Stabilization of Centrifuged Fluid Fine Tailings Using Native Vegetation

by

Scott Leslie Laberge

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University of Alberta

Abstract

Managing fluid fine tailings (FFT) is a defining challenge of the oil sands industry in Alberta due to low solids content, and extremely slow self-weight consolidation. One technology to increase the solids content of these tailings is centrifugation to produce centrifuged fluid fine tailings (CFFT). Although centrifugation results in a tailings product with a much greater solids content than raw FFT, deposits of CFFT can take centuries to densify under self-weight conditions. This research aims to assess the potential for four native plant species: *Carex spp*., *Salix interior*, *Elymus trachycaulus*, and *Rumex occidentalis* to dewater a centrifuged tailings poduct from an oil sands mine operator. This assessment was conducted on five one cubic meter totes, each containing approximately 600L of tailings that were located outside at a research facility in Peace River, AB. Several geotechnical parameters were collected through the study which lasted two years from June 2018 to October 2019 including: solids content, undrained shear strength, water table height, settlement, matric suction and volumetric water content. In addition, plant data including above and below ground biomass, as well as LAI were determined to allow assessment of the impact the plant species have on dewatering and strength gain in the samples of CFFT.

The study shows these species can successfully grow and establish in these tailings in a region with similar climate conditions to the oil sands in northeastern Alberta. In general, the totes with vegetation did show a modest increase in solids content and shear strength when compared to the control tote that contained no plants. The greatest biomass generation in addition to strength and solids content gains were observed in totes containing *Salix interior* and *Elymus trachycaulus*. All totes experienced similar settlement in the first year, with an equivalent settlement atributable to freeze-thaw over the winter period. In Year 2, only the totes containing vegetation showed notable settlement, with nearly no additional settlement measured in the control tote. One

challenge identified was the susceptability of these tailings to rewetting. Significant precipitation events could contribute to swelling of the tailings in the totes, and subsequent loss of solids content and strength gain. This swell was found to be the most pronounced in the control tote, suggesting the plant species may have allowed the totes to weather these water influxes more successfully.

The findings indicate that planting species of *Salix interior* and *Elymus trachycaulus* will likely result in the greatest geotechnical performance gains in these types of tailings material. Undrained shear strength, strain, and solids content gain was greatest in totes containing these two species (in combination). Any application of plants as a dewatering method should be supported by a robust water management plan. This would minimize the risk from rewetting of the tailings that can result in a complete loss of previous shear strength and solids content gains in these tailings. It should also be noted that the material properties of the tailings such as clay content, hydraulic conductivity, and chemistry (among others), will also have a significant impact on plant growth and related dewatering potential.

Preface

This thesis is an original work by Scott L. Laberge under the supervision of Dr. Nicholas Beier. Technical guidance and critical feedback were provided for this research by Dr. Beier, with additional support provided by Dr. Ahlam Abdulnabi.

The research conducted for this thesis forms part of a multi-institution research collaboration, co-led by Dr. Michael Lipsett, and Dr. Nicholas Beier at the University of Alberta, and Dr. Amanda Schoonmaker at the Northern Alberta Institute of Technology's Centre for Boreal Research in Peace River, AB. This work was jointly funded through an NSERC Collaborative Research and Development (CRD) grant and by industry collaborators Imperial Oil Ltd. (IOL) and Canadian Natural Resources Ltd. (CNRL).

The plants used in the tote study described in Chapter 3 and 4 were selected and planted by NAIT personnel in Peace River, AB. Plant data in Chapter 3 and 4 was collected by NAIT personnel in Peace River, AB and provided to the author for analysis and discussion. Geotechnical data for the tote study was collected primarily by NAIT personnel who were trained and directed by the author to collect this data, with some measurements collected directly by the author when in Peace River at the study location. This data was supplied to and compiled by the author for analysis and discussion at the end of each growing season. Geotechnical instrumentation was installed by the author at the beginning of year 1 with assistance from NAIT personnel. Data from the sensor loggers was collected by NAIT personnel and provided to the author for analysis. The work in Chapter 1, Chapter 2, the data analysis, interpretation, and discussion in chapter 4, and the conclusions and recommendations for future work in Chapter 5 are the authors original work. This thesis manuscript was written by the author.

Chapter 3 is a slightly revised version of a paper published in the proceedings of the 2019 Tailings and Mine Waste conference in Vancouver, BC as Laberge, S., Beier, N., and Schoonmaker, A., "Utilizing Native Plants to Increase the Strength and Solids Content of Treated Oil Sands Tailings". Part of the results of the data described in Appendix B have been published in the proceedings of the 2018 International Oil Sands Tailings Conference in Edmonton, AB as Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G., "Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands

Tailings Deposit". Parts of Chapter 3, Chapter 4 and Appendix B have also been published in a pair of companion papers published in the proceedings of the 2021 Tailings and Mine Waste Conference in Banff, AB as Schoonmaker, A., Chigbo, C., Walton-Sather, K., Abdulnabi, A., Beier, N., Laberge, S., and Smith, W., "Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns"; and Abdulnabi, A., Paul, A., Beier, N., Laberge, S., and Smith W., "Plant growth on oil sands tailings from bench-scale to a field pilot: Part 2 key geotechnical performance indicators". The author provided all relevant geotechnical data and analysis from the outdoor tote study discussed in these papers. Information on materials and methods, and some results were also provided by the author to the second paper.

Acknowledgements

I would like to thank my supervisor Dr. Nicholas Beier for his guidance, his patience, his encouragement, and his understanding throughout this journey. Given the strain and the length of time it took to complete, Dr. Beier provided nothing but understanding and support during challenging personal and professional obligations that demanded my time outside my thesis. It has been a true pleasure and an honour to have had the opportunity to work with Dr. Beier as well as the greater geotechnical research team at the University of Alberta.

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I would also like to extend my sincere thanks to Dr. Amanda Schoonmaker at the Northern Alberta Institute of Technology's (NAIT) Centre for Boreal Research in Peace River, AB for her technical expertise and her fantastic guidance regarding the plant species used in this thesis. The study would not have been possible without her diligence and knowledge. Thank you to her entire team at the Centre, especially Kaela Walton-Sather for their hard work monitoring the totes and collecting data from the totes when I could not be in Peace River myself.

I acknowledge with gratitude, the financial support given to complete this work by Dr. Beier and the University of Alberta, IOSI, and NSERC. Specific thanks to Imperial Oil Ltd., and Canadian Natural Resources Ltd. for their support and allowing access to their sites and tailings materials where required. Thank you again to NAIT for providing the plants used for planting in the totes used in this study.

I would like to express my deepest gratitude to my family including my dad, my mom, and my brother for their unending support and encouragement that helped see me through the most challenging moments of my degree. I would also like to thank my best friend Vanessa Warren for her constant belief in me, and knowing more than I did that I would eventually complete this degree. I hope they understand I would never have reached this milestone in my life without their support and care.

Finally, I would like to thank Nav Dhadli, Ben Sheets, Dale Kolstad and my many other wonderful colleagues and mentors at Barr for their support while I worked to complete this degree over my first two years of my time as part of the Barr family. Their understanding, encouragement and flexibility is something I am incredibly grateful for, particularly in the final stages of my thesis preparation when it imposed the greatest demands on my time. I look forward too many more exciting years to come working together!

TABLE OF CONTENTS

List of Tables

List of Figures

1 Introduction

1.1 Statement of Problem

The Canadian Oil Sands of Alberta's boreal forest represent the third largest oil reserves in the world, with an estimated initial volume in-place of more than 1.8 trillion barrels of natural bitumen. Alberta is Canada's largest producer of oil and natural gas, with roughly 66 percent of all of Canada's oil and equivalent production coming from marketable bitumen (AER, 2020). As the demand for energy continues to grow globally, Canada and Alberta stand to supply a reliable and responsible crude product for global oil buyers. Raw bitumen production was three million barrels of crude bitumen per day, and is forecasted to continue modest growth (AER, 2021).

Bitumen differs from light or sweet crude oils in its viscosity and density, often having an API in the range of 8°- 10° compared to most conventional crudes with API's of 25°- 40°. This means that bitumen is near solid at ambient temperature and pressure, and will not flow freely under these conditions (Mossop, 1980).

The extraction of this bitumen comes at a significant environmental cost. Fresh water use, and the production and storage of the waste from the processing of the oil sands are the most significant challenges facing the oil sands mining industry today. Chiefly amongst these concerns is the generation of fluid fine tailings (FFT) comprised predominantly of clay fines at a solids content of 10%. This FFT has been shown to densify to a solids content ranging from 30 to 40% solids by weight after 3 to 5 years, with little to no development of effective stress. Further consolidation of the FFT is limited, and it is usual that the FFT will remain in an unconsolidated state for decades or centuries (Chalaturnyk et al., 2002; Jeeravipoolvarn et al., 2008). There are currently 1270 million cubic meters of FFT stored in tailings ponds covering an area in excess of

250 square kilometers (AER, 2020). A significant area of research and technological development in the oil sands is focused on managing this massive inventory of FFT. Most focus on finding ways to speed dewatering and physical stability of these tailings to allow reclamation and eventual closure of these tailings storage facilities.

Addressing the challenges posed by these tailings is the reason for the development and implementation of numerous technologies to both speed dewatering of “legacy” FFT, and reduce or eliminate the accumulation of new FFT. Various technologies have been studied at scales ranging from laboratory or bench scale studies, to pilot or full-scale commercial operation at many of the oil sands mine sites (Sobkowicz, 2012). These technologies can be novel in nature or taken from other industries or even treatment of tailings in other parts of the global mining industry. These technologies can include: thickeners, centrifuges, chemical amendments such as flocculants and coagulants, and utilization of natural processes such as frost heave or plant evapotranspiration. One of the most significant challenges with nearly all of these technologies is that you are often still left with a soft tailing’s material even after FFT treatment. This causes further challenges to eventual closure and reclamation of these tailings deposits. Some of these technologies are discussed further in Chapter 0.

Utilizing natural processes such as plant evapotranspiration to speed dewatering of these tailings is again gaining consideration as a natural way to enhance dewatering rates of these fine tailings. The first studies testing the ability of plants to establish in an oil sands tailings material were completed in the early 1990’s, with additional work in 1999 and through the early 2000’s (Johnson et al., 1993; M. J. Silva, 1999). Unfortunately, most of this work was completed on tailings that contained significant quantities of coarse materials resulting in a matrix with very different characteristics than the FFT described above. Interest in utilizing plants to dewater this most challenging tailings material is driving additional studies and research to assess the potential for native plant species to be utilized as dewatering aids of oil sands FFT.

1.2 Research Objectives

This research forms part of a larger, on-going Natural Sciences and Engineering Research Council of Canada (NSERC) Collaborative Research Development (CRD) program being undertaken by the University of Alberta in partnership with the Northern Alberta Institute of Technology. The intent of the CRD project is to determine viable plant establishment approaches suitable for the unique conditions presented by soft FFT deposits in Canada's oil sands. The CRD is also assessing the viability of different plant species to establish in these tailings utilizing different planting methods and ultimately evaluate plant growth and geotechnical performance. In additional, the overall CRD program would also assess the scalability of the various technologies and plant species.

The research conducted as part of this thesis work focused on the specific objective of evaluating different plant species ability to improve the geotechnical performance in centrifuged fluid fine tailings. The research included plant and geotechnical data collection for a meso-scale and macro-scale study conducted on samples of centrifuged fluid fine tailings from two different oil sands sites. The work presented in this thesis focused on the mesoscale study, with significant work on the macroscale study conducted by other parts of the wider research team and published in other literature. Several species including willows and slender wheatgrass were considered, utilizing contrasting plant life forms (herbaceous, grass, and woody shrubs). The scope of this research includes the following:

1. Collect geotechnical and plant data from a meso-scale study conducted at NAIT's Centre for Boreal Research in Peace River, AB from June 2018 to October 2019
2. Assess the impact of several plant species and their combinations on dewatering and strength gain in five totes containing a centrifuged fine tailings product
3. Comparison of published results on the macro-scale study with those from the meso-scale study

All other objectives of the CRD program are beyond the scope of this thesis.

1.3 Organization of Thesis

This thesis is comprised of five chapters. This chapter, Chapter 1, provides an introduction of the research topic and summarizes the objectives and scope contained herein. Presented below is an overview of the remaining chapters.

Chapter 2 provides an overview of some of the key technologies that have been or are currently being studied to improve the geotechnical characteristics of fluid fine tailings. The chapter concludes with a review of past work done on the use of plants to speed dewatering and strength gain of mine tailings through evapotranspiration.

Chapter 3 presents the results of the first year of the meso-scale ("totes") study conducted in Peace River, AB. This includes geotechnical data collected including settlement, water table drawdown, matric suction, and water content. Additional data was collected regarding surface plant growth and undrained shear strength of the tailings in the totes. The chapter concludes with a brief discussion of the results of year 1 of the study.

Chapter 4 presents the results from the second year of the meso-scale ("totes") study first introduced in Chapter 3 of this thesis. This includes a summary of the plants introduced to each tote as well as the results of additional geotechnical data collected during Year 2. Year 1 and Year 2 of the meso-scale study was split into two chapters due to the replanting required at the beginning of Year 2 in the totes, and a slightly different sampling matrix.

Chapter 5 summarizes the conclusions of the research conducted in this thesis and provides recommendations regarding further related work.

1.4 References

AER. (2020). *State of Fluid Tailings Management for Mineable Oil Sands, 2019*. Retrieved from Calgary, Alberta, Canada: https://static.aer.ca/prd/2020-09/2019-State-Fluid-Tailings-Management-Mineable-OilSands.pdf

AER. (2021). *ST98: 2021 Alberta's Energy Reserves & Supply/Demand Outlook*. Retrieved from

Chalaturnyk, R. J., Scott, J. D., & Özüm, B. (2002). Management of oil sands tailings. *Petroleum Science and Technology, 20*(9-10), 1025-1046. doi:10.1081/LFT-120003695

Jeeravipoolvarn, S., Chalaturnyk, R. J., & Scott, D. (2008, September 2008). *Consolidation Modeling of Oil Sands Fine Tailings: History Matching.* Paper presented at the GeoEdmonton, Edmonton, AB.

Johnson, R. L., Bork, P., Allen, E. A. D., James, W. H., & Koverny, L. (1993). *Oil Sands Sludge Dewatering By Freeze-Thaw and Evapostranspiration* (RRTAC 93-8). Retrieved from

Mossop, G. D. (1980). Geology of the Athabasca Oil Sands. *Science, 207 (4427)*, 145-152. doi:10.1126/science.207.4427.145

Silva, M. J. (1999). *Plant dewatering and strengthening of mine waste tailings.* (Doctor of Philosophy), University of Alberta,

Sobkowicz, J. (2012). *Oil Sands Tailings Technology Deployment Roadmaps: Project Report - Volume 1: Project Summary*: Alberta Innovates - Energy and Environment Solutions.

2 Literature Review

2.1 Introduction

The Athabasca oil sands have been commercially mined for bitumen resources since 1967, when the first oil sands mining megaproject was approved. This project was called the Great Canadian Oil Sands and would later become Suncor. This was followed by a second megaproject, Syncrude, in 1978 (Humphries, 2008). Since that time several large Canadian and international upstream oil producers opened new mining and in-situ bitumen extraction operations in northern Alberta, including Canadian Natural Resources Ltd., Imperial Oil, and Royal Dutch Shell. As of 2019, there were eight operating oil sands mines in the region north of Fort McMurray, AB (AER, 2020).

The Alberta oil sands are split into three regions, and four primary deposits covering over 142,000 square kilometers: Peace River, Cold Lake, and Athabasca. The bitumen is present in four primary deposits, with the largest being the Wabiskaw-McMurray deposit which covers a large part of the northeastern portion of the province of Alberta. This deposit contains the only reserves that are near enough to the surface (less than 75m below) to be extracted through truck-and-shovel surface mining operations. This area is referred to as the Surface Mineable Area (SMA) and represents only 3.4 percent of the total oil sands area (Government of Alberta, 2018), with the remainder of the oil sands resource exploitable only by in-situ methods such as SAGD (steam-assisted gravity drainage). Approximately 165.4 billion barrels of crude bitumen are recoverable using current technologies (Government of Alberta, 2018). Figure 2-1 provides a map showing the location of the major oil sands deposits of Alberta, including the area exploitable through surface mining.

Figure 2-1: Location of Alberta Oil Sands (King & Yetter, 2011)

The Wabiskaw-McMurray deposit is primarily comprised of bitumen, water, and minerals (quartz, silts, and clays), averaging 12% bitumen content. Clay primarily presents in the deposit as discontinuous beds or bands between 1 and 15cm in thickness (Chalaturnyk et al., 2002). These clay beds are made up of kaolinite (40-70 wt.%), illite (28-45 wt.%) and montmorillonite (1-15 wt.%). Mining of these deposits using truck and shovel is not selective enough to avoid excavating these layers, and as a result they are often processed along with the oil sands ore. Excessive quantities of these clays in the ore stream can have significant impacts on bitumen recovery and tailings properties (Hollander & Omotoso, 2018; Li, 2019).

Bitumen is liberated from the oil sands ore utilizing a hot water extraction processes pioneered by Dr. Karl Clark in the 1930s (FTFC, 1995). Bitumen ore is mixed with hot water and processing aids such as caustic (sodium hydroxide) and calcium citrate in a primary separation vessel that separates the ore slurry into bitumen froth, middlings, and underflow (coarse tailings). This extraction method requires significant quantities of water, generally demanding between 2 and 4.5 barrels of water for each barrel of synthetic crude oil produced (King & Yetter, 2011). The underflow is primarily coarse sands, while the middlings are comprised of fine silts and clays which are then sent to a secondary extraction process to recover as much residual bitumen as possible (Mercier et al., 2018), yielding bitumen recoveries of ~90% (de Klerk, 2020; Masliyah et al., 2004). The primary separation vessel underflow and the middlings produced during secondary bitumen recovery produce tailings containing mineral solids (on a regional average basis) of 85 wt.% coarse material (> 44μm), 14 wt.% fines, and 1 wt.% bitumen (Hockley, 2018). The tailings produced from this process are generally classified into one of three streams (Kasperski & Mikula, 2011):

- Coarse tailings (primarily particles > 44 μm)
- Fluid Fine Tailings (< 44μm, dominated by clays [< 2μm])
- Froth-treatment tailings

These streams are generally transported as slurries and deposited either individually or combined into dedicated disposal areas (DDAs) where the sand quickly segregates and forms a beach, while the fines (FFT) run out into the pond as a slurry (Kasperski & Mikula, 2011). This FFT has been observed to densify to approximately 30-50 wt.% after several years, but generally averages around 35 wt.% solids and will not densify further without active intervention (Mercier et al., 2018). These tailings are generally referred to as mature fine tailings (MFT), but current industry practice is to define all fines dominated tailings as FFT. The Canadian Oil Sands Innovation Alliance (COSIA) defines FFT as "a liquid suspension of oil sands fines in water with a solids content of > 2 wt.% but less than the solids content corresponding to the liquid limit" (COSIA, 2012). In general, it can be assumed that the mineral fines present in the FFT is ~50% clay, although notable variation has been seen between different mine operators (Mikula, 2018). Table 2-1 presents the typical range of the key components of untreated FFT in the Alberta oil sands.

Table 2-1: Typical range of bitumen, solids, and fines content in untreated oil sands fluid fine tailings (Cossey et al., 2021)

Parameter	Untreated Fluid Fine Tailings (FFT)
Bitumen Content (wt.%)	0.7-5.6
Solids Content (wt.%)	22-81
Fines Content (<44μm) (dry wt.%)	50-100
Sand to fines ratio (SFR)	0-1.1
Methylene Blue Index (meq/100g)[1]	1.4-14

[1] Methylene Blue Index (MBI) is a measure of water active surface area and is indicative of clay content.

On average, for each barrel of oil produced, approximately 1 m^3 of sand and 0.25 m^3 of MFT is produced (Nicholas Beier & Sego, 2007). There are currently 1270 million cubic meters of FFT stored in tailings ponds at the eight currently operating oil sands mines (AER, 2020). Management of these tailings to reduce current inventory, and avoid production of new FFT is an area of significant concern for the oil sands industry. This concern is driving regulation and research to find better ways to manage this challenging material, and increase the rate at which tailings storage facilities can be closed and reclaimed.

2.2 Fluid Fine Tailings Management

Initial project applications made by oil sands operators for mining operations proposed that fluid tailings be converted to deposits that would become trafficable in a reasonable amount of time and allow reclamation activities to begin. Despite implementation of available technologies to reduce fluid tailings production and total storage inventories, the Alberta Energy and Utilities Board (EUB – superseded by the Energy Resources Conservation Board [ERCB]) identified a series of long-term objectives for tailings management in the minable oil sands. These objectives formed the basis of joint panel decisions in 2004 dictating the establishment of industry-wide performance criteria by early 2008. This work eventually resulted in the ERCB (superseded by the Alberta Energy Regulator [AER]) issuing *Directive 074* in February 2009 (ERCB, 2009). This directive required a reduction in FFT accumulation through a minimum fines capture of 50% in dedicated disposal areas (DDAs); deposits were also mandated to achieve a minimum undrained shear strength of 10 kPa within 5 years to create a trafficable surface that could allow reclamation activities to begin.

Despite the significant increased investment in research and development of technologies by mine operators to meet the objectives defined in *Directive 074,* industry performance did not meet the expectations regarding fine tailings management defined in the directive. These results, in addition to mounting public pressure resulted in additional regulations put in place by the Government of Alberta and AER. The first was the Tailings Management Framework (TMF) put in place by the Alberta Government to allow and encourage progressive reclamation of tailings deposits in the oil sands. The intent being that this would manage and decrease the liability and environmental risks associated with the storage of large quantities of fluid tailings (Government of Alberta, 2015). Issuance of the TMF drove the AER to develop a new directive to replace *Directive 074* that was more in line with the objectives of the TMF. *Directive 085 – Fluid Tailings Management for Oil Sands Mining Projects* came into effect on October 12th, 2017, and sets out clear requirements for managing fluid tailings volumes in the minable oil sands (AER, 2017). The directive aims to drive further development of tailings treatment technologies, and ultimately reduce legacy and future fluid tailings inventory by mandating tailings deposits be ready-to-reclaim (RTR) within 10 years of the end of mine life. RTR, as defined by the AER, refers to tailings that have been processed with an accepted technology, placed in a final landscape, and meet certain performance criteria (AER, 2017). Performance criteria is generally proposed by the operator, and accepted or rejected by the AER. This approach allows for a flexible approach to fluid tailings management that is optimized for each mine sites unique characteristics and needs.

2.3 Fluid Fine Tailings Treatment

To meet the objectives and regulations described above, operators are required to examine and implement cost-effective technologies to manage new and legacy FFT produced during mining operations. Effective management of these tailings is required to fulfill regulatory responsibilities of these company’s operations, in addition to minimizing liability and environmental risk associated with these projects. These technologies aim to reduce storage volumes of these fine tailings by promoting consolidation and dewatering. Increasing the density and strength of these deposits of FFT is also essential to any eventual terrestrial closure and reclamation objectives.

These objectives are most often aligned with producing a tailings deposit of significant strength to allow the eventual capping of the deposit to support the construction of terrestrial landforms. In order to be able to safely construct a terrestrial landform on a fine tailings deposit, these underlying tailings need to have residual settlement no greater than 2m, and have undrained shear strengths greater than 25 kPa (Hyndman et al., 2018). In general, the first stage of terrestrial reclamation of an oil sands tailings deposits involves the placement of a soil cap (comprised of sand, coke, or other reclamation material) over top of the tailings material. Generally the capping method and material is based upon the undrained shear strength and solids content of the underlying tailings material (McKenna et al., 2016). Figure 2-2 presents a summary of the strength and solids content suitable for several different capping technologies and approaches. It demonstrates that as strength and solids content increase, the risk of failure and significant post closure settlement decrease.

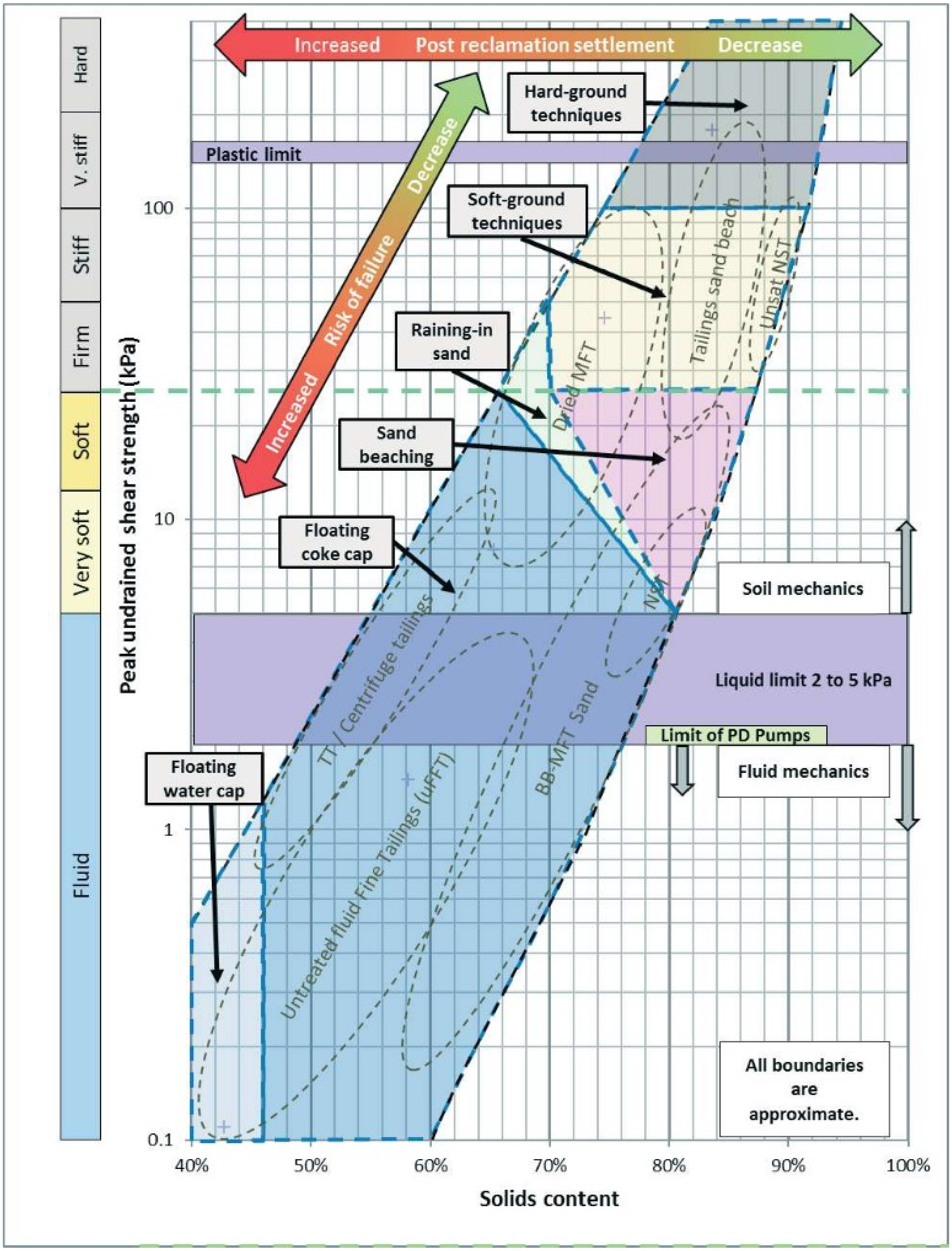


Figure 2-2: Applicability of capping technologies for approximate ranges of oil sands fine tailings shear strength and solids contents (McKenna et al., 2016)

Over the history of oil sands operations, hundreds of technologies ranging from lab scale to commercial operation have been tested on these tailings to meet these objectives (Corriveau, 2018). Research into resolving the fine tailings challenge begun almost immediately after the first oil sands mine began operations in 1967. Two decades of failures to adequately address fine tailings in the oil sands culminated in the formation of the Fine Tailings Fundamentals Consortium (FTFC) in 1989 ((FTFC, 1995). The initial mandate of the FTFC was to provide sufficient scientific understanding of fine tailings that could be used to form the basis of potential engineering solutions. This resulted in the first major publication (*Advances in Tailings Research)* summarizing the state of oil sands tailings research being published in 1995. More recent compilations include a 2010 report prepared by BGC Engineering Inc. for the Oil Sands Research and Information Network (OSRIN) intended to describe the state of knowledge for technologies concerned with oil sands tailings treatment (BGC Engineering Inc., 2010). Building upon these and other studies and reports on tailings technology development were expanded upon further when Alberta Innovates commissioned a project to develop the Oil Sands Technology Roadmap and Action Plan (Sobkowicz, 2012). The objective of this work was to lay out a clear and comprehensive roadmap to support both regulators and industry members to meet the tailings management goals defined in ERCB's *Directive 074* (ERCB, 2009).

