this is the most critical difference between application of PVD in normal soils and slurry materials. In the author's opinion, clogging of wick drains associated with other factors (e.g. properties of tailings, stresses and strains imposed on the soil-PVD system, prevailing hydraulic conditions etc.) are main concerns in the evaluation of the feasibility of applying PVD technologies in disposal of fine oil sands tailings. In previous research, soil properties related to PVD technologies (e.g. particle size distribution, porosity, compressibility and permeability) have been investigated. In this chapter, the concern of clogging of PVD is discussed.

Bell and Hicks (1980) described three basic clogging mechanisms for PVD: (1) clogging of the core by the passage of too many particles through the filter jacket, (2) clogging of the filter jacket by too much particles remaining inside the fabric structure, (3) blinding of filter jacket by a low permeability filter cake forming on the surface (Figure 7.1). For oil sands tailings, another mechanism may be added, which is blinding of the openings of filter jackets by bitumen. The clogging potential of PVD is directly related to physical and mechanical properties of the geotextile filter jacket used, e.g. pore size, porosity, tensile strength and compressibility of geotextiles etc. Therefore, selecting an appropriate filter jacket is critical for an application. Filter jackets used in a specific application should be selected according to the particle size distributions of the soils. Some empirical methods have been proposed. According to Geosynthetic Design and Construction Guidelines (US Department of transportation, NHI, 1998), for example, the apparent opening size (AOS) of the geotextile filter should meet the retention criteria: AOS or $O_{95} \leq B \times D_{85(soil)}$. O_{95} is the opening size of geotextile such that 95% of the openings are smaller than this value. B is a coefficient which depends on type of geotextile, uniformity coefficient of soil and flow conditions. In steady state flow conditions, B is equal to 1.8 for nonwoven geotextiles used in clayey soils with $C_u >$ 8. The filter jacket should also meet the permeability requirement: $k_{geotextile} \ge 10 k_{soil}$, and the permittivity requirement of $\varphi \ge 0.1s^{-1}$. Permittivity is the ratio between permeability of geotextile and thickness of geotextile and is a function of the hydraulic head. Although empirical methods present a quick estimation of geotextile filtration characteristics, the most

realistic approach for a specific application is to perform a laboratory test which simulates the field conditions (Holtz, et al., 1998). Based on engineering experience gained in the past, drainage of water from soft tailings to vertical drains may be hampered by formation of consolidated clay layer around the drain. This behaviour is governed by permeability of sludge which is a function of void ratio and density.



Figure 7.1 Definitions of clogging and blinding of geotextile filter jacket of PVD (Bell and Hicks, 1980)

This chapter describes a series of column filtration tests that were carried out to evaluate the clogging potential of geotextile filter jacket and the drainage behaviour of the sludge – geotextile system. Through the results, filterability of various tailing materials were compared. The detailed information of the tests is presented in Section 7.2, the measurements and observations are presented in Section 7.3 followed by analyses and discussions in Section 7.4. Finally, a summary is given in Section 7.5.

Part of this chapter was published.

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7.2. Experimental work

7.2.1. Materials

7.2.1.1. Tailing materials

The tailings samples used in this work were prepared from the tailings sludge stored in buckets. The tailings (TT and MFT) were thoroughly mixed to form homogenous tailing suspensions at initial solid content of 35% (186% in gravimetric water content). A part of MFT samples were treated with polymer at dosage of 1g/kg under both the optimum (500 rpm, 1.5 min) and over-mixing conditions (500 rpm, 5 min).

7.2.1.2. Geotextile filter jackets

Three non-woven geotextiles were selected and used in this research. These geotextiles were supplied by a Dutch PVD manufacturer and they are distinguished by materials, densities and permeabilities. The white coloured polyester geotextile (LDFD) is lighter and more permeable than the other grey coloured polypropylene geotextiles (D165 & 5417HS). Table 7.1 presents specifications of the selected geotextiles. The selected geotextiles meet all the requirements suggested by the guidelines presented before. The geotextiles filter jackets were cut to circular disks with a radius of 133 mm (Figure 7.2). The inner diameter of filtration column is 10cm and thus the actual filtration area of the filter was 78.5 cm^2 .

	D165	5417HS	LDFD
Material	Polypropylene	polypropylene	polyester
Unit weight (g/m^2)	165	140	95
Thickness at 20 kPa (mm)	0.39	0.40	0.30
Elongation at break (%)	50	50	39
Tensile strength (kN/m)	12.9	11.7	6
Opening size O ₉₅ dry (µm)	<75	75	75
Opening size O_{95} wet (μ m)	-	75	< 65
Permeability (mm/s)	11	12	39
Permittivity (1/s)	0.3	0.3	

 Table 7.1 Characteristics of the geotextiles used in this work



Figure 7.2 Geotextile filter jackets used in this work

7.2.2. Apparatus

7.2.2.1. Filtration set-up

A column filtration set-up was designed and manufactured for this research. The design was based on the apparatus used in the gradient ratio test (ASTM D5101) with some modifications. A total of two set-ups were fabricated. Figure 7.3 shows the schematic drawing of the column filtration device. The column is composed of three Perspex glass moulds, which are mounted on top of each other and tightly screwed to ensure air tightness. These moulds are nominated as the pressure chamber, the filtration chamber and the collection chamber, which have identical inner diameter of 100 mm with various heights at 300 mm, 200 mm and 100 mm, respectively. The pressure chamber is used to transmit the imposed air or water pressure to the tailing sample which is contained in the filtration chamber, and the collection chamber is used to collect the filtrate. On the top of the pressure chamber, there are two openings, one is the inlet for water or compressed air and the other is equipped with a valve which is opened during filling of water to allow the entrapped air to escape. Filtration of tailing sludge takes place in the filtration chamber. Pore pressures of tailings are measured by transducers installed on the side wall of the filtration chamber. The geotextile filter disc is placed between the filtration chamber and collection chamber supported by a wire mesh plate. A rubber -ring is placed above the filter disc ensure good water tightness. Filtrate collected in the base chamber is discharged through the outlet. The whole column is placed on a concrete block. An electrical balance is placed below the outlet of collection chamber. The discharged water is collected by the beaker which stands on the balance. In order to prevent evaporation of water, the beaker is closed by a plastic sheet with a hole to let the filtrate to drop in.

7.2.2.2. Pressure supplier

Compressed air generated by air compressor is the pressure source of filtration tests. Compressed air is either injected directly into the pressure chamber if the air pressure is used to induce filtration or converted to the water pressure with a converting device illustrated in Figure 7.4. The converting device is composed of a rigid cell with a bladder inside of it. To convert air pressure to water pressure, water is first injected into the space between the bladder and the cell wall to compress the bladder while value 2 is kept open to discharge the air. After filling, valve 2 is closed and the outlet of the cell is connected to the pressure chamber which is fully filled with water. Compressed air is then admitted to the bladder. Once valve 3 is opened, water pressure is applied to the tailing sample in the filtration chamber. The magnitude of the water pressure is equal to the imposed air pressure.

7.2.2.3. Measuring system

On the wall of the filtration chamber, there are three ports for pore water pressure measurement. Shown in Figure 7.4, Port 1 is located at the medium height of the filtration chamber, Port 2 and Port 3 are 50 mm and 25 mm above the filter, respectively. In the test, only two ports can be used simultaneously, and the rest one is blocked. Pore pressures were measured by pressure transducers with an accuracy of 0.1 kPa. The pressure transducers were calibrated with water pressure before the use. The accumulated mass of filtrate was measured by electrical balance to the nearest 0.01 g. Both the pressure transducers and the balance were connected to computer and the acquired data was logged automatically with time by software.



In addition, the height of surface of sludge was recorded manually at different time during testing.

Figure 7.3 Schematic drawing of filtration set-up used in this work



Figure 7.4 Schematic drawing of air-water pressure transfer device
7.2.3. Methods and procedure

7.2.3.1. Application of load

The initial fine tailing slurry is regarded as a "heavy" fluid (Wells & Caldwell, 2009). When the PVDs are installed in the tailing pond, the expected total pressure in the tailings at a depth (h) is $P_t = \gamma_t h$, where γ_t is the unit weight of tailings slurry. For homogenous fine tailings with 35 wt% solids, γ_t is approximately 12 kN/m³. The hydraulic potential (P_d) at a depth h inside the drain is $P_d = \gamma_w h$, where γ_w is the unit weight of water and it is about 10 kN/m³. Due to the pressure differential between the outside and the inside of the drain, water flows from the tailings into the PVD. In this research, magnitude of the pressure applied to the tailing sample was selected to simulate the pressure/potential at the depth where the PVD would be installed in the tailing pond. A constant load of 20 kPa was utilised in most of the tests, which was approximately representing the initial pressure difference of PVD at the depth of 10 m in the pond.

In this research, load was applied either through water or compressed air to the sludge (Figure 7.5). Filtration test using water pressure was used to evaluate clogging potential of PVD filter jackets when they are applied in fluid fine tailings as there is continuous supply of water after the formation of filter cake. The air pressure filtration tests were used to compare the filterability of TT, MFT and flocculated MFT by measuring the specific resistance to filtration (SRF) parameter. These two tests vary in the magnitudes of total pressure generated in the tailing and the boundary conditions. In the air pressure filtration test, initial total pressure at any depth (h) of tailing is $P_t = \gamma_t h + P_a$, where P_a is the air pressure. To prevent drying of geotextile filter and filter cake, the collection chamber is filled with water. When the valve of the base chamber is opened while the other values are closed, water in the collection chamber is held by atmospheric pressure. In the water pressure filtration tests, the initial total pressure (pore pressure) in the tailing at any depth h is calculated as: $P_t = \gamma_t h + P_w + P_c$, where P_w is the water pressure applied to the column; P_c is the overburden from the 30 cm water layer. Different from the air pressure test, water in the top chamber can enter the tailing and water released from tailing can add to the thickness of the supernatant water. In order to maintain the imposed water pressure, water is continually supplied to the filtration column.





7.2.3.2. Procedure

To perform the filtration tests, the following sequential procedures were applied:

• Preparation of samples

Before the tests, the tailing slurries were agitated to achieve homogeneous state; the flocculated MFT was produced by following the procedures mentioned in Chapter 4; the geotextile filter discs were water saturated using the vacuum saturation device.

- Assembling of filtration apparatus
 - 1. The valve of the collection chamber was closed and the chamber was filled with deaired water.
 - 2. The wire mesh plate was placed on top of the collection chamber, and the saturated geotextile filter disc and the O-ring were placed in sequence on the mesh plate. The filtration chamber was then mounted on the base chamber, and the screw bolts were tightened up in turn in a symmetrically diagonal position.
 - 3. The tailing material to be filtered was poured slowly into the filtration chamber to the required height. Any gas bubble during filling was removed carefully.
 - 4. A circular plastic sheet, which is slightly larger than the cross-section area of the filtration column was placed on the sludge surface. The plastic sheet was used to temporarily separate sludge and water to be filled above the sludge. The top chamber was then mounted on the filtration chamber and the screw bolts were tightened.
 - 5. The pressure chamber was filled with water. After filling, a knife with extended bar was inserted into the column from the top and a cross cut was made on the plastic sheet.
 - 6. The top plate was mounted to the top chamber and screwed.
- Application of load

After the set-up was assembled, the compressed air or water was admitted to the filtration column through the inlet on the top plate. The pressure was adjusted to the required value by the controller.

• Measurement

Filtration of sludge started when the valve of the collection chamber was opened. Changes of height of sludge, pore pressures and accumulated weight of discharged water were monitored throughout the tests.

After completion of the tests, the imposed pressure was removed. Water above the mud was then removed. Soil samples were taken layer by layer (1 cm each layer) from the top to the bottom from the tailing. Water content of the samples taken at different height of the tailing was measured. After all the tailing was removed from the filtration chamber, the filter disc was washed and dried in the oven.

7.2.3.3. Test plan

Table 7.2 provides the plan for the filtration tests. The meaning of letter and number used in the sample ID is explained as follows. The first letter represents the type of load (e.g., "W"= water pressure, "A"= air pressure). The second letter refers to the tailings used (e.g., "T" = TT, "M" = MFT and "F" = flocculated MFT). In order to evaluate the clogging potential of filter jacket, filter discs of three types of geotextile were tested individually with TT in water pressure filtration tests (Test WT-1, WT-2 and WT-3). After filtration, filters were analyzed in terms of changes in dry weight. To investigate the effect of magnitude of load on the filtration behavior, various surcharge pressure values were utilized in the tests. In order to study the effect of chemical treatment on the filterability of fine tailings materials, filtration results of MFT and flocculated MFT under the same applied pressure were compared (WM-1 vs. WF-1). Last, filterability of the flocculated MFT samples prepared in different mixing conditions were compared through tests AF-1 and AF-2.

Test ID	Tailing Type	Geotextile Filter	Air / water pressure	Pressure [kPa]	Soil analysis	Note
WT-1	TT	LDFD	Water	20		
WT-2	TT	5417HS	Water	10	\checkmark	
WT-3	TT	D165	Water	10 to 20	\checkmark	
WM-1	MFT	5417HS	Water	20		
WF-1	FMFT	5417HS	Water	20 to 40		Over-mixed
AT-1	TT	5417HS	Air	20	\checkmark	
AF-1	FMFT-1	5417HS	Air	20	\checkmark	Over-mixed
AF-2	FMFT-2	5417HS	Air	20	\checkmark	Optimum

 Table 7.2 Information of the tests carried out in this research

7.3. Results

7.3.1. Measurements and observations

7.3.1.1. Water pressure filtration tests

Figure 7.6, Figure 7.7 and Figure 7.8 provide the monitoring results for the TT samples used in Test WT-1, WT-2 and WT-3, respectively. In each figure, the left graph shows the accumulative weight of discharged water and height of mud surface changing with filtration time, and the right graph presents the pore water pressures monitored throughout filtration. Changes in discharged flow and settlement showed similar trends for each test despite of various geotextiles and magnitude of pressures used. As soon as the valve at the bottom of the column was opened, there was an immediate large flow coming out through the outlet before a sharp decrease in the rate of flow. The lower transducer recorded an initially higher pore pressure than the upper transducer did due to difference in hydraulic potential. Consolidation of tailing sludge was reflected by continuous decrease of pore pressures detected by all the transducers, but the lower transducer detected a faster decrease of pore pressure compared to the upper transducer as consolidation occurred firstly at the bottom of the tailing. For all the three tests, there was a sudden increase in the rate of flow as well as the pore pressure detected by the lower transducer after an observation period of 15 to 20 days. This phenomenon was believed to be caused by cracking of the sample (Figure 7.9) which created a shortcut for pore water to be drained more readily. The formation of cracks may be attributed to uneven settlement as being affected by side wall friction and/or the gas generation phenomenon. The produce of gas by biological activity occurring in the tailing may break the continuity of floc/aggregate structure, which may prompt cracking.

The results indicate that all of the filter jackets selected in this research functioned properly in retaining solids. Varieties in the discharged volumes and settlements among the samples were attributed to various loads applied in the tests. It is easy to imagine that pore water is expelled faster from a tailing under a higher surcharge pressure than under a lower pressure. Over the same period say 15 days, the total amount of water collected from Sample WT-1 (at 20 kPa), WT-2 (at 10 kPa) and WT-3 (10 kPa for 14 days and 20 kPa for 5 days) was 560 g, 430 g and 440 g, respectively. The corresponding settlements of the tailings were 10.2 cm, 9.3 cm and 8.8 cm, respectively. It is noted that the tailing under 20 kPa showed 30% more discharged water while 10% more settlement than the tailing under 10 kPa, indicating that additional water coming from the overlapping water layer was drained.



Figure 7.6 Monitored weight of discharged water, height of tailing and pore pressures for TT and LDFD geotextile filter at constant pressure of 20 kPa



Figure 7.7 Monitored weight of discharged water, height of tailing and pore pressures for TT and 5417HS geotextile filter at constant pressure of 10 kPa



Figure 7.8 Monitored weight of discharged water, height of tailing and pore pressures for TT and D165 geotextile filter at constant water pressure of 10 kPa up to Day 14 and 20 kPa afterwards



Figure 7.9 Cracks formed at the TT sample

The measurements for the MFT sample (Test WM-1) and the FMFT sample (Test WF-1) are presented in Figure 7.10 and 7.11, respectively. Comparing these samples, it is clear that the FMFT had significantly larger accumulative amount of discharged water and faster settlement than the MFT under the same pressure (20 kPa). By Day 4, for example, the discharged weight and the surface settlement was 740 g and 8 cm for the FMFT, which were almost twice as large as the values for the MFT (310g and 5 cm). It indicates that polymer treatment of MFT can effectively improve the filtration performance. Notice that by the end of the observation period the MFT was still consolidating (indicated by the settling curve and continuous decrease of pore pressure monitored by Port 3) while the settling of the FMFT had been ceased since Day 3 (indicated by flat settlement vs. time curve and pore pressure vs. time curve after Day 3). Due to high yield strength of floc structure, the FMFT would remain the height that was formed after Day 3 unless a pressure being higher than current pressure level was applied on the tailing. It is seen that there was an acceleration in the flow rate of the FMFT after the applied water pressure being increased to 40 kPa. The increase of the settlement was relatively small and was not displayed by the settling curve.



Figure 7.10 Monitored weight of discharged water, height of tailing and pore pressures for MFT under constant water pressure of 20 kPa



Figure 7.11 Monitored weight of discharged water, height of tailing and pore pressures for FMFT under constant water pressure of 20 kPa

7.3.1.2. Air pressure filtration tests

Figure 7.12 and 7.13 present the measurements of FMFT in Tests AF-1 and AF-2, respectively. The flocculated tailing used in Test AF-1 was prepared by mixing the MFT-polymer mixture at 500 rpm for 5 min. The resulted tailing showed obvious over-mixed state compared to the other sample (AF-2) which was prepared in the optimum mixing condition (see Chapter 4). Due to rapid settling of flocs and aggregates, a layer of supernatant water was created in both tests. The air pressure forced the supernatant water to seep through the underlying sediment. The sediment continued to consolidate after the supernatant water was drained. Comparing the results between Test AF-1 and AF-2, it is apparent that the optimally treated MFT (AF-2) had obviously larger filtration rate than the over-mixed sample (AF-1). In Test AF-2, for example, the total amount of water discharged from the optimally mixed MFT was 740g, which was obtained after a filtering time of 2 days. In Test AF-1, however, it took 3.8 days to produce the same amount of discharged water. The difference was due to larger permeability of the optimally treated MFT.



Figure 7.12 Measurements for the over-mixed FMFT sample (Test AF-1) under constant air pressure of 20 kPa



Figure 7.13 Measurements for the optimally treated FMFT sample (Test AF-2) under constant air pressure of 20 kPa



Figure 7.14 Measurements for TT sample (Test AT-1) under constant air pressure of 20 kPa

Figure 7.14 presents the results for TT in Test AT-1 at 20 kPa. Compared with the FMFT, the TT had an smaller dewatering rate as it was intensively mixed. In this test, some

gas bubbles were found at the outer surface of the TT sample. These gas bubbles affected the pore pressure measurement because of poor contact between the transducer and the soil. It can be seen from the graph that the pore pressure data discontinued at Day 18, and the pressure detected by the upper transducer was zero from Day 19 to 22.