In general, tailings treatments can be split into one of five categories as defined by BGC in their 2010 report (BGC Engineering Inc., 2010):

- Physical/Mechanical Processes
- Natural Processes
- Chemical/Biological Amendments
- Mixtures/Co-disposal
- Permanent Storage

This classification was generally based upon how the technology acts on the tailings and when. Some technologies focus on improving the performance of the tailings stream before deposition (such as in-line flocculation and thickened tailings), or work by increasing density and strength of the tailings after they have been placed in a deposit. In physical and mechanical technologies, water is separated from the tailings solids using physical and/or mechanical means. Some examples of these technologies are filtered tailings, pre-fabricated vertical drains (also known as wick drains), and centrifuged fine tailings (BGC Engineering Inc., 2010). These technologies utilize physical or mechanical action to pull water out of tailings. Centrifugation is of particular relevance to this work, as the plant evaporation study discussed in Chapter 3 and Chapter 4 was conducted on totes of centrifuged fluid fine tailings. Centrifugation involves spinning FFT at a high rate of speed that imposes many times the force of gravity on the tailings to extract water. This produces a tailings product with a solids content of 55 to 65% (Hyndman et al., 2018; Spence et al., 2015). The effectiveness of centrifugation can be further increased by the addition of coagulants and/or flocculants to the tailings before they are spun in the centrifuge. Early studies suggested that this centrifuged material would further densify to a solids content of 70 to 80% solids when placed in a shallow (<2m) deposit; commercial scale implementation of this technology have noted challenges achieving this solids content gain, particularly when centrifuged fine tailings is placed in a deep deposit, which is anticipated to take centuries to settle and densify to a point that is adequate for capping and eventual reclamation (Hyndman et al., 2018).

Chemical and biological amendments involve introducing chemical or biological agents to the FFT to promote dewatering. One of the most prominent of these technologies currently in use is flocculation of tailings. Flocculation encourages chemical bonding of colloids (in this case clay particles) which results in these aggregated particles settling out, resulting in additional expressed water and increased density (N. Beier et al., 2013; BGC Engineering Inc., 2010; Jeeravipoolvarn, 2010). Biological amendments including inoculation with micro-organisms such as bacteria can be used to both support plant growth on the tailings (V. Collins et al., 2018), or encourage densification as a result of methane production within the tailings (C. Collins et al., 2016; Guo, 2009).

Mixtures and co-disposal techniques focus on mixing tailings material with reclamation soils or other waste streams to densify and improve the consolidation performance of tailings deposits in the oil sands (BGC Engineering Inc., 2010). Permanent storage solutions are less concerned with achieving a deposit amenable to terrestrial reclamation at closure, and more about minimizing or eliminating the risks due to potential settlement and strength normally associated with oil sands tailings deposits. An example of such a technology is an end pit lake (EPL), which is a waterbody containing oil sands waste materials that are stored below grade in exhausted mining pits. Work from pilot to commercial scale is being actively researched at multiple mine sites in the oil sands, with some of the major concerns with this technology being the potential for resuspension of contaminants contained within the tailings; negatively impacting water quality (Cossey et al., 2021).

The final category of technologies defined by BGC were natural processes. These technologies take advantage of climate and other naturally-occurring phenomena to speed dewatering and consolidation of fine tailings. Examples of this include dewatering through freeze-thaw, and dewatering through evapotranspiration of vegetation planted in the tailings (BGC Engineering Inc., 2010; Sobkowicz, 2012). Freeze thaw takes advantage of freezing temperature for a significant proportion of the year in the oil sands region to increase dewatering of tailings deposits in the oil sands. When the pore fluid trapped in the tailings freezes, significant suctions are created that results in a lattice structure forming during thaw that both reduces the amount of water retained in the soil, and significantly increases permeability (N. Beier et al., 2009; Proskin, 1998). Consolidation and strength gain through freeze thaw can be significant (Dawson et al., 2011), but the majority of the impacts are limited to surface layers of the deposit, and lab testing has shown that peak strength gain is achieved after 5 cycles of freeze thaw (Rima & Beier, 2021).

Dewatering through evapotranspiration of vegetation planted in oil sands tailings has been studied at a number of scales since the early 1990's. Assessment of selected native plant species to dewater a sample of centrifuged fluid fine tailings is the focus of this thesis work. State of practice and a summary of available literature pertaining to this technology is discussed in the section below.

2.4 Plant Dewatering

As stated in Chapter 1 of this paper, the focus of the research described herein focused on the impact that the establishment of select native plant species could have on the geotechnical characteristics of a centrifuged fluid fine tailings product. This sub section will provide further background on the use of plants as a method of dewatering and strength gain in oil sands tailings.

The idea of utilizing plants to dewater oil sands tailings came from seeing its use in other industries to dewater and potentially reduce contaminants in dredged fine sediments. Dewatering these materials reduces the volume required for storage and can also de-risk some of these materials through the natural degradation and removal of contaminants (Euliss, 2005; K. E. Smith et al., 2009).

Early studies conducted in the 1990's suggested that suitable plant species that are able to successfully establish in high water content tailings could assist significantly in dewatering these tailings by evapotranspiration through their leaves (Johnson et al., 1993; M. J. Silva, 1999). Initial interest in study and development of this technology arose from the fact that plants are capable of transpiring significant quantities of water during their growing season; the idea behind their application as a dewatering tool being that this water loss may be greater than that of free water evaporation alone, in addition to being able to continue dewatering even after a surface crust has formed (BGC Engineering Inc., 2010). The surface of treated tailings (such as flocculated or centrifuged fluid fine tailings) forms a hydrophobic layer as it dries that reduces further evaporation of subsurface material (Schoonmaker et al., 2018). A 2010 report by BGC Engineering Inc. that was prepared for OSRIN (Oil Sands Research and Information Network) identified several advantages and disadvantages to the use of plants as a dewatering method. These are summarized in Table 2-2.

Table 2-2 Identified Potential Advantages and Disadvantages of Using Plants to Dewater Oil Sands Tailings (Adapted from: BGC Engineering Inc. (2010) pg. 29-30)

Potential Advantages	Potential Disadvantages
– Suitable plant species growing in tailings can remove water by transpiration through their leaves – Plants can transpire significant quantities of water during growing season – Absorption of CO_2 by the plant – Increases to bearing capacity of the tailings because of root development which may allow access by some equipment for reclamation – Vegetation may assimilate minerals and various toxic compounds and can then be harvested to remove these elements from the environment	– High concentrations of salts and other potential toxins can inhibit establishment and healthy growth of the plants – Challenges getting seeds to develop in the deposit – greatest success is generally with seedlings (which may be challenging to place) – Placement of fertilizers, seedlings/seeds and other amendments onto large deposits is not well developed – Depth of dewatering is limited by root depth – Likely limited to use of native species due to the risk of non-native or invasive species to the natural ecosystem

The first studies on use of plants to dewater oil sands tailings were done by Johnson in 1993 (Johnson et al., 1993). This study focused on assessing the solids content increase and strength gain that could be achieved in one growing season on an oil sands tailings sludge (~50% solids). This sludge was prepared by combining a low-solids fine tailings sludge at 20-30% solids and mixing it with sand or allowing it to go through a cycle of freezing and thawing that resulted in the final sludge used in the study being approximately 50% solids by weight. It was noted that even at 50% solids by weight, the tailings sludge had a custard-like consistency with shear strengths no greater than 1kPa, making them incapable of supporting any weight. The study generally assumed that if the sludge could be brought to approximately 80% solids by weight, sufficient shear strength would be developed to allow surface access for people, animals, and reclamation equipment. This study also noted that for maximum dewatering to be achieved, no standing water could be allowed to remain on the area of treated tailings as it would significantly impede the ability of natural processes to evaporate and dewater the tailings sludge. Johnson also included an assessment of viable plant species to be tested. Considering several key factors that each candidate species should have: high leaf area index, deep root systems, readily available access to seeds and the seeds should be capable of germinating quickly, even in cooling weather conditions to maximize the length of the growing season in Ft. McMurray. It was also noted that any plants would likely require additional nutrients be added to the tailings to ensure viability, particularly nitrogen and phosphorus. This initial screening of plant species was completed at a lab scale before a secondary assessment was completed in a greenhouse experiment to further narrow down the species that would be used in a field test in Ft. McMurray in the spring of 1986. Of the nine species examined in the greenhouse study, four were identified as capable of growing reasonably well in sand-sludge mixtures with the addition of fertilizers: reed canary grass (*Phalaris arundinacea)* and northern reed grass (*Calamagrostis stricta*), western dock (*Rumix occidentalis),* and timothy *(Phleum patense).* Reed canary grass and western dock demonstrated the greatest dewatering potential in the selection studies. The field pilot was done in twelve pits, each with an area of $5m^2$ and a depth of 2.5 m, which were seeded with various selections of reed canary grass, northern reed grass, and western dock. The study was further expanded in additional studies conducted in Vegreville, Alberta the following year. The final results of this work determined that in optimal and well controlled conditions, certain plant species can increase the solids content and strength of an oil sands tailings sludge in as little as one growing season; but that for this to occur, the surface must remain free of water, and it requires substantial plant densities that demand external nutrient supplies via fertilizers and other amendments.

M. J. Silva (1999) continued work on the use of plants for dewatering mine tailings in his 1999 thesis. The objective of this work was to develop a theoretical approach to predicting the strength characteristics of a tailings material based on vegetation. This model was developed using a two-phase greenhouse experiment that assessed the dewatering potential of select plant species in composite oil sands tailings (CT) and copper mine tailings (CMT). The oil sands CT was supplied from Syncrude Canada Ltd.'s Mildred Lake mine site north of Ft. McMurray, Alberta; The CMT tailings were provided by the Kennecott Copper Mine in the south western United States. The results of this work were that the strength of the tailings was increased through a combination of increased matric suction from the plants pulling water from the tailings, and reinforcement from the root systems developed by the plants. The model was found to reasonably match the trends observed in the greenhouse experiment, although it was noted the model slightly overpredicted the amount of settlement that may be achieved. These results were used to inform a model that Syncrude would use to predict behavior of their CT tailings deposits based on climate data. Silva identified five and three plant species for the CT and CMT tailings respectively that warranted further study. One of the major problems with Silva's work is that the experiments included plant species that were note native to northeastern Alberta, and therefore may not be feasible for use in the oil sands due to concerns regarding the risk posed by potentially invasive plant species to the local ecology. Silva further built upon his model to developed a physically based model that could predict the contributions of vegetation on bearing capacity of an oil sands tailings deposit (Silva et al., 2009). The model was validated by a greenhouse study that again used CT supplied by Syncrude Canada for the assessment. Results showed good agreement between the simulated and measured values, though it was noted the model still failed to account for the impacts of freeze-thaw consolidation on the dewatering of the tailings material. Silva provided recommendations for further study in the use of plants to dewater oil sands tailings: add the impacts of freeze-thaw and other physical processes into the model to allow for predictions encompassing multiple growing seasons, further develop and optimal approach for plant establishment, identify native species to replace non-native species used in these studies, and improve the accuracy of the soil water characteristic curve (SWCC) in these applications. He also agreed with the work by Johnson that surface water must be carefully controlled for the plants to be effective dewatering agents, especially during the seeding period (if applicable).

Renault and others published several papers from 2000 to 2004 that examined the ability of several plant and tree species to successfully establish in oil sands tailings material or FFT-amended natural soils. The 2000 paper focused on the impact that the addition of FFT to natural or reclaimed soils would have on the health and viability of dogwood, jack pine, white spruce, and raspberries. Renault noted significant impact on the health of the plants, noting that the more sensitive species experienced a mortality of 45-56% when compared to the control (Renault et al., 2000). Renault followed this work with a greenhouse study on the establishment of barley (*Hordeum vulgare L.)* in a CT oil sands tailings material. He found a significant reduction in germination rate and biomass growth in the plants, largely due to the high salinity of the tailings. It was noted overall that barley was relatively tolerant, but that amendments including peat addition and fertilizers would be required for ensure survival of the barley. Ultimately it was concluded that barley would not be suitable for long term remediation of the CT material, but it recommended additional work a field scale to assess dewatering potential of the species (Renault et al., 2003). The third study in 2004 built off the results of Renault's earlier work and studied the ability of two species (Altai wildrye (*Leymus angustus)* and slender wheatgrass (*Elymus trachycaulus)*) for initial reclamation of a highly saline oil sands CT material. This study focused on the survivability of these two species in CT treated with different combinations of alum, gypsum and peat. Overall, it was noted that slender wheatgrass had a greater challenge germinating in the tailings while the wildrye struggled more in its early growth stages. Both species established better when peat was added an amendment and the alum treated tailings were more favourable to the plants than the gypsum treated tailings (Renault et al., 2004). Although Renault's work focused more on the ability of plant species to tolerate and grow in tailings, rather than considering dewatering potential or improvements to the geotechnical characteristics of the tailings. Assessment of plan viability and establishment is beyond the scope of this thesis, but it provides valuable information to support that species can successfully establish in these challenging materials.

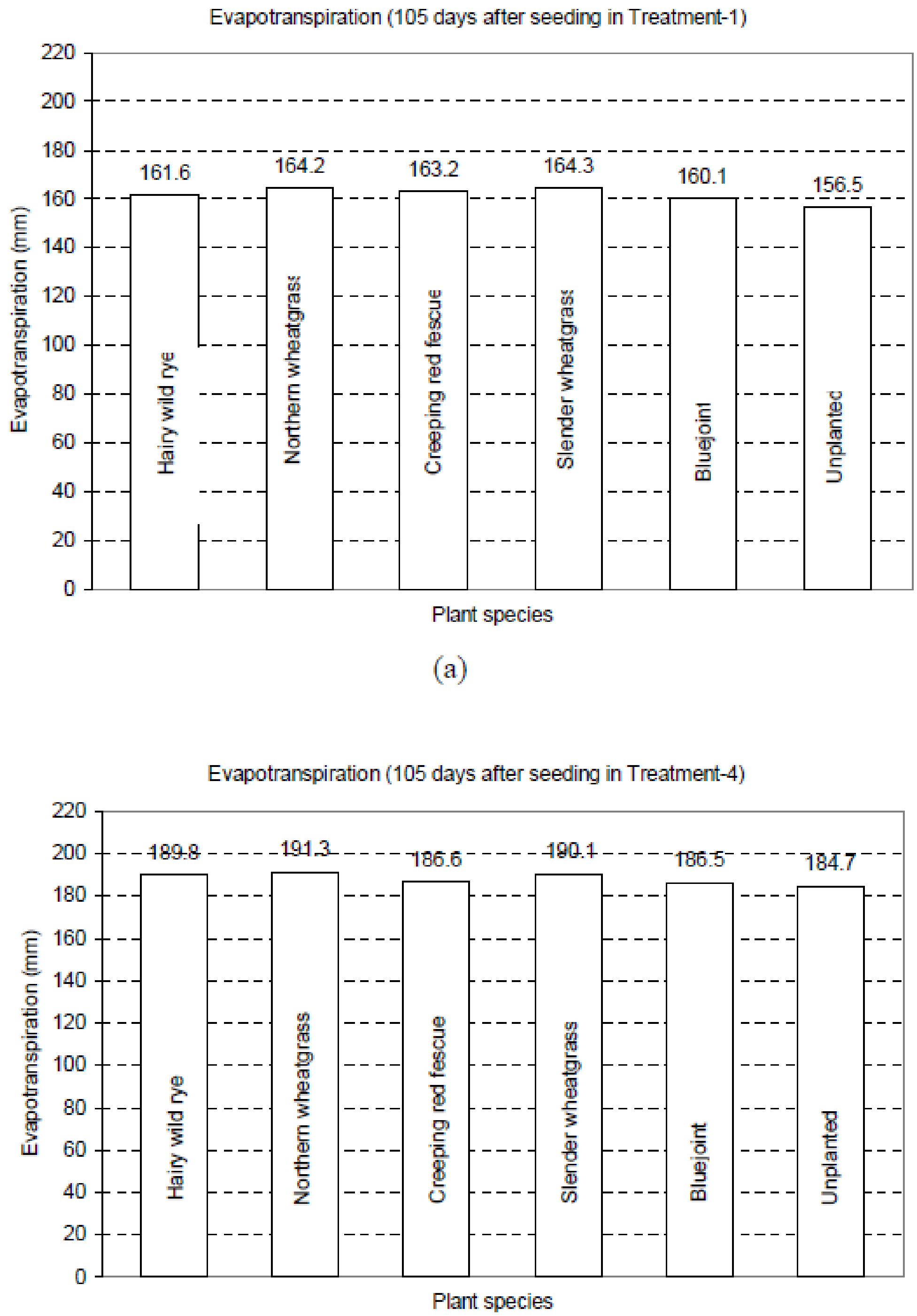
Wu (2009) 's thesis work involved a greenhouse study at the University of Alberta that aimed to evaluate the dewatering capacity of give native plant species in CT tailings from an oil sands mine operator. It is important to note that as in Silva's work, CT tailings have very different geotechnical properties than the centrifuged fine tailings described in Chapter 3 and Chapter 4. The geotechnical parameters of the CT tailings used in the study are presented in Table 2-3.

Table 2-3: Geotechnical Properties of Tailings Samples Used in Greenhouse Study (Wu, 2009)

Tailings sample		Water content (%)	Solids content (%)	Fines content (%)
MFT	Barrel 1	121.6	45.1	64.6
	Barrel 2	243.3	29.1	93.0
Sand		3.8	96.3	3.0
Gypsum		7.5	93.0	N/A
CT mixture		63.6	65.1	20.0

These tailings were noted as not being acutely toxic to the native plant species chosen for study which included Bluejoint, Northern Wheatgrass, Creeping red fescue, Slender wheatgrass, and Hairy wild rye. The results of the study demonstrated that all species except for the Bluejoint could successfully establish in the CT, with Northern wheatgrass and Slender wheatgrass showing the greatest tolerance and growth during the study period. It was concluded that these two native grass species would be most suitable for use in dewatering CT due to their initial growth success.

Wu also reported that addition of a fertilizer at seed placement did not impact germination rates of the species; concurrent applications of fertilizer added biweekly after 8 weeks did show an appreciable increase in growth rate and biomass for the two-wheatgrass species. Based on the water loss recorded throughout the study and the dimensionless dewatering capacity, all native plant species tested demonstrated a greater quantity of water uptake through plant evapotranspiration than via evaporation from the CT surface alone. Evapotranspiration results for all species in two treatments are presented in Figure 2-3.



(a)

(b)

Figure 2-3: Evapotranspiration of CT after 15 weeks plant growth (a) Treatment-1: broadcast seeding: (b) Treatment-4: 4-6 mm fresh discharge CT slurry seeding (Wu, 2009)

Wu published three additional conference papers in 2010 and 2011 on the work initially published in her 2009 thesis described above (Wu et al., 2010; Wu, Naeth, et al., 2011; Wu, Sego, et al., 2011). The 2011 papers both focused more on plant viability and establishment, rather than the dewatering potential of the plants which was the focus of the 2010 paper. Assessment of vegetation success was beyond the scope of the research described in Chapter 3 and Chapter 4.

A field trail was conducted by Schoonmaker et al. (2018) at Canadian Natural Resources Albian Sands in an atmospheric fines drying (AFD) tailings deposit with a surface crust. The purpose of this work was to determine the ability of several different plant species to establish in this type of tailings material, and assess the potential of these plant species to further dewatering these deposits. The study included assessment of native and non-native plant species, including seeding of fall rye (*Secale cereal L.*) and slender wheatgrass (*Agropyron trachycaulum* (Link) Malte ex H.F. Lewis) in September 2016 and May 2017. Balsams poplar (*Populus balsamifera* L.), and sandbar willow (*Salix exigua* Nutt.) that were planted in 2015 were also evaluated. Greatest water content reduction was achieved approximately 15cm below the tailings surface with the area seeded with Fall rye. Increases in matric suction at 30 and 45 cm depths were also observed for all vegetated plots, with Fall rye again demonstrated the greatest increase from initial. A positive relationship between above-ground plant biomass and solids content at all sampling but mean solids content according to the treatment (planted/seeded vs. control) demonstrated little effect. Ultimately the work concluded that appropriate plant select was essential to ensure growth of the plant species that would support dewatering of the treated fine tailings. It recommended that further work to optimize the mix of plant species for dewatering and shear strength should be done, and it again reiterated work by Wu (2009) that highlighted nutrition for the plants also warrants further examination to optimize plant growth and resultant dewatering.

Recent work on the use of native plant species to dewater oil sands fine tailings included a multi-year, pilot-scale study conducted at Canadian Natural Resources Ltd.'s Albian Sands operation north of Ft. McMurray, AB. Select results from the first 21 months of the study period were published by Smith et. al. at the International Oil Sands Tailings Conference (IOSTC) in 2018. This pilot involved filling a 30 m wide by 60 m long test cell with centrifuged fluid fine tailings (CFFT) to a depth of 4.65 m in 2016. In 2017, the deposit was seeded and planted with two native plant species: slender wheatgrass (*Elymus trachycaulus),* and sandbar willow (*Salix interior).* Wick drains (also referred to as pre-fabricated vertical drains) were also installed in the test cell. This CFFT product was produced at a different oil sands site than the centrifuged fine tailings described in Chapter 3 and Chapter 4. The index properties of the tailings in the test cell are summarized in Table 2-4.

Table 2-4: Index Properties of CFFT Used in Plant Dewatering Pilot Study (W. Smith et al., 2018)

Parameter	Bitumen Included	Range of Values (Average)	# of Tests
Bitumen Content (%)	-	0.8-2.3 (1.6)	39
Liquid Limit (%)	Yes	71-90 (80)	16
Plastic Limit (%)	Yes	22-29 (24)	16
Plasticity Index (%)	Yes	43-66 (57)	16
Specific Gravity	Yes	2.37-2.55 (2.47)	17
Hydrometer Fines Content (<45 μm) (%)	No	97-99 (98)	7
Hydrometer Clay Content (<2 μm) (%)	No	9-32 (22)	7

After 21 months (which included three site investigations and continuous monitoring), the CFFT deposit had settled approximately 20% of its original thickness at its deepest point. A surface crust of approximately 40 cm was measured, although this was primarily attributed to freeze-thaw actions and evaporative drying. An average strength gain in the centre of the deposit of 5 kPa was measured, but it is important to note that major strength gains in the crust were rapidly lost when rewetted. Zones with wick drains installed had limited impact on the strength, solids content, and settlement of the deposit compared to similar zones in the centre of the deposit. Measurements collected after one growing season showed a fourfold increase in undrained shear strength in the top 30 cm of the deposit. The lowest strength gains were recorded in the flooded areas of the deposit where vegetation survivorship was poor. The flooded areas were limited to the centre of the deposit, by virtual of its concave "tub" shape which is also the deepest point of the deposit. Given the challenges with flooding, the authors recommended potential examination of the use of wetland species in deposits at risk of flooding, and a longer study on the upland native species used to allow the planted species to generate additional biomass. This increase biomass may further increase dewatering of the tailings deposit.

The field trial described above was also included in work published as two companion papers presented at Tailings and Mine Waste 2021 in Banff, AB by Schoonmaker et al. (2021) and Abdulnabi et al. (2021). These conference papers compared the results from the field trial described above at Albian Sands with a greenhouse study and outdoor tote study in Peace River, AB. The outdoor tote study is the same as that described in Chapter 3 and Chapter 4 of this thesis. The greenhouse study involved 100L barrels containing centrifuged fluid fine tailings from the same mine site as the field scale study, which differed from the centrifuged tailings in the outdoor tote study. Key findings related to the plants noted vigorous growth of the plants in the controlled greenhouse study, and the barrels containing plants consumed three times more water over the study period than what was observed in the control barrels. For the outdoor and field scale studies, slower growth and less consistency amongst all species was observed. The author noted that it was challenging to isolate what specific factor may be behind these slower rates of growth given the magnitude in the difference of scale, and the different chemistry of the centrifuged tailings in the outdoor tote trial. The second paper has greater relevance to the objectives of this thesis, namely the key geotechnical parameters studied in each of the three trials, and how they may relate to the establishment of native plant species. Abdulnabi noted there was a variable degree of strength gain in the greenhouse and outside tote studies for those containers with vegetation, but this was not as clearly demonstrated in the field trial at Albian. Figure 2-4 and Figure 2-5 present the peak undrained shear strength profiles for the greenhouse and field studies respectively. Strength profiles for the outdoor tote study is presented in this paper in Figure 4-9.

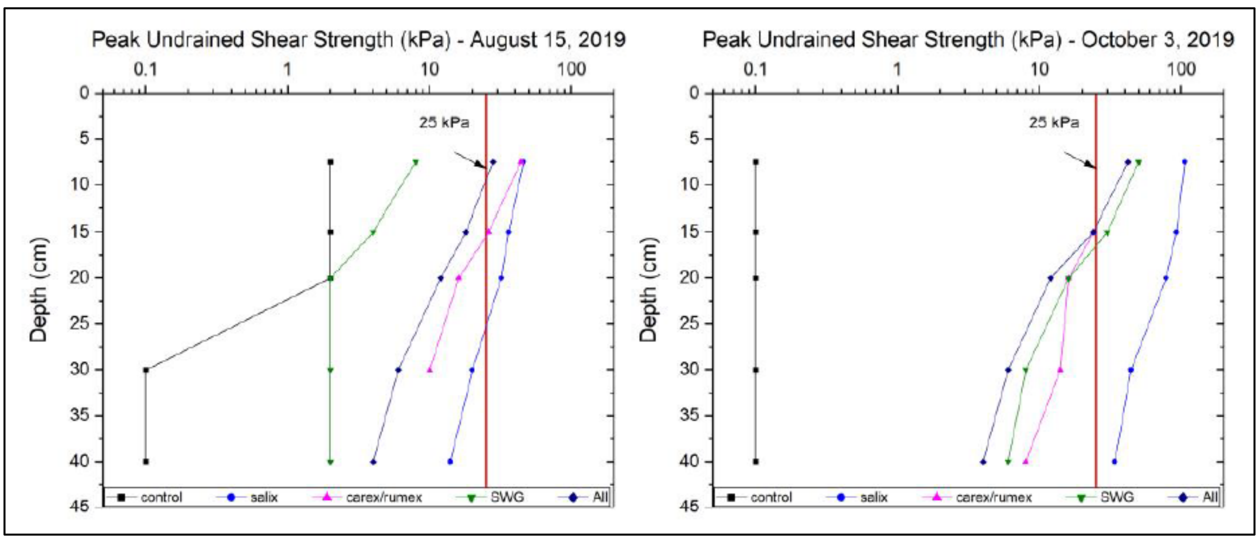


Figure 2-4: Peak Undrained Shear Strength Profile after 83 days (left) and 132 days (right) for a greenhouse study on vegetated tailings (Abdulnabi et al., 2021)

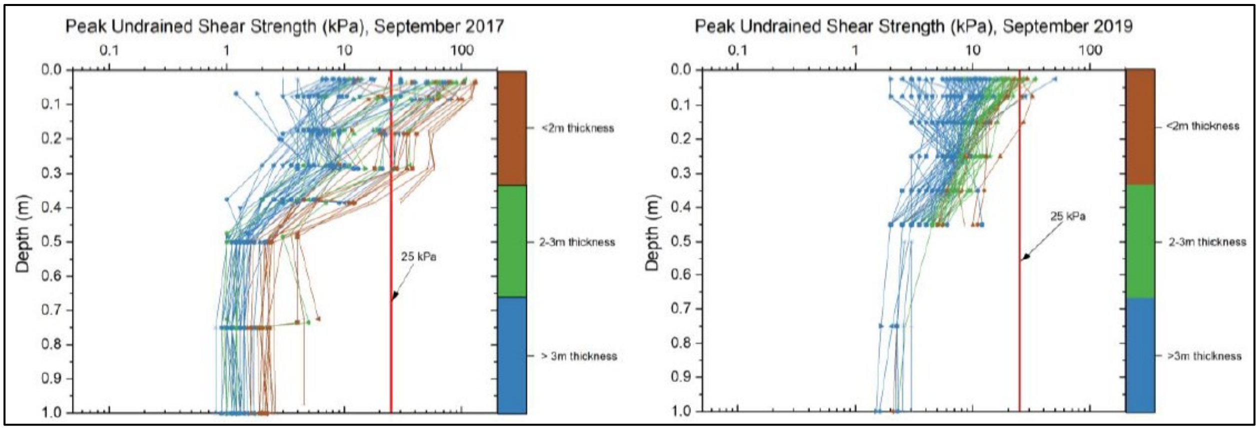


Figure 2-5: Peak undrained shear strength of field deposit of vegetated tailings in 2017 (left) and 2019 (right) (Abdulnabi et al., 2021)

Similar to the earlier work published by W. Smith et al. (2018), it was noted that any strength gain in the field scale trial was primarily limited to the top 35 cm of tailings, and that these gains seemed more dependent on water control and climactic conditions in the field. Strength measurements revealed that nearly all strength gains were reversed if the deposit was flooded due to precipitation accumulation in the deposit. This was evidenced by the reduction in strength from measurements collected in 2017 (a drier year) to 2019 (a wetter year).

2.5 References

Abdulnabi, A., Paul, A., Beier, N., Laberge, S., Schoonmaker, A., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 2 key geotechnical performance indicators*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

AER. (2017). *Directive 085 - Fluid Tailings Management for Oil Sands Mining Projects*. Calgary, AB: Alberta Energy Regulator.

AER. (2020). *State of Fluid Tailings Management for Mineable Oil Sands, 2019*. Retrieved from Calgary, Alberta, Canada: https://static.aer.ca/prd/2020-09/2019-State-Fluid-Tailings-Management-Mineable-OilSands.pdf

Beier, N., & Sego, D. (2007). *The Oil Sands Tailings Research Facility*, Ottawa, Ontario, Canada.

Beier, N., Alostaz, M., & Sego, D. (2009). *Natural dewatering strategies for oil sands fine tailings*. Paper presented at the Tailings and Mine Waste, Banff, AB.

Beier, N., Wilson, W., Dunmola, A., & Sego, D. (2013). Impact of flocculation-based dewatering on the shear strength of oil sands fine tailings. *Canadian Geotechnical Journal*(50(9)), 1001-1007.

BGC Engineering Inc. (2010). Oil Sands Tailings Technology Review. In Oil Sands Research and Information Network (Ed.), (pp. 136 pp.). Edmonton, Alberta.

Chalaturnyk, R. J., Scott, J. D., & Özüm, B. (2002). Management of oil sands tailings. *Petroleum Science and Technology, 20*(9-10), 1025-1046. doi:10.1081/LFT-120003695

Collins, C., Foght, J. M., & Siddique, T. (2016). Co-occurrence of methanogenesis and N2 fixation in oil sands tailings. *The Science of the total environment*(565), 306-312. doi:https://doi.org/10.1016/j.scitotenv.2016.04.154

Collins, V., Schoonmaker, A., Kaminsky, H., Sedgwick, A., Chigbo, C., & Mussone, P. (2018). *Development of bacterial inoculum for the promotion of plant growth on tailings material*. Paper presented at the International Oil Sands Tailings Conference, Edmonton, AB, Canada.

Corriveau, D. (2018, December 9-12). *Keynote Address.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB.

COSIA. (2012). *Technical Guide for Fluid Fine Tailings Management.* Retrieved from Calgary, AB:

Cossey, H. L., Batycky, A. E., Kaminsky, H., & Ulrich, A. C. (2021). Geochemical Stability of Oil Sands Tailings in Mine Closure Landforms. *Minerals, 11*(8), 830. doi:10.3390/min11080830

Dawson, R. F., Sego, D. C., & Pollock, G. W. (2011). Freeze-thaw dewatering of oil sands fine tails. *Canadian Geotechnical Journal*(36(4)), 587-598. doi:10.1139/cgj-36-4-587

de Klerk, A. (2020). *Future Energy - Improved, Sustainable and Clean Options for Our Planet* (Third ed.). Cambridge, MA: Elsevier.

ERCB. (2009). *Directive 074 - Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes*. Calgary, AB: Energy Resources Conservation Board of Alberta.

Euliss, K. W. (2005). *Dewatering and Remediation of Contaminated Dredged Sediments.* (Doctor of Philosophy Dissertation), Purdue University,

FTFC. (1995). *Advances in oil sands tailings research*. Edmonton, Alberta: Fine Tailings Fundamentals Consortium, Alberta Department of Energy, Oil Sands Research Division.

Government of Alberta. (2015). *Lower Athabasca Region - Tailings Management Framewor for the Mineable Athabasca Oil Sands*. Edmonton, AB: Government of Alberta.

Government of Alberta. (2018). Oil Sands Facts and Statisitics. Retrieved from https://www.alberta.ca/oil-sands-facts-and-statistics.aspx

Guo, C. (2009). *Rapid Densification of the Oil Sands Mature Final Tailings (MFT) by Microbial Activity.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB. Retrieved from https://dx.doi.org/10.7939/r3k988

Hockley, D. (2018). Clay effects on geotechnical properties of tailings. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 183-211). Chantilly, Virginia, USA: The Clay Minerals Society.

Hollander, E., & Omotoso, O. (2018). Clays impact on bitumen-extraction processes. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 109-127). Chantilly, Virginia, USA: The Clay Minerals Society.

Humphries, M. (2008). *North American Oil Sands: History of Development, Prospects for the Future* (9781606926802). Retrieved from

Hyndman, A., Sawatsky, L., McKenna, G., & Vandenberg, J. (2018). *Fluid Fine Tailings Process: Disposal, Capping, and Closure Alternatives*. Paper presented at the International Oil Sands Tailings Conference, Edmonton, Alberta, Canada.

Jeeravipoolvarn, S. (2010). *Geotechnical behavior of in-line thickened oil sands tailings.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB. Retrieved from http://pqdt.calis.edu.cn/detail.aspx?id=RQZFOt6KJ2I%3D

Johnson, R. L., Bork, P., Allen, E. A. D., James, W. H., & Koverny, L. (1993). *Oil Sands Sludge Dewatering By Freeze-Thaw and Evapostranspiration* (RRTAC 93-8). Retrieved from

Kasperski, K. L., & Mikula, R. J. (2011). Waste Streams of Mined Oil Sands: Characteristics and Remediation. *Elements, 7*(6), 387-392. doi:10.2113/gselements.7.6.387

King, K. S., & Yetter, J. (2011). Groundwater and Alberta's Oil Sands Mines. *Groundwater, 49*(3), 316-318. doi:10.1111/j.1745-6584.2011.00819.x

Li, A. (2019). *Role of clays in bitumen extraction of water-based oil sands processing.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB.

Masliyah, J., Zhou, Z. J., Xu, Z., Czarnecki, J., & Hamza, H. (2004). Understanding Water-Based Bitumen Extraction from Athabasca Oil Sands. *The Canadian Journal of Chemical Engineering, 82*, 628-654. doi:https://doi.org/10.1002/cjce.5450820403Citations

McKenna, G., Mooder, B., Burton, B., & Jamieson, A. (2016). Shear Strength and Density of Oil Sands Fine Tailings for Reclamation To a Boreal Forest Landscape. *IOSTC 2016: Proceedings of the 5th International Oil Sands Tallings Conference, 2*(604).

Mercier, P. H. J., Omotoso, O., & Hockley, D. (2018). Oil-sands clays. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 9-32). Chantilly, Virginia, USA: The Clay Minerals Society.

Mikula, R. (2018). The role of clays in the performance of oil-sands tailings management options. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 129-181). Chantilly, Virginia, USA: The Clay Minerals Society.

Proskin, S. A. (1998). *A geotechnical investigation of freeze-thaw dewatering of oil sands fine tailings.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB.

Renault, S., Zwiazek, J. J., Fung, M., & Tuttle, S. (2000). Germination, growth and gas exchange of selected boreal forest seedlings in soil containing oil sands tailings. *Environmental Pollution, 107*(3), 357-365. doi:10.1016/S0269-7491(99)00167-0

Renault, S., MacKinnon, M., & Qualizza, C. (2003). Barley, a Potential Species for Initial Reclamation of Saline Composite Tailings of Oil Sands. *Journal of Environmental Quality, 32*(6), 2245-2253.

Renault, S., Qualizza, C., & MacKinnon, M. (2004). Suitability of altai wildrye (Elymus angustus) and slender wheatgrass (Agropyron trachycaulum) for initial reclamation of saline composite tailings of oil sands. *Environmental Pollution, 128*(3), 339-349. doi:10.1016/j.envpol.2003.09.009

Rima, U. S., & Beier, N. A. (2021). Effects of seasonal weathering on dewatering and strength of an oil sands tailings deposit (in press). *Canadian Geotechnical Journal*. doi:https://doi.org/10.1139/cgj-2020-0533

Schoonmaker, A., Degenhardt, D., & Floreani, T. (2018). *Evaluating the Potential to Establish Plants to Aid in Dewatering of an Atmospheric Fine Drying Tailings Deposit at Muskeg River Mine.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Schoonmaker, A., Chigbo, C., Walton-Sather, S., Abdulnabi, A., Beier, N., Laberge, S., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Silva, J, M., Ulrich, C, A., Biggar, W, K., . . . C, D. (2009). A model for the prediction of bearing capacity on vegetated tailings. In: University of Alberta.

Silva, M. J. (1999). *Plant dewatering and strengthening of mine waste tailings.* (Doctor of Philosophy), University of Alberta,

Smith, K. E., Banks, M. K., & Schwab, A. P. (2009). Dewatering of contaminated sediments: Greenhouse and field studies. *Ecological Engineering, 35*(10), 1523-1528. doi:10.1016/j.ecoleng.2009.07.002

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G. (2018). *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Sobkowicz, J. (2012). *Oil Sands Tailings Technology Deployment Roadmaps: Project Report - Volume 1: Project Summary*: Alberta Innovates - Energy and Environment Solutions.

Spence, J., Bara, B., Lorentz, J., & Mikula, R. J. (2015, 2015). *Development of the Centrifuge Process for Fluid Fine Tailings Treatment at Syncrude Canada Ltd.* Paper presented at the World Heavy Oil Congress, Edmonton, AB, Canada.

Wu, S. (2009). *A Greenhouse Study of Selected Native Plant Species for Dewatering CT.* (Master of Science), University of Alberta,

Wu, S., Sego, D., Naeth, A., & Wang, B. W. (2010). *Evapotranspiration Dewatering Effect on CT Deposits by Grasses*. Paper presented at the 63rd Canadian Geotechnical Conference and 6th Canadian Permafrost Conference, Calgary, Alberta.

Wu, S., Naeth, M., Sego, D., & Wang, B. (2011). *A Greenhouse Study of Grass Response on Composite Tailings Discharged from an Alberta Oil Sands Mine*. Paper presented at the 5th Mining and the Environment International Conference, Sudbury, Ontario.

Wu, S., Sego, D., Naeth, A., & Wang, B. (2011). *Responses of Wheatgrass Species to Composite/Consolidated Oil Sands Tailings*. Paper presented at the Tailings and Mine Waste 2011, Vancouver, BC. http://www.dx.doi.org/10.14288/1.0107703

3 Meso-scale Study of Plant Evapotranspiration on Dewatering of Centrifuged Fluid Fine Tailings – Year 1

3.1 Introduction

Mining operations in the Athabasca oil sands deposit of northern Alberta, Canada, produce significant quantities of clay-rich tailings as a result of extracting bitumen from oil-laden sands. One of the most significant challenges facing the industry is how to achieve more rapid dewatering of these fluid fine tailings (FFT). These tailings are known to have low strength and low consolidation rates due to their relatively low densities and permeability (Kasperski & Mikula, 2011). As of 2019, there was in excess of 1270 Mm^3 of these tailings in storage across these oil sands mining sites (AER, 2020).

The Government of Alberta and the Alberta Energy Regulator (AER) implemented Directive 085 in 2017, which stipulates that these fine tailings deposits must reach a ready-to-reclaim state within 10 years (AER, 2017). This has pushed the industry to develop new ways to speed the rate at which strength gain can be achieved in these fine tailings deposits. One of these potential technologies is the use of plants to speed the dewatering of these tailings through evapotranspiration (Boswell et al., 2012).

Using plants to dewater tailings was first studied in the 1990s, with work by Johnson et al. (1993) and M. J. Silva (1999). Research has continued to demonstrate that plants could survive and assist in the dewatering of these tailings, as well as provide reinforcement as a result of their root systems developing at depth and near the surface (Renault et al., 2003; Renault et al., 2004; Schoonmaker et al., 2018; W. Smith et al., 2018; Wu, 2009).

The objective of this study was to determine the ability of three native boreal forest plant species to establish and persist in amended fine tailings. The study's key focus was to evaluate the potential for these plants to dewater the amended tailings material to a greater degree relative to evaporative drying. The study took place from June to October 2018. Parameters including water content, shear strength, settlement, and matric suction were recorded to compare the dewatering and strength gain in each tote.

3.2 Materials and Methods

This study used five, one cubic metre plastic totes, containing centrifuged fine tailings from an oil sands mine site in northern Alberta. These totes were filled at the same time from the same commercial-scale centrifugation plant on the operators site, and are therefore considered to be as similar as possible for the purposes of this research. The tailings were characterized by Rima et al. (2021) and the initial index properties of the centrifuged fine tailings contained in the totes is summarized in Table 3-1. Rima noted the solids fraction of these tailings were composed of approximately 52% clay minerals, with the remaining 48% being dominated (40%) by quartz. The clay minerals are comprised primarily of kaolinite (36%) and illite (15%).

Table 3-1: Index Properties of Centrifuged Fine Tailings Used in Meso-scale Tote Study (Rima et al., 2021)

Property	Value
Water content, w (%)	89
Solids content, s (%)	53
Bitumen content (%)	5.7
Specific gravity, G_s	2.24
[1] Fines content (%)	87
[2] Clay content (Dispersed hydrometer) (%)	52
[3] Clay content (MBI) (%)	52
[4] D_{50} (μm)	1.5
Liquid limit (%)	57
Plastic limit (%)	26
Liquidity index	2

[1] Fines content = Material finer than 0.045 mm. [2] Clay content = Material finer than 0.002 mm. [3] Clay content by Methylene Blue Index (MBI). [4] Median particle diameter.

The chemistry of the centrifuged tailings material in the totes was characterized in a paper published in the proceedings of Tailings and Mine Waste 21' by Schoonmaker et al. (2021). These results are presented in Table 3-2. The properties presented for the "Greenhouse barrels" is in reference to the 100L (barrels) greenhouse study presented as a part of that published work. It is discussed in greater detail in the literature review of this thesis (see Section 2.4).

Table 3-2: Chemical Properties of Centrifuged Fine Tailings Used in Meso-scale Tote Study (Schoonmaker et al., 2021)

		Outdoor totes		Greenhouse barrels	
		mean	SD	mean	SD
Available Nitrate (N)	mg kg^{-1}	8.3	9.2	<2	-
Available Phosphorus (P)	mg kg^{-1}	4.9	1.2	5.3	0.3
Available Potassium (K)	mg kg^{-1}	144.0	21.9	204.0	23.0
Available Sulphur (S)	mg kg^{-1}	758.0	194.9	220.0	26.5
Soluble Chloride (Cl)	mg L-1	424.0	75.0	234.0	33.6
Electrical Conductivity	dS m^{-1}	6.7	0.7	3.2	0.4
Soluble (CaCl2) pH		6.8	0.2	7.5	0.1
Sodium Adsorption Ratio		10.8	1.7	8.0	0.8

The totes were placed outdoors and exposed to the elements at NAIT's Centre for Boreal Research in Peace River, Alberta. The totes were initially in storage and sampled at a lab at the University of Alberta in Edmonton, which led to some water release and pooling at the surface of the totes. After moving them to the study site in Peace River, most of the excess water was decanted using a bucket before planting, and the material was sampled to determine initial moisture content within the totes. The totes remained sealed on the bottom, representing a single, upward draining consolidation process in this study.

The plant species used included slender wheatgrass (*Elymus trachycaulus*), sandbar willow (*Salix interior*), and water sedge (*Carex aqualitis*). The *Carex* (grown from seed) and *Salix* (grown from unrooted cutting) were both grown in a greenhouse prior to planting in the totes. Slender wheatgrass was introduced as seeds, and the initial seeding was 70g per tote. After planting, a small quantity of fertilizer was added to the totes. Fertilizer was spread by hand in its dry form on the surface of each tote at the beginning of the growing season. The alfalfa and urea (as pellets) was added in a similar manner. Each tote was given 15g each of starter fertilizer (29-59-14) and urea (46-0-0), in addition to 500g of alfalfa (Western Alfalfa Milling Co. Ltd., Norquay, Saskatchewan). These provided additional key nutrients, including nitrogen to support plant establishment and growth in the totes.

Each of the five totes contained a different selection of these species to allow for the comparison in dewatering and strength gain between each plant species. Tote A contained *Carex aqualitis*, which was transplanted from the greenhouse into the tailings. Tote C contained *Salix interior* plants that were also transplanted from the greenhouse. Tote D was seeded with an initial 70g of *Elymus trachycaulus* seeds, and Tote E contained all three species. Tote B contained no plant species to provide a "control" tote for comparison with the vegetated totes.

Electronic sensors (Decagon Devices Inc., 2016, 2017) were installed 25, 50, and 75 centimetres below the initial surface in each tote, and were connected to Decagon D50 data collectors (Decagon Devices Inc., 2015). Decagon MPS-6 and MPS-2 sensors were used to measure matric suction in each tote, while Decagon 5TE sensors recorded volumetric water content, and temperature. The data was recorded hourly using Decagon Em50 dataloggers. The air entry value of the ceramic used in the MPS-6 and MPS-2 sensors are equal to -9 kPa, therefore values equal or greater than this value was taken as reading between 0 kPa and -9 kPa.

Other metrics determined manually in the totes included height measurements, water table depth below surface, moisture content of the crust, and undrained shear strength. Settlement in the totes was measured by the change in surface height over time. This was determined as the distance between the bottom of a transect placed diagonally across the tote and the tailings surface. The transect was constructed from wooden survey stakes, and five measurements were taken along the length of the transect to give a mean settlement rate of the tailings in the totes. Water table measurements were collected using a piezometer, located in the centre of the tote, which was constructed from PVC pipe with holes drilled throughout its length and an open bottom wrapped in a fine mesh nylon material that allowed the movement of water but not solids. Both these measurements were taken on a weekly basis. Strain was also calculated from this settlement data by dividing the total settlement overtime by the initial thickness of the tailings in each tote.

The solids content of the crust was measured at three times over the course of the growing season, using a 10cm length auger to remove samples at depth intervals of 0-10 and 10-20 cm. The auger samples were placed in sample tins and dried for a minimum of 48 hours (or until weight constancy). The change in mass was taken to be the quantity of water contained within the sample. Sampling was attempted at greater depth but was unsuccessful due to challenges recovering a sufficient quantity of sample.

Undrained shear strength was taken in situ using a handheld Geonor H60 (Geonor Inc., 2018) vane tester which was calibrated to an error of 10%. Three vane sizes were used to take these measurements based on the strength of the centrifuge cake: 16 mm diameter by 32 mm height, 20 mm diameter by 40 mm height, and 25.4 mm diameter by 50.8 mm height. Measurements were taken in September at 25, 50, and 75 cm below surface and compared against the initial strength of the centrifuged cake tailings of 345 Pa at an initial solids content of 53 wt.% (Rima & Beier, 2018; Rima et al., 2021). The liquid and plastic limit of the tailings material was 57% and 26% respectively (Schafer & Beier, 2019).

Weather data was collected via a station located within ten meters of the totes. This station collected precipitation (rainfall), air temperature, and wind speed and direction, with data recorded hourly.

Vegetation growth was measured at the end of the growing season in four surface quadrants (~0.25 m^2) in each tote. At each quadrant, the following was collected: percentage ground area covered and above ground biomass where all leaf tissue was harvested, dried, and weighed. Percentage ground are covered represents an estimate based on a visual assessment of the tailings surface, and is different than the leaf area index (LAI) calculated at the end of Year 2 discussed in Chapter 4.

3.3 Results

All three species demonstrated observable growth in these tailings. *Elymus trachycaulus* had the greatest cover and biomass accumulation of the three species, while leaf biomass (though not cover) was similar between *Carex aquatilis* and *Salix interior* (Figure 3-1). A bar chart of raw data is provided in Appendix A.1.

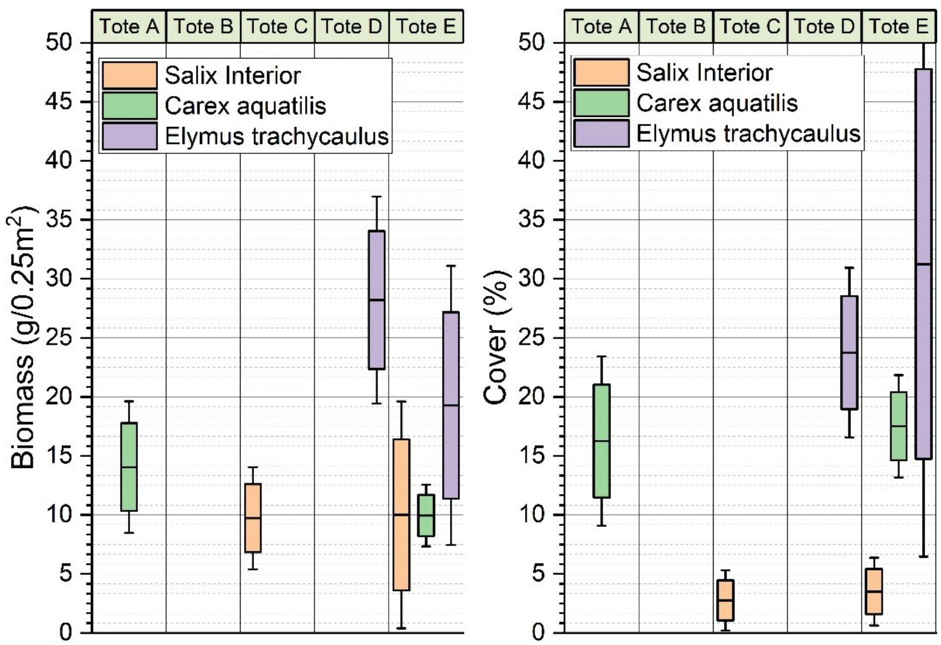


Figure 3-1: Percentage of cover (area covered by vegetation) and biomass (dry weight of above-surface plant biomass) of Salix interior, Carex aquatilis, and Elymus trachycaulus in each tote after one growing season (May-October 2018). The mean is represented by the black horizontal line in each box of the plot, and the error bars represent one standard deviation from the box of each plot.

Development of an approximately 10 cm thick crust with significant desiccation and cracking was observed (Figure 3-2 (ii)). Shrinkage resulted in pulling from the sides of the tote, and cracking was observed on the surface of all five totes; even after large precipitation events these cracks did not fully close.

Figure 3-2: Image of (i) Tote B after decanting on day 0, (ii) Tote B after 91 days of drying, visible desiccation of surface (iii) Tote E after decanting and planting of all three plant species, (iv) Tote E after 91 days of drying, showing significant plant growth and desiccation of the surface

There was a sustained drawdown of the water table over time in all five totes. There was a sudden rise in the water table after the major rain events around day 37 and day 78. Between these two events, all totes experience a prolonged period of drying that resulted in a drawdown of the water table in all five totes.

All totes recorded an initial volumetric water content of approximately 37% which reduced during drying cycles and increased during periods of rainfall. The sensor located 25cm below the surface in Tote B, Tote C and Tote E reached maximum volumetric water contents of approximately 43%. Tote D and Tote A both reach an approximate peak volumetric water content of 35%. All totes except for tote A peaked after the first large rainfall event around day 40. Tote A reached its peak after the second significant rainfall around day 80 (Figure 3-3). Key climate metrics collected from the nearby weather station during the two years of the study are summarized in Table 4-6. The volumetric water content then continued to decrease in all totes until an apparent rewetting occurred around day 80. All totes experienced an increase in water content after this second rainfall, however; Tote D was the only tote that had sustained redrying after this rain event (Figure 3-3 (ii)). Tote D had a minimum volumetric water content of less than 5%, reached around day 110 before rising again to approximately 13%, which was the lowest among all five totes.

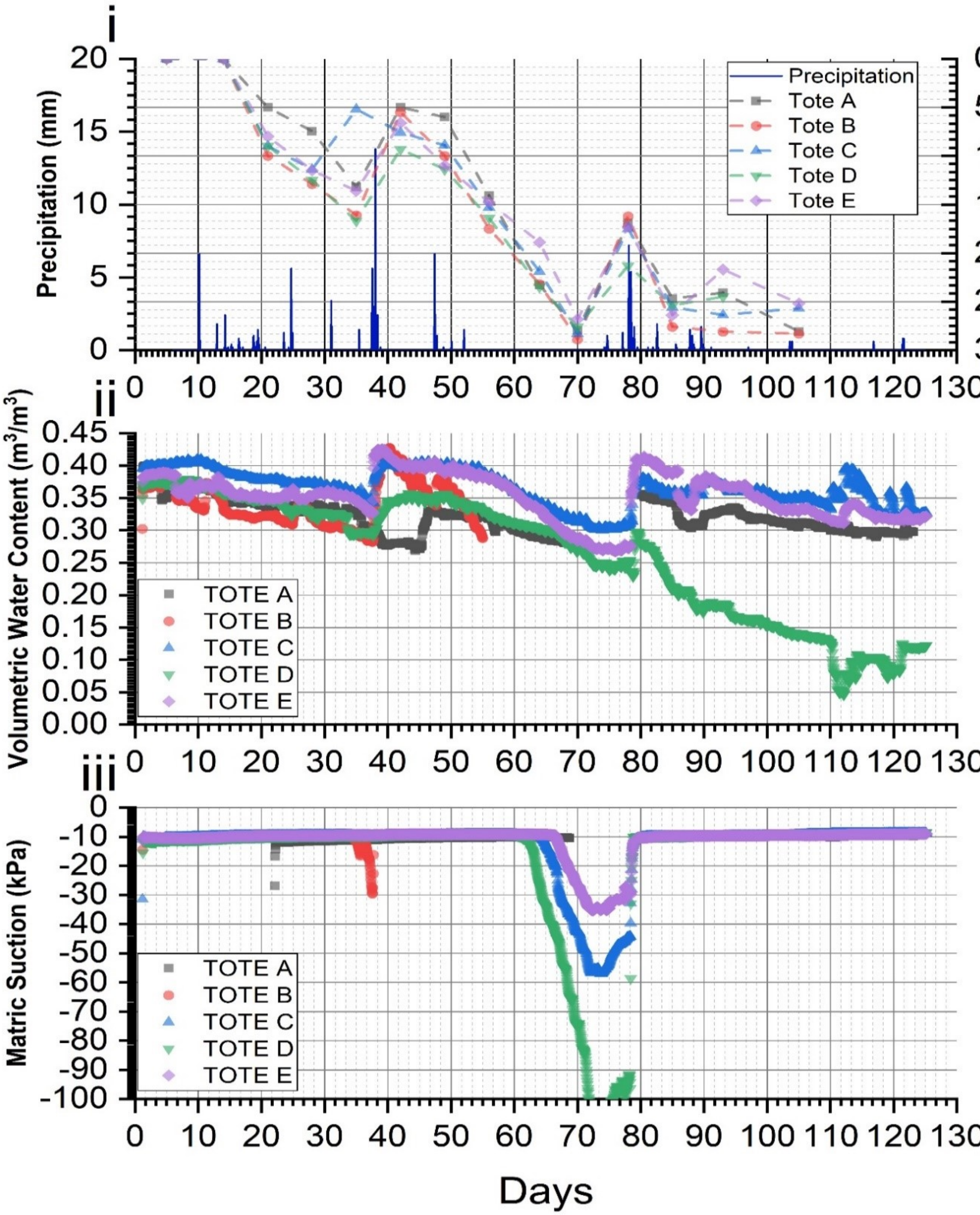


Figure 3-3: (i) Precipitation as recorded by weather station is plotted with the change in the depth of the water table below the tailings surface over time; (ii) The volumetric water content over time at 25cm depths of each tote; (iii) Matric suction is plotted for all five totes over time at 25cm depth. Tote B data after day 55 is excluded from (ii) and (iii) due to meaningless data likely due to development of a crack or air pocket. Tote A data at 25cm depth was corrupted between day 68 and 80, explain the gap in plots (ii) and (ii). The sensors at 50cm and 75cm recorded no noteworthy data and were also excluded.