7.3.2. Results of sample analysis

7.3.2.1. Tailing samples

In the water pressure filtration test, the tailing sample is always under water. Therefore the void ratio for the saturated tailing can be computed from the water content using the basic volume-mass relationship: $e = G_s \times w$. Figure 7.15 shows the water content and void ratio profiles determined for different tailing samples after filtration. According to the figures, the maximal water content is at the top of the tailing, which decreases with the increasing depth. The profiles of various TT samples are generally similar. It indicates that the various geotextiles did not exert significant effect on the filtration results. It is noted that after filtering the water content value at the top of a sample was equal to its initial water content value prior to filtration. This suggests that no consolidation took place at the top of the tailing throughout the test. In Test WT-1, the layer of consolidated tailing adjacent to the filter jacket had the minimum void ratio around 1.0. According to the permeability – void ratio relationship shown in Chapter 5 (Figure 5.32), the hydraulic conductivity of MFT at e = 1 is in the magnitude of 10^{-10} m/s. For the FMFT sample, the hydraulic conductivity of the tailing adjacent to the filter was in the magnitude of 10^{-8} m/s. These values are both two magnitudes larger than the hydraulic conductivity values at the top layer of each sample. It implies that the flow rate of the system is decided by permeability of the consolidated layer formed above the filter.



Figure 7.15 Water content and void ratio profiles for various tailing samples after a filtering time of 18 days for Test WT-1 at 20 kPa, 22 days for WT-2 at 10 kPa, 27 days for WT-3 at 10 and 20 kPa and 5 days for WF-1

Figure 7.16 compares the final vertical water content distributions of two FMFT samples after the completion of air pressure filtration tests. It can be seen that the optimally treated FMFT (Test AF-2) had a lower mean water content value than the over-mixed sample (Test AF-1) despite of a shorter filtration period it ever experienced. The obtained water content profiles are different from those of water pressure filtration tests. This behaviour will be discussed in the next section.



Figure 7.16 Water content profiles for the optimally treated FMFT (AF-2) and overmixed FMFT samples (AF-1) after filteration

Figure 7.17 shows the water content analysis results for the TT sample in Test AT-1. After a relatively long period of filtration (24 days), the obtained water content distribution seems to be uniform over the height. The water content at the top part of the soil is smaller than that at the bottom, indicating some air drying occurred. The possible reason for air drying is that the air injected into the column had a lower RH compared to the RH in the column.



Figure 7.17 Water content profile for the TT (Test AT-1) at the end of air pressure filtration test

7.3.2.2. PVD filter jackets

After filtration, a small piece was cut from the filter jacket (Type 5H17HS) and put under the electrical microscope to get a close inspection on the fabric structure of the geotextile and to see if viscous bitumen adheres to the geotextile fabric. Figure 7.18 shows that the non-woven geotextiles used to manufacture the PVD filter jackets are made of fibres with randomly distributed three dimensional pores. According to the scale of image, the fibres have averaged width of 100 μ m and the pores formed among the fibres are not uniform in size. On the left side of the image, some bitumen fills the pores forming a film which may prevent water from entering these pores. On the right side, as indicated by the arrow, some solids are found within the fabric structure. The image indicates that both the bitumen and solids may clog the pores and the filter jacket has a risk of clogging if the bitumen and particles are abundant on the filter.

Figure 7.19 compares the two filter jacket discs used in test WT-1 and WT-2 before and after filtration. Looking at the filter LDFD, quite a few bitumen droplets were visible on the margin area of the filter after the usage. This is due to the fact that the rubber ring placed above the filter was not thick enough to prevent seepage of the sludge into the gap between the filter and the rubber ring. However, there was little bitumen remaining in the effective filtration area of the filter. The initial white coloured filter jacket turned brown after the test, indicating that some particles were trapped within the geotextile. On the other filter 5417HS, the bitumen and solids were found only in the effective filtration area since a thicker rubber ring was adopted in the test. As shown in Table 7.3, the amount of trapped solids is relatively small compared to the total amount of solids in the tailings. The sample analysis indicates that the filter jacket was not seriously clogged after filtration.



Figure 7.18 A microscopic view of bitumen and solids left on the geotextile filter (Type 5417HS) after the filtration test



Figure 7.19 Presentation of unused and used filter jackets samples: LDFD in test WT-1 (up) and 5417HS in test WT-2 (down)

 Table 7.3 Weight comparison of the filters before and after the tests

Geotextile filters	LDFD	5417HS	D165
Dry weight before (g)	1.49	1.92	2.33
Dry weight after (g)	1.77	2.28	2.76
Weight of solids trapped (g)	0.28	0.36	0.43
Percentage of total solids (%)	0.04	0.05	0.06

7.4. Discussions

7.4.1. Filtration process

Assuming the density of filtrate is equal to the density of water (i.e.1g/ml), the volume of discharged fluid is obtained from the measured mass. Dividing the discharged volume by the effective area of filter disc, an equivalent settlement of tailing sludge is yielded. In order to analysis the filtration process, the equivalent settlement is compared to the measured settlement of tailing sludge. A typical result obtained from Test WF-1 (flocculated MFT in water pressure test) is shown in Figure 7.20. It can be seen that at the beginning the actual settlement of sludge exceeds the equivalent settlement calculated from discharged volume. A few days later, as the settling speed of tailing surface slows down, the equivalent settlement exceeds the measured settlement.



Figure 7.20 Comparison between the measured settlement and the equivalent settlement for MFT in water pressure test

The difference between the measured settlements and the equivalent settlements calculated from discharged water can be explained by the process illustrated in Figure 7.21. Initially, the height of tailing sample is denoted as H_0 . The height of mud surface at time t is denoted as H_m . Difference between H_0 and H_m is the observed settlement of mud, denoted as S_m . The calculated settlement is denoted as S_d . At the beginning of filtration, S_m is larger than S_d , indicating that there is upward flow in the column due to sedimentation of solids in the slurry. The up flow creates a layer of supernatant water with a thickness of S_s . This layer was not visible in the test as it was mixed with overlapping water. The measured settlement (S_m) of the tailing surface is the sum of S_d and S_s , as shown in Figure 7.21(b). After a certain time, the settling rate of the mud surface decreases sharply, and the difference between S_d and S_m , which is S_s , reduces and finally vanishes ($S_d = S_m$, in Fig. 7.21(c)). As filtration continues, the overlapping water seeps through the sediment and is drained through the outlet, and therefore the equivalent settlement calculated from volume of discharged volume exceeds the measured settlement (Fig. 7.21(d)).



Figure 7.21 Schematic drawing of filtration process in water pressure test



Figure 7.22 Comparison between the measured settlement and the equivalent settlement calculated from the discharged flow for FMFT in Test AF-1

In the air pressure filtration tests, the discharged water was entirely from the tailing because there was no supply of water to the column. As shown in Figure 7.22, the monitored settlement of top surface of the tailing in Test AF-1 is identical to the equivalent settlement derived from volume of discharged water. Figure 7.23 illustrates the filtration process of the air pressure test. Initially, air pressure is applied on the deposited FMFT forcing the pore water to drain from the bottom. Meanwhile, flocs and aggregates settle at a speed which is faster than the discharge speed, and consequently a layer of supernatant water is created above the mud. After the consolidation of the tailing completes, air pressure forces stagnant water to seep through the sediment. After the supernatant water is gone, air pressure is applied directly to the soil surface, expelling pore water out of the soil.



Figure 7.23 Schematic drawing of filtration process in air pressure test



Figure 7.24 Comparison of settling results for the FMFT in the air pressure filtration test and the water pressure test

The settling curves presented in Figure 7.20 and 7.22 are plotted in one graph for comparison, as shown in Figure 7.24. It can be seen that the settling curves for the mud surface measured in two tests are identical. In addition, the settling curve of the top surface (including stagnant water) of the air pressure sample coincides with the settling curve (red curve) derived from the changing volume of discharged water from the water pressure test. The red curve can be taken as the fictitious upper surface of stagnant water created in the water pressure test. The results indicate that the air pressure test shares a similar filtration process to the water pressure test in the period from start till stagnant water is drained. After this period, the boundary conditions in the two tests are different. In the water pressure tests, a water layer with changing height was always above the tailing. At the top surface of tailing, no effective stress was developed. This may explain why water content obtained at the top of tailing was equal to the initial value after filtration.

In air pressure tests, once the supernatant water is drained, the water table is expelled underneath the surface of the sludge and the air pressure acts directly on both particles and pore water, and thus the soil consolidates. According to the theory of consolidation with one-side drainage, the minimum water content is at the bottom of soil while the maximum water content is at the top. However, the measurements (see Figure 7.17) showed that the top layer of the tailing (1-2 cm thick) had obviously smaller water content compared to the underneath 1-2 cm thick layer. This phenomenon may be attributed to the shrinkage observed on the top part of tailing, which is illustrated in Figure 7.25. The shrinkage may be caused by drying (i.e. lower RH of the air).



Figure 7.25 Shrinkage at the top part of soil sample in the air pressure test

7.4.2. Drainage behaviour of tailing – geotextile system

7.4.2.1. Filterability of tailings

Since the geotextile filter has several magnitudes larger permeability than the tailing material has, the filtration behaviour is determined by filterability of the tailing. In order to compare the filterability of different tailing samples, the pressure filtration tests are interpreted using a cake filtration model which can be found in many publications or chemical engineering text book (e.g. McCabe et al.,1975; Cao and Jahazi, 2005). In this model, the flow rate of the filtrate depends on pressure difference across the filter cake and the resistance from both the filter medium and the filter cake. The volumetric flow rate can be described by the following equation:

$$\frac{dV}{dt} = \frac{AP}{\frac{\mu \, SRF \, w \, V}{A} + \mu R}$$
[7.1]

Where V = volume of filtrate (m³), A = filter area (m²), P = the pressure applied on the top of filter cake (Pa), $\mu =$ viscosity of filtrate (Pas), w = concentration of solid in suspension (kg/m³), *SRF* = the specific resistance to filtration (m/kg), and R = resistance of filter medium (m⁻¹). If the filter cake is incompressible and the initial condition is V = 0 at t = 0, intergration of Eq. [7.1] leads to:

$$\frac{t}{V} = \frac{\mu SRF w}{2 P A^2} V + \frac{\mu R}{PA}$$

$$[7.2]$$

Therefore, *SRF* can be calculated from the slope (b) of the t/V versus V profile using:

$$SRF = \frac{2PA^2}{\mu w}b$$
[7.3]

The SRF is a measure of the resistance of the formed cake to the flow of the filtrate, and therefore it is a measure of filterability of sludge. The lower SRF value, the better filterability. According to the experimental data, the plots of t/V and V were linear for the tailings in the water pressure filtration tests and in the air pressure test in the range before stagnant water was drained. After supernatant water was drained, the relationship between t/V

and V was not linear due to sample drying. Figure 7.26 shows the t/V vs. V plots obtained from different tailing samples used in current research. It can be seen that all the plots give straight lines with different slope, b, values. Table 7.4 shows the SRF values calculated from the b values of the t/V versus V plots. It can be seen that the MFT has the largest SRF value among all the tailings. The SRF values obtained for the TT are lower than that of MFT but they are in the same magnitude. The optimally mixed FMFT sample (AF-1) has lower SRF compared to the over-mixed FMFT (AF-2). It indicates that the SRF value can be used to compare the flocculation results.



Figure 7.26 Plots of t/V against V for different tailings in water and air pressure filtration test at 20 kPa

Test ID	Material	Slope, b	SRF (m/kg)
WM-1	MFT	3.73×10^{12}	1.89×10^{13}
AT-1	TT	3.53×10^{12}	1.79×10^{13}
WT-1	TT	3.41×10^{12}	1.72×10^{13}
WF-1	FMFT	0.70×10^{12}	3.54×10^{12}
AF-1	FMFT	0.66×10^{12}	3.34×10^{12}
AF-2	FMFT	0.37×10^{12}	1.88×10^{12}

Table 7.4 The SRF values for different tailings at 20 kPa

Xu et al. (2008) conducted pressure filtration tests on oil sands tailings to investigate filterability of the tailings with different fines content and before and after polymer treatment. In their work, the largest SRF value $(1.8 \times 10^{13} \text{ m/kg})$ was obtained from the 83% fines content tailing at a filtration pressure of 150 kPa. The SRF reduced dramatically by 5 orders to $2.2 \times 10^8 \text{ m/kg}$ for the tailing with a fines content of 4.3%. It suggests that fines content plays a critical role in filtering the oil sands tailings. Xu et al. proposed that the effectiveness of flocculation in improving the filterability decreased as the fines content increased. In their research, the addition of high-molecular weight polymer reduced the SRF of low fines content

tailings (e.g. 10-20 wt.% fines) by three orders. However, for the high fines content tailings (i.e., 45% to 83% fines), the SRF values was reduced only by 1 order or even less after flocculation. In current research, the minimum SRF for the polymer treated MFT was 1.88×10^{12} m/kg, which is one magnitude lower than that of non-treated MFT (1.89×10^{13} m/kg), this result is in accordance with the literature. Due to this reason, Xu et al. concluded that it is challenging to use filtration technique to dewater fine oil sands tailings in commercial scale even with the assist of polymer since it requires very large filtration area.

7.4.2.2. Discharge rate

Figure 7.27 presents the flow rates determined for the TT in the water pressure tests using different geotextile filters (AT-1, AT-2 and AT-3). Due to a large flow coming out as soon as the valve was opened, the initial flow rate was as high as 10^4 ml/day. The flow rate then dropped sharply to the magnitude of 10^2 ml/ day. Afterwards, the flow rate decreased gradually with time. After 15 days, the flow rate in Test WT-1 (at 20 kPa) tended to be constant at 18 ml/day. In Test WT-2 (at 10 kPa), the flow rate was about 12 ml/day after filtering for 20 days. In Test WT-3, the filtration pressure was increased to 20 kPa at Day 14 and it resulted in an immediate rise of flow rate but this rate dropped quickly and maintained at a level which is higher than that before the increase of pressure.



Figure 7.27 Flow rates measured in water pressure filtration tests with TT

Flow rates measured for MFT and FMFT in water pressure filtration tests (at 20 kPa) are compared in Figure 7.28. It can be seen that the FMFT had a significantly larger flow rate compared to the MFT at the same time. At Day 4, for example, the flow rate of the FMFT was about 100 ml/day while it was 38 ml/day for the MFT. The difference in the flow rates was due to different permeability of the consolidated tailing above the filter. Test WM-1 performed on MFT was stopped at Day 10 due to technical problems, which did not allow the flow rate to reach a stable state. At the end of the test, the flow rate of MFT was 21 mm/day, this value is similar to the that of TT in Test WT-1 at Day 10.



Figure 7.28 Flow rates measured for MFT (Test WM-1) and FMFT (Test WF-1) at filtration pressure 20 kPa

Above graphs show that at a constant filtration pressure the flow rate of the tailing – geotextile system reaches a stable state after a certain filtering time. The stable flow rate obtained from water pressure filtration tests for TT at 20 kPa was 18 ml/day which means that the volume discharged through unit area of filter was 0.23 ml/cm² per day. Assuming this value is the average flow rate of water from the tailing into the PVD and does not change with time, it can be estimated that approximately 4.6 liter water is drained per day by a single wick drain that is 10 m long and 0.1 m wide. Given a fine tailing deposit with average solids content of 35%, a target solids content of 60%, a depth of 10 m, and a single wick drain installed for every 1 m² surface area, the total amount of water that needs to be removed by a single drain is 3000 Liter. This gives a total drainage duration of 652 days. If the PVDs are applied in the polymer treated MFT deposit, the estimated drainage duration to achieve the same target is only 118 days. It indicates that permeability of the tailing greatly affects the flow rate of the system and the drainage duration. It must be pointed out that in practice it is not reasonable to assume a considerable and continuous flow from tailings to wick drains over a long duration because the stresses and strains in the PVD and the hydraulic conditions in real situation are complicated and the long term drainage behaviour of PVD may be influenced by some other factors (e.g., effect of deformation of the drain due to large strain of soft tailings, effect of possible air bubbles trapped in the drainage path).

7.4.3. Clogging behaviour of filter jackets

In this research, one polyester (LDFD) and two polypropylene (D165 and 5417HS) PVD geotextile filter jackets were cooperated with TT to investigate the clogging behaviour of filter jacket of PVD. The well selected geotextiles meet the criteria suggested by guidelines for geotextile filter design. As introduced in the first section, there are some different mechanisms of clogging of PVD. In the following paragraphs, these mechanisms are discussed one by one based on the observations.

The first clogging mechanism is passage of too much fines through the filter jacket and hence clogging of the core of PVD. It may happen if the opening size of filter jacket is too large. The apparent opening size (O_{95}) of the geotextiles used in this work is around 75 μ m, which is larger than 80% of particles in TT. During filtration it was observed that some

particles passed the filter and were discharged through the outlet. However, this phenomenon occurred only during the first minute, the filtrate soon became clean. The observations demonstrate that the selected filter jackets functioned well in retaining particles. It is thus concluded that clogging of cores of PVD is unlikely to happen in the field unless the filter jacket of PVD is poorly designed.

The second mechanism is clogging of filter jacket by particles trapped within the fabric structure. When the amount of trapped particles accumulates to a high level, the permeability of filter jacket may be seriously reduced. Results presented in Table 7.2 showed that an average amount of 0.36g fines were trapped within the filters, which was only 0.05% of total solids in the tailing sample. Such a small amount of fines is considered unlikely to cause a serious reduction of permeability. This has been confirmed by the comparative tests performed individually on the new and the used filters by filling the column with water and measuring the time required to empty the column. Results showed that there was no difference between the two filters. It is concluded that the filter jackets will not be clogged by fine particles as long as the filter is well selected.

The third mechanism is formation of filter cake with very low permeability adjacent to the filter jackets. This mechanism is more likely to happen in fine grained slurry materials. The data presented in Figure 7.16 showed that a consolidated layer with water content as low as 40% was formed above the filter. According to previous research, the hydraulic conductivity of the consolidated layer was in the order of 10^{-10} m/s, which was significantly lower than the permeability of the geotextiles $(1.1 \times 10^{-2} \text{ to } 3.9 \times 10^{-2} \text{ m/s})$. Therefore, the permeability of filter cake controlled the flow rate of the system. Despite of the low permeability clay layer adjacent to the filter, the function of the filter was not affected and a constant flow rate was obtained from the tests.

Finally, for oil sands tailings, the residual bitumen may have adverse effect on drainage by blinding the filter jackets and blocking the drainage channels in filter cake. This is more likely to happen in bitumen-rich tailings. In current study, we did not see much bitumen remaining on the effective filtration area of the filter. The tailings used in the tests contained only a small fraction of bitumen since some bitumen was lost to the container walls and caps during sample preparation and a part of bitumen was released to the supernatant during settling. In addition, in high solids content tailings, majority of bitumen was bonded by clay particles and did not migrate with flow.

7.5. Summary

In this research, a series of pressure filtration tests were performed on TT, MFT and FMFT sludge at equal solids content of 35%. Three different geotextile filter jackets were used in the tests to examine whether they are seriously clogged by fine particles and bitumen. Filtration pressure applied to the column was transmitted through either water or compressed air to the 20 cm high tailing sample, creating different upper boundary conditions and soil profiles after filtration. The monitored flow rate was used to determine the specific resistance to filtration (SRF), an indicative of filterability of sludge for comparison. The clogging potential of the filter jackets were evaluated by visually inspecting the filter discs after the tests. The following major findings and conclusions may be derived.