An increase in matric suction was measured at 25 cm depth after an extended period of relative dryness. There was a steady increase in the magnitude of matric suction from day 68 to 75 in all totes until the second major rain event led to a decrease as the material became rewetted. The greatest suction was experienced in Tote D, which reached a maximum suction greater than 100kPa on day 73. Totes C and E reached suctions of 55kPa and 35kPa respectively. After the second major rain event on day 78. All totes then returned to a matric suction less than the air entry value of the instruments and could not be measured.

The initial gravimetric moisture content of the centrifuge cake at the beginning of the study was 56.9% and 56.8% for Totes B and E, respectively. There was a period of drying over the first 60 days of the study that reduced the moisture content in the top of the crust to less than 20% in both Totes B and E. The tailings at 10 cm to 20 cm depth had a minimum moisture content of less than 35% for all totes except Tote A (Figure 3-4). Tote A likely experienced an increased amount of drying relative to the other totes due to it being the smallest tote with the shallowest sample of tailings. All totes experienced rewetting and increases in moisture content after the large rain event on day 78 of the study.

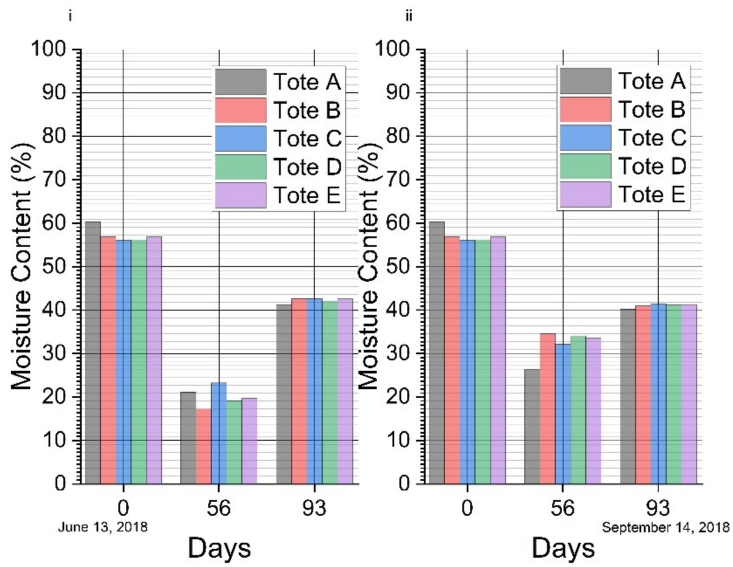


Figure 3-4: Moisture content (%) of totes at a depth of (i) 0-10 cm and (ii) 10-20 cm. Collected three times on June 13th (day 0), August 08th (day 56), and September 14th (day 93).

All totes experienced a maximum settlement of approximately 8cm (Figure 3-5 (i)). After the large rain event on day 38, swelling was observed in each tote. Then unvegetated tote (Tote B) experienced the most pronounced swelling of the five totes. Tote B experienced a swelling of more than 1% and took a further 20 days to shrink again and return to a total settlement similar to the other four totes. The tailings in the other totes experienced little to no swelling after the major rain event compared to Tote B.

The shear strength of the totes near the end of the study (day 94), was compared to the initial strength of the centrifuge cake of 345 Pa (Rima & Beier, 2018). Shear strength measurements were taken at 25 cm, 50 cm, and 75 cm depths from the tailings' surface. The tailings in all totes experienced a strength gain from their original state, with Tote E showing the greatest overall strength gain, peaking at nearly 13 kPa (Figure 3-5). Higher relative strength near the bottom of the tote could be attributed to initial rapid settlement at the base of the totes that then consolidated and further strengthen over time. Based on a visual inspection of the crust and previous work by N. A. Beier (2015), we can conclude that the crust was over-consolidated while the remainder of the tailings sample below the crust was normally-consolidated. All totes experienced similar settlement of 8 cm, except for Tote A which was slightly less at 7 cm (Figure 3-5).

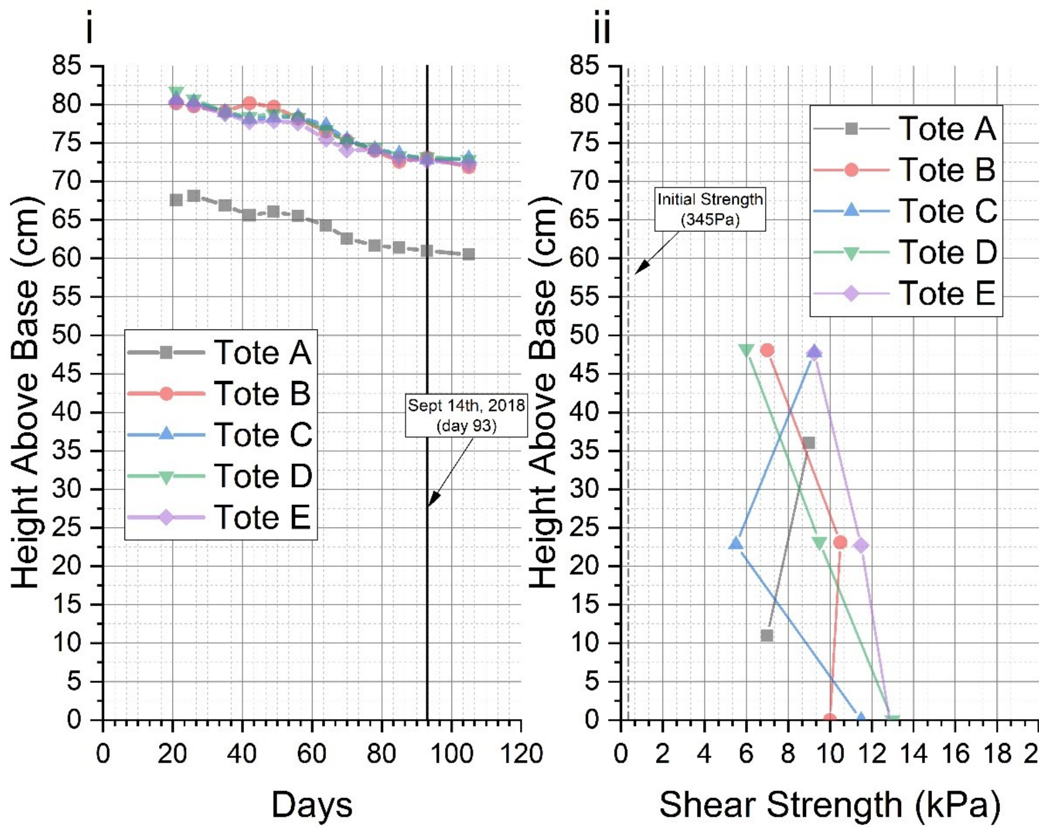


Figure 3-5: (i) Settlement of the tailings surface relative to the base of the tote demonstrating consolidation over time. Sept 14 (day 93) is highlighted for comparison to: (ii) Showing the shear strength at three depths (relative to tailings surface) in each tote. Tote A was too shallow for a third point at 75cm depth. The initial strength of the tailings of 345kPa is also shown

The maximum and average shear strength was plotted against the vegetation biomass and cover to determine the existence of any relationship between plant growth and strength in the totes. A relationship was found to exist between peak shear strength and the plant metrics of biomass and cover, with an r-squared value of 0.23001 for peak shear vs. average biomass (Figure 3-6).

Tote A had poor strength gain relative to the biomass and cover and had lower peak and average strength compared to Tote B which contained no plants. This suggests that *Carex aquatilis* was the least effective at dewatering and strength gain in this type of tailings material. Tote E, which contained all species, consistently performed well with the greatest strength and the greatest plant growth. Tote D, which contained only *Elymus trachycaulus*, also performed well compared to the control and *Carex*-only totes.

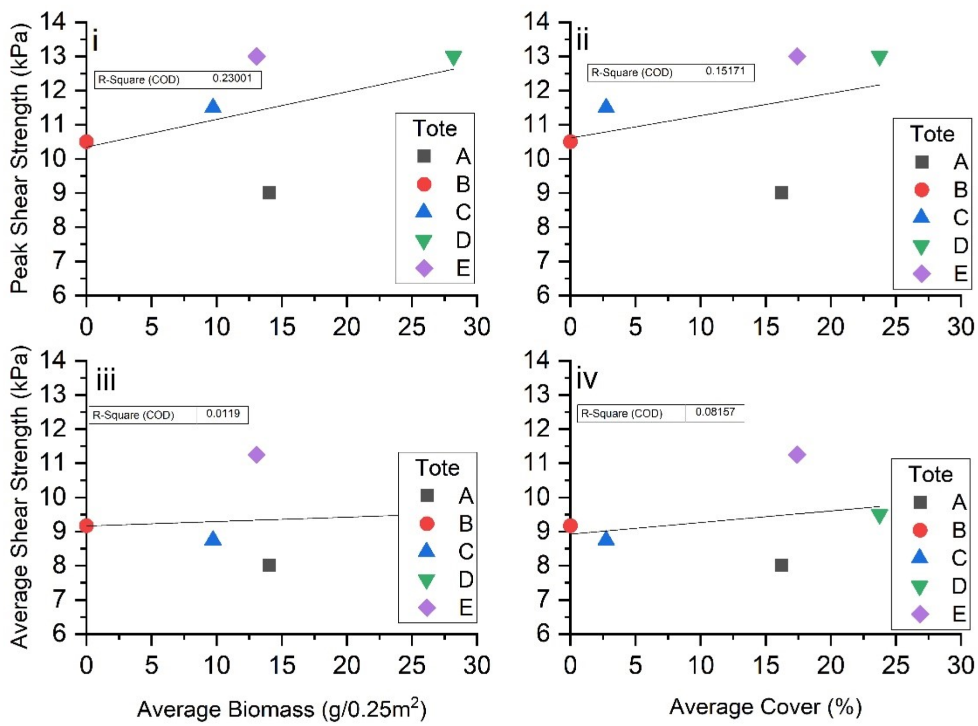


Figure 3-6: Average shear plotted against average biomass (iii) and average cover (iv). Peak shear strength was also plotted against average biomass (i) and average cover (ii). A linear trendline was calculated for each data set and the r-squared value is shown

3.4 Discussion

This study demonstrated that these species can grow on centrifuge fine tailings material and, combined with evaporation, can contribute further to dewatering through evapotranspiration. A major contribution of the plant species in this study was their assistance in managing new water inputs during major rain events. Totes containing plant species were observed to swell significantly less relative to the tote containing no plants after rewetting. This suggests an uptake by the plants that prevented the same quantity of water being reabsorbed by the tailings. Totes containing plants still experienced water table rises after such a rain event, but to a lesser degree when compared with the control tote. This further indicates that the introduction of plants into a tailings cake material can improve the tailings material's ability to buffer the impacts of significant precipitation events.

The study also showed that, in general, the totes containing larger quantities of leaf mass (and therefore evapotranspiration potential) also had greater average and maximum shear strengths. Totes containing *Elymus trachycaulus* and *Salix interior* generally showed greater strength relative to the tote planted with *Carex aquatilis* only. This may be attributed to the ability of the woody *Salix* and *Elymus* to quickly establish extensive fibrous root systems (Renault et al., 2004; Wani et al., 2011). This allows these species to be more adept at extracting moisture from tightly bound soils such as oil sands clays. In conclusion, *Elymus trachycaulus* and *Salix interior* are the more effective species at strength gain in the totes and would be the best species to be included in future studies. This was also a conclusion in the paper by W. Smith et al. (2018).

Future research should aim to develop a complete strength and solids content profile throughout the depth of the totes. Biomass below the surface should also be collected to determine the impacts of deeper root depths on increasing solids content and strength, as well as contrast the potential difference between fine root species such as the *Salix* and *Elymus*, and wetland species with lesser root development such as the *Carex*.

3.5 References

AER. (2017). *Directive 085 - Fluid Tailings Management for Oil Sands Mining Projects*. Calgary, AB: Alberta Energy Regulator.

AER. (2020). *State of Fluid Tailings Management for Mineable Oil Sands, 2019*. Retrieved from Calgary, Alberta, Canada: https://static.aer.ca/prd/2020-09/2019-State-Fluid-Tailings-Management-Mineable-OilSands.pdf

Beier, N. A. (2015). *Development of a Tailings Management Simulation and Technology Evaluation Tool.* (Doctor of Philosophy), University of Alberta,

Boswell, J., Davachi, M., & Sobkowicz, J. (2012). Oil Sands Tailings Technology Deployment Roadmap Project Report – Volume 2. *2*, 166-166.

Decagon Devices Inc. (2015). [Em50/Em50R/Em50G Em50 Series Data Collection System, Operator's Manual. Version: June 25, 2015 - 14:00:15. Pullman, Washington, 81 pp].

Decagon Devices Inc. (2016). [5TE Water content, EC and temperature sensor, Operator's Manual. Version: March 11, 2016 - 11:55:57. Pullman, Washington, 26 pp].

Decagon Devices Inc. (2017). [MPS-2 & MPS-6 Diaelectric Water Potential Sensors, Operator's Manual. Version: July 10, 2017 - 16:08:16. Pullman, Washington, 30 pp].

Geonor Inc. (2018). [H-60 Hand-Held Vane Tester, Data Sheet. Augusta, New Jersey. 2pp].

Johnson, R. L., Bork, P., Allen, E. A. D., James, W. H., & Koverny, L. (1993). *Oil Sands Sludge Dewatering By Freeze-Thaw and Evapostranspiration* (RRTAC 93-8). Retrieved from

Kasperski, K. L., & Mikula, R. J. (2011). Waste Streams of Mined Oil Sands: Characteristics and Remediation. *Elements, 7*(6), 387-392. doi:10.2113/gselements.7.6.387

Renault, S., MacKinnon, M., & Qualizza, C. (2003). Barley, a Potential Species for Initial Reclamation of Saline Composite Tailings of Oil Sands. *Journal of Environmental Quality, 32*(6), 2245-2253.

Renault, S., Qualizza, C., & MacKinnon, M. (2004). Suitability of altai wildrye (Elymus angustus) and slender wheatgrass (Agropyron trachycaulum) for initial reclamation of saline composite tailings of oil sands. *Environmental Pollution, 128*(3), 339-349. doi:10.1016/j.envpol.2003.09.009

Rima, U. S., & Beier, N. A. (2018, 2018). *Evaluation of Temperature and Multiple Freeze- Thaw effects on the Strength Properties of Centrifuged Tailings.* Paper presented at the GeoEdmonton, Edmonton, AB, Canada.

Rima, U. S., Beier, N. A., & Abdulnabi, A. (2021). Modeling the Effects of Seasonal Weather on Centrifuged Oil Sands Tailings. *Processes, 9(11)*(1906), 17. doi:https://doi.org/10.3390/pr9111906

Schafer, H. L., & Beier, N. A. (2019). Estimating the SWCC from the SFCC for mine waste tailings using TDR. *Canadian Geotechnical Journal*, 1-52. doi:10.1139/cgj-2018-0145

Schoonmaker, A., Degenhardt, D., & Floreani, T. (2018). *Evaluating the Potential to Establish Plants to Aid in Dewatering of an Atmospheric Fine Drying Tailings Deposit at Muskeg River Mine.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Schoonmaker, A., Chigbo, C., Walton-Sather, S., Abdulnabi, A., Beier, N., Laberge, S., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Silva, M. J. (1999). *Plant dewatering and strengthening of mine waste tailings.* (Doctor of Philosophy), University of Alberta,

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G. (2018). *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Wani, B. A., Khan, A., & Bodha, R. H. (2011). Salix: A viable option for phytoremediation. *African Journal of Environmental Science and Technology, 5*, 567-571. doi:10.4314/ajest.v5i8.72048

Wu, S. (2009). *A Greenhouse Study of Selected Native Plant Species for Dewatering CT.* (Master of Science), University of Alberta,

4 Meso-scale Study of Plant Evapotranspiration on Dewatering of Centrifuged Fluid Fine Tailings – Year 2

4.1 Introduction

The meso-scale study of the contributions of plant evapotranspiration to dewatering and strength gain of centrifuged fluid fine tailings from the Alberta oil sands was continued into a second year to allow for additional data collection and assessment. Exposing the totes to the outdoors over the winter period of the study also allowed for a high-level discussion of how freeze-thaw mechanisms may also contribute to greater rate of consolidation and dewatering of the amended tailings over time.

The objective of Year 2 of this study was to build on the work already completed in Year 1 (see Chapter 3) and further assess the ability of select native boreal plant species to establish and persist in amended tailings. The primary focus being to evaluate the potential for these plant species to speed the dewatering of the centrifuged tailings material to a greater degree than evaporative drying alone. This chapter focuses on Year 2 of the tote study described in the previous chapter. As the result of a frigid 2018-2019 winter, all species in the totes perished, and new plants were introduced to each tote at the beginning of Year 2 (2019) of the study which took place from May 7th to October 4th, 2019.

Manual measurements of settlement, water table height, shear strength, and moisture content were collected during this period. The electronic sensors continue to collect hourly measurements of matric suction, water content, and temperature through the full study period (June 13th, 2018 to October 4th, 2019). Also included in this chapter is a brief discussion of the potential contribution of freeze-thaw consolidation to the settlement and dewatering of the amended tailings material in each tote.

4.2 Materials and Methods

As expressed above, this chapter discusses the continuation of the tote study introduced in Chapter 3. The study focused on five, one cubic metre plastic totes which each contained centrifuged cake tailings from an oil sands mine site in northern Alberta. The totes were not completely full, and contained approximately 600L of tailings each. The totes were located outdoors at NAIT's Centre for Boreal Research in Peace River, AB, and were initially set up in June 2018. The totes are sealed on all sides as well as the bottom, and therefore consolidation behavior will most likely be that of a cohesive soil under single drained conditions.

Plant species used in Year 2 of the study included the same species used in Year 1 (*Elymus trachycaulus*, *Salix interior*, and *Carex aqualitis*), as well as one additional species: western dock (*Rumex occidentalis*). The *Carex* and *Rumex* were both grown from seedlings, while the *Salix* species was grown from an unrooted cutting. All three were initially grown in a greenhouse prior to being planted in the totes. *Elymus trachycaulus* was seeded directly into the totes at a rate of 700 kg/ha. All totes containing plants received a small quantity of fertilizer at the beginning and midpoint of Year 2 of the study. The fertilizers used included starter fertilizer (29-59-14) and urea (46-0-0), which were applied at a rate of 225 kg/ha and 150 kg/ha respectively. The intent of the fertilizer addition to the tailings was to provide additional required nutrients to further support plant establishment and growth in the totes.

As in Year 1 of the study, each of the five totes in Year 2 contained a different selection of these plant species to allow for a possible comparative performance analysis each plant species ability to speed dewatering and increase shear strength of the tailings material. Tote A contained plants of both *Carex aquatilitis* and *Salix interior*. Tote B was again used as a control, and had no vegetation planted. Tote C was populated with *Salix interior*, and Tote D with both *Salix interior* and *Elymus trachycaulus*. All four species were planted in Tote E.

Table 4-1: Comparison of species planted in each tote in Year 1 and Year 2 of mesoscale study

	Year 1	**Year 2**
Tote A	*Carex spp*. (water sedge)	*Carex spp*. And *Rumex occidentalis* (western dock)
Tote B	Control – No plants	Control – No plants
Tote C	*Salix interior* (sandbar willow)	*Salix interior*
Tote D	*Elymus trachycaulus* (slender wheatgrass)	*Salix interior* and *Elymus trachycaulus*
Tote E	*Carex spp., Rumex occidentalis, Salix interior* and *Elymus trachycaulus*	*Carex spp., Rumex occidentalis, Salix interior* and *Elymus trachycaulus*

Electronic sensors (See Chapter 3.2) were installed in each tote to collect hourly measurements of matric suction, volumetric water content, temperature and electric conductivity (see Figure 4-1). The air entry value of the ceramic used in the MPS-6 that measured matric suction is equal to -9 kPa, therefor values reported as equal or greater than this value can only be concluded to equal some value greater than -9 kPa. These instruments were placed at 25, 50, and 75 cm below the initial tailings surface in each tote and connected to Decagon D50 data collectors (Meter Group Inc., previously Decagon Devices Inc. (2015)). It should be noted that instruments were installed based on depth from surface, and the stakes were not contacting the bottom of the tote. As a result, instruments may have shifted as the tailings contained within each tote settled, maintaining their position relative to the surface of the tailings in each tote.

Figure 4-1: Photo showing Decagon 5TE and MPS-6 sensors at 25 and 50 cm depths attached to stake before placement in tailings-filled totes

Manual measurements of settlement and water table height were collected weekly; in-situ shear strength and solids content samples were collected at the beginning and end of Year 2 of the tote study. Tailings height measurements were collected to assess settlement of the material in the totes by measuring the distance between the tailings surface the bottom of a transect placed diagonally across the top of the tote. The transect was constructed from wooden survey stakes and was secured such that its height remained unchanged throughout the entire study period. Five measurements were taken along the transects length, and the measurements were averaged to account for any unevenness in the tailings surface resulting from differential settlement in the totes. Water table measurements were collected the same as in Year 1 by measuring the height of water in a PVC tube placed in the centre of the tote with openings along its length that were covered with nylon mesh such that only water could pass through the openings.

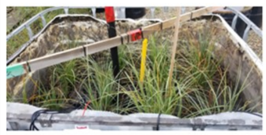
Shear strength and solids content measurements were also collected at the beginning and end of Year 2 to assess final dewatering and strength gain along the depth profile of each tote. Samples for solids content assessment were collected every 10cm starting from 5cm below tailings surface using a pedological soil sampler. These samples were placed in sample tins and dried for a minimum of 48 hours (or until weight constancy). The change in mass after oven drying was taken to be the quantity of water contained within the sample. Solids content was calculated as sample dry mass over total wet mass of the sample. Undrained shear strength was determined as in Year 1 using a handheld Geonor H60 (Geonor Inc., 2018) hand vane shear tool which was calibrated to an error of 10%. This tool came with three vane sizes: 16 mm x 32 mm (small), 20 mm x 40 mm (medium), and 25.4 mm x 50.8mm (large). Vane size was selected based on strength of centrifuge cake to ensure the best possible measurements were collected. Measurements were collected along a profile adjacent to that sampled for solids content at 10 cm intervals starting at 5 cm below tailings surface. These measurements were then compared against the strength data and solids content collected in Year 1, as well as the initial strength of the centrifuged cake tailings that were characterized by Rima and Beier (Rima et al., 2021). The liquid and plastic limit of the tailings material was taken to be 57% and 26% respectively (see Table 3-1.

The sampling for vegetation data was more robust in Year 2 than Year 1 of the study. Assessment of vegetation was split into above-ground and below-ground portions. Below ground sampling focused on root mass and length which were used to estimate root density in the totes. Above ground sampling included harvesting of plant material to calculate above ground biomass and leaf area of the plant species in the totes. Above and below-ground biomass were all calculated by taking a subsample of plant matter that was dried and weighed. This data was used to calculate the leaf area index (LAI) in each tote, and below-ground data was used to create a profile that could be compared to the solids content and strength profiles generated for each tote.

The weather station already located ~10m from the tote location at the Centre for Boreal Research collected precipitation (rainfall), air temperature, and wind data that was recorded hourly.

Table 4-2 summarizes the entire tote study period including plants populating each tote, as well as providing a photo of each tote at key points of Year 1 and Year 2 of the study (day 0, 105, 342, and 478).

Table 4-2: Summary Table of Plant Species in Each Tote in Season 2 of Study; Photographs of each tote on Day 0, 105, 342, and 477

	Plant Species (Season 2)	Day 0	Day 105	Day 342	Day 477
Tote A (C+R)	*Carex spp.* (water sedge) And *Rumex occidentalis* (western dock)				
Tote B (Control)	Control – No plants				
Tote C (S)	*Salix interior* (sandbar willow) and *Elymus trachycaulus*[1] (slender wheatgrass)				
Tote D (S+SWG)	*Salix interior* and *Elymus trachycaulus*				
Tote E (All)	*Carex spp., Rumex occidentalis, Salix interior* and *Elymus trachycaulus*				

Note(s): (1) *Elymus trachycaulus* in Tote C was Volunteer

4.3 Results

The key dates of Year 1 and 2 of the study are summarized in Table 4-3. Results in Chapter 4 will focus on observations and data collected from day 327 to 478 in 2019. Raw measurements can be found in Appendix A. These results include comments on potential freeze-thaw consolidation impacts from the winter period between day 105 and 327.

Table 4-3: Summary of Key Dates of Study

Date	**Day of Study**	**Phase of Study**
June 13th, 2018	0	Start of Year 1 (Study Begins)
September 26th, 2018	105	End of Year 1
May 7th, 2019	327	Year 2 Vegetation Planted
May 21st, 2019	342	Start of Year 2 Data Collection
October 4th, 2019	478	End of Year 2 (End of Study)

The 10cm thick crust observed in Year 1 of the study was no longer clearly visible after the totes froze over the course of the winter months. The cracking and desiccation originally noted in Year 1 had disappeared and did not reopen during year 2 of the study. This progression can be seen in the photos presented in Table 4-2.

All species exhibited observable growth in each of the four totes that were planted. The greatest total above and below ground biomass was recorded in Tote A, which also had the second highest leaf area index (LAI) of the four totes. Tote E had the greatest LAI of the four totes at 3.45. As the greatest proportion of biomass in Salix interior is attributed to the woody shoot rather than the leaf structures, the biomass values for the shoot and the leaf were separated for above-ground biomass. Below ground biomass in each tote represented the dried mass of root structures collected in each tote. Table 4-4 summarizes the total biomass results and LAI recorded in each tote at the end of Year 2.

Table 4-4: Leaf area index (LAI), above- and below-ground biomass for all totes (Sampled on Day 477)

Tote	LAI	Above-ground biomass (g)		Below-ground biomass (g)	Total biomass (g)
		Leaf	Shoots[1]		
A (C+R)	2.02	146.6		505.9	652.5
B (control)					
C (S)	0.07	5.0	122.0	59.6	186.5
D (S+SWG)	1.11	68.5	144.0	237.2	449.6
E (All)	3.45	142.0	84.0	185.6	411.6

Note(s): (1) *Salix interior* only

Figure 4-2 presents the total above ground biomass recorded for the ~1 square meter area of the tailings surface. It is delineated by both tote and species, with *Salix interior* being separated into biomass attributable to shoots and leaves separately. Tote E, which contained all species included in Year 2, had the greatest total above ground biomass of any of the totes at 226g. Tote C, which contained only *Salix interior* had the lowest at only 127g. For the *Salix* planted in each tote, approximately 5% of the above ground biomass of the *Salix* was made up by leaves, with the remaining mass being that of the woody shoots. For Tote E, a similar quantity of biomass was collected from the *Elymus trachycaulus* and *Salix interior*. The smallest proportion of above ground biomass in Tote E was attributed to *Carex aqualitis*.

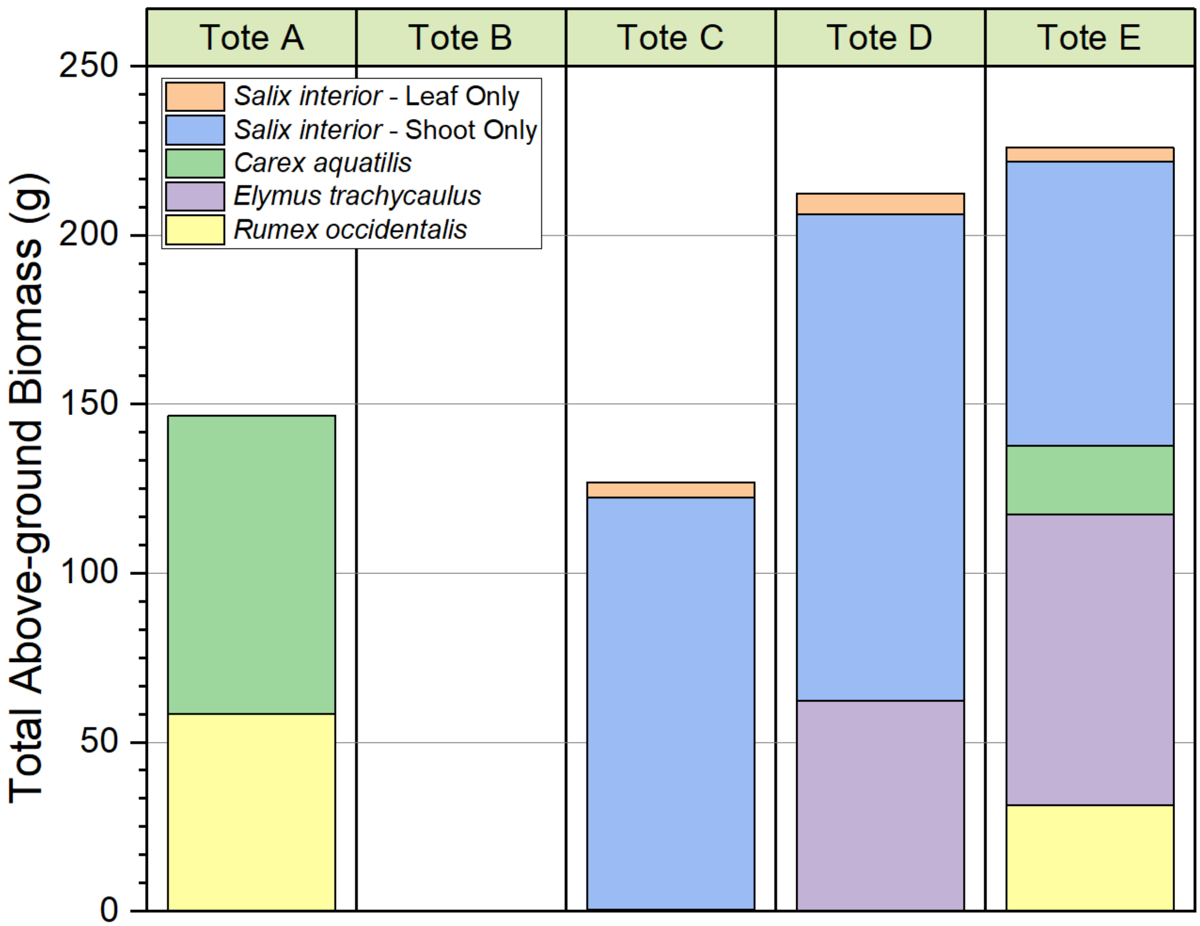


Figure 4-2: Composition of above-ground biomass in each tote by vegetation species (sampled on day 477)

Below ground biomass samples were collected throughout the depth of the tailings in each tote, with the below-ground biomass density (also referred to as root density) at 6 depths along the profile presented in Figure 4-3. Due to the smaller quantity of tailings in Tote A, only 5 sample points for below ground biomass could be collected. Tote A had the greatest root density along its profile overall, ranging from 33g/m^2 at 45cm above base, to 52g/m^2 at 15cm. Tote A had an average root density through its depth of approximately 39g/m^2. This was also the highest root density recorded in any of the totes. Tote C and E had average root densities of 24g/m^2 and 13g/m^2 respectively. Tote D had the lowest overall root density of 9g/m^2, and Tote C, which was the control tote, had no below-ground biomass recovered. All totes exhibited a variable root density along their profiles, with Tote E, which contained all species, having the most consistent root density through its depth.

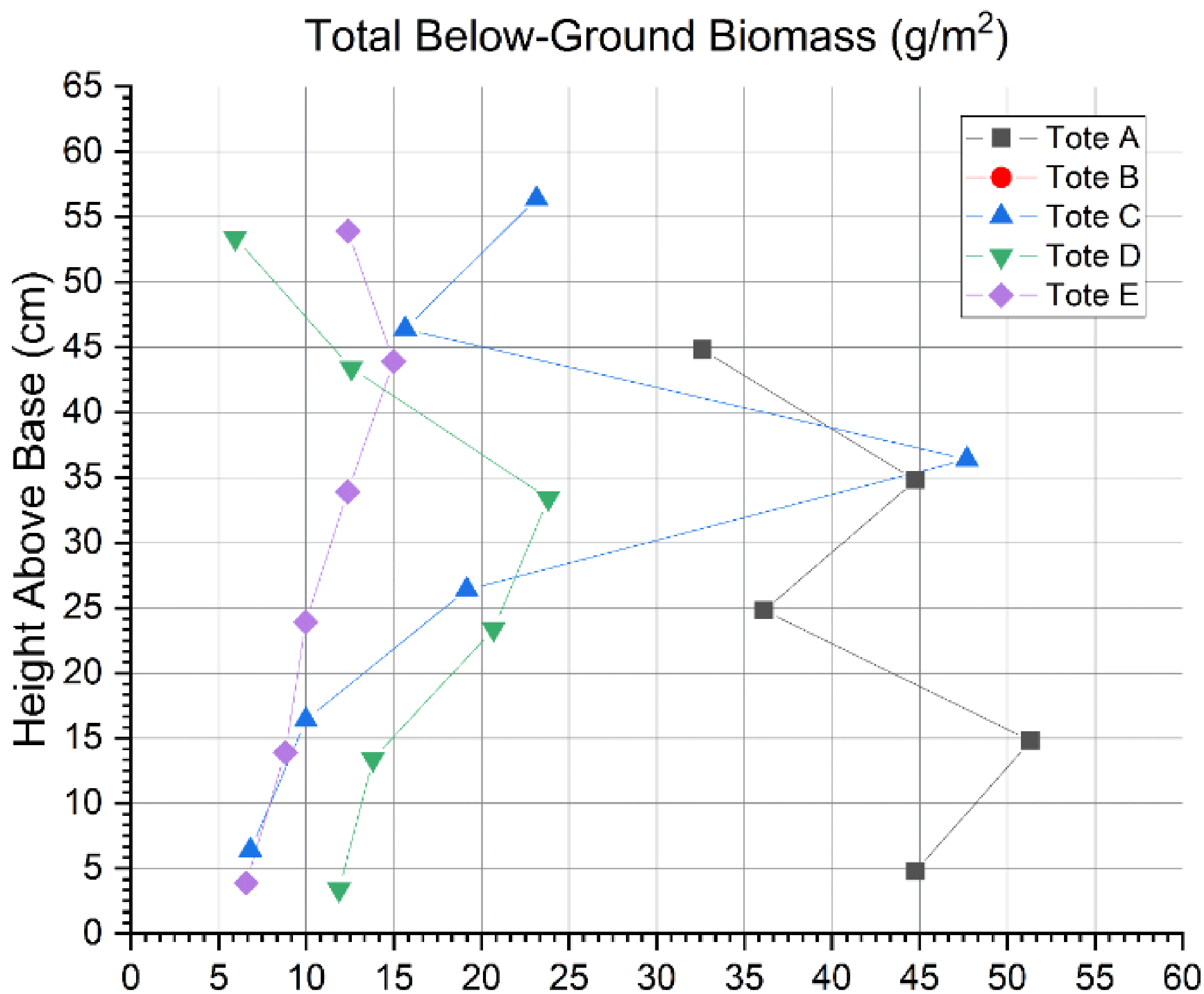


Figure 4-3: Total Below-ground Biomass profile in each Tote (sampled on day 477)

Settlement of the centrifuged tailings after the conclusion of Year 1 can be split into two different periods: the winter period (day 105 to 342), and the primary Year 2 growing period (day 342 to 478). During the winter period, the electronic sensors remained operational and recording hourly data, but no manual measurements were taken. The totes experienced settlement of 17.8 cm, 18.0 cm, 19.3 cm, 23.3 cm, and 21.5 cm for Tote A, B, C, D, and E respectively. Figure 4-4 shows the height measurements collected through the entire study period, and clearly demonstrate a significant drop over the winter period, with all totes except Tote B continuing to settle (although at a slower rate) through Year 2. All totes experienced some degree of swelling around day 430 of the study, with Tote B exhibiting the greatest magnitude of swelling of the five totes.

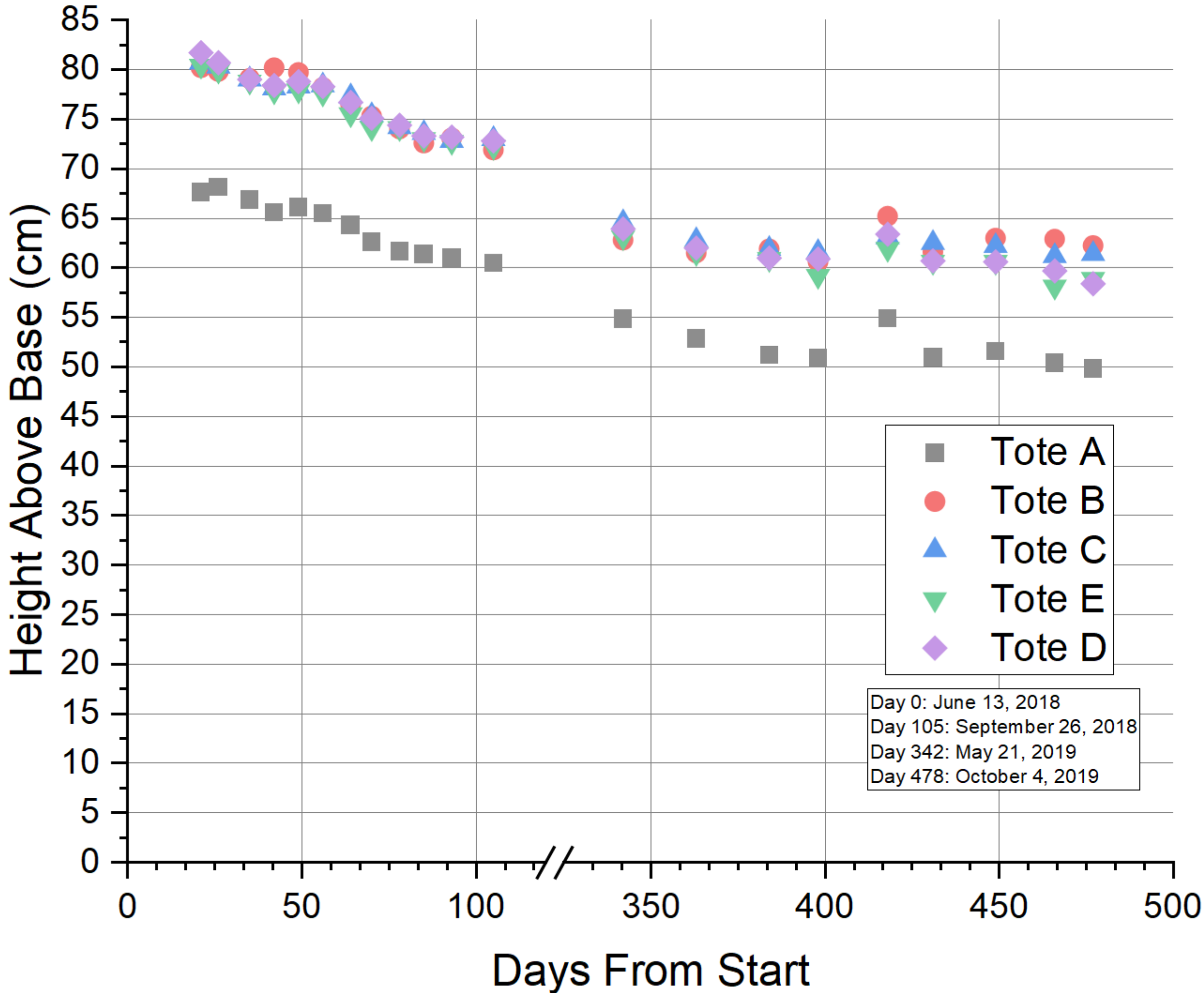


Figure 4-4: Settlement of Centrifuge Tailings in Each Tote Over Time

The settlement in each tote as described above represent a total vertical strain of the tailings in Tote A, B, C, D, and E of 26%, 22%, 24%, 29%, and 27% respectively (see Table 4-5). Tote A experienced an additional strain of 8% over the winter period, with the remaining totes straining a further 10-11%. All five totes continued to experience noteworthy settlement through Year 2, with the notable exception of the control tote, Tote B, which experienced less than 1% of additional vertical strain through the year 2 period. Strain in the vegetated totes in Year 2 ranged from a high of 7.5% in Tote A, to a low of 4.0% in Tote C.

Table 4-5: Total Strain at Key Points of Study

Period	Start Date	End Date	Strain (%)				
			Tote A	Tote B	Tote C	Tote D	Tote E
Year 1	18-Jul-18	26-Sep-18	10.5%	10.3%	9.5%	10.9%	10.2%
Winter	27-Sep-18	21-May-19	8.3%	11.3%	10.4%	10.9%	11.3%
Year 2	22-May-19	3-Oct-19	7.5%	0.7%	4.0%	6.8%	5.2%
		Total	**26.3%**	**22.4%**	**23.9%**	**28.5%**	**26.7%**

In addition to the solids content profile collected at the end of Year 2 (refer to Figure 4-10), additional sampling of the over-consolidated crust identified in Year 1 was sampled to assess dewatering potential of the top-most layers of tailings in each tote. These samples were split into the surface crust (0-10cm), and the lower crust (10-20cm). At the end of Year 1, all totes reach a gravimetric solids content in the top crust layer of approximately 55% to 60%. After the winter period, Totes A, B, C, and D slightly increased to around 65% solids, while Tote A rose to nearly 77% solids content in the top 10 cm of the tailings. At the end of Year 2, Tote E remained at nearly the same solids content, while the other four totes dried further to reach gravimetric solids contents ranging from 75% to 80%. For the slightly deeper portion of the crust which ranged from 10cm to 20cm below tailings surface, all totes concluded Year 1 at a solids content of approximately 60%. After the winter period, Tote A experienced a small amount of rewetting, decreasing solids content to 58%. The other four totes experienced only a minor solids content increase of less than 5%. At the conclusion of Year 2 of the study, all totes recorded an increase in solids content in the lower crust layer to a gravimetric solids content of between 75% and 80%. Solids content was calculated by dividing the dried weight of a soil sample by the total initial wet sample weight.

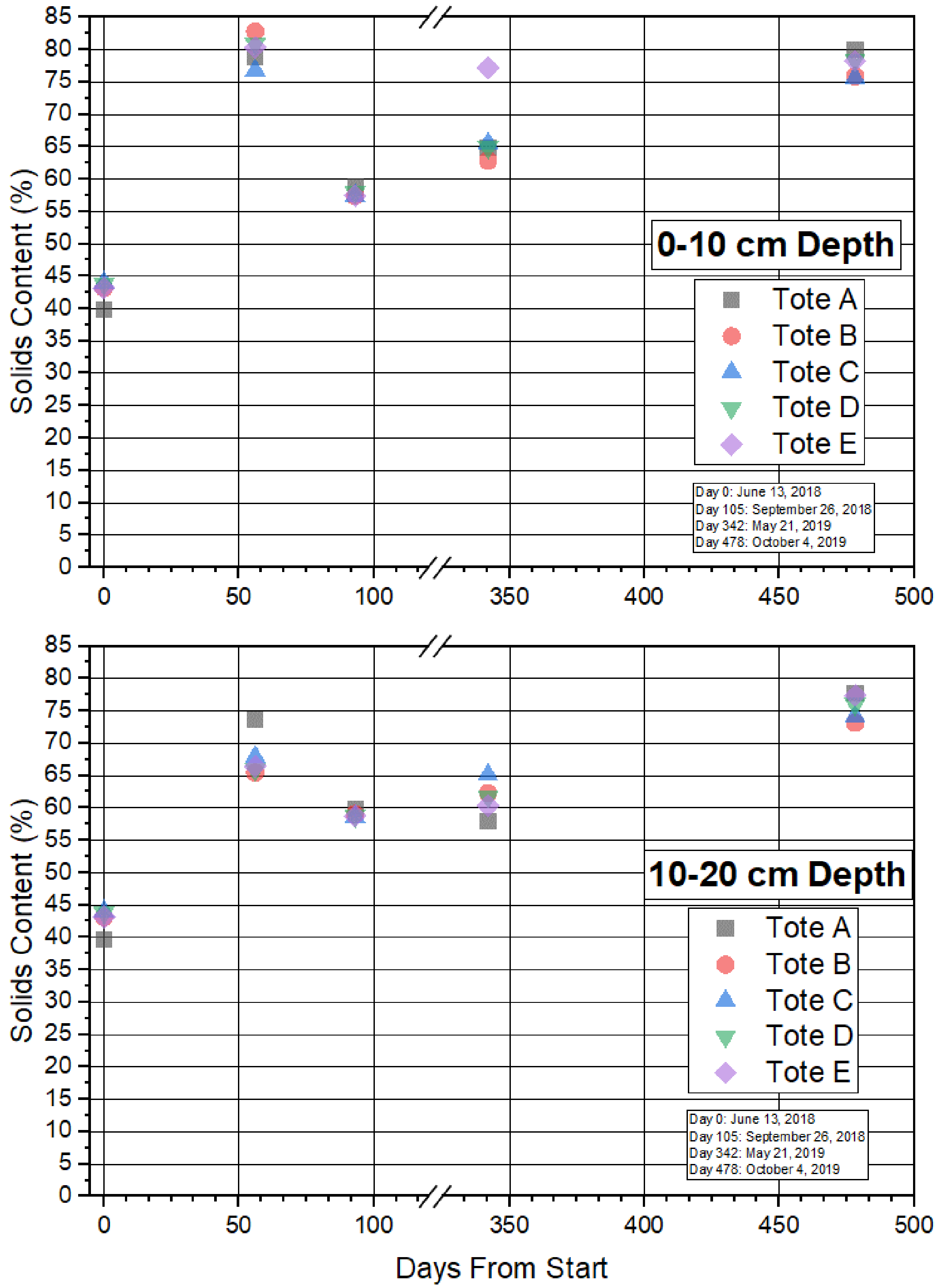


Figure 4-5: Solids Content in the consolidated crust of each tote on day 0, 56, 93, 342, and 478

All totes excluding Tote A continued to experience continued water table draw down through the winter period and through to day 380. The weather station recorded significant sustained precipitation through most of Year 2 until after day 450 (see Figure 4-6). This constant addition of water results in all totes undergoing some increase in the height of the water table in each tote around day 415 before again beginning to fall again towards the end of the study on day 478. Tote A, which was also the shallowest (contained lowest quantity of tailings initially), had no measurable amount of water in the PVC standpipe used to assess water table height relative to surface. Tote D experienced the greatest drop in the water table, while Tote B (the control), experienced very little reduction in water table level. No measurable water table was recorded in Tote E after day 425. A summary of climate data collected from the nearby weather station is provided in Table 4-6.

Table 4-6: Key Climate Characteristics of Tote Study in Year 1 and Year 2

	Year 1	**Year 2**
Start Date	19-Jun-18	13-May-19
End Date	20-Sep-18	20-Sep-19
Total Days	**93**	**130**
Mean Daily Temperature (°C)	15.17	15.46
Days Mean Daily Temperature > 10°C	76	125
Days Mean Daily Temperature > 15°C	57	80
Days Mean Daily Temperature > 20°C	21	11
Days with precipitation	34	47
Cumulative Precipitation (mm)	140	168

Data from the weather station was not available before June 19th, 2018, or after September 21st, 2019, so only 93 and 130 days of climate information was available for the growing period (May-September) of Year 1 and Year 2 respectively. Average daily temperatures during the period were approximately the same in both years of the study. A greater portion of days averaged above 10°C in Year 2 than Year 1, but substantially more days exceeded 20°C in Year 1 than Year 2. Cumulative average daily precipitation was slightly higher (~1.5mm/day) in Year 1 than in Year 2 (~1.3mm/day). Complete weather data is provided in Appendix A.

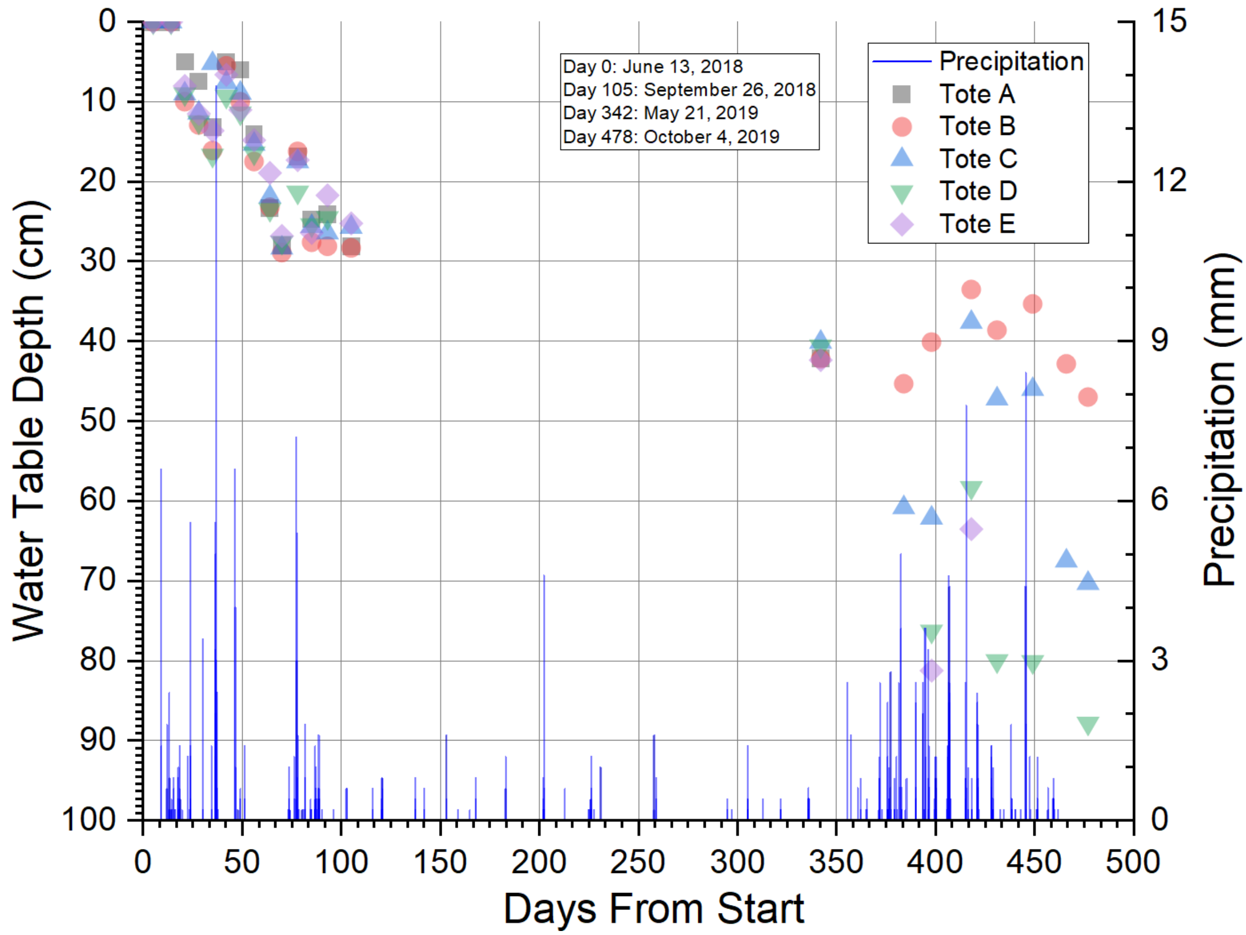


Figure 4-6: Depth of water table in each tote throughout trial period; Daily precipitation in mm collected from nearby weather station

Figure 4-7 and Figure 4-8 present the volumetric water content and matric suction data collection by the electronic sensors installed in each tote through the full trial study length. Based on temperature data collected from all sensors, it was confirmed that all totes experienced a complete freeze of all tailings material in the tote. Insulation that was installed around the totes was unable to prevent this freezing after a colder than normal winter. Temperature of the tailings during the frozen period ranged from approximately -10°C to -20°C. The frozen period was estimated to be between day 150 to day 300 of the study, with the top of the tote freezing first in the fall, and thawing first in the spring. Sensor data recorded during this period should be viewed in the context of the tailings being in a frozen state. This is particularly important for volumetric water content measurements, as the instruments are unable to collect accurate insitu water content values when the pore water in frozen.

Volumetric water content showed little variance in all totes except at surface. In the shallowest part of the tote, volumetric water content at the beginning of year two was higher than the initial readings from the start of the study. This was likely due to precipitation accumulation as well as melting of snow cover accumulated over the winter period. At the surface sensor (25cm), volumetric water content rose to a Year 2 peak around day 400. Cumulative precipitation between day 342 and 400 was measured by the nearby weather station to be approximately 69 mm. Tote A was the only tote where sensors other than surface showed variance in volumetric water content. This deviation is most likely due to Tote A having the smallest initial quantity of tailings and therefore drainage paths are shorter than the other totes, impacting potential water movement from deeper in the tote.

Little variance was noted in matric suction in any of the totes in Year 2. There was some increase in the magnitude of matric suction in all totes except Tote C, with Tote E exhibiting behavior suggesting that the tailings material around the sensor may have pulled away or dried completed. At the deeper sensors, Tote A notes some increase in matric suction to approximately -125 kPa, but this suction was always lost again, returning to an effective value of 0 kPa.