- The selected geotextile filter jackets (D165, 5417HS and LDFD) all functioned properly in the testing period as long as 40 days. They produced similar flow rate and settlement results for the same tailings at the same filtration pressure. The bitumen and fines in the tailings did not cause serious blinding or clogging of the filter jackets. The layer of consolidated fine tailings formed adjacent to the filter jackets decreased the permeability of the system but did not affect functioning of the filter jacket.
- At a given filtration pressure, the flow rate tended to become constant after a certain filtering time. In the water pressure filtration tests, the steady flow rate was 12 ml/day for the TT-geotextile system at the filtration pressure of 10 kPa and 18 ml/day at 20 kPa. The stable flow rate obtained from the optimally flocculated MFT was 100 ml/day.
- In the air pressure filtration tests at the pressure of 20 kPa, a total amount of 740 g water was discharged from the optimally flocculated MFT after a filtering period of 2 days. In order to reach the same amount of discharged water, the filtration time required for the over-mixed FMFT and TT was 3.8 days and 19 days, respectively. The flow rate of the system and the drainage duration required depend greatly on the permeability of the tailing material.
- The specific resistance to filtration (SRF) values can be used as a measure of filterability of different tailings. Among the tailings studied in this work, MFT had the largest SRF value $(1.89 \times 10^{13} \text{ m/kg})$ indicating the worst filterability. The SRF of sheared TT (e.g. $1.72 \times 10^{13} \text{ m/kg})$ was slightly smaller than that of MFT. After flocculation, the SRF decreased by one magnitude for the optimally flocculated MFT (e.g. $1.88 \times 10^{12} \text{ m/kg})$. The SRF of the optimally flocculated MFT was 47% less than that of the over-mixed FMFT.

This research suggests that clogging of wick drains may not be a decisive factor in deciding whether application of PVD in fine oil sands tailings is feasible. The discharge capacity of the drains is more dependent on hydraulic conductivity of the tailings which is controlled by the consolidation behaviour. In order to completely evaluate the performance of PVD in dewatering fine oil sands tailings, large scale tests should be performed using real wick drains.

Air Drying Tests

8.1. Introduction

Laboratory experiments presented in previous chapters specific investigated some aspects of tailing behaviour related to thin lift sub-aerial drying technology. However, these aspects were developed independently and most of the tests utilised remoulded and small tailing samples. Therefore, the results may not completely demonstrate the tailing behaviour in the real dewatering processes. In order to evaluate the feasibility of thin lift drying in the disposal of fluid fine tailings, it is required to analyse the specific behaviour together to establish an improved understanding of complete dewatering process. To achieve this, the common and economical method is to perform bench scale air drying tests in laboratory. By physical modelling the key processes that would occur in practice, desiccation performance of tailings under controlled conditions can be investigated. Some laboratory investigations on drying behaviour of tailings materials have been undertaken by different researchers. These investigations are worthy of our reference as they provided the idea for the development of experimental work in current research. A brief review on these experiments are presented as follows.

Qiu and Sego (2001) conducted column drying tests on four different types of mine tailings including copper tailings, gold tailings, coal wash tailing and oil sands composited tailings. Each type of tailings were allowed to desiccated by air in two plastic cylinders, one was used for monitoring the actual evaporation rate from the surface and the other was used for sampling. An additional column was filled with water and put at the same height as the tailing surface to measure the potential evaporation rate. The monitored normalized evaporation rates (ratio of between the actual evaporation rate and the potential evaporation rate) were compared among the different tailings. The results showed that the drying processes involved two stages. In the first stage (from 0 to 10 days), the normalized evaporation rates of all the tailings dropped from 1 to different values around 0.6. The decrease in actual evaporation rate was caused by the decrease in hydraulic conductivity of the surface. In the second stage (from 10 to 35 days), the hydraulic conductivity decreased more slowly, and the evaporation rate dropped gradually from 0.6 to 0.2 for copper tailings, from 0.6 to 0.15 for gold tailings, from 0.64 to 0.52 for coal tailings, and from 0.64 to 0.6 for CT (Qiu & Sego, 2011). Unfortunately, Qiu & Sego did not provide any details about the changes of samples during drying (e.g., shrinkage, cracking, side wall adhering) nor gave any analysis on the results. Fasking et al. (2012) carried out box drying tests on the tailings solvent recovery unit (TSRU) tailings produced from Shell Canada Energy's Muskeg River Mine to evaluate changes in geotechnical parameters after additional lifts were placed and dried. The TSRU tailings (SFR = 1) were placed in two lifts (50 cm each) into a test box (0.75m by 0.75 m in cross section). Air was continually circulated into the box producing average 6 mm/day potential evaporation. The second lift was placed when the peak shear strength of the first lift exceeded 20 kPa. The placement of the second lift re-wetted the underlying first lift but the wetting effect was temporary. Before the placement of Lift 2, the matric suction profile for Lift 1 was all above 30 kPa. After the placement, the matric suction in Lift 1 dropped to below 5 kPa. After the placement of Lift 2, the underlying lift lost some strength, but the loss was modest (i.e. < 10 kPa). By Day 6 after placement of Lift 2 the first lift had regained and exceeded the shear strength previously achieved. The second lift developed shear strength more rapidly than the first lift, and to a magnitude disproportionately larger than its water loss or matric suction gain. This is largely attributable to the degree of dryness achieved in the first lift (Todd et al. 2012). Innocent-Bernard (2013) performed small scale column drying tests and multiple lifts box drying tests on oil sand thickened tailings obtained from the Total E&P's Pilot Plant in Alberta, Canada to study the effect of salinity of the tailing on the drying behaviour and to understand the cracking behaviour of the tailings. Results showed that tailings containing lower salt concentrations in the pore-water had higher evaporation rates because lower suction was developed at the surface. Crack formation in the tailings was a main contributor to the increase in actual evaporation rates. The increase in surface area due to cracking and relatively low suctions at the surface gave rise to very high actual evaporation rates but when crack surface area was factored in, they were found to be lower (Innocent-Bernard, 2013).

This chapter presents a study to investigate the air drying behaviour of fluid fine tailings. The main objectives were to determine evaporation rate, surface settlement and soil profiles of the deposited tailings in controlled environment. This program was proceeded chronologically in three stages listed as follows:

• Box drying tests

This group of tests include drying tailings in glass boxes to determine the drying potential of oil sands thickened tailings under different conditions.

• Column drying tests – Phase 1

This test includes air drying the tailing sample in single layer to quantify the evaporative water loss from the tailing surface and correlate it with different factors.

• Column drying tests – Phase 2

This test includes drying the tailing in two layers, one by one, to investigate the comprehensive desiccation and rewetting behaviour.

In this chapter, the content of box drying tests is presented in Section 8.2. The column drying tests are presented in Section 8.3 (Phase 1) and 8.4 (Phase 2), respectively.

Section 8.2 was published.

Yao, Y., van Tol, A.F., van, Paassen, L.A., Everts, H.J. & Mulder, A., 2010. Experimental research on mud farming of fine oil sands tailings. Second international oil sands tailings conference, December, 2010, University of Alberta, Edmonton, Canada: 59-68.

8.2. Box drying tests on Thickened Tailings

8.2.1. Methods and test plan

Box drying tests were performed on fluid thickened tailings (TT) to explore the consolidation and drying behaviour in different conditions. The TT samples used were classified into two groups (i.e., Group A and B) according to different sampling processes. Tailings in Group A were originated from a barrel that had never been opened since the arrival. Group B was the remaining materials stored in the plastic buckets after the classification tests and filtration tests. These materials experienced intensive mixing process in previous experiments and had been stored for three months before they were used in the box drying tests. Use of these two groups of tailings was to see if the degree of shearing can significantly influence the behaviour of TT since TT is a flocculated material. The homogenous tailing sludge (at solid content of 35%) was poured into 10 glass aquariums, 30 cm by 30 cm in dimension of cross section, to a fixed height of 30 cm except one which was 40 cm (Figure 8.1). These glass boxes were placed in different environment, seven boxes were put in two climate controlled chambers with controlled temperature at 20°C and 10°C, respectively. The remaining three boxes were placed in the open air (on a balcony), sheltering from rainfall. For all the outdoor samples and part of the climate room samples, water released from the tailings was removed on a daily basis to accelerate drying. Three boxes were kept as control tests without manually removing water. In the climate room, the fluorescent lights were kept on 24 hours to provide good illumination. Two boxes were put under the table and the side of the table was covered by a black plastic sheet to create a dark environment. The outdoor samples were subjected to alternation of day and night and significant climatic changes. An overview of the box drying tests is given in Table 8.1.



Figure 8.1 Two boxes of tailings with various heights placed in the open air on the balcony

After the stagnant water was evaporated and the surface soil showed some strength, a shallow groove (2 cm deep and 3 cm wide) was made on the surface of the tailing to simulate the effect of "furrowing" applied in sub-aerial dying (mud-farming) of dredged sludge from Rotterdam Harbour (See Chapter 2). During the observation period (approximately 3 months

for indoor samples and 4 months for outdoor samples), height of the tailing (including supernatant water) was recorded with time. Water content and undrained shear strength measurements were conducted at the top part (i.e. 2 cm deep) of the tailing at different time during drying.

Tests	Sample ID	Group (A/B)	Height (cm)	Illumination	Remove water (Y/N)	Temperature (°C)	RH (%)
Outdoor tests	1	А	30	Varying	Yes	Min. 2%	
	2	В	40	Varying	Yes	$\frac{1}{1000}$	40 - 95
	5	А	30	Varying	Yes	Max. 30 C	
Indoor tests	7	А	30	Bright	Yes	20	60-70
	8	А	30	Bright	Yes	10	65-75
	9	В	30	Bright	Yes	20	60-70
	10	В	30	Dark	Yes	20	60-70
Indoor	3	А	30	Bright	No	10	65-75
control	4	А	30	Dark	No	20	60-70
tests	6	В	30	Bright	No	20	60-70

 Table 8.1 Overview of air drying box tests on TT

8.2.2. Results

8.2.2.1. Control tests

Since the rate of evaporation was less than the rate of release water from the tailings, a layer of supernatant water was created in the sample. In indoor control tests, this water was not removed manually. Figure 8.2 shows the temporal evolution of height of the top surface (mud + supernatant water) and mud surface for the samples used in control tests. It is seen that Sample 3 and Sample 4 in Group A had significantly larger initial settling rate than Sample 6 in Groups B (i.e. 3.5×10^{-7} m/s vs. 2.3×10^{-8} m/s). The values of initial settling rates are close to the column settling results presented in Chapter 5 for the samples with various degree of shearing (Figure 5.21). At Day 10 the settling rate in Group A samples decreased to virtually zero while for sludge type B the settling rate decreased gradually over the observation period. At Day 35, a significant elevation of both the supernatant surface and the mud surface occurred in Sample 4 (Group A, 20 °C). This phenomenon was believed to be caused by generation of gas from the tailing since some air bubbles and foams were visible on top of the tailing (Figure 8.3). Gas generation was also observed in Sample 3 which was placed in 10°C environment, but the phenomenon was less pronounced. It demonstrates that the biological reactions, the main cause for gas generation, greatly slowed down at a lower temperature.

In the box drying tests, accumulation of generated gas started to influence the settling of the tailing at about 40 days after the placement. In previous column settling tests (Chapter 5), gas generation was not observed in the TT samples and the reason could be that the observation period was too short. In the column filtration tests (Chapter 7), some gas babbles were observed on the outer surface of the TT at 20 days after the disposition, but there was not any rebound in the upper tailing surface due to high pressure applied on the tailing. For the MFT and flocculated MFT materials used in this project, phenomenon of gas generation was not pronounced in the experiments. Therefore, it is hypothesized that the gas generation in TT was related to the chemical additives used in the conditioning process or some other factors. This cause of gas generation in oil sands tailings could be an interesting topic for the future research but it is out of the scope of this work.

The distinct behaviour between Group A and Group B samples were considered to be the result of degradation of flocs. In this test, the "fresh" tailings (Group A) exhibited typical settling characteristic as a well flocculated tailing with high initial settling rate followed by sharp decrease in the rate. No gas generation was observed in type B samples, which could be explained in two aspects. On the one hand, gas production had been completed in the tailings before they were used in the drying tests. On the other hand, intensive mixing destroyed the environment required by gas generation. Based on the observations, it is concluded that the gas generation had the effect of retarding the self-weight consolidation. However, it did not affect the long term settlement after the dissipation of the air bubbles.



Figure 8.2 The tailings heights for climate room control tests



Figure 8.3 Gas bubbles and foams formed on the surface of TT sample

Rate of evaporation from the supernatant water layer can be estimated from its settling rate. Shown in the Figure 8.2, there was a general linear decrease in the height of the water

surface over the observation period, indicating that there was no significant change in the rate of potential evaporation (PE) in the climate room. Water surface of Sample 6 decreased from 30 to 23 cm in 80 days with an average evaporation rate of 0.88 mm/day at 20 °C. For sample 3 which was placed at 10 °C, the measured average evaporation rate was 0.50 mm/day. At this rate of evaporation, it will take at least 180 days before the stagnant water is completely evaporated. Desiccation of tailing will not occur until the mud surface is exposed to the air. Therefore, it is necessary to take some measures to drain the excess surface water. The results also demonstrated the effect of illumination on evaporation. The tailing (Sample 4) placed in the dark environment showed lower rate of evaporation than the tailing (Sample 3) exposed to light.

8.2.2.2. Climate room drying tests

In the climate room drying tests, water released from the tailing was removed manually on a daily basis. Figure 8.4 shows the heights of the sediment beds for different samples during the tests. Generally, the settling behaviour of the samples are similar to those in Figure 8.3. Gas generation was found in two Group A samples (i.e. Sample 7 and 8). The different magnitudes of the rebounds were caused by different temperature in the environment. For Sample 7, no water was released after Day 15. As the water content of the tailing decreased, it was possible to groove the surface at Day 38. The rebound in the surface of Sample 7 was due to gas production occurring at Day 45. The soil surface dropped quickly with the dissipation of the gas bubbles. The final height of Sample 7 was 4 cm lower than that of Sample 4 in control tests. It showed great benefit of dewatering from the removal of stagnant water.



Figure 8.4 The tailings heights for climate room drying tests

Figure 8.5 shows the water content measured at the top part (i.e. 2 cm) of the soil. From the provided data, it is seen that Sample 7 at 20°C was desiccated at a higher rate than Sample 8 at 10°C. The Group A sample dried faster than the Group B sample. Besides the effect of illumination, more water being released and removed could also be a reason. After a drying period of 80 days, water content at the tailing surface decreased from initially 190 % to the values varying from 70 to 110%. These values are well above the liquid limit of TT, indicating that dewatering of fluid fine tailings by atmospheric evaporation in the climate room is very slow.



Figure 8.5 Changes of water content on the tailing surface for climate room drying samples

8.2.2.3. Outdoor drying tests

Figure 8.6 shows the changing heights for the samples in the outdoor drying tests. Group A (Sample 1 and 5) and Group B (Sample 2) tailings are distinguished by the shape of the setting curves in the initial period. Placed in the open air rather than in the climate room, water was evaporated much faster from the tailings, this is mostly due to the larger air circulation rate in outdoor condition. Similar to Sample 7 in the climate room, no additional water was released from Sample 1 and 5 after Day 16, which is the start of the desiccation. For Sample 2 which was 10 cm higher than other samples, it required a much longer drying duration (i.e. 65 days) before grooving on the surface is possible. Several days after the groove was made on the tailing, a crack initiated at the bottom of the groove, as shown in Figure 8.7 for Sample 1. According to Figure 8.8, the crack initiated at a very high soil water content around 95%. This value is almost twice the cracking water content of MFT and flocculated MFT determined for thin tailing layer (see Chapter 6). This phenomenon suggests that furrowing the evaporating surface can enable the occurrence of desiccation cracks at relatively high water content. The cracks became wider and deeper as drying progressed. At Day 65, for example, the crack formed in Sample 1 had an average width of 19 mm and a maximum depth of 53 mm.



Figure 8.6 Changes of tailing height for outdoor drying samples



Figure 8.7 Initiation of crack at the groove made on the surface of TT (Sample 1)

Figure 8.8 shows the water content and the vane shear strength measured on the top part of Sample 1 and Sample 2. Results of Sample 5 was similar to that of Sample 1, which are not shown for clarity. The graph shows a continuous decrease of water content with the increasing time. At Day 100, the water content measured at Sample 1 was 25%, which is half of the value measured at the surface of Sample 2. Look at the vane shear strength measurements, it is found that it took about 65 days for Sample 1 to reach the undrained shear strength of 5 kPa. For Sample 2 which has 33% more material than Sample 1, the corresponding desiccation duration was 90 days which is 54% longer.



Figure 8.8 Water content and peak vane shear strength measured on the top part of Sample 1 and 2



Sample 1





The outdoor drying tests started from late March with a mean daily temperature at 5°C. The average temperature then increased to about 10°C and 15°C in April and May, respectively. The warmest period during the whole drying process was in July, with the average temperature exceeding 20°C. The average relative humidity varied between 60% and 70% throughout the tests, with the relatively lower values being found in April and July. The results show that Sample 1 and Sample 5 had the accelerated rate of desiccation from June due to rise of temperature. After the 120 days drying, Sample 1 and Sample 5 were dried out and they were split into two parts by the cracks, as shown in Figure 8.9. From the figures, it is also seen that large gaps between the soil and the side wall were formed in each sample and there some soils adhering to the side walls.

8.2.3. Summary of box drying tests

As a preliminary study on atmospheric fines drying, the box drying tests provided an insight into the phenomenon of consolidation and desiccation for thickened tailing. The following observations and conclusions have been reached:

- The fresh and less sheared TT samples (Group A) had a larger water release rate than the old and intensively mixed samples (Group B). Gas was generated in the fresh TT samples at 30-40 days after the deposition. Gas generation behaviour was influenced by temperature. A less amount of gas was generated from the tailings placed in the climate room at 10°C compared to the tailing placed at 20°C. The gas bubbles exerted a retarding effect on self-weight consolidation.
- Excess water released from consolidation must be removed regularly, otherwise the total duration of drying will be extended. Desiccation rate of the tailing was affected by several environmental factors such as the air temperature, the relative humidity of the atmosphere and the air flow velocity above the tailing surface. For the tailing put in the constant 20 °C climate room, the water content measured at the surface of the tailing dropped from initially 186% to 65% after 90 days. However, this value was 95% for the tailing at 10 °C. After the same duration, water content measured at the surface of the surface of the outdoor tailing sample was 35%. The outdoor samples dried obviously faster than the indoor samples mostly due to better air circulation condition.
- Tailing with a larger thickness required longer duration of drying to achieve the desiccation target. When placed in the open air, it required 65 days for a 30 cm thick tailing to reach 5 kPa undrained shear strength at the top part of the soil. For a 40 cm thick layer, it took 90 days to achieve 5 kPa. Therefore, thickness of the tailing may influence the dewatering efficiency. From an operational standpoint, it is suggested that tailings deposition thickness should be adjusted based on climatic variability in each month in order to maximize the potential for evaporative drying.
- Several days after a shallow groove was made on the tailing surface, desiccation cracks initialised at the bottom of the groove while the whole tailing still had high water content (e.g. 80-90%). The crack developed rapidly during drying and it prompted desiccation.