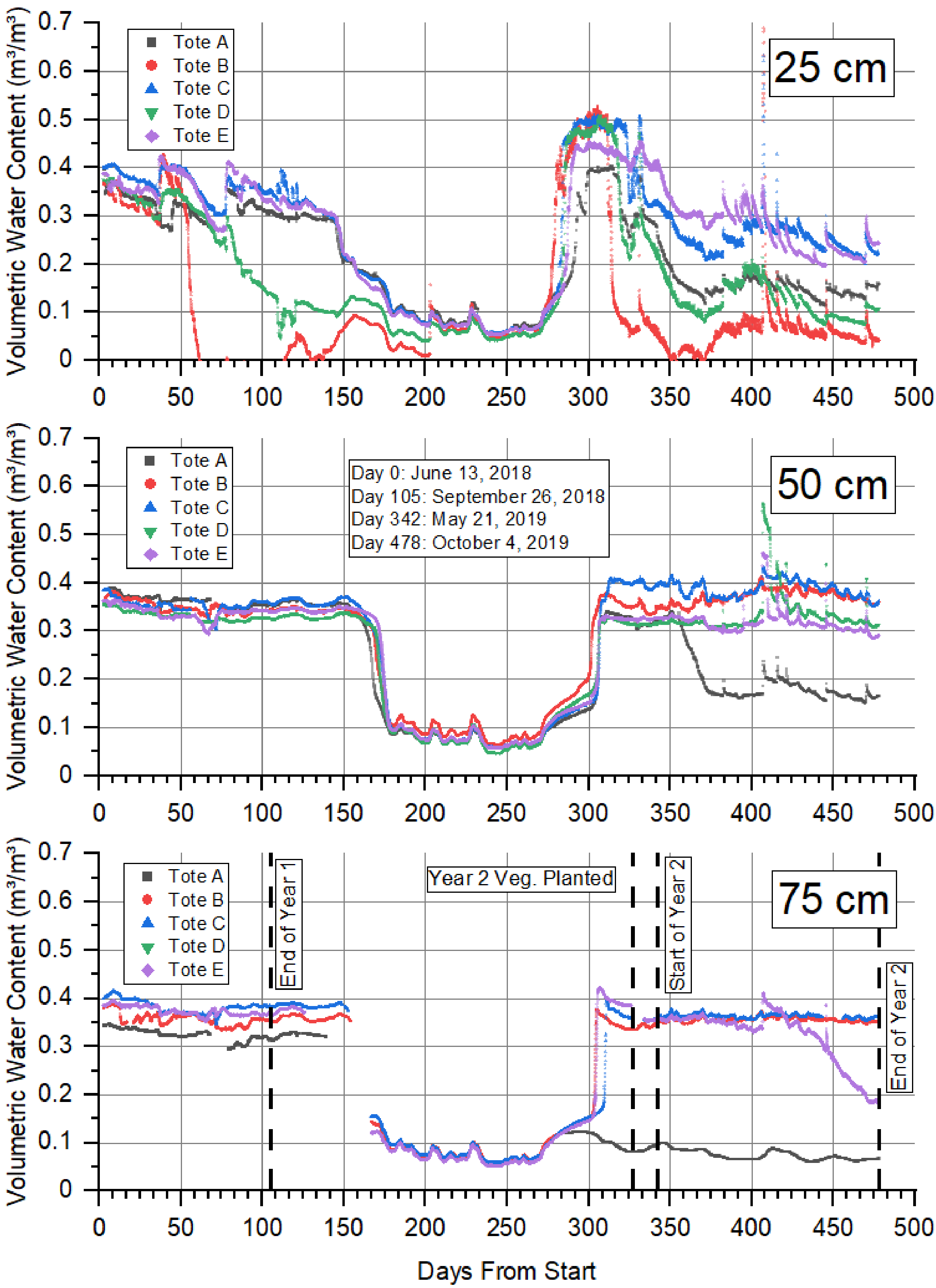


Figure 4-7: Volumetric water content in each tote at 3 depths

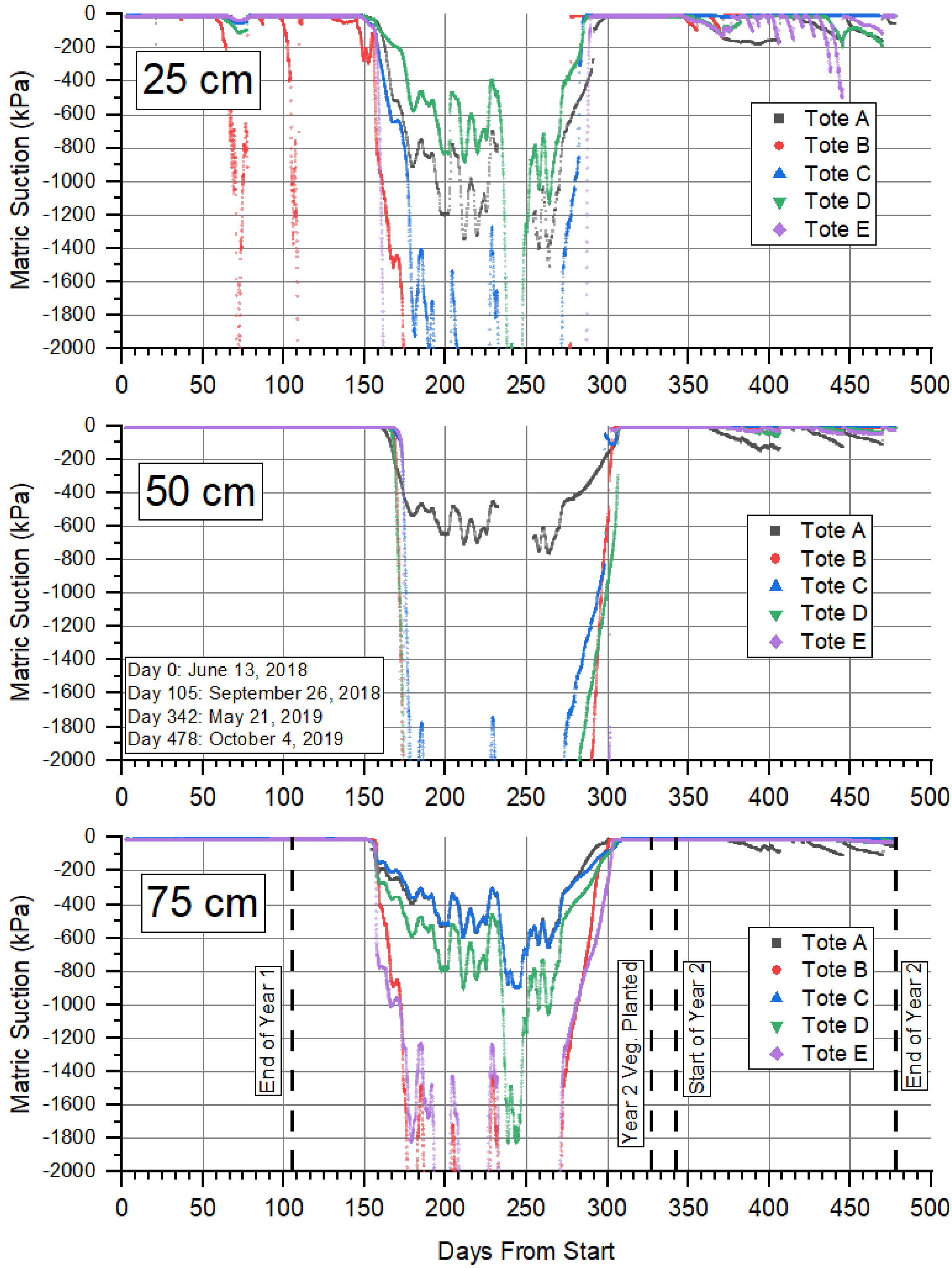


Figure 4-8: Matric suction in each tote at 3 depths

Undrained shear strength measurements were collected through the depth profile of each tote and compared to assess strength gain through each period of study (Figure 4-9). Measurements were collected near the end of Year 1 (day 93), beginning of Year 2 (day 342), and the end of Year 2 (day 478). No significant strength gain was noted between the strength profiles collected on day 93 and 342. This suggests little to no increase in undrained shear strength in the totes over the winter period. In Year 2, all totes other than B (control) realized an increase in shear strength between day 342 and 478. This strength gain was greatest in tote A and E, which had an increase in average shear strength of 27 kPa and 34 kPa. Tote D had an average increase in shear strength along its profile of 47 kPa. Tote C realized a limited increase of the average shear strength from 12 kPa to approximately 16 kPa. No significant change in strength was observed in Tote B. All totes except Tote A generally followed an overall pattern of decreasing shear strength with depth. Tote A reached a peak measured shear strength of 52 kPa on day 478 at 20 cm above the tote base. Tote E had the highest strength at the surface, with a peak measured shear strength of 63 kPa on day 478 at approximately 45 cm above tote base. Tote E was a highly vegetated tote, and it is possible that the crust underwent more dewatering and consolidation in addition to the greater root density near surface. Both factors may have contributed to the very high shear strength reading collected in Tote E. Greater strengths at surface would generally be expected based on previous visual inspection in Year 1 and work done by Beier (2015), it was concluded that the tailings near surface were most likely over-consolidated, while the remaining tailings material was normally consolidated.

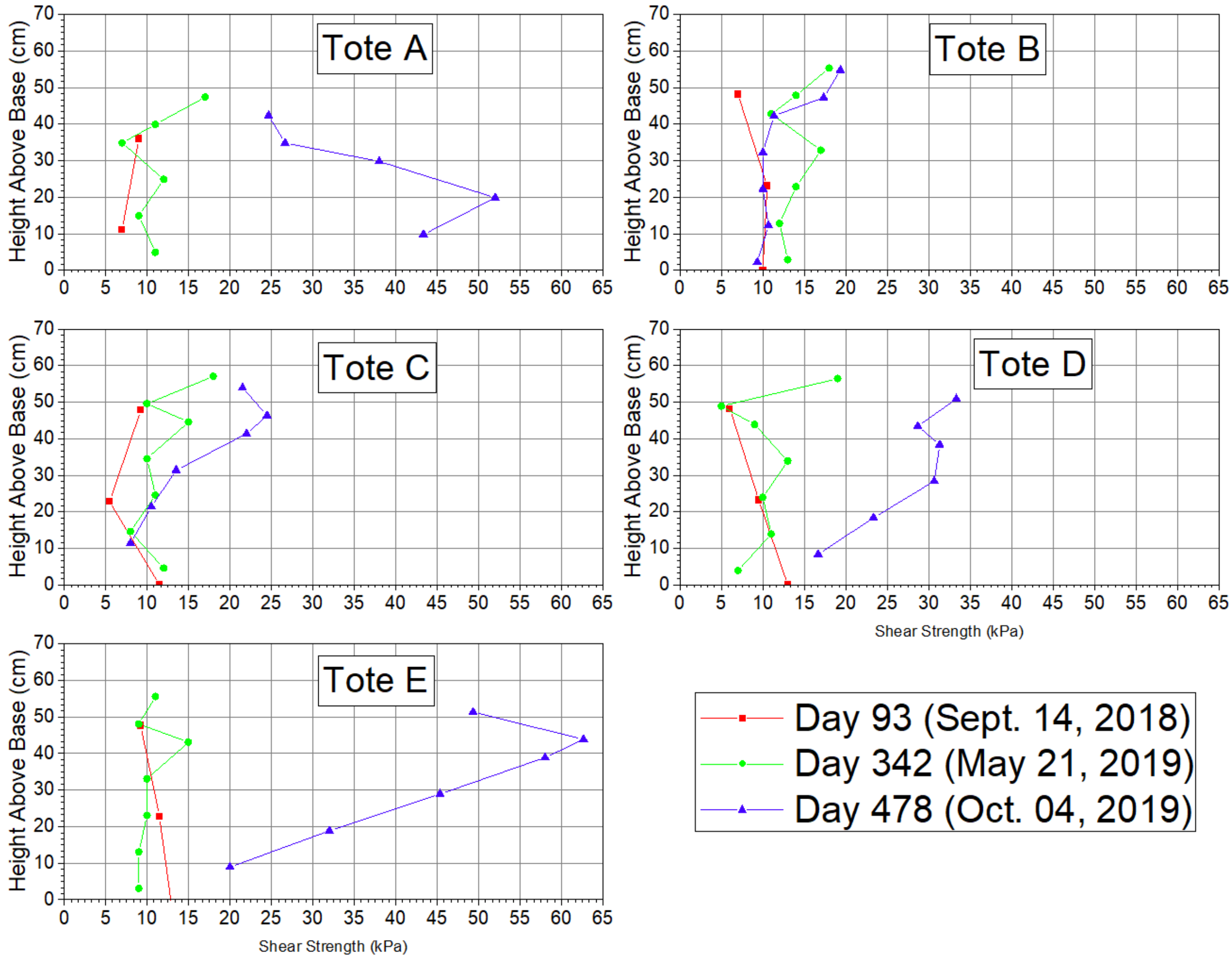


Figure 4-9: Shear strength profiles in each tote on Day 93, 342, and 478 of trial

Figure 4-10 presents the solids content and shear strength profiles generated from data collected at the end of Year 2 (day 478). In all five totes, samples collected nearer to the surface had higher solids contents than samples collected deeper in each tote, ranging from around 80 wt.% in tote A and roughly 76 wt.% in totes B and C. Tote A had the highest overall solids content profile of the totes, and Tote C had the lowest overall solids content. Tote A likely experienced the overall greatest increase in solids content because of it being the tote with the smallest quantity of initial tailings at the start of the study. Generally, it would be expected that greater solids content would also translate to greater undrained shear strength in the tailings, and this was generally true when comparing the profiles in Figure 4-10. Totes B and C had the lowest shear strength through their profiles, which also corresponded to lower overall solids content when compared to the other totes. Totes D and E also followed this general trend, but Tote A did not. The results for shear strength in Tote A were unusual as the strength measured at surface was lower than the strengths recorded deeper into the tailings material. This could also potentially be attributed to the shallower quantity of tailings initially in Tote A that may have allowed for a greater amount of densification to occur at depth compared to the other totes that were much deeper. Figure 4-4 shows that Tote A had approximately 13 cm less tailings than the other four totes, although it experienced similar strain to the other vegetated totes.

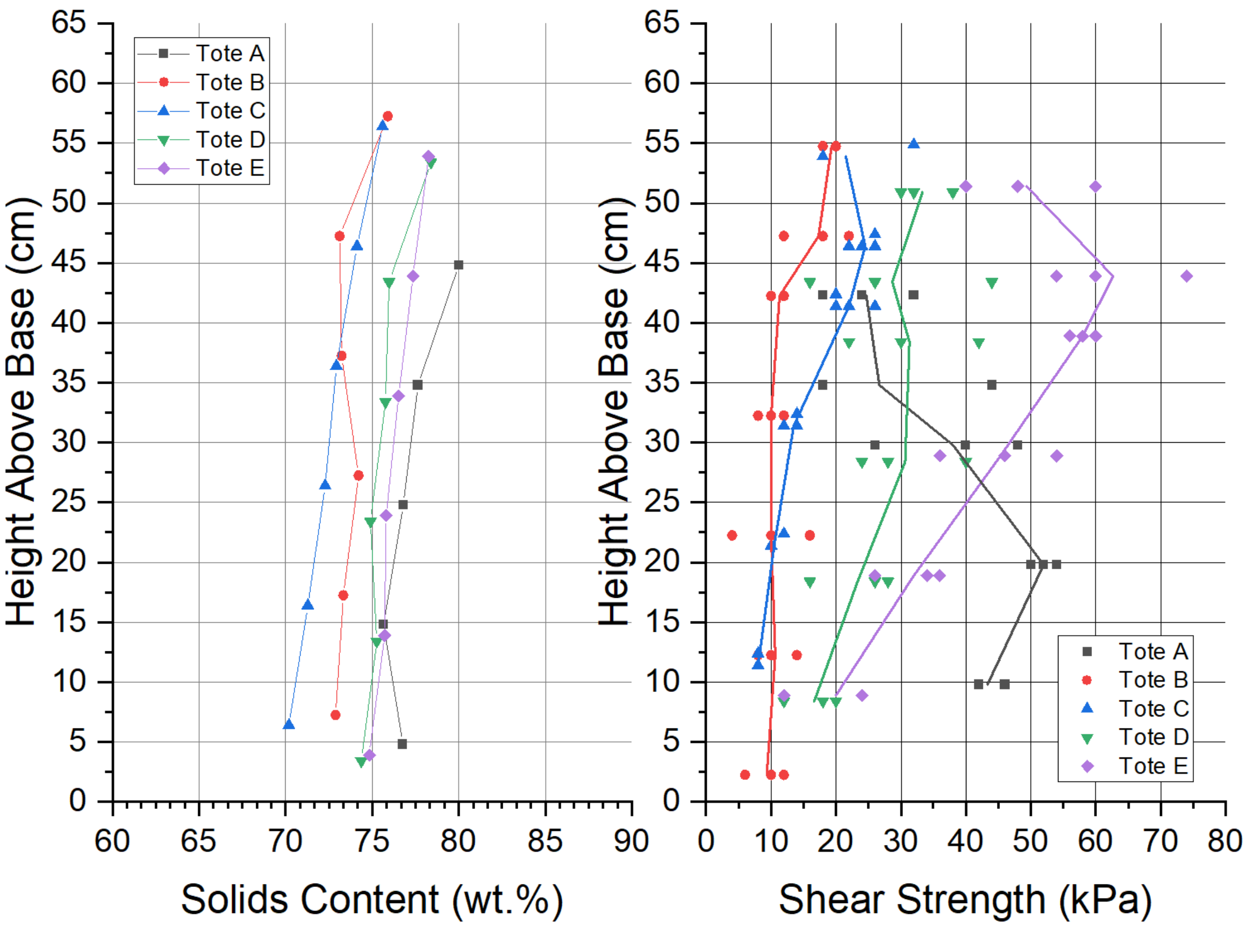


Figure 4-10: Solids content and Shear strength profile in each tote on day 478 of trial (lines on the shear strength profile represent the mean of replicate measurements at each depth)

The final shear strength profile (shown in Figure 4-10) was completed in triplicate. This allowed for the calculation of the standard deviation at each measurement depth in each tote, and this value is reflected in the error bars shown in Figure A-2 in the appendix. In general, greater variance was noted at less depth, likely due to influences of the roots from the plants in each tote.

4.4 Discussion

The intent of native vegetation on deposits of fines-dominated tailings is to increase dewatering and strength gain in these materials to allow these deposits to reach a ready-to-reclaim (RTR) status sooner for the purposes of eventual closure and reclamation. The ability of the plants to meet these objectives was examined through the collection of geotechnical and plant data from a 2-year, mesoscale study done on one cubic meter totes containing centrifuged FFT. This discussion also provides commentary on sources of error and challenges inherent in the data collected during the study.

4.4.1 Data Collection

As described in Section 3.2 and 4.2, 6 electronic sensors were installed in each tote to measure temperature, volumetric water content, and matric suction at three depths in each sample tote. The survey stake that the instruments were attached to in the tailings was not fixed vertically or horizontally within the tote. As a result, the instruments were subject to potentially shifting (particularly vertically) due to the settlement of the tailings in the tote. This is a particular concern for the 25 and 50 cm sensors as that survey stake was shorter than the one used for the 75 cm instruments and therefore had more potential to shift vertically as the tailings settled. The distance between the 25 and 50 cm sensors (which was ~25 cm) was consistent for all five totes as they were fixed to the same stake. This meant that the exact vertical depth of the sensors likely changed over the course of the trial. The instruments were installed nominally at the specified depth in cm below the surface, but were free to shift vertically as the tailings settled. These instruments were not fixed in the totes to prevent damage to the sensors as the tailings settled. The one exception to this is the 75cm instruments in Tote A. This tote had less than 75cm of initial tailings depth, and therefore the survey stake with the sensors attached was inserted until it contacted the bottom of the tote, limiting vertical movement of these sensors. The total potential shift may be small, likely less than the total settlement experienced in each tote, but it is important to keep this information in context when assessing the data provided by these instruments.

Another source of potential error in the results provided by the electronic sensors stems from the risk of material pulling away from the sensors and creating “pockets” of air around the sensors, resulting in potential error in the values provided by those sensors. This “pulling away” of the tailings material from the sensor could be misinterpreted as the tailings being dried when it is possible the surrounding tailings are not actually dry.

Collection of manual measurements in the totes also presented some challenges. One of the most significant being obtaining solids content profiles in the tailings, particularly early in the trial. Sampling equipment and techniques available were not selective enough to collect a profile through the entire depth of the totes for much of the trial. This is due to the material characteristics of the tailings that can cause it to “bunch up” in any sort of coring implement, and the tendency to quickly fill in any hole excavated in the tailings. As the tailings densified, it was eventually possible to collect solids content samples through the profile using a pedological sampler (also known as a dutch auger). As the crust was formed relatively quickly, samples could be collected in the first 20 cm of the tailings in each tote using the pedological sampler, but samples were only collected four times over the two-year study period. The reason for the reduced sample frequency was because sampling using a spade or pedological sampler is a destructive method of sample collection. Excessive sample collection would have resulted in potential impacts to vegetation and overall trial assessment due to the hole created by this sampling process. A full solids content profile was collected only once, at the end of the study for similar reasons.

Water table and settlement data was relatively simply to collect, but some sources of error were present. Water table measurements using the PVC pipe/nylon mesh apparatus could be impacted if the nylon mesh acting as a filter for the holes in the PVC pipe became blocked off. None of the data indicates that such a blockage occurred in any of the totes, but it was not possible to be sure as the pipe could not be removed from the tailings for inspection. Settlement was also prone to some source of error stemming from slight variations in the vertical placement of the transect used to calculate the change in tailings height in each tote. The transect, constructed using plastic zip-ties and survey stakes was prone to sagging as it was constructed by connecting two survey stakes together. When measurements were collected, the transect was straightened to ensure it was parallel (~90 degrees) to the tailings surface, but there is the potential that I could shift during measurements resulting in the distance between the tailings surface and the bottom of the transect being potentially under estimated.

The final manual measurements collected from the totes was undrained shear strength, measured using a Geonor H-60 hand vane shear tool (hVST). Potential for over estimation of strength was possible, particularly in the first 35 cm of the tailings as a result of the vane blades catching on roots and therefore being influenced by the tensile strength of the plant roots. When selecting a spot to perform vane testing, efforts were made to select a spot that appeared likely to have minimal root presence. This effort also meant that for each profile collected (three during the two-year study), that the profile was done in a slightly different location. This means that comparison of strength profiles between measurement dates may be measuring a different part of the tailings in the totes each time. Selection also considered edge effects, so generally the location of the vane insertion was targeted to be a minimum of two vane widths from any open or material interface (such as the edge or bottom of the tote). Any strengths less than 1 kPa could not be measured due to the limitations of the hVST used to collect measurements. Any strengths less than 1 kPa were recorded as zero. The final strength profile collected on day 478 was completed in triplicate for Totes A, B, D, and E, and four measurements collected at each depth in Tote C. This allowed for the calculation of a standard deviation and relative standard deviation to assess potential for error in the measurements. In general, greater errors were calculated in the shallow parts of the totes, with relative standard deviations in the top 20cm of the totes averaging 20%. Consistency was best through the profile measured in Tote C (the control), which had an average relative standard deviation down to 50cm of 10%. The measurements collected from 30 to 50 cm had a lower average relative standard deviation across all totes of 14%. This higher variability at shallow depths is likely attributable to influences of the root systems generated by the plants in each tote. All totes had high relative standard deviations of 23-57% in the measurements collected at 60cm. Potentially due to adhesion of the soil to the vane, and potential edge effects at the bottom of each tote. During execution of the research described above, an opportunity to compare the shear strength measurements collected by the Geonor H-60 vane to two other vane instruments used in a pilot-scale deposit of CFFT. This comparison is presented in Appendix B.

Several factors must be considered when interpreting the plant data collected by NAIT personnel. The plant sampling matrix for Year 2 was more robust than in Year 1, and this was primarily because plant harvesting for sampling is destructive. The initial intent was to insulate the totes over the winter to allow the plants from Year 1 to survive to allow assessment for species over more than one growing season. The insulation was insufficient, and the tailings ultimately froze through, causing a complete die-off of the vegetation planted in the totes in Year 1. The end of Year 2 also represented the end of the study, therefore plant destruction was less of a concern so additional data was collected to assist in assessing the objectives defined for this research.

In addition to the considerations described above, it is essential that the results presented in this research are representative only for the specific tailings contained within the totes used in this study. The material properties of the specific tailings material can play a significant role in how effective native plant species can be on stabilizing centrifuged fluid fine tailings. Tailings characteristics such as clays, fines content, hydraulic conductivity, water availability, and chemistry (such as salinity and nutrient availability) all influence dewatering behavior and plant growth in these tailings. Even tailings treated in the same manner (in this case centrifugation) can have vastly different material properties depending on the specific bitumen extraction process, variations in the tailings feed, and the chemistry of the tailings themselves. Currently, only two oil sands mine sites utilize centrifugation as a commercial-scale treatment technology of their FFT. Despite the technologies being similar, they produce a final CFFT product that can differ greatly due to the geology and extraction processes specific to that oil sands mining operation. As discussed in Section 2.4, the outdoor tote study in Peace River, AB was a part of a larger research effort that also include a 100L (barrels) greenhouse study and a larger field-scale deposit study. The CFFT used in these two trials was provided by the same oil sands mine site (though collected at different times), while the tailings used in the tote study were supplied by a different operator. The characteristics of these two different sources of tailings can vary greatly. The chemistry of the tailings used in the greenhouse study and outdoor tote study is provided in Table 3-2. Index properties of the tailings used in the field study and the tote study are shown in Table 2-4 and Table 3-1 respectively. Chemistry of the tailings used in the field study were not available.

4.4.2 Impact of Plant Species on Dewatering and Strength Gain

Three of the vegetated totes measured an overall increase in solids content through its depth, with most of the densification occurring in top 20 cm of each tote. Solids content, like strength, generally decreased non-linearly with depth in each tote. Samples collected from the surface crust measured the greatest increase in solids content. Measurements in the first year also demonstrated this material is very susceptible to rewetting, reducing solids content after significant precipitation. This decrease in solids content can also impact shear strength. The susceptibility of these centrifuged fine tailings material to rewetting and subsequent strength and solids content loss was also noted in Abdulnabi et al. (2021); Rima and Beier (2021); W. Smith et al. (2018).

Shear strength is a key geotechnical parameter in the capping and eventual closure and reclamation of oil sands tailings deposits. Although *Directive 085* does not specify a required undrained shear strength to classify a tailings deposit as ready-to-reclaim, work by McKenna et al. (2016) stated that the lower bound to facilitate safe capping is ~25 kPa. Three strength measurements were taken in each of the five totes during the study period: at the end of Year 1, at the beginning of Year 2, and at the end of the study. No significant gain in shear strength was measured during the winter period of the study, suggesting any freeze-thaw effects contributed little to strength gain in the tote. All the vegetated totes demonstrated some increase in shear strength over the second growing season, but all the totes except for Tote A measured their greatest shear strengths near the surface of the tailings. This observation corroborates the conclusions from Abdulnabi et al. (2021) and W. Smith et al. (2018) which also found that strength gain was generally limited to the top layers (~35cm) of a tailings deposit. The only exception in this study was Tote A, where surface strengths were measured as lowest along the strength profile after the second growing season. This may be the result of Tote A containing the lowest quantity of tailings, and therefore the shallowest depth of tailings in the study, allowing a greater amount of densification and strength gain deeper in the tote. Tote E had substantially higher average shear strengths along its profile. This could potentially be explained by this tote having all four plant species. This could have allowed greater contribution to strength gain by the vegetation. The additional root systems could also have made finding an unencumbered spot for measuring shear strength challenging, and therefore may have been influenced to a greater degree by plant roots than the other totes.

Although assessment of plant viability is beyond the scope of this thesis work, a few comments can be made based on the observations made during the study. Work by Schoonmaker et al. (2018) suggested that for perennial species (such as those planted in this study), would be most advantageous to dewatering if allowed to grow for more than one season. During this study, the extreme cold experienced by the totes resulted in a complete die off in the first year, requiring replanting in Year 2. There is potential that greater dewatering may have been observed in Year 2 if the plants from Year 1 had survived. In a field-scale deposit, this complete freezing through the full deposit would not happen, and perennial species may be able to continue dewatering over multiple years. This conclusion was also drawn in W. Smith et al. (2018), which noted there may be potential for greater dewatering over a longer period of time (two to five years). Plant viability is also likely heavily impacted by the growth medium. In this case the tailings used in the totes present a more challenging material for the plants to thrive in than tailings material sourced from other oil sands operators, as discussed in Schoonmaker et al. (2021). Surface water management was less of a concern in the tote study after the initial decant at the start of the study, but W. Smith et al. (2018) noted significant challenges for upland species (such as those planted in the totes) growing in a larger field deposit in flooded areas. They suggested examination of species more suited to flooding (wetland species) may be valuable if there is concern of standing water or flooding on these tailings deposits.