Although the box drying tests demonstrated the air drying potential, the evaporation and desiccation behaviour of the tailings were not fully developed due to some limitations summarized as follows:

- The actual evaporation rate from the tailing surface was not determined because every box with the tailing had a total weight above 40kg and it was difficult to find a reasonably priced scale with sufficient accuracy say 0.1g.
- Desiccation of tailing in the climate room by air evaporation without acceleration was very slow. Outdoor tests lacked well control of the environmental conditions.
- The soil property measurements during the tests were limited only in the top part of the tailing. Profiles of the soil properties were not provided.

• Only one tailing layer was deposited and the rewetting mechanism was not included.

In order obtain an improved understanding of the desiccation behaviour, column drying tests were carried out by considering the limitations of the box drying tests. The content is presented subsequently.

8.3. Laboratory column drying tests - Phase 1

8.3.1. Materials and methods

The main objective of the column tests was to investigate the consolidation and desiccation behaviour of fluid fine tailings. A group of plastic cylinders, 88 mm in inner diameter and 2 mm in side wall thickness, were used to contain the tailings. Different fine tailings materials (TT, MFT and the FMFT) were used in the tests. The TT and MFT samples were prepared as homogenous suspensions with an initial solids content of 35% (void ratio of 4.3). The FMFT samples were prepared from the 35% MFT after the flocculation under the optimum condition. In each column, the fluid tailing was filled to the fixed height of 30 cm. In order to avoid disturbing the sample, water released from consolidation of the tailing was not decanted. To shorten the duration of drying, air pumps with the capacity of 200L/h and 400L/h were used to blow air to the top of the tailing surface. Shown in Figure 8.10, the cylinder was closed by a rubber stopper with an inlet and an outlet. The bottom of the stopper was 4 cm above the filling height of the tailing or water, and the distance between the inlet and the outlet was also 4 cm. The column was placed on an electrical balance connected to a computer, with the total weight of the column being automatically logged with a software. Other parameters such as temperature, relative humidity and height of the sample were monitored throughout the tests.



Figure 8.10 Set-up of column drying test – phase 1

Since the number of air pump was limited at the time of testing, the column drying tests were performed in two groups. The test protocol is shown in Table 8.2. All of the tests

were performed in a climate-controlled room where the air temperature was controlled at 24 °C with the deviation of ± 0.3 °C. The relative humidity of air was fluctuating between 30 and 60% during the tests. In the first group, one MFT column and one water column were allowed to dry naturally by the atmosphere in the climate room. The water column was used to determine the potential evaporation (PE). In order to examine the reproducibility of the drying behaviour, two duplicate tailing samples were prepared in each group (e.g. Column A and B, Column G and H). The total height of sample and the water-sludge interface were recorded with time and the weight of the cylinder was measured one or two times a day. After the completion of drying, the plastic cylinder was cut off and the soil column was sampled layer by layer from the top to the bottom. A small portion of clay was taken from each layer and its water content was determined. A profile of water content was thus obtained and it can be used for analysing the consolidation and drying behaviour.

Group 1							
Column ID	А	В	С	D*	W1		
Materials	MFT	MFT	MFT	FMFT	Water		
Air flow rate (L/h)	200	200	0	200	0		
Group 2							
Column ID	Е	F	G	Н	W2		
Materials	FMFT	FMFT	TT	TT	Water		
Air flow rate (L/h)	400	200	200	200	200		

 Table 8.2 Protocol of column drying tests in controlled environment

8.3.2. Results and analysis

8.3.2.1. Surface settlement

8.3.2.1.1. MFT columns

Since there is no run off mechanism in the column tests, desiccation of the tailings will occur after the excess water released from consolidation is completely evaporated. Figure 8.11 shows the surface settlements of MFT in Column C and the data of the water column (W1) placed in the same environment. It can been seen that the in Column C the excess water was completely evaporated at Day 17. During the period from 0 to 17 days, the settling curve of the sludge was S-shaped while the surface of supernatant water dropped almost linearly. After 17 days from the start, desiccation of the tailing occurred, which resulted in a higher surface settling rate compared to that due to consolidation. Since Day 20, the effect of side wall adhesion started to influence the settlement. As drying proceeded, a growing amount of clay adhered to the side wall and therefore the height of the sample was not correctly measured. In Column W1, the settling rate of the water surface was generally constant in the presented period with an average value of 2.2 mm/day.

For the other MFT columns in Group 1 (e.g. column A and B) which were dried by constant air flow at 200 L/h, no stagnant water was observed in these columns because the water evaporation rate exceeded the water release rate. Since some clay clods adhered to the side wall, the height of the tailing was not accurately measured.



Figure 8.11 Changes of sample height for column C (MFT) and W1 (water) with time at the normal drying rate. Note that the top surface of MFT refers to the sum of the height of mud and the height of stagnant water



Figure 8.12 Settlement of FMFT (column F) and water (Column W2) with air flow drying at the rate of 200L/h and FMFT (Column E) at the air rate of 400L/h

8.3.2.1.2. Flocculated MFT columns

Figure 8.12 shows the settlement curves of two FMFT samples (Column E and Column F) with air pump drying from top at various rates (400L/h vs. 200L/h). The initial settling rates of tailing particles were larger than the evaporation rates, and therefore excess water layers were observed in the both columns. The different consolidation rates of the two tailings were attributed to various mixing conditions during sample preparation. The supernatant water was completely evaporated at Day 13 for Column E and Day 21 for

Column F. Unlike the MFT, there was no serious side wall adhesion effect on the FMFT during drying. Therefore, the sample height was correctly measured. According to Figure 8.13, the height of Column E under a higher rate (400L/h) air flow decreased faster than that of Column F at a lower air rate (200L/h). By comparing the results of Column F and W2, it can been seen that the water surface dropped faster than the tailing surface in the same air drying condition despite of an obvious decreasing trend in the settling rate (evaporation rate). The reason for the decreasing water evaporation rate with time will be discussed in the following section.

8.3.2.2. Rate of evaporation

In practice, rate of evaporation is usually presented as the equivalent depth of water evaporated from the whole area per unit of time. In current research, evaporation rate was determined from the reduced weight of the tailing over the selected interval. The transfer from the mass of the evaporated water to the equivalent depth is 1g = 0.164 mm. The measured rate of evaporation from pure water in Column W2 is shown in Figure 8.13(a). It can be seen that there is a continuous decrease of the evaporation rate during the observation period. The measured evaporation rate at the end of the test was only 44% of the value at the beginning. In this work, the temperature and rate of air flow created by the air pump were kept constant, with the air relative humidity (RH) being variable. Shown in Fig. 8.13(a), the RH fluctuates randomly between 40% and 60%, which is unlikely to create a significant and continuous decrease of evaporation rate. In this test, the source of air flow was fixed at the top of the cylinder while the water surface was falling during drying. It is hypothesized that the decrease of the evaporation rate is related to the increase of the space above water. To confirm this, the evaporation rates are plotted against the distance between the water surface and the bottom of the stopper, as shown in Figure 8.13(b). The figure shows a clear decreasing trend in the evaporation rate with the increasing distance. It is thought that the air flow velocity on the water surface reduces when the distance from the source of air flow increases. As a result, the water vapour is not effectively transported away, leading to higher RH above the water surface.



Figure 8.13 Evaporation rates from pure water (Column W2) changing with time and relative humidity (a) and distance from the water surface to the air inlet (b)



Figure 8.14 Correlation between the evaporation rates measured from different columns in Group 1 and the relative humidity



Figure 8.15 Correlation between the evaporation rates measured from different columns in Group 2 and the relative humidity
Tests information			Mean RH			Mean evaporation rate		
				(%)		(mm/day)		
Column	Matorial	Flow rate	0-15	15-30	>30	0-15	15-30	>30
ID	Material	(L/h)	days	days	days	days	days	days
А	MFT	200				4.3	3.6	-
В	MFT	200	39	44	43	4.4	3.6	3.0
С	MFT	0				1.8	1.8	1.8
W1	Water	0				2.2	2.1	2.1
D	FMFT	200	17	32	-	4.3	3.6	-
E	FMFT	400				5.2	3.9	3.1
F	FMFT	200	48	51	51	3.3	3.6	3.1
G	TT	200				3.8	3.5	3.3
Н	TT	200				3.7	3.5	3.3
W2	Water	200				5.2	3.9	3.1

Table 8.3	Comparison	of mean	evaporation	rates for	samples	in (different	columns
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The whole set of evaporation rates measured from the testing columns in Group 1 and Group 2 are shown in Figure 8.14 and 8.15, respectively. The mean evaporation rates and the mean relative humidity calculated in three different periods (i.e. 0-15 days, 15-30 days, >30 days) during drying are shown in Table 8.3. Based on the data, the main features are summarized as follows.

- The duplicate tests carried out in each group showed good general agreements in the evaporation results. It indicates that the drying tests performed in the same controlled condition are reproducible.
- For all the tailing samples, there was a general inverse relationship between the evaporation rate and the RH. In the main, an increase of RH will result in a decrease of evaporation rate, and vice versa. For example, shown in Figure 8.14, the RH peaked at Day 14 and Day 28, where the measured evaporation rates were lower than that in the adjacent regions. According to Table 8.3, at the temperature of 24 °C and average RH around 40%, the average atmospheric evaporation rate in the climate room was about 2 mm/day and 1.8 mm/day for water and MFT, respectively.
- Experimental results showed that the air flow velocity greatly influenced the progress of drying. In accelerated drying condition, the measured evaporation rates decreased rapidly with the increasing distance between the tailing surface and the source of air flow. However, this performance was not identified in Column C and W1 without accelerated drying. Therefore, rate of evaporation from Column W1 can be used as correct rate of Potential Evaporation (PE) while the evaporation rate measured from Column C is the rate of Actual Evaporation (AE). Figure 8.16 shows the ratio between AE and PE during the 40 days drying. It can be seen that during the first 17 days the value of AE/PE varies between 0.74 and 0.82 with a mean value about 0.8. During this period, a layer of tailing water was created above the sludge (see Fig. 8.12). The data show that the rate of evaporation from tailing water was about 20% lower than that from pure water. One possible reason is that some bitumen floating on the surface of tailing water (see Figure 8.17) may prevent some water molecules from escaping into the air. Another possible reason is that the tailing water contains considerable amount of salts. In the same condition,

evaporation from a salted water is more difficult than from pure water. According to Figure 8.16, the ratio of AE/PE increased to 0.9 at Day 28, regardless of the increase of RH from 30% to 60% during the same period. This behaviour is different from the theory that the value of AE/PE decreases with time due to decreasing soil permeability (Fredlund et al., 2012). In this test, after about 20 days, the top of the soil became fragmentary due to the effect of side wall adhesion. In a cracked soil, the interior of moist soil will lose water by evaporation through the cracks. This amount of water will add to the total evaporation measured from the soil, therefore the evaporation rate from the cracked soil is higher than that of the non-cracked soil. This may explain why the AE/PE value increased after Day 20 in the test. It is assumed that the evaporation rate from the tailing would decrease as the soil properties (i.e. permeability, water retention characteristic) start to influence the evaporation.

For those columns which were subjected to accelerated drying (i.e. Column F, G, H and W2), the actual evaporation rate was affected by both RH and changing height of the sample. The water column, which was used as indicative of PE, evaporated faster than the tailing did, and therefore the evaporation rate dropped faster with the dropping water surface. At a given time, the evaporation rate obtained from water was smaller than the value obtained at the height of the tailing. Due to above reason, the normalised evaporation rates (ratios between AE and PE) are not applicable for the columns in accelerated air drying.



Figure 8.16 Ratio between AE and PE for the MFT column in natural drying condition



Figure 8.17 The bitumen film on the surface of released water above the tailing

8.3.2.3. Sample analysis

At the end of tests, the plastic cylinder was cut off and the soil column was sampled layer by layer from top to bottom. Figure 8.18 shows the water content profiles determined for column A and B after various desiccation periods of 30 and 60 days, respectively. In column A, the minimum water content attained was 34%, which occurred at the top. The water content increased to the maximum of 167% at the depth of 11cm. Due to consolidation, the water content decreased to 140% at the base. It can be seen that, due to drying, the water content values for the top 5 cm soil are below the liquid limit. However, the lower part is not influenced by evaporation. In column B, the difference of water content between the top and the bottom is narrower than that in column A. During the additional 30 drying days, the minimum water content occurring at the top decreased further to 17%. This value was close to the shrinkage limit, indicating a hard crust on the top of the column.



Figure 8.18 Water content profiles for the MFT after 30 days and 60 days drying

8.4. Column drying tests – Phase 2

8.4.1. Modifications to Phase 1

In Section 8.3, consolidation and drying phenomena for fluid fine tailings were well presented by column drying tests, albeit with some limitations which are summarized as: (1) impossible to directly compare AE and PE for the tailing with accelerated drying; (2) only one layer of tailing was deposited; and (3) limited property measurements on the tailings. In order to better describe the tailings behaviour and provide more direct measurements for numerical modelling, additional column drying tests were carried out. The experimental investigations undertaken in this section are nominated as the Phase 2 tests in order to distinguish from the previous research which is referred to as the Phase 1 tests. The modifications made in Phase 2 are highlighted in this section.

8.4.1.1. Design of the test

The Phase 1 tests investigated the drying behaviour of a single tailing layer which was 30 cm thick. In Phase 2, two layers of tailings were deposited and desiccated in each column. Previous tests showed that the soil was soft after 30 days' drying with the air flow being applied at 200L/h. Therefore, in the new tests the air flow rate was increased to 400 L/h. In Phase 1, the height of the sample decreased by 50% after the 40 days drying. Therefore, in the new tests the height of each layer was set to 20 cm to ensure that there is enough room for the second layer to be filled with the same height as the first layer. Table 8.4 provides the protocol of the modified column drying tests. Seven columns, three MFT, three FMFT and one water, were allowed to dry simultaneously in the climate room.

	C1	C2	C3	C4	C5	C6	C7
Materials	MFT	MFT	MFT	FMFT	FMFT	FMFT	Water
Height of 1 st lift (cm)	20	20	20	20	20	20	30
Height of 2 nd lift (cm)	20	20	20	20	-	20	-
Air flow rate (L/h)	400	400	400	400	400	400	400

 Table 8.4 Test protocol for column drying tests – Phase 2

In Phase 1, the drying column was closed by a stopper with air inlet and outlet. This design resulted in a decreasing rate of (potential) evaporation with the reducing height of the tailing sample. In Phase 2, the set-up was modified attempting to keep the distance between the source of air flow and the tailing surface constant throughout the test. The new design is shown in Figure 8.19. It can be seen that the cylinder is not closed and the air is admitted to the cylinder through a funnel with an extended bar held by a clamp. During drying, the position of the funnel is adjusted according to the settlement of the tailing. The distance between the bottom of the funnel and the tailing surface is kept as 4 cm, which is identical to the Phase 1 tests. Compared with the previous design, the modified set-up is able to create more favourable condition for evaporation since the vapour or moisture can be blown away quickly from the soil surface. Before the filling, the inner wall of the cylinder was coated by Vaseline to reduce the interface friction between the clay and the side walls.



Figure 8.19 Set-up used in column drying tests – Phase 2

8.4.1.2. Application of CT technique

The sample analysis results from Phase 1 tests showed that a dense zone was formed in the top part of the column and this zone developed downward during drying. In this research, it is interesting to obtain the distributions of soil density over the height of the tailing. The destructive sampling analysis can be performed only when drying is completed. Therefore, it does not provide information on evolution of desiccation in the tailing during drying. In the Phase 2 tests, the non-destructive x-ray computed tomography (CT) scanning technique was applied to determine bulk density distributions with tailing samples at different time during drying. Compared to other measuring techniques, the main advantages of CT scanning technique include time savings and minimal sample disturbance. In this research the tailing columns were scanned with a medical CT scanner (SIEMENS SOMATOM Plus 4 Volume zoom) which is available in Laboratory of Petroleum Engineering at Delft University of Technology. The plane of image acquisition was vertical, in the direction of the central axis of the cylinders. The intervals of scanning varied between 1 and 5 days, depending on the progress of drying. Since the column was scanned through a single fixed slice, a series of twodimensional x-ray images were obtained. In this work, the CT technique was mainly used to identify the changes of soil density during drying. The soil with high density will attenuate more x-rays than will a low-density soil, therefore, the dense zone and less dense zone in a tailing column will appear differently in an x-ray image. The CT system was calibrated through the correlation between the linear attenuation coefficients of different homogenous materials and their respective tomographic unities obtained by the image reconstruction program.

8.4.1.3. Sample analysis

Compared to the Phase 1 tests, more property parameters such as water content, vane shear strength, total suction and bulk density were determined for the tailing column after drying was completed. The column was split into two parts using a wire saw, one part was used for vane shear strength measurement and the other part was for water content and density measurement (Figure 8.20). The undrained shear strength was measured by inserting a vane (1 cm in diameter and 1.2cm tall) into the soil and rotating the vane until it breaks. The measurements were proceeded alternatively in two parallel lines. The vertical distance between the adjacent measurements was 1cm. The other half of the column was sliced into multiple layers, each layer was 1cm thick. Small portions of clay were then obtained from each layer to determine the water content, density and suction. The density was measured using the paraffin coated method and the suction was measured using the WP4C dew-point potentiometer.



Figure 8.20 Sampling of the column for analysis of vane shear strength, suction, water content and bulk density

8.4.2. Results and discussions

8.4.2.1. Evaporation rate

Figure 8.21 shows the evaporation rates measured from pure water filled in Column 7 and compares them with the simultaneously measured RH of ambient atmosphere. In Figure 8.21a, it can be seen that the decreasing trend occurring in the evaporation rates from Phase 1 tests was eliminated with the use of the modified set-up. In this case, the evaporation rate changed inversely with the change of RH. Fig. 8.21b shows the plots of the evaporation rates against the corresponding RH values. According to the results, there is no well-defined relationship between the two variables. It indicates that the evaporation rate was not solely dependent on the RH but was affected by other uncertain factors. In this group of tests, rate of air flow applied to the column was 400L/h, which twice as large as the air flow rate used in the Phase 1 tests for the water column (W2). In this test, the average rate of evaporation from water was 12.6 mm/day with an average RH value of 40% during the first 6 days. For Column W2 in previous tests during the same period, the average water evaporation rate was 5.6 mm/day with a mean RH of 50%. It shows that in the similar conditions (i.e. the water surfaces are both initially 4 cm from the air inlet) the evaporation rate is proportional to the air flow rate. It again highlights the importance of air flow velocity to evaporation. In this group of tests, the evaporation results obtained from Column 7 were used as PE for the tailing samples placed in the same environment.



Figure 8.21 Evaporation rates measured from water during the drying tests (a) and relationship between evaporation rate and relative humidity (b)



Figure 8.22 The measured rates of AE for MFT and FMFT in comparison with the measured rates of PE

Figure 8.22 shows the measured evaporation rates for two MFT samples (Column 2 and 3) and one FMFT (Column 6). The evaporation rates measured from water column are provided for reference. It can be seen that the evaporation rates from Column 2 fluctuate about a mean value of 4 mm/day in the first 10 days. After that there is a sudden increase in evaporation and a peak value of 9.9 mm/day is reached at Day 13. A similar trend was observed in the second layer. The sharp increase of evaporation rate in Column 2 was caused by significant change in the shape of the tailing surface due to the side wall adhesion. It was found that up to Day 10 a considerable amount of soils had adhered to the side walls while the central part of the tailing was still settling. As a result, shrinkage cracks and fragmentary surface were formed in the column. The increase of evaporation is because the surface area of

the tailing is enlarged and the cracks expose new material of low suction to the air flow. In the second layer, a similar change in evaporation rate took place at Day 22, which was 7 days after the placement of the second layer. At Day 28, the evaporation rate reached the peak value followed by continuous decrease till the end of test. It indicates that the formation of low permeability crust obstructs the water removal from the soil surface. Column 3 exhibited similar evaporation behaviour compared to Column 2. The difference was that the significant change of tailing started earlier, this is why the increase of evaporation rate took place earlier in Column 3 compared to Column 2.

From the results of Column 6, it can be seen that the evaporation rate measured from the FMFT changed synchronously with the evaporation rate from water. The data indicate an average AE/PE ratio of 0.7 for the tailing when the supernatant water was presented. This value was slightly less than that of the MFT containing supernatant water (Figure 8.16). Besides of the bitumen film, some unabsorbed polymer solution was found in the supernatant water of FMFT. The viscous polymer may also decrease the evaporation rate measured from supernatant water. Fig. 8.22 showed that the AE/PE ratio for the FMFT was about 0.6 after the excess water was evaporated. This value was lower than the average monthly AE/PE ratio (0.75) reported by Kolstad et al. (2012) for a newly deposited FMFT in the field tests. The field AFD tests have run-off mechanism for excess water and due to this the floating bitumen may flow away. This mechanism is not applicable in the column drying tests. Therefore, some floating bitumen dropped to the tailing surface after the stagnant water was evaporated. This bitumen may to some extent obstruct evaporation. Unlike the different mine tailings described by Qiu & Sego (2001), the AE/PE ratio for MFT was smaller than 1 in the range when the soil is fully saturated. Besides of the bitumen on top of tailing, the evaporation behaviour could also be affected by the salinity of pore water. In this test, some salt crystals were visible on the surface of the desiccated tailing (Figure 8.23). These salts are likely to be $CaCO_3$ or/and CaSO₄ as they are found insoluble. The salts increased the salinity at the surface, which may suppress evaporation by development of high osmotic suctions. Innocent-Bernard (2013) proposed that tailings containing lower salt concentrations in pore-water had higher evaporation rates.



Figure 8.23 Presence of salt crystals on a desiccated MFT sample

8.4.2.2. Surface settlement

Figure 8.24 shows the settlement results for the FMFT sample in Column 6 during the whole drying period. The blue diamonds on the graph stand for the total height of the material (mud + water) and the red squares represent the height of the mud surface. Column 4 and 5 have similar results to Column 6, therefore they are not presented for clarity. It can be seen that the height of the first tailing layer decreased from initially 20 cm to 11 cm after the period of 16 days. The stagnant water surface and the mud surface converged at Day 11, indicating that the stagnant water was completely removed by evaporation and desiccation of the sediment started. From Day 11 to 16, the tailing surface settled at a gradually decreasing rate. The second layer was filled with 1450 g tailing material which is equivalent to a thickness of 19.1 cm. However, after the filling the height of the tailing was increased by 18.1 cm, it means that about 1 cm thick sludge (about 61 cm³) was filled the shrinkage gap between the first layer and the side wall. The settling behaviour for the second layer was similar to that in the first layer. At Day 40 the final height of the tailing was 16.3 cm. In Column 4, the final height attained after 40 days was 17 cm. In column 5, only one tailing layer was filled and this layer was dried for 24 days. The final height of the sample was about 9.5 cm.

In this column, about 7 cm settlement of the tailing in the first layer was caused by sedimentation and self-weight consolidation. It means that a total amount of 426 ml stagnant water was evaporated, which is 43% of the total water in the tailing. The average water content of the remaining sediment was 106 % and the average density was 1.38 g/ml. The final volume of the first layer can be estimated from its height measured at Day 16. It is noted that the equivalent depth of the shrinkage gap volume must be deducted. The calculated average water content for the first layer at Day 16 was 71% and the average density was 1.5 g/cm³. In this test, it took 11 days of drying to lower the tailing water content from 185% to 105% and 5 days to further reduce it to 71%. It suggests that rate of evaporation from water is larger than from tailing. Therefore, a tailing with fast settling rate will show higher dewatering efficiency. For the polymer treated MFT, the settling rate is largely affected by flocculation. This highlights the importance of investigating the flocculation behaviour.



Figure 8.24 Changes of the height of the FMFT in Column 6

8.4.2.3. Results of CT scanning

8.4.2.3.1. MFT

Figure 8.25 shows the exported x-ray images for one MFT sample (Column 2) at different time during the whole drying process. In these x-ray images, the grey-scale level (or brightness) increases linearly with the increasing density. In other words, the denser material is brighter than less dense material on the image. For example, the bulk density of the plastic cylinder (i.e. $\approx 900 \text{ kg/m}^3$) is smaller than that of the MFT sample ($\approx 1200 \text{ kg/m}^3$), therefore the side walls and the base of the cylinder have a lesser brightness compared to the tailing. The air has a very low density close to zero, and therefore it totally black in the image. The xray images reveal some features of drying which were not found in the previous tests. As shown in the first image (at t = 0) in Figure 8.25, the sludge in the column was uniform in grey scale, indicating high homogeneity of the tailing sludge before drying. Looking carefully into this image, one can see a few dark dots, which are randomly distributed in the sludge. These dots are the air bubbles which were mixed in the sludge during the filling. From the second image (at Day 2), it is interesting to note that some brighter zones appear in the sludge. It is thought that these zones were some clay lumps formed by aggregation of naturally occurring flocs and particles. From the third image (at t = 3), some additional clay lumps were produced. These lumps were suspended in the tailings and settled slowly. Not only in Column 2, clay lumps of various shape were also found in Columns 1 and 3. In order to show the density ranges of the clay lumps, the x-ray images are transferred into the colour ones using a MATLAB program, with different colours representing different density values. Figure 8.26 shows the colour density images for the three MFT samples during the first 8 days. It can be seen that the lumps formed in the MFT have varying density values in the range from 1460 to 1670 g/cm³. These lumps had significantly larger density than the surrounding tailings which was about 1280 g/cm³ in bulk density. The image of Column 3 at Day 3 shows that the bottle shaped clay lump dropped to the bottom of the column and turned an angle about 30°. The settlement of the lump may be caused by the disturbance during transportation of the cylinders. Comparing the images between Day 3 and Day 8, it can be seen that the densities of the exiting lumps did not change until the desiccating zones reached these lumps. Without the CT technique, these clay lumps cannot be identified. This phenomenon was not reported in the open literature. In the author's opinion, the higher density lumps are formed by the aggregation of clay particles in MFT mostly due to attraction of surface charges. The bitumen and the turbulence during the tests may also play a role.









Figure 8.25 The whole set of the original x-ray images for Column 2 during the period of 40 days (continued)



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8.4.2.3.2. Flocculated MFT

Figure 8.27 shows the x-ray images obtained from CT scanning for a fixed vertical slice of Column 4. The images for Column 6 are provided in Figure 8.28. From different grey scale levels, the stagnant water, the desiccated first layer, and the wet second layer are well distinguished. As is shown by the 2-D images, after the stagnant was evaporated, lateral shrinkage occurred at the top of the tailings and a gap was created between the soil and the side wall. This gap became larger and deeper as drying continued. After the filling of the second layer, the interface between the first and the second layer was initially very sharp. About 20 days later this interface became blurred as the densities of the two layers approached. Finally, the interface disappeared and the two layers merged. It is noted that in Column 6 there were three large gas bubbles in the lower part of the tailing. These bubbles were not released nor compressed during the tests, however, the distances between each of them were reduced due to consolidation of soil. Some additional gas bubbles were produced in the later stage of the tests and they were distributed mostly in the lower part of the column. Bajwa (2015) reported that the MFT had 6.5% organic and 93.5% inorganic contents and the polymer amended MFT did not alter the fractions of organic and inorganic contents of MFT. These gas bubbles were produced by decomposition of organic material. Since these bubbles were relatively small (i.e. average 2mm in diameter) and they occurred at the later stage of drying, the gas production did not influence the consolidation of the tailing.

Figure 8.29 and Figure 8.30 present two sets of bulk density profiles for Column 4 and Column 6, respectively. The bulk density profiles were derived from the x-ray images by plotting the average density values calculated from the grayscale values of the pixels (excluding the cylinder) with the height. In the main, Figure 8.29 and 8.30 illustrate similar features of consolidation and desiccation except slight difference in the rate of progress. Since the MFT-polymer mixture was well mixed before the filling, the bulk density profile at t = 0in each figure was almost linear over the height with an average bulk density of 1260 kg/m³. The boundary between the stagnant water and the settling sludge can be easily recognized by the step in the corresponding profile (i.e. at t = 3 days). Looking at Fig. 8.29, it is noted that from Day 3 to Day 10 there was a sharp increase of the density at the surface of the tailing while the densities for the lower part did not change much. It indicates that a thin desiccated crust was formed. The thickness of the crust increased as drying progressed, in particular after the occurrence of lateral shrinkage at the top. For example, the profile at Day 14 shows that the thickness of the crust was about 2 cm. In this profile, it is found that the density values at the top part was lower than that of the previous profile. This is due to the density of air in the shrinkage gaps between the soil and the side walls was reckoned when calculating the average density of the tailing. According to the profiles, the maximum bulk density attained at the surface of the tailing after 16 days was about 1680 kg/m³ for both Column 4 and 6. The corresponding values at the bottom were also similar, which was around 1500 g/cm^3 .



Figure 8.27 The whole set of the original x-ray images for FMFT in Column 4 during the drying period of 40 days

Column 6



Figure 8.28 The whole set of the original x-ray images for FMFT in Column 6 during the drying period of 40 days



Figure 8.29 Bulk density profiles derived from CT scan for FMFT in Column 4 during drying



Figure 8.30 Bulk density profiles derived from CT scan for FMFT in Column 6 during drying.

The second layer was filled above the existing layer at Day 16. The last density profile for the first layer is compared with the profiles determined at Day 17 and Day 26, as shown in Figure 8.31. It can be seen that one day after the filling of the second layer the peak density of the first layer decreased from 1680 to 1550 kg/m³. Meanwhile, at the bottom, the soil density decreased from 1500 to 1450 kg/m³. It indicates that the wet tailing layer exerted a rewetting effect on the underneath layer. The figures show a minor increase of the density at the lower part of the column at Day 26, this is considered the consequence of consolidation by the weight of overlapped layer. It should be pointed out that the filling of the second layer did not cause significant swelling in the first layer. This highlights the potential advantage of depositing the tailing in multiple layers. Compared to the first layer, the second layer was allowed to dry for additional 8 days. During these days, the density at the bottom of the newly deposited layer was approaching the value at the top of the existing layer. The final density profiles at Day 40 show a continuous transition from the upper layer to the lower layer.



Figure 8.31 Comparison of the density profiles before and after the filling of the second layers

Figure 8.32 shows part of the density plots for the FMFT in Column 5. In this column, the tailing was desiccated for 24 days and then soaked with water for another 16 days. The image at Day 36 shows that the volume of the sample increased both laterally and axially after a soaking period of 12 days. However, the magnitude of swelling was relatively small. According to the measurements, the maximum increase of the sample height after the 16 days soaking was only 0.4 cm, which was 4.3% of the tailing height before wetting. It is noted that the gas bubbles in the desiccated tailing were not filled by water. This is because the desiccated soil had very low permeability and water did not seep into the soil matrix.



Figure 8.32 The plots of bulk density for the FMFT in Column 5. The tailing was desiccated for 24 days followed by a soaking period of 16 days



Figure 8.33 Bulk density profiles derived from CT scan for Column 5. Water was filled at Day 24

Figure 8.33 shows the set of density profiles for Column 5. The exhibited desiccation behaviour from 0 to 24 days is similar to that of Column 4 and 6. At the end of drying, the maximum bulk density attained at the tailing surface was about 1690 kg/m³. This values was not much significantly larger than the corresponding values in Column 4 and 6 where were dried only for 16 days. This is because a wider gap between the soil and the cylinder was formed at the top part of the tailing and therefore the calculated average density was underestimated due to the low density of the gap. At Day 26, two days after filling with water, the maximum density decreased to 1590 kg/m³. Four days later (Day 30), this value was

decreased to 1500 kg/m^3 . The last two images show minor increase in densities, which was caused by consolidation.

8.4.2.4. Sample analysis after the tests

After the source of air drying was removed, the samples in Column 4 and 6 were split vertically into two halves. One half was sliced over the height for the measurement of water content, bulk density and total suction. The other half was used to determine the undrain shear strength using a laboratory scale vane. Figure 8.33 shows the profiles of (a) water content, (b) bulk density, (c) peak vane shear strength and (d) total suction for the two samples. In general, all the profiles have smooth transitions from the upper layer to the underlying layer. It is concluded that the lowest water content of the tailing is accountable for the largest value of bulk density, vane shear strength and total suction, and vice versa. In Column 4, the minimum soil water content was 35%, which was obtained from the top 1 cm thick slice of the tailing. From the same height, the maximum values of bulk density, vane shear strength and total suction were 1.64 g/cm³, 135 kPa and 500 kPa, respectively. In Column 6, the water content at the top part of the tailing was 32% and the other parameters were 1.66 g/cm³, 163 kPa (peak vane shear strength) and 740 kPa (total suction), respectively. It is noted that the minimum strength of the tailing did not present at the bottom but at a height over the bottom (i.e. 4 cm for Column 4 and 3 cm for Column 6) where the water content value was the highest. Comparing the data between Column 4 and 6, it is found that that Column 6 was slightly drier than Column 4.



Figure 8.34 Experimental measurements for FMFT (Column 4 and 6) in two layers after 40 days

The bulk density values determined using the paraffin-coated method (Fig.8.34b) are compared with the density profiles obtained from CT scan results to see whether they are equivalent. It is known that the densities obtained from CT scan underestimate the average bulk density due to the gaps between the soil and the side wall. However, the results obtained using the paraffin-coated method may also underestimate the density, since all the samples were taken from the core of the column, which was lower in density compared to the outer part of the column where a desiccation crust was formed. Due to the compensation effect, the measured results and the CT scan results are in general good agreement (Figure 8.35).



Figure 8.35 Comparison between the measured densities and the CT scan results



Figure 8.36 Profiles of void ratio (a) and degree of saturation (b) for FMFT after 40 days

Using the determined water content and bulk density, the void ratio and degree of saturation values of the soil at different heights can be calculated using the constitutive relationships (Eq.[6.3] and [6.4]), as shown in Figure 8.36. The void ratio profiles are similar to the water content profiles. The degree of saturation values are a bit scattered due to measurement errors. The average degree of saturation was 94% for Column 4 and 93% for Column 6, indicating that most of the tailings were partially saturated. The vane shear

strength measurements on the samples provide a measure of shear strength of the tailing. In the following paragraphs, some analysis are made based on the plots of water content and other parameters.

Firstly, the void ratio values obtained from Column 4 and 6 are plotted against the corresponding water content values, which yields the shrinkage data of the tailing. These data are compared with the shrinkage curve assessed using remoulded samples, as shown in Figure 8.37. In the provided ranges, the void ratio – water content plots are generally linear. This feature belongs to the normal shrinkage stage. Unlike the delicately measured shrinkage curve, the shrinkage data deviated from the 100% saturation line. The explanation for this deviation is that the samples have been wetted by the overlapped tailings and thus show some hysteresis on the plots. In this test, the minimum water content attained was around 35%, which was larger than the shrinkage limit of the material. It means that the desiccation was not completed.



Figure 8.37 Plots of the measured water content and void ratio of FMFT in Column 4 and Column 6

In Figure 8.38, the measured total suctions are plotted against water content in a semilogarithmic scale. The results are also compared with the total suction - water content relationships and the soil water characteristic curve (SWCC) assessed using remoulded FMFT (see Chapter 6). It can be seen that the column tests data are different from the separately measured data for the FMFT in water content range between 40% and 60%. Again, the deviations are caused by the hysteresis effect, which has been demonstrated in Chapter 6. It is noted that at lower water content values (i.e. < 40%) the column tests data coincide with the independently measured suctions. According to Figure 8.34a, the values falling into this range were obtained from the upper layer, which was not subjected to rewetting. Similarly, water content values above 60% were mainly from the lower part of the first layer. The overlapped tailing exerted a smaller wetting effect on this part of soil. Therefore, the measured total suctions from this part were similar to the independently measured data. Above phenomenon indicates that suctions in a multiple lifts tailing deposit is dependent on the wetting and drying processes.



Figure 8.38 Plots of the measured suction and water content values for FMFT in Column 4 and Column 6 and comparison to independently measured values



Figure 8.39 Plots of vane shear strength and water content for the FMFT columns and comparison to the vane shear strength data measured on remoulded FMFT

Finally, the vane shear strength values are plotted against the water content. In the literature, undrained shear strength is conventionally correlated to void ratio of the soil. In this work, it was thought that water content is direct measurement data which is more accurate and reliable than void ratio. Therefore, in Figure 8.39, the vane shear strength data are correlated to water content and the results are compared with the peak vane shear strength values determined for remoulded FMFT samples in the preliminary work (Yao et al. 2010). As shown in the figure, the shear strength values obtained from the desiccated columns are significantly larger than the values of the remoulded FMFT at the same water content. According to the author's understanding, this difference could be understood in the following two aspects. First, it is due to various saturations of the samples. The remoulded FMFT

samples were prepared as saturated until the water content decreased to 35%. Compared to the saturated soils, the unsaturated soils behave as if over-consolidated to some degree (Blight, 2013) and they are more tough at the same water content. Secondly, it is due to varieties in floc structures. The remoulded samples were thoroughly mixed before they were filled layer by layer into the sample cups. It is believed that majority of the floc bonds were broken due to mixing. On the contrary, in the column tests, the vane shear strength was measured in-place with a minimum disturbance on the soil structure. Blight (1969, 2013) pointed out that the vane shear strength value for the undisturbed soil represents the strength of intact material between desiccation-caused discontinuities while the value for remoulded sample represents the strength on artificially produced fissure surface, and that the undisturbed vane shear strength far exceeds the remoulded vane shear strength.

8.4.3. Summary of column drying tests

Laboratory column drying tests were performed on fluid fine tailings investigate the evaporation rates and the changes in sample height, density and some other property parameters during air drying. Compared with the box drying tests, the main advantages of the column tests are the availability of the evaporation rate measuring and the analyse of the soil property profiles. The column tests were performed in two phases. In Phase 1, the consolidation and desiccation phenomenon in fluid fine tailings was described. Effects of air relative humidity, air flow velocity, side wall adhesion and shrinkage cracking on the evaporation rates were explored. In Phase 2, the tests were modified based on the results of Phase 1 in the following main aspects: (1) the position of the source of air flow was adjusted according to the settlement of the sample; (2) tailings were deposited in two layers and the rewetting effect on the existing layer was investigated; (3) CT scanning technique was applied to determine the soil density profile and the interior changes; (4) suction and shear strength were measured after the tests. The results indicate that these modifications helped to gain a deeper insight into the desiccation behaviour of the tailings. The main observations and conclusions from the column drying tests are summarized in the following paragraphs.