4.5 References

Abdulnabi, A., Paul, A., Beier, N., Laberge, S., Schoonmaker, A., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 2 key geotechnical performance indicators*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Beier, N. A. (2015). *Development of a Tailings Management Simulation and Technology Evaluation Tool.* (Doctor of Philosophy), University of Alberta,

Decagon Devices Inc. (2015). [Em50/Em50R/Em50G Em50 Series Data Collection System, Operator's Manual. Version: June 25, 2015 - 14:00:15. Pullman, Washington, 81 pp].

Geonor Inc. (2018). [H-60 Hand-Held Vane Tester, Data Sheet. Augusta, New Jersey. 2pp].

McKenna, G., Mooder, B., Burton, B., & Jamieson, A. (2016). Shear Strength and Density of Oil Sands Fine Tailings for Reclamation To a Boreal Forest Landscape. *IOSTC 2016: Proceedings of the 5th International Oil Sands Tallings Conference, 2*(604).

Rima, U. S., & Beier, N. A. (2021). Effects of seasonal weathering on dewatering and strength of an oil sands tailings deposit (in press). *Canadian Geotechnical Journal*. doi:https://doi.org/10.1139/cgj-2020-0533

Rima, U. S., Beier, N. A., & Abdulnabi, A. (2021). Modeling the Effects of Seasonal Weather on Centrifuged Oil Sands Tailings. *Processes, 9(11)*(1906), 17. doi:https://doi.org/10.3390/pr9111906

Schoonmaker, A., Degenhardt, D., & Floreani, T. (2018). *Evaluating the Potential to Establish Plants to Aid in Dewatering of an Atmospheric Fine Drying Tailings Deposit at Muskeg River Mine.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Schoonmaker, A., Chigbo, C., Walton-Sather, S., Abdulnabi, A., Beier, N., Laberge, S., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G. (2018). *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

5 Conclusions

The potential of native vegetation to dewater and increase undrained shear strength in samples of centrifuged fluid fine tailings has been evaluated. The conclusions of this research are summarized below:

This study demonstrated that *Carex spp*., *Salix interior*, *Elymus trachycaulus*, and *Rumex occidentalis* could successfully grow and establish in these types of materials in a region with similar climate conditions to that of an oil sands mine site in northeastern Alberta. Select species of *Salix Interior* and *Elymus trachycaulus* produced the greatest biomass over a single growing season. None of the species could survive a complete freeze of the tailings material during the winter period between the two growing periods, requiring replanting at the beginning of Year 2 of the study.

Overall, the vegetated totes did demonstrate a modest increase in solids content, and a somewhat more substantial increase in shear strength than the control tote that contained no vegetation. In general, totes with a greater amount of vegetation yielded slightly higher solids contents in the centrifuged fine tailings. These increases were greatest in the totes that contained *Salix Interior* and *Elymus trachycaulus*.

Rewetting potential was a significant identified challenge, as this work, as well as work by others demonstrated that strength and solids content gains could be completely lost if the tailings are flooded or experience significant precipitation. This also resulted in swelling of the tailings in the totes after major precipitation events. The vegetated totes appeared to weather this influx of water better than the control tote, which experienced substantially more swelling after the major rain events in Year 1 and Year 2 than the totes containing plant species.

All totes experienced similar settlement in Year 1. Settlement due to freeze-thaw effects during the winter period contributed a similar amount of settlement in all totes to that in Year 1. In Year 2, additional settlement was observed in all vegetated totes, but nearly no additional settlement occurred in the control (no plants) tote.

Overall, the greatest enhancement to strength and dewatering was achieved in totes that were planted with *Salix Interior* and *Elymus trachycaulus.*

5.1 Recommendations for Future Work

During the work described in the thesis to meet the objective of assessing the ability of native plant species to dewater and increase shear strength in samples of centrifuged fine tailings, additional questions that warrant further investigation arose. These recommendations for further study are listed below:

Assessment of water availability to plants, and potential impact on their growth. This may allow for finding an optimal plant density per volume of water (and hence volume of tailings) to optimize dewatering.

Evaluation the contributions that fibrous root structures may have to trafficability of a deposit. Study if the rapid establishment of species such as slender wheatgrass allows capping to be safely carried out sooner, even if the rest of the deposit has not reached a sufficient undrained shear strength.

More robust assessment of strength profile changes over time in a similar or smaller study that will allow for a more direct assessment of the impacts that rewetting has on strength loss in these tailings, and how long it takes that gain to be recovered should be examined.

Assessment of the impact of the tailings properties (clay content and type, hydraulic conductivity, etc.) on plant growth and subsequent dewatering potential. Further assessment of the chemistry and nutrient availability of the tailings deposit to support plant species to maximize dewatering. Determining an optimum nutrient addition strategy based on the plan species, and the tailings comprising the deposit should be evaluated. This would likely require samples of tailings from multiple sources in a more controlled environment, where the water balance of each sample vessel can be controlled, and nutrient application can be assessed.

Bibliography

Abdulnabi, A., Paul, A., Beier, N., Laberge, S., Schoonmaker, A., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 2 key geotechnical performance indicators*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

AER. (2017). *Directive 085 - Fluid Tailings Management for Oil Sands Mining Projects*. Calgary, AB: Alberta Energy Regulator.

AER. (2020). *State of Fluid Tailings Management for Mineable Oil Sands, 2019*. Retrieved from Calgary, Alberta, Canada: https://static.aer.ca/prd/2020-09/2019-State-Fluid-Tailings-Management-Mineable-OilSands.pdf

AER. (2021). *ST98: 2021 Alberta's Energy Reserves & Supply/Demand Outlook*. Retrieved from

ASTM. (2018). D2573M / D2573-M18, Standard Test Method for FIeld Vane Shear Test in Saturated Fine-Grained Soils. In. West Conshohocken, PA: ASTM International.

Beier, N., & Sego, D. (2007). *The Oil Sands Tailings Research Facility*, Ottawa, Ontario, Canada.

Beier, N., Alostaz, M., & Sego, D. (2009). *Natural dewatering strategies for oil sands fine tailings*. Paper presented at the Tailings and Mine Waste, Banff, AB.

Beier, N., Wilson, W., Dunmola, A., & Sego, D. (2013). Impact of flocculation-based dewatering on the shear strength of oil sands fine tailings. *Canadian Geotechnical Journal*(50(9)), 1001-1007.

Beier, N. A. (2015). *Development of a Tailings Management Simulation and Technology Evaluation Tool.* (Doctor of Philosophy), University of Alberta,

BGC Engineering Inc. (2010). Oil Sands Tailings Technology Review. In Oil Sands Research and Information Network (Ed.), (pp. 136 pp.). Edmonton, Alberta.

Boswell, J., Davachi, M., & Sobkowicz, J. (2012). Oil Sands Tailings Technology Deployment Roadmap Project Report – Volume 2. *2*, 166-166.

Briaud, J. (2013). *Geotechnical Engineering: Unsaturated and Saturated Soils* (1 ed.): John Wiley & Sons, Incorporated.

Chalaturnyk, R. J., Scott, J. D., & Özüm, B. (2002). Management of oil sands tailings. *Petroleum Science and Technology, 20*(9-10), 1025-1046. doi:10.1081/LFT-120003695

Collins, C., Foght, J. M., & Siddique, T. (2016). Co-occurrence of methanogenesis and N2 fixation in oil sands tailings. *The Science of the total environment*(565), 306-312. doi:https://doi.org/10.1016/j.scitotenv.2016.04.154

Collins, V., Schoonmaker, A., Kaminsky, H., Sedgwick, A., Chigbo, C., & Mussone, P. (2018). *Development of bacterial inoculum for the promotion of plant growth on tailings material*. Paper presented at the International Oil Sands Tailings Conference, Edmonton, AB, Canada.

Contreras, I., & Harvey, J. (2021). *The role of the vane shear test in mine tailings*. Paper presented at the Tailings and Mine Waste, Banff, AB.

Corriveau, D. (2018, December 9-12). *Keynote Address.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB.

COSIA. (2012). *Technical Guide for Fluid Fine Tailings Management.* Retrieved from Calgary, AB:

Cossey, H. L., Batycky, A. E., Kaminsky, H., & Ulrich, A. C. (2021). Geochemical Stability of Oil Sands Tailings in Mine Closure Landforms. *Minerals, 11*(8), 830. doi:10.3390/min11080830

Dawson, R. F., Sego, D. C., & Pollock, G. W. (2011). Freeze-thaw dewatering of oil sands fine tails. *Canadian Geotechnical Journal*(36(4)), 587-598. doi:10.1139/cgj-36-4-587

de Klerk, A. (2020). *Future Energy - Improved, Sustainable and Clean Options for Our Planet* (Third ed.). Cambridge, MA: Elsevier.

Decagon Devices Inc. (2015). [Em50/Em50R/Em50G Em50 Series Data Collection System, Operator's Manual. Version: June 25, 2015 - 14:00:15. Pullman, Washington, 81 pp].

Decagon Devices Inc. (2016). [5TE Water content, EC and temperature sensor, Operator's Manual. Version: March 11, 2016 - 11:55:57. Pullman, Washington, 26 pp].

Decagon Devices Inc. (2017). [MPS-2 & MPS-6 Diaelectric Water Potential Sensors, Operator's Manual. Version: July 10, 2017 - 16:08:16. Pullman, Washington, 30 pp].

ERCB. (2009). *Directive 074 - Tailings Performance Criteria and Requirements for Oil Sands Mining Schemes*. Calgary, AB: Energy Resources Conservation Board of Alberta.

Euliss, K. W. (2005). *Dewatering and Remediation of Contaminated Dredged Sediments.* (Doctor of Philosophy Dissertation), Purdue University,

FTFC. (1995). *Advances in oil sands tailings research*. Edmonton, Alberta: Fine Tailings Fundamentals Consortium, Alberta Department of Energy, Oil Sands Research Division.

Geonor Inc. (2018). [H-60 Hand-Held Vane Tester, Data Sheet. Augusta, New Jersey. 2pp].

Geonor Inc. (2021). H-60 Hand-Held Vane Tester. Retrieved from https://geonor.com/live/products/geotechnical-test-equipment/h-60-hand-held-vane-tester/

Government of Alberta. (2015). *Lower Athabasca Region - Tailings Management Framewor for the Mineable Athabasca Oil Sands*. Edmonton, AB: Government of Alberta.

Government of Alberta. (2018). Oil Sands Facts and Statisitics. Retrieved from https://www.alberta.ca/oil-sands-facts-and-statistics.aspx

Guo, C. (2009). *Rapid Densification of the Oil Sands Mature Final Tailings (MFT) by Microbial Activity.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB. Retrieved from https://dx.doi.org/10.7939/r3k988

Hockley, D. (2018). Clay effects on geotechnical properties of tailings. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 183-211). Chantilly, Virginia, USA: The Clay Minerals Society.

Hollander, E., & Omotoso, O. (2018). Clays impact on bitumen-extraction processes. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 109-127). Chantilly, Virginia, USA: The Clay Minerals Society.

Humphries, M. (2008). *North American Oil Sands: History of Development, Prospects for the Future* (9781606926802). Retrieved from

Hyndman, A., Sawatsky, L., McKenna, G., & Vandenberg, J. (2018). *Fluid Fine Tailings Process: Disposal, Capping, and Closure Alternatives*. Paper presented at the International Oil Sands Tailings Conference, Edmonton, Alberta, Canada.

Impact Test Equipment Ltd. (2021). Pilcon Hand Vane Tester - SL815 User Guide. Retrieved from https://www.impact-test.co.uk/docs/SL815_HB.pdf

Jeeravipoolvarn, S., Chalaturnyk, R. J., & Scott, D. (2008, September 2008). *Consolidation Modeling of Oil Sands Fine Tailings: History Matching.* Paper presented at the GeoEdmonton, Edmonton, AB.

Jeeravipoolvarn, S. (2010). *Geotechnical behavior of in-line thickened oil sands tailings.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB. Retrieved from http://pqdt.calis.edu.cn/detail.aspx?id=RQZFOt6KJ2I%3D

Johnson, R. L., Bork, P., Allen, E. A. D., James, W. H., & Koverny, L. (1993). *Oil Sands Sludge Dewatering By Freeze-Thaw and Evapostranspiration* (RRTAC 93-8). Retrieved from

Kasperski, K. L., & Mikula, R. J. (2011). Waste Streams of Mined Oil Sands: Characteristics and Remediation. *Elements, 7*(6), 387-392. doi:10.2113/gselements.7.6.387

King, K. S., & Yetter, J. (2011). Groundwater and Alberta's Oil Sands Mines. *Groundwater, 49*(3), 316-318. doi:10.1111/j.1745-6584.2011.00819.x

Li, A. (2019). *Role of clays in bitumen extraction of water-based oil sands processing.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB.

Masliyah, J., Zhou, Z. J., Xu, Z., Czarnecki, J., & Hamza, H. (2004). Understanding Water-Based Bitumen Extraction from Athabasca Oil Sands. *The Canadian Journal of Chemical Engineering, 82*, 628-654. doi:https://doi.org/10.1002/cjce.5450820403Citations

McKenna, G., Mooder, B., Burton, B., & Jamieson, A. (2016). Shear Strength and Density of Oil Sands Fine Tailings for Reclamation To a Boreal Forest Landscape. *IOSTC 2016: Proceedings of the 5th International Oil Sands Tallings Conference, 2*(604).

Mercier, P. H. J., Omotoso, O., & Hockley, D. (2018). Oil-sands clays. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 9-32). Chantilly, Virginia, USA: The Clay Minerals Society.

Mikula, R. (2018). The role of clays in the performance of oil-sands tailings management options. In O. Omotoso & D. Hockley (Eds.), *An Introduction to Oil Sands Clays* (Vol. 22, pp. 129-181). Chantilly, Virginia, USA: The Clay Minerals Society.

Mossop, G. D. (1980). Geology of the Athabasca Oil Sands. *Science, 207 (4427)*, 145-152. doi:10.1126/science.207.4427.145

NZGS. (2001). Guideline for hand held shear vane test. https://fl-nzgs-media.s3.amazonaws.com/uploads/2016/06/Hand-held-shear-vane-test-2001.pdf

Olmedo, N. A., Fisseha, B., Wilson, W., Barczyk, M., Zhang, H., & Lipsett, M. G. (2020). An automated vane shear tool for environmental monitoring with unmanned ground vehicles. *Journal of Terramechanics, 91*, 53-63. doi:https://doi.org/10.1016/j.jterra.2020.05.003

Proskin, S. A. (1998). *A geotechnical investigation of freeze-thaw dewatering of oil sands fine tailings.* (Doctor of Philosophy (Ph.D.)), University of Alberta, Edmonton, AB.

Renault, S., Zwiazek, J. J., Fung, M., & Tuttle, S. (2000). Germination, growth and gas exchange of selected boreal forest seedlings in soil containing oil sands tailings. *Environmental Pollution, 107*(3), 357-365. doi:10.1016/S0269-7491(99)00167-0

Renault, S., MacKinnon, M., & Qualizza, C. (2003). Barley, a Potential Species for Initial Reclamation of Saline Composite Tailings of Oil Sands. *Journal of Environmental Quality, 32*(6), 2245-2253.

Renault, S., Qualizza, C., & MacKinnon, M. (2004). Suitability of altai wildrye (Elymus angustus) and slender wheatgrass (Agropyron trachycaulum) for initial reclamation of saline composite tailings of oil sands. *Environmental Pollution, 128*(3), 339-349. doi:10.1016/j.envpol.2003.09.009

Rima, U. S., & Beier, N. A. (2018, 2018). *Evaluation of Temperature and Multiple Freeze- Thaw effects on the Strength Properties of Centrifuged Tailings.* Paper presented at the GeoEdmonton, Edmonton, AB, Canada.

Rima, U. S., & Beier, N. A. (2021). Effects of seasonal weathering on dewatering and strength of an oil sands tailings deposit (in press). *Canadian Geotechnical Journal*. doi:https://doi.org/10.1139/cgj-2020-0533

Rima, U. S., Beier, N. A., & Abdulnabi, A. (2021). Modeling the Effects of Seasonal Weather on Centrifuged Oil Sands Tailings. *Processes, 9(11)*(1906), 17. doi:https://doi.org/10.3390/pr9111906

Schafer, H. L., & Beier, N. A. (2019). Estimating the SWCC from the SFCC for mine waste tailings using TDR. *Canadian Geotechnical Journal*, 1-52. doi:10.1139/cgj-2018-0145

Schoonmaker, A., Degenhardt, D., & Floreani, T. (2018). *Evaluating the Potential to Establish Plants to Aid in Dewatering of an Atmospheric Fine Drying Tailings Deposit at Muskeg River Mine.* Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Schoonmaker, A., Chigbo, C., Walton-Sather, S., Abdulnabi, A., Beier, N., Laberge, S., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Silva, J, M., Ulrich, C, A., Biggar, W, K., . . . C, D. (2009). A model for the prediction of bearing capacity on vegetated tailings. In: University of Alberta.

Silva, M. J. (1999). *Plant dewatering and strengthening of mine waste tailings.* (Doctor of Philosophy), University of Alberta,

Smith, K. E., Banks, M. K., & Schwab, A. P. (2009). Dewatering of contaminated sediments: Greenhouse and field studies. *Ecological Engineering, 35*(10), 1523-1528. doi:10.1016/j.ecoleng.2009.07.002

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G. (2018). *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.

Sobkowicz, J. (2012). *Oil Sands Tailings Technology Deployment Roadmaps: Project Report - Volume 1: Project Summary*: Alberta Innovates - Energy and Environment Solutions.

Spence, J., Bara, B., Lorentz, J., & Mikula, R. J. (2015, 2015). *Development of the Centrifuge Process for Fluid Fine Tailings Treatment at Syncrude Canada Ltd.* Paper presented at the World Heavy Oil Congress, Edmonton, AB, Canada.

Wani, B. A., Khan, A., & Bodha, R. H. (2011). Salix: A viable option for phytoremediation. *African Journal of Environmental Science and Technology, 5*, 567-571. doi:10.4314/ajest.v5i8.72048

Wu, S. (2009). *A Greenhouse Study of Selected Native Plant Species for Dewatering CT.* (Master of Science), University of Alberta,

Wu, S., Sego, D., Naeth, A., & Wang, B. W. (2010). *Evapotranspiration Dewatering Effect on CT Deposits by Grasses*. Paper presented at the 63rd Canadian Geotechnical Conference and 6th Canadian Permafrost Conference, Calgary, Alberta.

Wu, S., Naeth, M., Sego, D., & Wang, B. (2011). *A Greenhouse Study of Grass Response on Composite Tailings Discharged from an Alberta Oil Sands Mine*. Paper presented at the 5th Mining and the Environment International Conference, Sudbury, Ontario.

Wu, S., Sego, D., Naeth, A., & Wang, B. (2011). *Responses of Wheatgrass Species to Composite/Consolidated Oil Sands Tailings*. Paper presented at the Tailings and Mine Waste 2011, Vancouver, BC. http://www.dx.doi.org/10.14288/1.0107703

Appendices

Appendix A: Mesoscale Study Raw Data

Appendix A.1: Manual Measurement Data

Supplemental file is available on the University of Alberta Education and Research Archive (ERA)

Relevant summary plots are provided below:

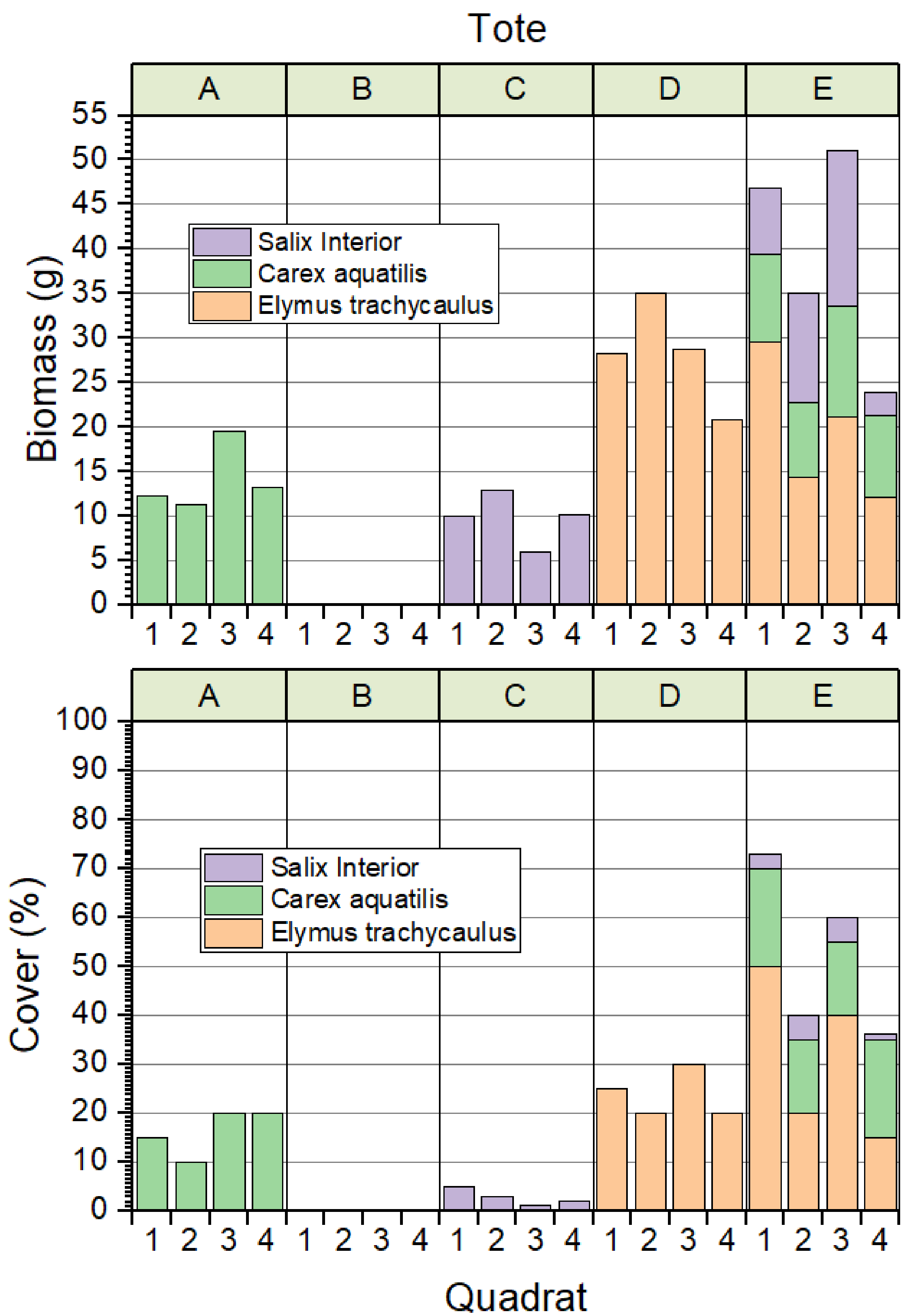


Figure A-1: Bar Chart of Raw Data Presented in Figure 3-1

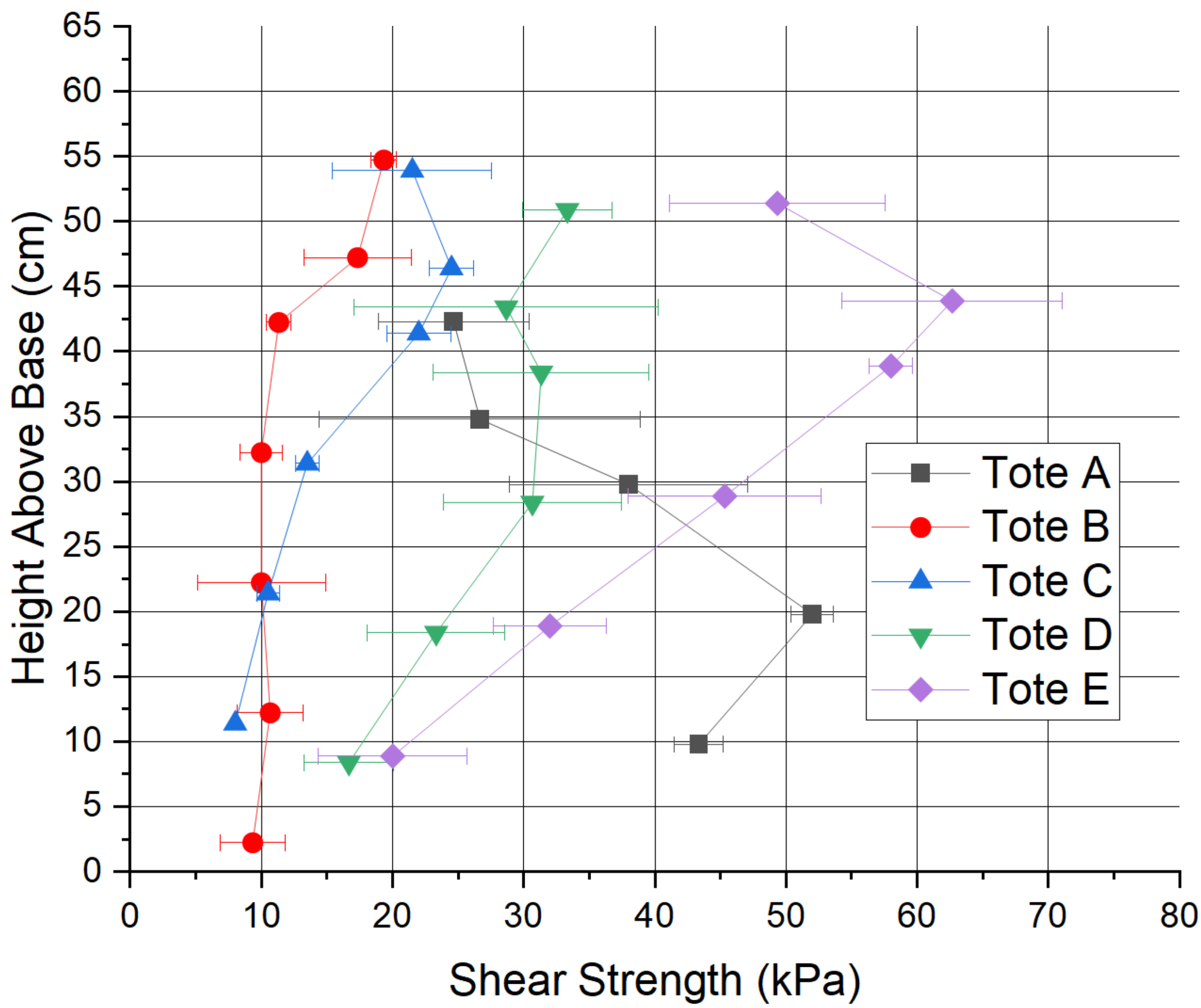


Figure A-2: Shear Strength Profile on Day 478 with Error Bars

Appendix A.2: Electronic Sensor and Weather Station Data

Supplemental file is available on the University of Alberta Education and Research Archive (ERA)

Appendix B: Compilation of In-situ Vane Testing Methods in an Oil Sands Centrifuged Fluid Fine Tailings Deposit

Introduction

As part of the larger CRD program described in Chapter 1 of this thesis, in-situ undrained shear strength (Su) was measured in a pilot-scale deposit of centrifuged fluid fine tailings using three different vane shear tools (VSTs). The test cell was located at Canadian Natural Resources Ltd.'s Albian Sands operation in northeastern Alberta. The deposit had dimensions of 30 m wide by 60 m long, with a maximum depth of 4.65m of tailings when the test cell was filled in 2017. This deposit was seeded and planted with a selection of native plant species in addition to wick drains to assess the potential for these installations to dewater and increase undrained shear strength in the deposit over multiple years. This deposit is discussed in greater detail in Chapter 2 of this thesis based on information from W. Smith et al. (2018). Additional information on the test cell is also published in Schoonmaker et al. (2021) and Abdulnabi et al. (2021)

Measurement of undrained shear strength in cohesive soils is conducted using some type of vane shear tool (VST). The majority of vanes generally have four blades of approximately 2mm in thickness, and have an area ratio (volume of soil displaced by the vane blades upon insertion to cylindrical volume of soil swept by vane when rotated) less than 10-12% (Contreras & Harvey, 2021). Generally, in-situ undrained shear strength is measured using either a field vane or a hand vane. Undrained shear strength of the soil (S_u or C_u) is measured by the VST using the relationship between applied torque (T_v) and undrained shear stress on the soil (C_u) which is a function of the vane geometry. This relationship is given by Equation 1, where h and d are the height and diameter of the rectangular vane respectively (Briaud, 2013).

$$T_v = C_u \pi \left(\frac{hd^2}{2} + \frac{d^3}{6} \right) \quad \textbf{(1)}$$

Field vanes (fVST or eVST) generally involve a piece of special equipment that mechanically rotates the vane to failure, collecting relevant data according to the procedure defined in ASTM Standard D2573/D2573-M18 (ASTM, 2018). Hand vanes (hVST) are comparatively simple instruments used by geo-science professionals to perform preliminary undrained shear strength measurements in the field. Due to the variety of equipment and the uncertainty introduced by the operator of such tools, no standard exists. Measurements are generally collected according to the procedure provided by the manufacturer of the instrument. VST's can be used to measure peak, residual, or remolded strength of the soil, but the work discussed below compares only peak measurements between instruments.