- Results of column tests performed in the controlled environment demonstrated that evaporation rate was heavily dependent on the relative humidity of ambient atmosphere. The rate of water evaporation changed synchronously and inversely with the changing RH. In the water column (natural drying condition) in Phase 1, the average evaporation rate was 1.81 mm/day when the average RH was 52%, when the RH decreased to 30% the evaporation rate increased to 2.63 mm/day.
- The evaporation rate was also greatly influenced by air flow velocity. When the air pump was used to provide an air circulation in the column, the evaporation rate was greatly increased. For different water columns placed in the environment with similar RH, e.g. 50%, the measured evaporate rates were 1.9 mm/day in natural drying condition, 5.2 mm/day with accelerated drying at the rate of 200L/day and 10 mm/day at the air flow rate of 400L/day. In the tests with accelerated air drying (Phase 1), the air flow velocity decreased with the increasing distance between the sample surface and the source of air flow. For example, in the water column desiccated by air at 200L/h, the evaporation rate was about 6 mm/day when the water surface was 5 cm away from the air inlet. The evaporation rate dropped significantly to about 2.8 mm/day when the water surface was 22 cm away from the air inlet.

- The evaporation rate measured from the tailing column was influenced by the surface shape and permeability. The MFT suffered greatly from the side wall adhesion in particular in the accelerated drying condition. In these columns, clay on the boundary adhered tightly to the side wall while the central part of tailing dropped, resulting a quick and sharp increase of the surface area exposed to the air. Therefore, the measured evaporation rate was significantly higher than that from the original tailing surface. This phenomenon was not observed in FMFT samples as the particles bonds in the tailing after flocculation are strong enough to resist the soil plastic interface cohesion and the tailing column remained as whole throughout drying. Although the lateral shrinkage led to increase of the surface area, this increase was small and did not cause large change of the evaporation rate.
- After calibration, the CT scanning technique provided correct and accurate bulk density values. With this technique, the density profiles of the tailing can be obtained. In general, the desiccation process of a single tailing layer can be described as follows. After the stagnant water was evaporated, desiccation started from the surface. The densest part occurred at the top of the tailing where a high density crust was formed. The thickness and density of the crust increased as drying was proceeded in particular after the occurrence of lateral shrinkage. At the bottom the soil densities increased slightly due to consolidation under the self-weight and the weight of the overlapped layer. However, the magnitude of the increase in density caused by consolidation was not comparable to that caused by drying.
- In Phase 2, an initially 20 cm high FMFT sample (35% solid content) was dried by air flow at constant rate of 400L/h. After 16 days, the height of the tailing decreased to 11 cm with obvious lateral shrinkage at the top. During this period, the average evaporation rate was 6.4 mm/day and the AE/PE ratio was around 0.6 after the removal of stagnant water. Some bitumen and salt crystals were found at the surface of desiccated tailings, indicating that the actual evaporation may be supressed by the bitumen film on the tailing surface and high osmotic suction by the salinity of pore water. The second tailing layer was filled above the first one and dried at the same condition for another 24 days. Two days after the filling of the second layer, the peak density of the first layer decreased from 1680 to 1550 kg/m³, however, there was almost no vertical swelling on the first layer. The difference in bulk density between the two layers decreased as drying continued and the two layers eventually merged. The final height of the tailing column was about 16 cm, with the second layer being 5 cm. Sample analysis results show that the tailing columns were partially saturated after drying. The shear strength values obtained from the column were much higher than the independently measured values for remoulded FMFT. The total suction measurements on the columns demonstrate the hysteresis effect between drying and rewetting.
- With the help of CT scanning technique, interior changes of the tailing samples can be identified from the changes in soil density values. In this research, the x-ray images provided two new features regarding the settling and drying behaviour of fine tailings. The first one is that some large and dense clay lumps were formed in the MFT slurry 1-2 days after the deposition. These irregular lumps had the density values varying from 1460 to 1670 kg/m³. Most of the lumps were suspended in the slurry throughout the tests while several larger ones dropped to the bottom. Once formed, density of the lumps did not change until the desiccation zone reached them. The second one is that some gas bubbles were observed in both the MFT and FMFT samples. These gas

bubbles were relatively small (i.e. 1 to 3 mm in diameter) and did not appear to influence the consolidation behaviour.

Numerical Simulation

9.1. Introduction

In previous chapters, important engineering properties of fine oil sands tailings have been investigated. These investigations provided the material properties that can be used for the prediction of tailing behaviour and the Column drying tests data used for validation of numerical model. In this project, a numerical model has been developed to characterise atmospheric fine drying behaviour. This model was based on an existing drying model proposed by Kim et al. (1992) and extended by Van der Meulen (2012) and Nijssen (2013) in two MSc projects at Delft University of Technology, with a realistic rewetting behavior being involved. In these MSc projects, multiple calculations on consolidation and desiccation behaviour of deposited fluid fine tailings have been carried out. The model was validated with results from the laboratory self-weight consolidation tests and column filtration tests presented previously in this thesis. The predicted and measured surface settlements and void ratio profiles were in good agreement. A Tailing Drying Simulation Tool was developed by Vardon (2014) using the Matlab interface for the ease of operating the model. In current work, the developed simulation tool was utilised to simulate the laboratory column drying test (phase 2) described in Chapter 8 and the field AFD tests undertaken by Shell on the polymer treated MFT. The objective was to test the computational performance of the model, which was achieved by comparing the simulation results and the experimental data.

This chapter first presents the developed numerical model. In Section 9.2, the basic elements of the model including governing equation, equations for material properties and boundary conditions are presented. Model implementation is then described, with a number of features designed to allow models to be solved within reasonable timescales for design purposes. In Section 9.3, simulation results for laboratory column drying test and field AFD drying tests are presented. The results have been published by Vardon et al. (2014) prior to the availability of field tests experimental data to the author. Therefore the field test simulations are called Class A blind predictions. Some additional simulations have been undertaken for the field tests based on comparison of the Class A predictions and the experimental results. The updated results are then compared and analysed. A summary is then given in Section 9.4.

9.2. Numerical model

9.2.1. Theoretical formulation

9.2.1.1. Governing equation

The basis of the model is the conservation of mass and Darcy's Law made from the components of soil matric potential, gravitational potential and overburden potential. The conservation of mass equation can be expressed as:

$$\frac{\partial \Theta}{\partial t} = -\nabla v \tag{9.1}$$

where Θ is the volumetric water content, defined as $(V_w/V_t$ where V_w and V_t are the volumes of water and solids), *t* is the time, ∇ is the gradient operator and *v* is the Darcy velocity, with Darcy's Law expressed as:

$$v = -K\nabla\phi$$
[9.2]

where *K* is the hydraulic conductivity and \emptyset is the total potential formed from the components of soil matric potential, gravitational potential and overburden potential:

$$\phi = \varphi + z + \Omega \tag{9.3}$$

where φ is the soil matric potential, z is the gravitational potential and Ω is the overburden. Combing equations 9.1 to 9.2 and resolving for a single dimension, leads to the conservation of mass equation as stated by Kim et al. (1992) for one-dimensional water movement in a shrinking marine clay (incorporating Darcy's Law):

$$\frac{\partial\theta}{\partial t} = \frac{\partial}{\partial m} \left[K^* \left(\frac{\partial\varphi}{\partial m} + SF1 + SF2 \cdot \frac{\partial\theta}{\partial m} \right) \right]$$
[9.4a]

$$SF1 = (1+e) - (\theta + \gamma_s) \frac{\partial e}{\partial \theta}$$
[9.4b]

$$SF2 = \frac{\partial^2 e}{\partial \theta^2} \int_0^m (\theta + \gamma_s) \, dm \tag{9.4c}$$

where, θ is the volumetric water ratio $(V_w/V_s$ where V_w and V_s are the volumes of water and solids, $\theta = \Theta/(1 + e)$), the material coordinate, *m*, has been chosen in the Lagrangian system, such that Eulerian vertical coordinate *z* can be recovered by z = m (1+e), K^* is the hydraulic conductivity transformed into the Lagrangian coordinate system $(K^* = K/(1 + e))$, *e* is the void ratio and γ_s is the density of the solids. By including $\partial \varphi/\partial \theta$, $\partial e/\partial \theta$ and K^* as material parameters, θ is then able to be solved spatially and temporarily utilising numerical methods such as the finite difference method that is employed in this model.

9.2.1.2. Soil water retention characteristics

The soil water retention, i.e. $\partial \varphi / \partial \theta$, is modelled using the well-known van Genuchten (1980) equation for drying:

$$\theta = WCR + \frac{WCS - WCR}{(1 + (\alpha_{WRC} \cdot \varphi)^{n_{WRC}})^{m_{WRC}}}$$

or $\varphi = \frac{1}{\alpha_{WRC}} \left[\left(\frac{WCS - WCR}{\theta - WCR} \right)^{1/m_{WRC}} - 1 \right]^{1/n_{WRC}}$ [9.5]

where WCR is the residual (volumetric) water content, WCS is the water content at full saturation and α_{WRC} , n_{WRC} and m_{WRC} are fitting parameters, where m_{WRC} is defined as $m_{WRC} = 1 - 1/n_{WRC}$.

The theoretical van Genuchten SWRC predicts infinitely high suctions at very low water contents, which are neither realistic or easy to numerically solve. Therefore, a modified relation has been introduced that yields a (log) linear portion at low moisture contents (Romero and Vanaut, 2000), in terms of the effective saturation (S_e):

$$S_{e} = \frac{\theta - WCR}{WCS - WCR}$$

$$S_{e} = C(s) \left(\frac{1}{(1 + (\alpha_{WRC} \cdot \varphi)^{n_{WRC}})^{m_{WRC}}} \right)$$

$$C(s) = 1 - \left(\frac{ln \left[1 + \frac{\varphi}{a_{WRC}} \right]}{ln(2)} \right)$$
[9.6]

This relation is known from herein as the modified van Genuchten relation (note that a is a new parameter and alpha is a different parameter than in equation 9.5). There is no analytical inverse, therefore this is solved iteratively in the code when needed.

As this model is designed for virgin soils (sludge) the first re-wetting re-drying loop is likely to be significantly different from the original drying behaviour, with a lower water content yielded for the same suction value. Therefore, following the approach of Rijniersce (1983), a ten times stiffer relationship in a log-linear space has been utilised, expressed as follows:

$$\varphi = 10^{A_{WRC}\theta + B_{WRC}}$$
[9.7a]

where A_{WRC} and B_{WRC} are material parameters defined as follows:

$$A_{WRC} = \frac{1}{\varphi_{max}} \frac{\partial \varphi}{\partial \theta} \Big|_{\varphi = max}$$
[9.7b]

$$B_{WRC} = \frac{\log(\varphi_{max})}{A_{WRC}\theta_{min}}$$
[9.7c]

This equation does not include hysteresis in every subsequent loop.

9.2.1.3. Shrinkage behaviour

The shrinkage behaviour, i.e. $\partial e/\partial \theta$, is defined following the approach of Fredlund et al. (2002) whereby the water content reduces at a constant degree of (high) saturation until the shrinkage limit where the water content reduces with only limited further reduction in void ratio. The shrinkage curve is defined as:

$$e = A_{sh} \left(\frac{\theta^{c_{sh}}}{B_{sh}^{c_{sh}}} + 1 \right)^{\frac{1}{c_{sh}}}$$
[9.8]

where A_{sh} is the minimum void ratio, B_{sh} is a parameter defining the slope and C_{sh} is a parameter defining the transition between the linear portion and the minimum void ratio as shown in Figure 9.1. The degree of saturation at which the sludge initially dries from is defined as B_{sh}/A_{sh} .



Figure 9.1 Shrinkage curve and rewetting path

Re-wetting, i.c. swelling behaviour where the void ratio increases with water content faster than initial drying is incorporated via the approach of Chertkov (2012) defined as:

$$e = v_h - b(\theta - \xi_h)^2 \tag{9.9a}$$

$$b = \frac{v_h - v_z}{{\xi_h}^2}$$
[9.9b]

where v_h is void ratio at the maximum swelling, ξ_h is the water content at the maximum swelling and v_z is the minimum void ratio of the previous shrinkage phase, illustrated in Figure 9.1.

For further re-drying, parameter B_{sh} is redefined from the maximum swelling position, so that the material approaches the minimum void ratio (A_{sh}) and Equation [9.7] is again used:

$$B_{sh}^{new} = S_l A_{sh}$$

where S_l is the degree of saturation. For larger overburden pressures, the minimum void ratio (A_{sh}) may be reduced. This is included by modifying the parameter based upon a non-linear (logarithmic) displacement relationship (e.g. Verruijt, 2012). Consequently B_{sh} must also be modified, maintaining the same degree of saturation:

$$A_{sh}^{new} = A_{sh}^{old} - A_{sh}^{old} \frac{1}{c_{10}} \log\left(\frac{\sigma}{\sigma_{0}}\right)$$
[9.11a]

$$\frac{\partial A_{sh}^{old}}{\partial B_{sh}^{old}} = \frac{\partial A_{sh}^{new}}{\partial B_{sh}^{new}}$$
[9.11b]

where C_{10} is a material parameter determining the compressibility, σ' is the effective stress and σ'_0 is a reference effective stress.

9.2.1.4. Hydraulic conductivity behaviour

The (saturated) hydraulic conductivity of the system, K, is related to the water content by log-linear relation (Kim et al., 1992):

$$K_{sat} = 10^{A_{HCC}\theta - B_{HCC}}$$
[9.12]

where A_{HCC} and B_{HCC} are material parameters determined from experimental data.

For unsaturated conditions, the hydraulic conductivity will be reduced based on the area available for flow (e.g. Fredlund and Rahardjo, 1993). The hydraulic conductivity is modified by a factor called the relative permeability, K_{rel} , which ranges from 1 at full saturation to 0 in dry conditions. The relation utilised is that of Brooks and Corey (1964).

$$K_{rel} = S^{\delta} \tag{9.13}$$

Where S is the degree of saturation and δ is a material parameter which is related to the pore size distribution.

The hydraulic conductivity at the surface of the sludge will be altered by changes due to tension caused by suction stresses. These include fabric changes, surface cracking, and chemical changes due to oxidation of sludge material. Research on these processes are ongoing and in addition this model is also implemented here in 1D, therefore this process cannot be fully characterised. This process is included via a factor in the permeability under certain conditions.

$$K_{dess} = 1 \quad \text{if} \quad h - z > d_{dess} \tag{9.14a}$$

$$K_{dess} = (1 - \epsilon_{dess}) + \epsilon_{dess} \exp(\xi_{dess}(1 - S_l)) \quad \text{if} \quad h - z < d_{dess}$$
[9.15b]

where z is the same as the gravitational potential (positive upwards), in this case with the zero datum at the base of the sludge, h is the total height of the sludge column, d_{dess} is the depth from the surface where desiccation and other surface effects act and ϵ_{dess} and ξ_{dess} are material parameters.

The final hydraulic conductivity is composed from the saturated hydraulic conductivity multiplied by the factors given in equation 9.13 and 9.14, given as following:

$$K = K_{sat} K_{rel} K_{dess}$$
[9.16]

9.2.1.5. Boundary conditions

The two boundaries are the top of the domain, in contact with the atmosphere, and the base of the domain, in contact with underlying soil. The boundary conditions that are implemented are:

Top boundary

Water can flow out of the sludge via liquid flow due to overburden or evaporation into the atmosphere. Atmospheric evaporation is modelled via fixing the matric potential on the boundary condition, but the flux is calculated and limited if it exceeds the open water evaporation (Penman evaporation). If the flux due to the overburden is higher than the Penman evaporation then the flux is set to the overburden. Otherwise, the flux is the lowest of the overburden plus the evaporation or the Penman evaporation rate.

Base boundary

The base boundary is either set to impermeable or permeable. The permeable boundary is set to be zero pore pressure. It is noted that this may allow water to flow into or out of the model.

9.2.1.6. Main limitations

The main limitations of the formulation derive from the single phase mass conservation basis of the formulation. In particular the mechanical behaviour is not explicitly calculated and, in particular, beyond the shrinkage limit this may have an impact on the analysis accuracy. The one-dimensional formulation implicitly assumes a number of things, which include no lateral deformation and no lateral stress influences. Treatment of such behaviour would require significantly more material characterisation and computational time; therefore these have been omitted currently. Part of these behaviour can be incorporated via the material parameters given above, if stress levels are comparable. Other limitations include the omission of cracking, chemical precipitates forming, horizontal and etc.

9.2.2. Model implementation

9.2.2.1. Numerical implementation

The theoretical formulation has been implemented in a discrete spatial domain via a finite difference formulation, and solved recognizing the highly non-linear behaviour utilizing an explicit Runge-Kutta method as implemented in Matlab. To account for hysteresis behaviour, a constant time delay, i.e. not based upon the timestep, has been incorporated, via the selection of the dde23 solver.

9.2.2.2. Software implementation

A Sludge Ripening Simulation Tool has been developed by Vardon (2014) utilizing the Matlab interface. With the developed user interface (Appendix C), the model can be operated easily. The simulations are able to be saved, loaded or run from the main window of the tool. A suite of datafiles is used to contain the analysis data (geometry, precipitation conditions), the material data and the results.

9.3. Simulation of fine tailings drying

Two set of experiments have been undertaken and are available to test the simulation tool developed and determine the performance of the model. The first set is the laboratory column drying tests (Phase 2) which have been described previously in this thesis (see Section 8.4). The second test is the field atmospheric fines drying tests undertaken by Shell Canada at the Muskeg River Mine. In this section, the numerical simulations are presented and compared to the experimental data with some analysis and discussions.

9.3.1. Laboratory column drying tests

9.3.1.1. Overview

In this work only the columns filled with polymer treated MFT have been simulated. Results undertaken for Column 6 are presented and compared with the experimental data presented in Section 8.4.2. The experimental column was filled with polymer treated MFT (at void ratio 4.3) to 20 cm height and after 16 days another 20cm height was added. An air pump was used to provide air circulation above the column surface throughout the test. A separate column filled with water was placed in the same condition and the water was found to evaporate at an average rate of 1.04 cm/day. Previous research indicated that the laboratory oedometer tests data and water retention tests data are similar to that of material in the field tests. Therefore, the water retention curve and hydraulic conductivity data for the field tests are used in the modelling. The shrinkage curve used in the model is obtained the experiments presented in Chapter 6.

9.3.1.2. Material properties

9.3.1.2.1. Shrinkage curve

The shrinkage curve of the flocculated MFT was fitted using Equation [9.8] as shown in Figure 9.3. The fitted parameters are $A_{sh} = 0.685$, $B_{sh} = 0.685$, and $C_{sh} = 4.47$. According to the experimental results shown in Figure 8.31, swelling due to rewetting is very small and therefore the rewetting swelling behaviour was not modelled in this test.



Figure 9.2 Experimental and numerical fit for the shrinkage curve

9.3.1.2.2. Water retention characteristic curve

The experimental water retention characteristic data have been shown in Figure 6.32 along with the field tests experimental data. Figure 9.3 shows the best fitted van Genuchten soil water retention curve. The fitted parameters are: WCR = 0.04, WCS = 2.2, a = 500000 cm, $\alpha_{WRC} = 0.12$ cm and $n_{WRC} = 1.232$.