Procedure

Measurements of undrained shear strength in the test cell were collected by three instruments in 2018. These included two hVST's, and one custom-built automatic vane shear tool (aVST). The two hVST's included a Pilcon SL815, and a Geonor H-60. The Pilcon was operated by another geo-science professional while the author operated the Geonor H-60 (the same device used in the outdoor tote experiments in Chapter 3 and 4). The aVST was designed and built by a team at the University of Alberta working on developing autonomous equipment for access and investigation of tailings facilities containing very low-strength waste materials. Specifics on the development and design of the aVST used to collect the measurements described in the following section were published in Olmedo et al. (2020). The equipment was operated by the author based on instructions developed by the designers. These three instruments are shown in Table B-1.

Table B-1: List of select vane shear tools (VST) for in-situ measurement of undrained shear strength

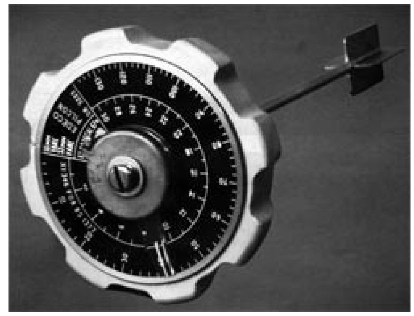
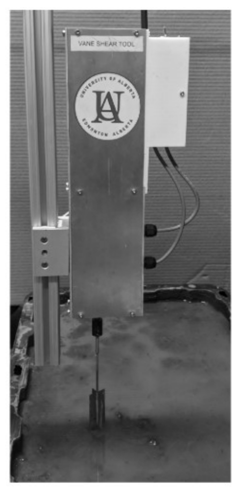
Pilcon SL815 hVST **(Impact Test Equipment Ltd., 2021)** *33 x 50 mm and 65 x 135 mm Diameter Vanes*	
Geonor H-60 hVST **(Geonor Inc., 2021)** *25.4 x 50.8 mm Vane*	
Custom aVST **(Olmedo et al., 2020)** *25.4 x 50.8 mm Vane*	

Figure B-1 is a photo showing the custom aVST and Geonor H-60 hVST as they were set up in the field for data collection.

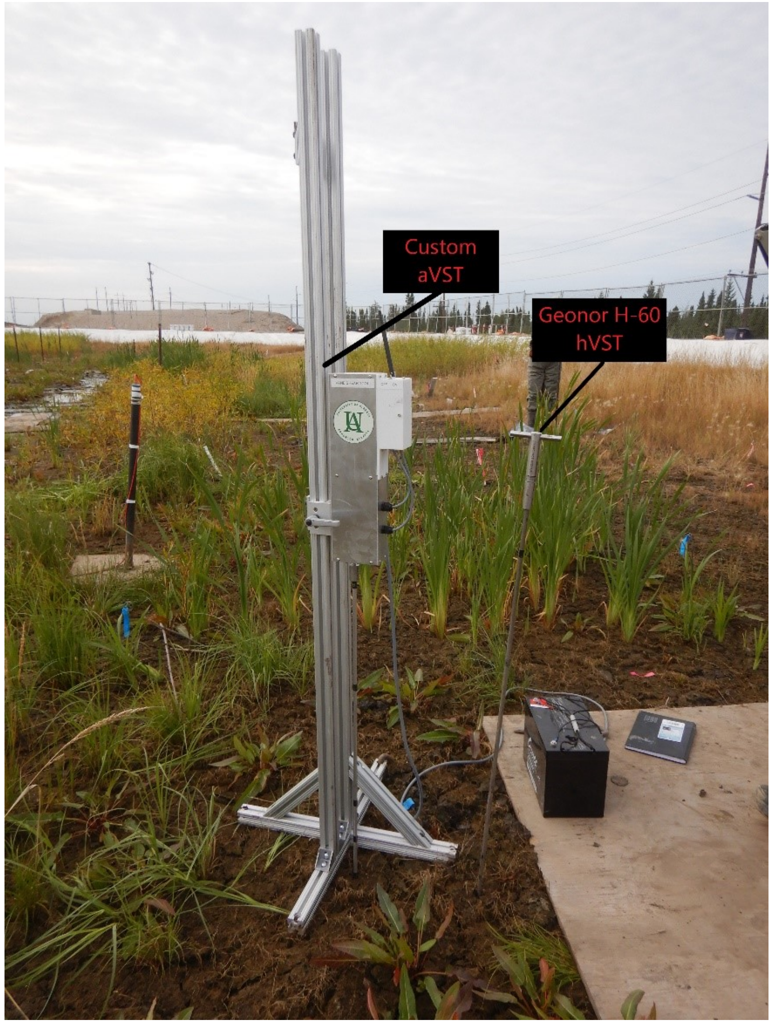


Figure B-1: Field photo of custom aVST and Geonor H-60 hVST at Albian test cell

As described previously, the procedure for operation of the hand vanes is generally provided by the equipment manufacturer. The general procedure involves inserting the vane to depth, and rotating at the desired speed, generally as slow as the operator can possibly achieve. After the soil fails, the maximum torque is read off the handle gauge and recorded. Some hand vanes allow the shear strength to be read directly off the gauge. The gauge is then reset to zero before pushing the vane to the next desired depth and repeating the process. An example of a detailed procedure of use of a hand vane shear tool is provided by the New Zealand Geotechnical Society (NZGS, 2001). The procedure for operating the aVST was relatively simple. The vane was inserted to a specified depth, and the motor was activated using a program provided by the aVST design team. The rotation and torque was presented visually on a computer screen, and rotation allowed to continue until the operator identified that peak strength had been reached. The recorded data was then saved and the vane pushed to the next depth of measurement before beginning the process again. Additional information on the operation of the aVST was published in (Olmedo et al., 2020).

Results

Peak undrained shear strength was collected with all three instruments described above in eight locations of the test cell. The measurements are presented in Figure B-2, Figure B-3, and Figure B-4 for the Pilcon, Geonor H-60, and Custom aVST respectively. Each figure shows a general trend of greater shear strengths measured at the surface of the deposit, generally the top 35 cm. Weaker material of less than 4 kPa was generally measured at depths below 45 cm where little strength gain was noted. The Pilcon and aVST had good agreement at these greater depths, generally measuring undrained peak shear strength of less than 2 kPa. However, the Geonor H-60 measured much higher shear strength values at these depths, ranging from less than 1 kPa up to approximately 6 kPa. Measurements in the top 30 cm were similar for all three instruments, ranging from 4 to 10 kPa, although the Geonor H-60 again had two locations where it measured significantly greater shear strengths than the Pilcon or aVST at approximately 7.5cm depth.

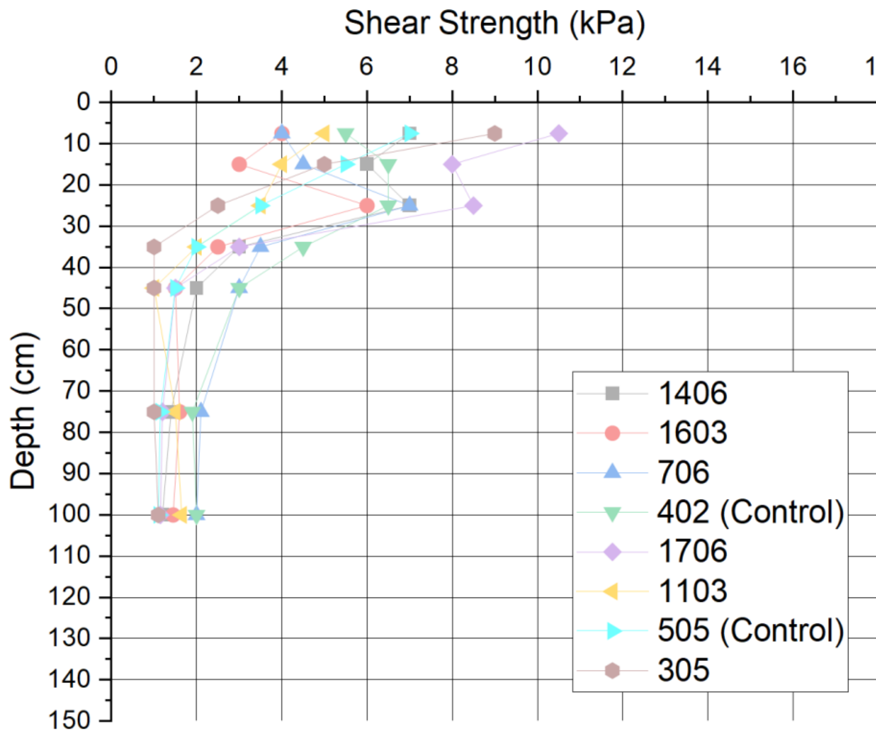


Figure B-2: Undrained Peak Shear Strength Measurements of CFFT - Pilcon SL815 hVST

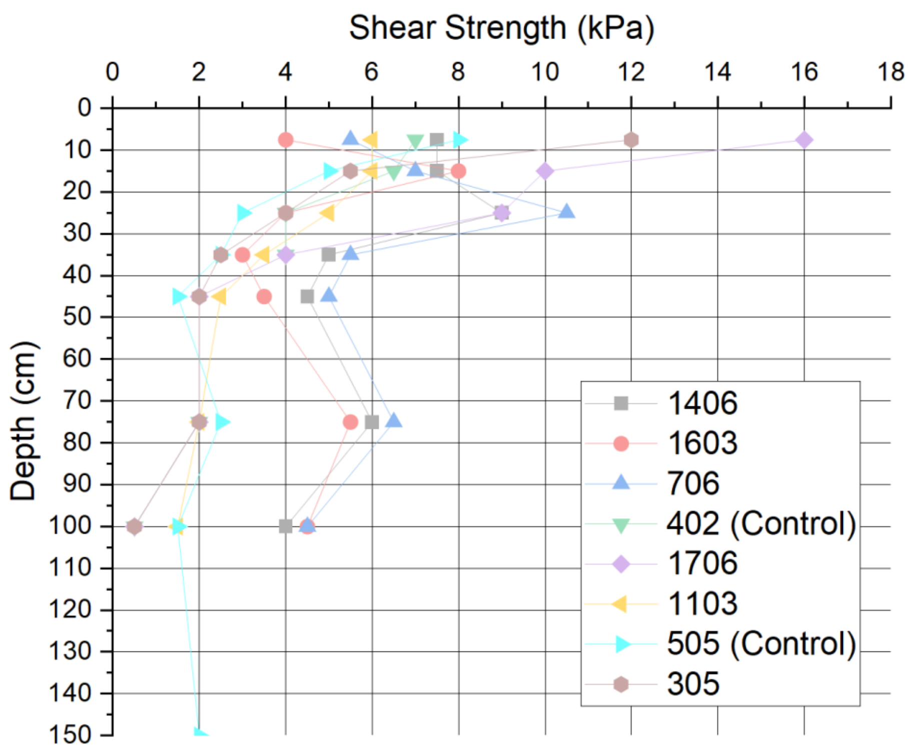


Figure B-3: Undrained Peak Shear Strength Measurement of CFFT - Geonor H-60 hVST

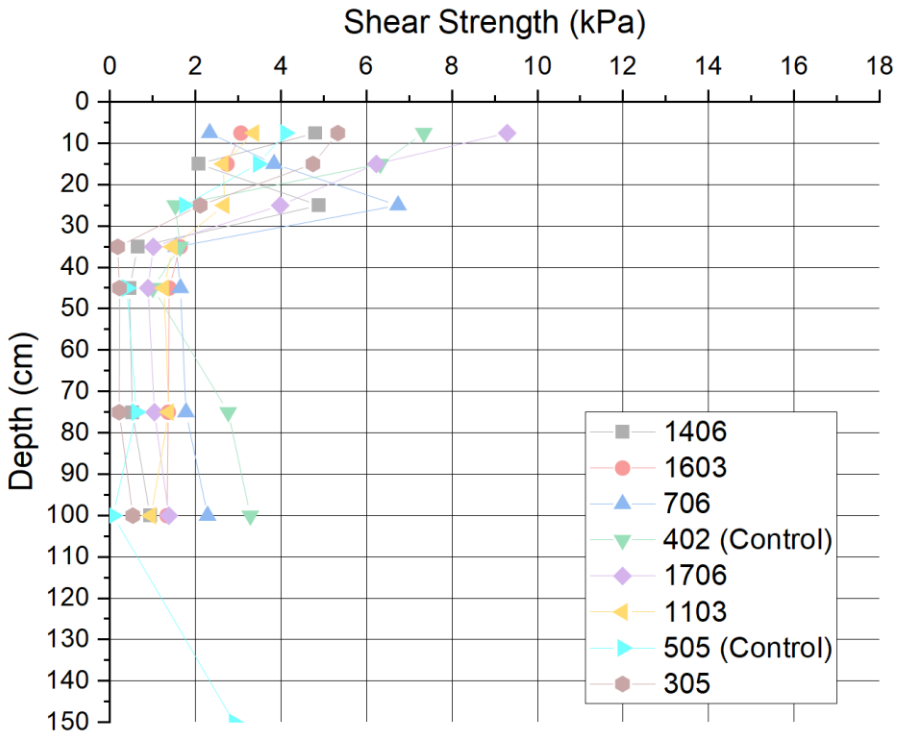


Figure B-4: Undrained Peak Shear Strength Measurements of CFFT - Custom aVST

To compare these results, the measurements collected by the Pilcon and the aVST were plotted against the measurements taken using the Geonor H-60 at the same depths to allow identification of any significant trends in the results. This comparison is presented in Figure B-5.

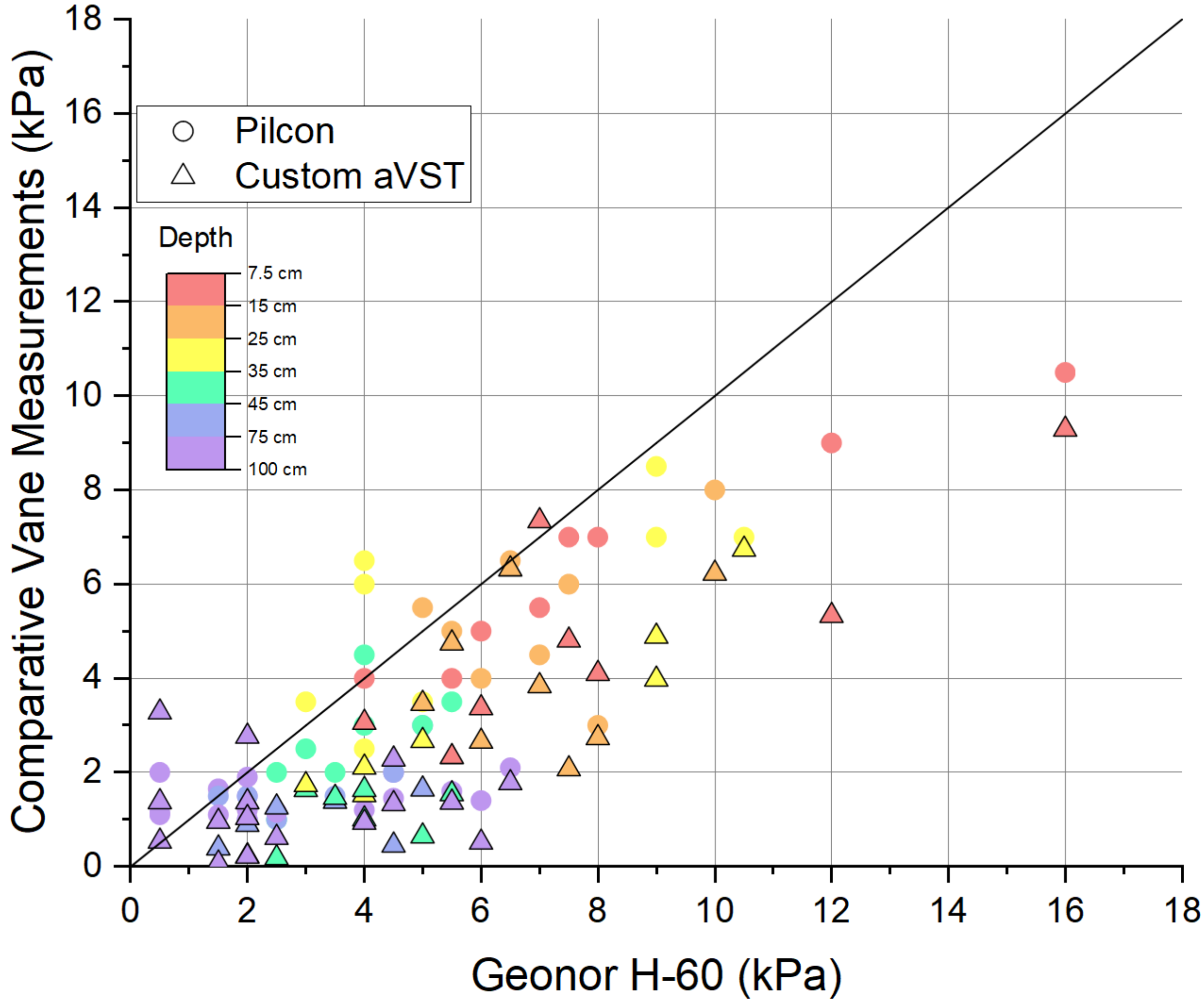


Figure B-5: Comparative Vane Measurements of Undrained Peak Shear Strength from Different VSTs in a Deposit of CFFT

This figure demonstrates that, overall, the Geonor H-60 measured higher shear strengths than either the Pilcon or the aVST. These higher measurement values were the most pronounced in the measurements collected deeper in the deposits (45-100cm depth) where shear strengths were the lowest (~1-2 kPa as measured by the Pilcon and aVST). Agreement between the tools was best in the top 35 cm of the deposit. Agreement was generally better between the Pilcon measurements, and those collected by the aVST. A comparison of these two vane measurements is presented in Figure B-6.

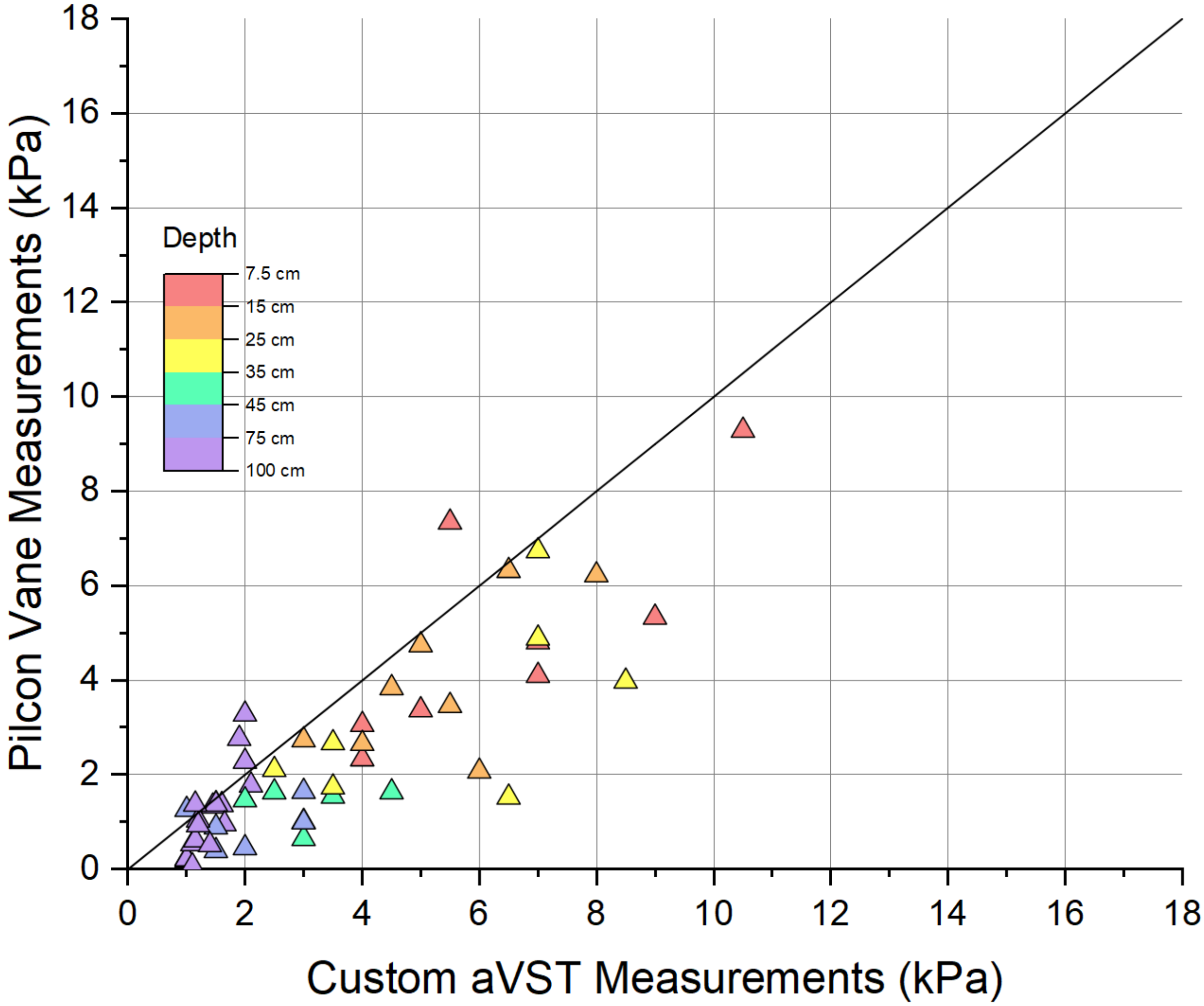


Figure B-6: Comparative Vane Measurements of Undrained Peak Shear Strength from a Custom aVST and Pilcon hVST

It is important to note when comparing these results, that the vane geometry was not the same for all three instruments. The Pilcon hVST differed from the vane used for both the Geonor H-60, and the custom aVST, both of which used the same 50.8 x 25.4 mm vane. The Pilcon used a 33 x 50 mm vane for measurements down to 45 cm depth, and a custom-machined 65 x 135 mm vane for measurements at 75 and 100 cm.

Conclusions

These results demonstrate the potential variability in measurement of undrained shear strength in cohesive soils using different instruments. These measurements can be impacted by several factors including location of measurement, the instrument used, and the operator of the equipment. Based on these results, several high-level conclusions can be drawn:

Hand vanes are excellent tools for preliminary investigation of in-situ shear strength of cohesive soils. They are easy to transport to location, can be operated by a single person by hand, and can complete a single measurement in a matter of minutes. However, these instruments have potential to overestimate the undrained shear strength of the cohesive soil, and accuracy is heavily dependent on the experience of the operator collecting the measurements, and their ability to manually apply a constant rate of rotation of the vane. There is also potential for variance in measurements because of the procedure used. Each instrument may have a different procedure as recommended by the instrument manufacturer, or the operator may use some other standard provided by another geo-science professional. For the data discussed above, the Pilcon and Geonor H-60 operators used nearly identical procedures, but the Pilcon operator was significantly more experienced than the Geonor H-60 operator. The measurement dial on the Pilcon is also generally better for readings in very low-strength materials due to a greater resolution in the dial. This likely contributed significantly to the comparatively higher shear strengths measured by the Geonor H-60 in the softer material deeper in the deposit. The vane size also can contribute to the accuracy of the instrument, with larger vanes more advantageous in very soft soils such as the material deeper in the test cell deposit. A larger vane size will produce a larger torque measurement that a smaller vane in a material with the same undrained shear strength. These greater torque measurements make it easier to measure shear strength at greater depth, and reduce the likelihood of over-estimating the shear strength in very soft soils such as fines-dominated oil sands tailings.

The custom aVST, which was used to measure undrained shear strength according to ASTM D2573 (ASTM, 2018). This much slower, and more controlled rate of rotation, and constant application of torque results in more accurate measurements of shear strength. Unfortunately, this equipment is less mobile than a hand vane, and therefore poses challenges for set up due to accessing these deposits to perform testing. In addition to initial set up, collection of measurements takes significantly longer, as rotation was set to 7 degrees per minute. This resulted in each measurement taking approximately 1-3 hours to reach a confirmed peak. Part of this time was due to limitations with the interface of the aVST which required visual identification that the residual strength had been reached. This generally meant additional time after peak strength had been reached to collect the required data. The field vanes used by deposit investigation companies generally can collect these measurements much faster.

Finally, this data demonstrates that accuracy for a tightly-controlled piece of equipment such as a field vane or the custom aVST used in this trial is likely higher than that which can be achieved with a hand vane. But hand vanes offer flexibility, ease of use, and quick results, and are therefore advantageous in situations where measurements need to be collected in a quick, cost-effective manner.

References

Abdulnabi, A., Paul, A., Beier, N., Laberge, S., Schoonmaker, A., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 2 key geotechnical performance indicators*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

ASTM. (2018). D2573M / D2573-M18, Standard Test Method for FIeld Vane Shear Test in Saturated Fine-Grained Soils. In. West Conshohocken, PA: ASTM International.

Briaud, J. (2013). *Geotechnical Engineering: Unsaturated and Saturated Soils* (1 ed.): John Wiley & Sons, Incorporated.

Contreras, I., & Harvey, J. (2021). *The role of the vane shear test in mine tailings*. Paper presented at the Tailings and Mine Waste, Banff, AB.

Geonor Inc. (2021). H-60 Hand-Held Vane Tester. Retrieved from https://geonor.com/live/products/geotechnical-test-equipment/h-60-hand-held-vane-tester/

Impact Test Equipment Ltd. (2021). Pilcon Hand Vane Tester - SL815 User Guide. Retrieved from https://www.impact-test.co.uk/docs/SL815_HB.pdf

NZGS. (2001). Guideline for hand held shear vane test. https://fl-nzgs-media.s3.amazonaws.com/uploads/2016/06/Hand-held-shear-vane-test-2001.pdf

Olmedo, N. A., Fisseha, B., Wilson, W., Barczyk, M., Zhang, H., & Lipsett, M. G. (2020). An automated vane shear tool for environmental monitoring with unmanned ground vehicles. *Journal of Terramechanics, 91*, 53-63. doi:https://doi.org/10.1016/j.jterra.2020.05.003

Schoonmaker, A., Chigbo, C., Walton-Sather, S., Abdulnabi, A., Beier, N., Laberge, S., & Smith, W. (2021). *Plant growth on oil sands tailings from the bench-scale to a field pilot: Part 1 plant development patterns*. Paper presented at the Tailings and Mine Waste, Banff, Alberta, Canada.

Smith, W., Olauson, E., Seto, J., Schoonmaker, A., Moussavi Nik, R., Freeman, G., & McKenna, G. (2018). *Evaluation of Strength Enhancement and Dewatering Technologies for a Soft Oil Sands Tailings Deposit*. Paper presented at the International Oil Sands Tailings Conference (IOSTC), Edmonton, AB, Canada.