Figure 9.3 Experimental and numerical fit for the soil water retention curve

9.3.1.2.3. Hydraulic conductivity curve

When Equation [9.12] was used to fit the saturated hydraulic conductivity data of field test flocculated MFT sample, the best fitted parameters were $A_{HC} = 1.7$ and $B_{HC} = 4.4$ (Figure 9.4). It was found that when these parameters were utilized in modeling of column drying tests, the simulated settlement rate was significantly higher than that of experimentally determined. The hydraulic conductivity data was thus calibrated against the oedometer tests results and a good qualitative agreement was obtained. The calibrated material parameters were $A_{HC} = 1.4$ and $B_{HC} = 4.5$.



Figure 9.4 Fitted data for saturated hydraulic conductivity

9.3.1.3. Results and analysis

In this section Column 6 with flocculated MFT has been simulated. This column has been discretized into 40 initially evenly spaced vertical divisions, i.e. 20 per layer. It was observed (Figure 8.24) that water had collected at the surface of the column initially for both layers. As the model presented does not have a facility to account for pooling, for the time periods where pooling was observed, no evaporation is applied to the boundary. Therefore in this time period, any consolidation is due to the overburden pressure. The simulated height for select initially evenly spaced layers, with the observed result is presented in Figure 9.5. The experimental results are shown in red squares and the layer surfaces are shown in dotted bold lines. It is seen that the results match both qualitatively and quantitatively with the experimental data. The major deviation is an underestimation of surface height in the first layer. It could be due to the sedimentation of particles which is not included in the model but occurred in the column test.

The calculated water fluxes at the same locations as the settlements are shown in Figure 9.6. The first layer is shown in blue and the second in red for clarity. The thicker lines for each layer are the layer surfaces. It can be seen that initially the fluxes due to the self-weight are high and reduce rapidly. These are responsible for the stagnant water on the surface. The step in water flux observed at Day 10 and Day 26 are due to evaporation starting

(being switched on in the simulation) as the pooled water is no longer observed. This step in the fluxes are responsible for the gradient change in the deformation in Figures 9.6.



Figure 9.5 Numerical and experimental settlement results for the column test



Figure 9.6 Calculated water fluxes for the column test

Figure 9.7 shows the temporal evolution of the void ratio profiles predicted for Column 6 along with the experimental data at Day 40. Comparing with the experimental data, it can be seen that the final height of the sample is in good agreement while significant overestimation of the void ratios is observed. In the author's opinion the possible reasons for this are: (1) lateral shrinkage of the soil column and (2) errors in measurement. Due to the lateral shrinkage (see Figure 8.28) occurring during drying, the assumption of 1-D flow and deformation of the model is not valid. After the soils pull away from the sides of the column, more water is evaporated from the sample due to increased surface area exposed to the air. As a result, the measured void ratios are lower than that of the column without lateral shrinkage. In addition, the void ratio data are calculated using the independently measured water content

and the soil density measured at the same height. Due to the fact that the soil properties were not consistent at the same height, slight difference in the measurements in particular the density may result in considerable deviation of the void ratios.



Figure 9.7 Void ratio profiles with experimental measurements for the column test, the black thick dashed curve represents the final void ratio distribution at the end of drying

9.3.2. Field atmospheric fines drying tests

9.3.2.1. Overview of field tests

Field tests of Atmospheric Fines Drying (AFD) have been undertaken by Shell Canada since late 2012 at the Muskeg River Mine near Fort McMurray, Alberta. Three different field tests were performed at the Muskeg River Mine, which were deep stack test, thick multi-lift stack and thin multi-lift stack (Shell, personal communication, 2014). Table 9.1 shows the field test experimental protocol.

Test	Lift	Days from start	Thickness (cm)		
Deep stack	1	0	450		
	1	0	100		
Thick multi-lift	2	257	180		
	3	346	130		
	1	0	90		
	2	37	50		
	3	257	50		
Thin multi-lift	4	290	50		
	5	317	60		
	6	346	110		
	7	365	40		

Table 9.1 Field test experimental protocol

The average initial water ratio (ratio between volume of water and volume of solids) of the deposited tailings was 3.5 with a standard deviation of 0.25. The evaporation potential and precipitation during the observation period has been measured daily and the monthly average values are shown in Figure 9.8. The material properties of used in the model have been presented previously.



Figure 9.8 Climatic data for the field tests, positive values are net precipitation and negative and mean evaporation

9.3.2.2. Simulation results and analyses

9.3.2.2.1. Deep stack tests

The simulation results and the field tests data from the Deep stack experiment are presented in Figure 9.9. The heavy dotted line represents the predicted surface of the deposited material and the finer lines (alternating between solid and dashed lines) are initially evenly spaced at 40cm depth. It shows good qualitative and quantitative match between the simulation results and the experimental data. The lack of experimental data between days 18 and 202, and again after day 403, is due to snow cover. It can be seen that towards the end of the test the model predicts approximately 8% higher settlements than the measurements. Possible reasons for this will be discussed later.



Figure 9.9 Temporal evolution for the deep stack numerical results with experimental results overlain (red squares). No data between 18 and 202 days, and after 403 days, due to snow cover

The experimental and numerical profiles of void ratio for the deep stack test are presented in Figure 9.10 in Lagrangian coordinates and Figure 9.11 in Cartesian (or real) coordinates. Only the experimental data close to the final simulation day are presented for clarity. Experimental results are measured in the Cartesian, or 'real', coordinate system and therefore Cartesian coordinates must be transformed to Lagrangian coordinates for comparison. The transformation from measured data to Lagrangian coordinates is presented in incremental form as below:

$$dm = \frac{dz}{1+e}$$
[9.17]

where *m* is the Lagrangian material coordinate, *z* is the Cartesian (real) coordinate and *e* is the void ratio. The coordinates and summed from the base. Figure 9.10 and 9.11 show good general agreement between measured and simulated data, albeit with some differences. In general, the key aspects of behaviour are well represented, including good representation of (1) void ratio throughout, and (2) switch between consolidation and evaporative behaviour. The main differences between numerical predictions and experimental data are: (1) there is a slight underestimation of the reduction of void ratio at the base of the stack until the evaporative 'crust'; (2) a slight underestimation of the surface of the stack. In Figure 9.9, it is shown that there is likely to be additional solid material (~10%) in the stack, which is in conjunction with the experimentally recorded additional heights and could contribute to the underestimation of void ratio at the base. Alternative reasons could be rapid changes in void ratio or uncertainties in the measurement.


Figure 9.10 Void ratio profiles in Lagrangian coordinates for the deep stack numerical prediction results with experimental results at 374 days overlain (red squares). Final numerical result (red dotted line) is 450 days



Figure 9.11 Void ratio profiles for the deep stack numerical results with experimental results at 374 days overlain (red squares), final numerical result (red dotted line) is 450 days

As a major conclusion in above simulations was that additional material was deposited. Therefore, additional new simulations were undertaken to attempt to provide a more direct comparison with the experimental results to determine the model performance. Calibration of layer thickness was carried out on solid content only rather than final or initial measured heights. It allows for some variation of solid content and initial high gradients of height change. Moreover, this would imply that the effective stresses (grain-to-grain stresses) would be consistent between the simulations and the field experiments. In the updated simulations, the layer thickness was increased from 450 to 480 cm, increased by 6.7%. The

simulation results are presented in Figure 9.12 and 9.13 for the surface settlements and the void ratio profiles, respectively. In both the figures, substantial qualitative and quantitative agreement are observed. Some differences can be observed, which is a slight underestimation of the reduction of void ratio at the base of the stack until the evaporative 'crust'.



Figure 9.12 Updated simulation results (surface settlement) for the deep stack tests with experimental results overlain (red squares)



Figure 9.13 Updated simulation results (void ratio profiles) for the deep stack tests with experimental results overlain (red squares)

9.3.2.2.2. Thick multi-lift tests

Figure 9.14 shows the temporal evolution of the thick stack numerical results with experimental results overlain. No experimental data was provided between days 53 and 256 because of snow cover. Look at the results, there is a clear and cumulating underestimation of

depths. However, the differences in gradients in settlement are well represented, e.g. higher settlement rates between days 300 and 350 rather than 400 and 450. The initial measurements of depth, as received from Shell, report 125 cm for the first stack, which does not fall to the initially anticipated 100 cm until 4 days later. Some reasons could be hypothesised for this, which are: (1) additional material was deposited and (2) a slope existed during deposition and deformation of the stack caused reductions. It is unclear from measurements (due to snow cover) how much this happened in the second layer, although the difference between the last reported depth and the first after deposition are 195 cm, which is more than the 180 cm reported for the total deposition. This behaviour does not seem to be reported in the third layer where 125 cm of additional material is reported (compared to 130 cm initially simulated).



Figure 9.14 Temporal evolution for the thick stack numerical results with experimental results overlain (red squares). No data between 53 and 256 days due to snow cover

Figure 9.15 shows the numerical and experimental profiles of void ratio for the thick multi-lift test in Cartesian coordinates. The dotted black line is from 450 days with the experimental profile from days 412. Therefore the experimental data should be compared with the third green line. The overall behaviour of the material seems to both qualitatively and quantitatively represented. In the main, the key features of behaviour are well represented, including (1) good representation of void ratio throughout; (2) good representation of dense layers, at the surface of the first two layers deposited; (3) good representation of behaviour of the top layer – at a slightly earlier time than shown for the final numerical results, indicating that the consolidation behaviour is well represented. The major differences are that in the model there are: (1) a slight underestimation of void ratio reduction in the second layer. Similar to the deep stack test, it is shown that there is likely to be additional solid material (approximately 25 %) in the stack.



Figure 9.15 Updated simulation results (surface settlement) for the deep stack tests with experimental results overlain (red squares)

 Table 9.2 Adjustment of simulation layer thickness for the thick multi-lift test

Test	Lift	Days from start	Initial simulation thicknesses (cm)	Modified simulation thicknesses (cm)
	1	0	100.0	130.0
Thick multi lift	2	257	180.0	230.0
muni-mi	3	346	130.0	150.0



Figure 9.16 Temporal evolution for the thick stack numerical results with experimental results overlain (red squares). No data between 53 and 256 days due to snow cover



Figure 9.17 Void ratio profiles for the thick stack numerical results with experimental results at 412 days overlain (red squares). Final numerical result (black dotted line) is 450 days

Additional simulation results have been undertaken after the calibration of layer thickness according to Table 9.2. The updated simulation results are presented in Figure 9.16 and 9.17 along with experimental results. In both the figures, substantial qualitative and quantitative agreement are observed. In particular, the void ratio profiles and switch between consolidation and evaporative behaviour are well represented. The main difference is that the reduced void ratio at the top of the second layer is under-represented. The reason for this difference is that the crust starts to develop at the end of the period where the second layer is formed due to elevated evaporative fluxes and reduced consolidation fluxes.

9.3.2.2.3. Thin multi-lift tests

The temporal settlement simulation results from the Thin multi-lift stack are presented in Figure 9.18. Generally, the behaviour is qualitatively well represented, with the same comments as in the preceding sections, being that (a) the qualitative behaviour and slopes are well represented, and that (b) it appears that the experimental results show less settlement/additional material than the numerical results.

The predicted and measured void ratio profiles in Cartesian coordinates are shown in Figure 9.19. The lowest profile is the results from 276 days (blue diamonds), encompassing the first 3 layers. The second profile shown in red squares, taken at 412 days, was limited in depth, therefore does not indicate the full material behaviour in the final simulation results from 465 days. The results at 412 days have limited settlement time compared to the final numerical results presented, and therefore consolidation is still occurring, as shown with the higher void ratios. It is again clear that more solid material seems to have been deposited than appears in the simulations. There are some specific locations where the model predicts a lower void ratio, e.g. in the second layer (from the base). There are two likely contributing causes: (1) if material is trapped between two layers that have been effected by evaporation, and consequently have a very low permeability, it will be difficult for consolidation to occur; (2) if additional material has been deposited these areas would take longer to consolidate. In

addition, the model would be more sensitive to minor changes in climate, material properties and dimensions with smaller layers. For example, if the material surface is affected by various environmental changes, e.g. cracking, this would also have a bigger impact on the comparative behaviour.



Figure 9.18 Temporal evolution for the thin multi-lift stack numerical results with experimental results overlain (red squares). No data between 54 and 242 days due to snow cover



Figure 9.19 Void ratio profiles for the thick stack numerical results with experimental results at 412 days overlain (red squares). Final numerical result (black dotted line) is 450 days

Test	I ift	Days from	Initial simulation	Updated simulation
Test	LIII	start	thicknesses (cm)	thicknesses (cm)
	1	0	90.0	100.0
	2	37	50.0	80.0
Thin	3	257	50.0	60.0
multi-lift	4	290	50.0	50.0
test	5	317	60.0	60.0
	6	346	110.0	130.0
	7	365	40.0	50.0

 Table 9.3 Adjustment of simulation thickness for the thin multi-lift test

Further simulations were undertaken with the increase of simulation thickness of each lift, as shown in Table 9.3. The simulation results and experimental data are presented in Figure 9.20 and 9.21, respectively. In both the figures, substantial qualitative and quantitative agreement are observed. The main differences which can be observed are (1) Some overestimation of height reduction and (2) overestimation of reduction in void ratio in the upper layers. In general, the gradients of height difference are well reproduced, with the exception of the final layer. It is thought that the final layer could have been influenced by ice conditions (being 1 year after when snow cover was considerable). In most layers, a new layer was added when the soil was still consolidating, with the exception of the second layer, where the void ratio results match well the experimental results. It is hypothesised that this makes the model sensitive to variations in initial water content, the deposition process, averaging of climatic data and the behaviour of the material in very wet conditions, where settling of particles may occur (as opposed to consolidation behaviour). It could also be possible that the top layer has more material, as it is not clear from the void ratio measurements, how close these were taken from the top.



Figure 9.20 Updated simulation results (surface settlement) for the deep stack tests with experimental results overlain (red squares)



Figure 9.21 Updated simulation results (void ratio profiles) for the deep stack tests with experimental results overlain (red squares)

9.3.3. Analyses and discussions

In general, the predictions of the numerical model are in good agreement with the experimental results. In particular, it can be seen that:

- The general settlement rates and amounts are in good agreement. Where significant deviation is observed, it was hypothesised that additional (solid) material was deposited. Further analyses with additional material provide close agreement with experimental and numerical results.
- The rates of settlement in time are very closely matching. In particular, both the typical consolidation curve at the beginning of each layer and the times where high evaporation are expected are well represented.
- The void ratio (therefore material density) distribution is generally well predicted. Both the general trend of denser material at the base and the denser layers due to evaporation are well predicted.

It was expected to have deviations of the predictions from the results of the experiments in the times where significant snow cover was seen. However, based on the settlement gradients, significant deviation is not seen. The possible reasons are: limited frost depth, excess pore pressures building up near the surface which can quickly dissipate when ice and snow melts or warmer water flowing out of the soil (from depths where the soil is unfrozen) due to consolidation. The model presented in Section 9.3.2.2.1 holds the most deviation from the experimental results, which is probably due to this test having the most layers. This means that it has the most uncertainty from initial deposition and the most processes happening at the surface. Some other uncertainties are briefly discussed below:

• The model is a one dimensional model and the real behaviour may have three dimensional effects, e.g. lateral shrinkage and slopes. Water may also flow through the soil under the surface downslope.

- Surface desiccation may occur, which decreases the surface flux.
- Oil on water surface may affect evaporation.
- Surface run-off on rainy days has not been explicitly modelled, although is included as water pooling is not allowed.
- Unsaturated hydraulic conductivity is unknown.
- The material is modelled as a uniform continuum, but some large voids (air or water filled) occur.
- Gas produced due to biological activities may affect consolidation and drying.

9.4. Summary

This chapter presented a one-dimensional numerical model which uses Darcy's law and shrinkage curve, water retention curve and permeability curve to simulate the consolidation and evaporation behaviour of fluid fine tailings. This model contains various features of drying, including overburden and evaporation driven pore pressure changes and changes due to swelling and shrinkage cycles.

The laboratory column drying tests performed on FMFT was simulated. A close agreement was obtained between the measured and the calculated tailing surface settlements. However, the 1-D numerical model did not well predict the void ratio distribution of the tailing at the end of the test. The measured values were significantly smaller than the predicted, which is attributed to the fact that the tailing column experienced 3-D deformation in the column.

Shell atmospheric fine drying field tests were simulated by the model. Initial modelling suggested that more (solid) material was deposited than indicated. Additional new simulations were made by calibrating the thickness of the deposited layer. Calibration of layer thickness was carried out on solid content only rather than final or initial measured heights. The updated simulations with additional material yielded improved results, which were able to reproduce almost all features of desiccation of the tailing in both a quantitative and qualitative manner. Therefore the model is considered validated in this case.



Conclusions and Recommendations

10.1. Observations and conclusions

As stated in Chapter 1, the main objectives of this research was to (1) investigate physical and engineering properties of fine oil sands tailings; (2) identify effects of polymer treatment on properties of MFT; and (3) investigate dewatering behaviour of fine oil sands tailings related to thin lift drying and vertical wick drain technology; and (4) implementation of a numerical model to simulate the drying process of tailing. With respect to these objectives, the following conclusions can be drawn.

10.1.1. Properties of fine oil sands tailings

The MFT obtained from Albian Sands Muskeg River Mine was classified as fine grained clay of medium plasticity. The physical and geotechnical index properties for the MFT as received were 32% in solids content, 1-2% in bitumen content, 2.30 in specific gravity of solids, 1210 kg/m³ in bulk density, 55% in average liquid limit, 28% in average plastic limit, 16% in average shrinkage limit, 90% in average fines (<44 μ m) content and 48% in average clay (< 2 μ m) content. The TT samples, as received, contained 35 wt% solids with 72 wt% fines and 28 wt% clay. The average liquid limit and plastic limit were 50% and 22%, respectively.

The measured index properties of the MFT used in current work are similar to those published in the literature for the MFT samples obtained from different mines. There are significant differences between the TT used in this work and that reported in the literature, particularly in terms of fines content of the material. One possible reason is that some flocs in TT were destroyed by laboratory mixing and sampling process prior to index testing. The MFT and TT are to some extent similar to sludge dredged from Rotterdam harbour in terms of index properties.

Upon deposition, high water content MFT slurries undergo different settling stages. Due to the attraction between particle surface charges, destabilised particles agglomerate forming flocs. The whole system of flocs settle at a constant rate creating a layer of supernatant water on the top, this stage is referred to as hindered sedimentation. Transition of sedimentation to consolidation occurs at a void ratio which is about 8.5 times the void ratio at the liquid limit. The naturally occurring flocs have a certain yield strength to resist external pressure and this strength was estimated to be about 0.23 kPa. The critical void ratio of the sediment at which the fragile floc structure collapses was 2.9 times the void ratio at the liquid limit. MFT studied in this research is similar to some dredged clay slurry and oil sands tailing cyclone overflow tailings reported from literature in terms of settling characteristics.

The compression curves (e-log P curves) obtained from oedometer tests depend on the initial conditions of the samples. The e-log P curves for MFT and TT are generally linear at low void ratios (e.g. < 2). The e-log P curves for MFT in this research coincide with different MFT samples reported in the literature in the range when effective stress is above 10 kPa. The measured consolidation parameters indicate that MFT has high compressibility and low permeability.

The TT materials were sensitive to shear. The TT slurry suffered from less disturbance settled faster than the intensively mixed TT. The sheared TT samples exhibited similar settling and compressibility characteristics to the MFT samples.

The shrinkage data (void ratio vs. gravimetric water content) of the fine tailing sample shows a J-shaped curve in a progressive drying pattern consisting of three stages (i.e. normal shrinkage, residue shrinkage and zero shrinkage).

When a desiccated tailing sample was rewetted, the swelling curve (axial strain vs. time) consisted three stages with the maximum degree of swelling occurring in the first stage. Magnitude of swelling was influenced by initial water content, thickness of sample, confining pressure and rewetting method. The calculated swelling potential values indicate that MFT is not an expansive soil. After a long period soaking, microcracks formed in the initial drying process reopened in case that the sample was not well confined during soaking.

Hysteresis exists in soil volume changes as a function of water content during shrinkage and swelling unless the initial drying does not extend below the shrinkage limit of the soil and the soil is rewetted. Hysteresis between shrinkage and swelling curves for a tailing sample vanished after the soil experienced at least four consecutive wetting-drying cycles.

For the fine oil sands tailings, osmotic suction is a major contributor to total suction. This was due to high salinity of pore water in the tailings. The independently measured shrinkage curve should be combined with the SWRC inferred using filter paper method and WP4C dew point potentiometer to obtain the correct air entry value (AEV) and the SWRC based on volumetric water content. The measured SWRC for MFT was in good agreement to those reported in the literature for the different samples of MFT.

Changes of the rate of evaporation measured from a thin (1 cm) tailing sample can be divided into three stages: constant-rate, falling-rate and low-rate. Most of volumetric change and desiccation cracks occurred in the constant-rate stage. Desiccation cracks initiated when the clay matrix was still fully saturated. During drying some clay in MFT adhered to the side walls of the cup due to clay-glass interface cohesion and this affected the crack pattern formed on the MFT sample. The crack pattern stabilised when the average water content dropped below the shrinkage limit of the soil. The observed crack pattern belongs to the category of orthogonal.

Laboratory properties of MFT are quite different from other types of mine tailings (e.g. copper tailing, coal wash tailing, gold tailing, oil sands CT) in the engineering. According to the tests results and literature data, MFT has larger compression index, smaller coefficient of consolidation, lower (saturated) permeability, smaller shrinkage limit, larger suction, higher air entry value compared to other types of tailings. The main cause for these differences is that MFT has a higher fines and clay content. The fine particles especially the clay size materials may govern the behaviour of the tailings due to the electro-chemical activity of clay. It suggests that dewatering of fine oil sands tailings based on consolidation and drying processes may be more challenging compared to other mine tailings.

10.1.2. Effects of flocculation on tailings properties

The effectiveness of flocculation of MFT was heavily dependent on the available flocculation conditions which include mixing method and mixing variables, polymer dosage and tailing concentration. Results of the flocculation tests indicate that an initial rapid mixing is desired for efficient flocculation. However, prolonged vigorous mixing can destroy the large flocs and form small flocs and microflocs in the tailing slurry, leading to mediocre dewatering results. There was an optimum range of mixing energy input into each MFT-polymer system. When mixing was operated outside this range, the obtained flocculation and dewatering outcomes were poor. The optimum dosage for the polymer (FLOPAM DPR 5285) was 1 g dry polymer per 1000g dry tailing (1 g/kg or 1000g/t). When the polymer was dosed above the optimum dosage, the excess polymer increased the viscosity of mixture and posed a negative effect on the settling of flocs. The results suggest that the original MFT (35% in solids content) should be diluted before flocculation to ensure the pumpability of the polymer treated material.

Flocculation of MFT significantly accelerated the sedimentation of the tailing slurry with a substantial increase of the amount of water released from the tailing. For an initially 21% solid content MFT, the initial settling velocity and the hydraulic conductivity of slurry increased by 4 magnitudes after the treatment at the optimum condition.

Flocculation of MFT influenced the compressibility of the tailing. Results of the oedometer tests suggest that the FMFT are more permeable than the MFT because they consolidate much faster. At the same effective stress, the FMFT sample had larger void ratio than the MFT due to the larger voids in the floc structure. The floc structure collapsed at higher surcharge pressure.

Flocculation of MFT affected the shrinkage curve of the material. Drying the FMFT resulted in a significantly larger void ratio in the residual shrinkage stage compared to drying the MFT in the same conditions. When there is no external pressure applied on the sample, the minimum void ratio of the FMFT is mainly influenced by polymer dosage and mixing conditions. In general, both the overmixed and underdosed FMFT sample have a lower void ratio compared to the optimally treated sample at the end of drying.

The flocculation changed the water retention behaviour of the tailing. The measured air entry valve (AEV) decreased from 700 kPa to 60 kPa after flocculation. The SWRCs show that the FMFT had lower suction values than the MFT at the same water content.

The flocculation increased the strength (e.g. tensile strength, shear strength) of the material, which was mostly due to much stronger particles bonds that were formed in the

tailing with the assistance of polymer. The FMFT was "tougher" than the MFT, this was reflected by two phenomena: (1) The desiccating MFT contained in the containers made of plastic or glass suffered a significant side wall adhesion effect while the FMFT did not; (2) The crack pattern formed on a thin MFT sample after initial drying process changed greatly with formation of additional cracks when the sample was subjected to several wetting and drying cycles. However, the crack pattern for the FMFT sample did not change after several drying and wetting cycles.

10.1.3. Dewatering behaviour

Laboratory filtration column tests performed on fluid fine tailings and samples of PVD filter jacket indicate that the well selected geotextile filter jackets functioned properly during filtration without serious clogging or blinding by particles or bitumen after a filtering period of several weeks.

The discharge rate of the tailing-PVD system was dependent on the magnitude of pressure applied on the sample, consolidation behaviour of the sludge and the permeability of the soil adjacent to the filter. At constant pressure, a constant flow rate was formed after a certain filtering time.

Filterability of fine tailings and effectiveness of flocculation can be compared through the experimentally determined SRF values. After flocculation the SRF of MFT was reduced by one order, which is relatively small considering its magnitude.

From the results of the bench scale drying tests, it can be concluded that three conditions are desired for efficient drying of fine oil sands tailings, which are: (1) the supernatant water created by consolidation of tailings must be drained effectively; (2) a favourable evaporation condition (e.g., higher air temperature, lower relative humidity of the ambient atmosphere and rapid circulation of air above the tailing surface) is created, and (3) the tailing is deposited in thin layers.

Biological gas was generated in the tailings. The fresh TT placed at the 20 °C environment generated a considerable amount of gas which retarded the self-weight consolidation. The TT placed at 10 °C released significantly less gas due to supressed biological processes. The gas production did not influence the long-term drying performance as the air was dissipated gradually. The MFT and FMFT samples also provided considerable quantities of entrapped gas, these entrapped gas bubbles were relatively small and did not affect the consolidation.

The actual evaporation rates measured from the tailings were always smaller than the evaporation rates measured from pure water which was dried at the same condition. Some bitumen and salt crystals were found at surface of the desiccated tailings, which implies that evaporation of water from the tailing surface can be obstructed by the formed bitumen film and/or high osmotic suction generated due to salinity of pore water.

The increase in surface area resulted from desiccation cracking and the effect of side wall adhesion as well as the relatively low suctions at the fresh tailing surface gave rise to very high actual evaporation rates measured from the MFT columns. Evaporation rates then decreased due to the increasing surface resistance to evaporation (i.e. decreasing soil permeability and increasing suctions). Deposition of a fresh tailing layer on top of the desiccated layer rewetted the underneath layer but caused little vertical swelling. This highlights one potential advantage of depositing the tailings in layers.

After being calibrated with known density objects, the CT scanning results can provide correct and accurate bulk density values for the soils. With this technique, the interior changes of the samples during drying can be identified.

10.1.4. Numerical modelling

The laboratory column drying tests performed on FMFT was simulated by the numerical model using the developed Tailing Drying Simulation Tool. A generally good agreement was obtained between the measured and the calculated tailing surface settlements. However, the 1-D numerical model did not well predict the vertical void ratio distribution since the tailing experienced 3-D shrinkage in the drying column.

The Shell AFD field tests were simulated by the model. Initial modelling suggested that more (solid) material was deposited than indicated. Subsequent simulations with additional material yielded improved results, which were able to reproduce almost all features of desiccation of the tailing in both a quantitative and qualitative manner.

10.2. Recommendations

10.2.1. Recommendations for future work

Soil suction plays a critical role in drying behaviour of tailings and thus should be correctly and accurately measured. In this research, matric suctions of the tailings were determined using filter paper method by employing the calibration curves established by Bulut in 2001. This calibration curve may not be completely compatible to the batches of filter papers used in current research. In the future work, it is recommended that the matric suctions are measured with a stricter protocol or using alternative method. For example, use of the Decagon Hyprop device is one of the alternatives. This advanced device is capable of generating a reliable water retention curve of a soil in 3-5 days.

Experimental research demonstrated that polymer treatment of MFT greatly amended the engineering properties of the material. Although most of these amendments were considered positive, the mechanisms behind these and other associated behaviour are still not well understood. It is recommended to investigate the microstructure of the flocculated tailings with the help of CT scanning and SEM technology to develop a deeper understanding of the material.

In this study, dewatering of fine tailings was assumed to be some kind of physical or mechanical processes. Pore water chemistry was not investigated in this study. The observations demonstrated that the high salinity of the tailing played a role in the evaporation and desiccation behaviour. Therefore, the future investigations should involve analysis of pore water chemistry and other properties. The column filtration tests demonstrated that the selected PVD filter jackets functioned well with fluid fine tailings under certain stress and hydraulic conditions. However, this is not sufficient to evaluate the technical feasibility of PVD technique in disposal of soft fine tailings. Large scale field tests using real wick drains are required to be conducted.

In the air drying tests, there was no run-off mechanism for the released water. In addition, the cracking behaviour was assessed only from a very thin tailing layer, this did not reflect the real cracking behaviour in the field. Therefore, in order to better understand the drying behaviour of the deposited tailings, larger scale drying tests including multiple lifts, freeze/thaw, snow cover and run-off mechanism are recommended.

In this PhD project, different aspects of tailing behaviour were determined independently. It is necessary to link all the aspects to one complete analysis in the future work.

10.2.2. Recommendations for industry

Mixing intensity or energy plays a substantial role in the flocculation of MFT. Overmixing usually results in mediocre dewatering results. However, compared to insufficient mixing, it is still acceptable.

The addition of polymer results in substantial dewatering in the short term (approximate 1 day) after flocculation. This has been well understood in industry. However, the polymer can also change longer term tailing behaviour by potentially changing the consolidation and water retention characteristics of the tailings. This behaviour should also draw attention in industry.

The highest drying potential in the Fort McMurray area exists between May and August in a year, this period is considered suitable for implementation of thin-lift drying. In order to maximize the benefit from potential evaporation, the thickness of the deposited lift should be changed according to climatic conditions, that is a thicker lift is deposited when the PE is higher and a thinner lift is deposited when the PE is lower. During the remainder of the year, tailing deposits undergo little evaporation-induced drying due to snow cover. The strength gain of the tailings should be achieved through other mechanisms.

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Appendix A Geotechnical Index Testing Data

Sample	w	Cs	Sample	W	Cs
ID	(%)	(%)	ID	(%)	(%)
TT1-1	185	35.1	MFT1-1	211	32.2
TT1-4	187	34.8	MFT1-2	213	32.0
TT2-2	189	34.6	MFT1-4	214	31.8
TT2-4	188	34.7	MFT2-1	215	31.7
TT3-2	182	35.4	MFT2-3	212	32.1
TT3-4	184	35.2	MFT2-5	216	31.6

Table A1 Gravimetric water contents (w) and solids content (Cs)

Table A2 Bitumen content (C_b) of oil sands tailings samples

Sample ID	<i>C_b</i> (%) (2010)	<i>C_b</i> (%) (2012)	Sample ID	C_b (%)
TT1-1	1.85	1.13	MFT1-1	2.11
TT1-2	1.91	1.21	MFT1-2	1.23
TT2-1	1.98	1.18	MFT2-1	1.41
TT2-2	1.75	1.04	MFT2-2	1.21

Table A3 Total densities (ρ_T) measured at 20 °C for tailing samples

Sample ID	ρ_T (kg/m ³)	Sample ID	ρ_T (kg/m ³)
TT1-1	1236	MFT1-1	1211
TT1-2	1231	MFT1-2	1213
TT2-1	1218	MFT1-4	1196
TT2-2	1233	MFT2-1	1205
TT3-1	1240	MFT2-2	1219
TT3-2	1229	MFT2-3	1216

Table A4 Specific gravity of solids, G_s, for tailing samples

Sample ID	Specific gravity	Sample ID	Specific gravity
TT1-1	2.305	MFT1-1	2.289
TT1-2	2.298	MFT1-2	2.291
TT2-1	2.304	MFT1-3	2.306
TT2-2	2.307	MFT2-1	2.304
TT3-1	2.289	MFT2-2	2.297
TT3-2	2.305	MFT2-4	2.307

Sampla	Voor	Liquid	Plastic	Shrinkage	Plastic
Sample	I Cal	limit	limit	limit	index
TT1-1	2010	52	21	13	31
TT1-2	2010	56	19	11	37
TT2-1	2010	49	19	10	30
TT2-2	2010	48	20	13	28
TT1-1	2012	55	24	13	31
TT1-2	2012	53	23	12	30
MFT1-1	2012	48	26	15	22
MFT1-2	2012	56	27	15	29
MFT2-1	2012	54	24	16	30
MFT2-2	2012	55	26	14	29

 Table A5
 Atterberg limits determined for oil sands tailing samples



Figure A1 PSD curve measured for Sample TT1-1 in 2010



Figure A2 PSD curve measured for Sample TT2-1 in 2010



Figure A3 PSD curve measured for Sample TT1-1 in 2012



Figure A4 PSD curve measured for Sample TT2-1 in 2012



Figure A5 PSD curve measured for Sample MFT1-2



Figure A6 PSD curve measured for Sample MFT2-1

Appendix B Impeller Torque Measurements in MFT-Polymer Mixtures



Figure B1 Impeller torques for the paddle in 21% MFT with flocculant in the baffled and unbaffled tank



Figure B2 Impeller torques for the PBT in 21% MFT with flocculant in the baffled tank and unbaffled tank



Figure B3 Impeller torques for the paddle in 32% MFT with flocculant in the un-baffled tank

Table B1	Mean torque values of different impellers in the MFT and MFT-polymer
	mixtures

Solids Impeller		Speed	Non-treated MFT $(10^{-3} \mathrm{N}{\cdot}\mathrm{m})$		MFT-Polymer mixtures $(10^{-3} \mathrm{N}{\cdot}\mathrm{m})$	
(%)	type	(rpm)	Baffled	Un-baffled	Baffled	Un-baffled
21	Paddle	150	2.982	0.710	2.917	2.525
21	Paddle	200	5.538	0.994	5.675	2.910
21	Paddle	250	8.804	1.704	8.961	5.424
21	PBT	400	0.852	0.852	1.812	1.537
21	PBT	600	2.698	1.562	3.682	3.037
21	PBT	800	5.680	2.698	6.243	5.556
32	Paddle	300		4.260		12.015
32	Paddle	400		6.532		20.308
32	Paddle	500		12.490		23.993

Appendix C Main Screen of Tailing Drying Simulation Tool

🛃 Sludge Ripening Simulation Tool	
This is the Sludge Ripening Simulation Tool written by TU Delft for Shell. For queries contact P.J.Vardon@tudelft.nl.	
Simulation Settings Material Parameters]
Run model Plot Results	
Save model and results]
Filename	

Figure C1 Main screen of the simulation tool

SimSettings				
Layering				
Laver thicknesses (cm)	[30 3	0]	Sublayer	3
Drying periods (days)	[10 1	51	thickness	
Diagona enter data	in matrix form e c	12.4.51	(CIII)	
	a in man ix form, e.g	. [2 4 3]		
Initial conditions		 Time stepping 	9	
Initial water content	5	Time step	(days) 1	
Boundary conditions				
Base drainage				
- Simple atmospheric co	onditions-			
Atmospheric potential	(cm) 1 - 000	Precipitation	15.00	
Atmospheric potential	-1e+008	start	[5 20	
Penman open wate	er 0.333333	finish (days)	[7 23]
evaporation (cm/da	iy)	Enter data	a in matrix form, e.	g. [2 4 5]
Recorded atompsheric	conditions-			
Days (start with 0)	[0 10 30]			
				-
Net average precip	[0.33 0.33 0.33]			^
or evap (-ive)				
				T
Enter data in matrix fo until the next time (Da	orm, e.g. [2 4 5] wit ys) or analysis end	h values lasting I	from this time	
Save and	close		Cancel	

Figure C2 Simulation settling screen
📣 Material Properties						
Basic properties				3		
Solid density 2.31	g/cm		Fluid de	ensity 1 g/cm		
Shrinkage curve proper	ies					
Drying curve		Re-wetting	g curve	Overburden compression		
Initial minimum void ratio, Ash	0.48	neta	2	On/off		
Bsh	0.48	v	2	Inital stress		
Csh	4.47			(kPa) Plot equations		
Water rentention curve Minimum water content Maximum water content Alpha	0 5.91 0.92	an Genuchte n m	n) 1.15 0.130435	Modified V 5 a 10000		
Permeability curve properties Permeability curve Unsaturated permeability Dessication surface permeability A 0.783 On/off V on/off V eta 5 denth						
B 5	delta	3	epsilon	0.05 affected 10 (cm) Plot equations		
Save and	close			Cancel		

Figure C3 Material properties screen

Plot Results Options	5					
Plot 1		Plot 2				
Time series	Water content Void ratio Coordinates (settlements)	Time series	Voider content Void ratio Coordinates (settlements)			
Point evolution	Nodes Water content Internodes Void ratio Suction vs	Point evolution	Nodes Water content Water content Void ratio Void r			
O Profiles	Water content Void ratio Coordinates (settlements) + Pure line (settlements) +	Profiles	Water content Number of Void ratio profiles Coordinates (settlements) profiles			
🗆 Plot 3		Plot 4				
Time series	Water content Void ratio Coordinates (settlements)	Time series	Water content Void ratio Coordinates (settlements)			
Point evolution	Nodes Water content Internodes Void ratio Suction vs	Point evolution	Wodes Water content Water content Void ratio Void r			
Profiles	Water content Void ratio Coordinates (settlements)	O Profiles	Water content Void ratio Coordinates (settlements) Coordinates (settlements) Coo			
Plot						

Figure C4 Plot results screen

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Curriculum Vitae

Yutian Yao was born on October 12, 1984 in Nanjing, Jiangsu province of China. He studied Civil Engineering at Southeast University, Nanjing, China. After obtaining his Bachelor's degree, he started his Master study in Geotechnical Engineering at Hohai University, Nanjing, China. In June of 2010, he obtained a Master degree of Geotechnical Engineering. As a PhD student in Geotechnical engineering at Delft University of Technology following the guidance of Prof. A.F. van Tol, he focused on investigation of dewatering behaviour of fine oil sands tailings.



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"Long live world peace" -- Chinese calligraphy by Yutian Yao