“Never, never, never, give up”
-Winston Churchill

“Done!”
-Simon Theodore Miller

University of Alberta

COMPARISON OF GEOENVIRONMENTAL PROPERTIES OF CAUSTIC AND NONCAUSTIC OIL SAND FINE TAILINGS

by

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A thesis submitted to the Faculty of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

in

GEOENVIRONMENTAL ENGINEERING

DEPARTMENT OF CIVIL AND ENVIRONMENTAL ENGINEERING

Fall, 2010

Edmonton, Alberta

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For my Mom and Dad, who laid the foundation and opened every door of opportunity,

For my brother, who trod the path and found the advertisement that meant so much,

For my wife, who lent her knowledge, support and remarkable patience over a long and winding road,

For my son, whose smile supplied limitless optimism, cheerfulness and perspective over the final steps of the journey.

ABSTRACT

A study was conducted to evaluate the properties and processes influencing the rate and magnitude of volume decrease and strength gain for oil sand fine tailings resulting from a change in bitumen extraction process (caustic versus non-caustic) and the effect of adding a coagulant to caustic fine tailings.

Laboratory flume deposition tests were carried out with the objective to hydraulically deposit oil sand tailings and compare the effects of extraction processes on the nature of beach deposits in terms of geometry, particle size distribution, and density. A good correlation exists between flume deposition tests results using oil sand tailings and the various other tailings materials. These comparisons show the reliability and effectiveness of flume deposition tests in terms of establishing general relationships and can serve as a guide to predict beach slopes.

Fine tailings were collected from the various flume tests and a comprehensive description of physical and chemical characteristics of the different fine tailings was carried out. The characteristics of the fine tailings is presented in terms of index properties, mineralogy, specific surface area, water chemistry, liquid limits, particle size distribution and structure. The influence of these fundamental properties on the compressibility, hydraulic conductivity and shear strength properties of the fine tailings was assessed. Fourteen two meter and one meter high standpipe tests were instrumented to monitor the rate and magnitude of self-weight consolidation of the different fine tailings materials. Consolidation tests using slurry consolidometers were carried out to determine consolidation properties, namely compressibility and hydraulic conductivity, as well as the effect of adding a coagulant (calcium sulphate

[$CaSO_4$]) to caustic fine tailings. The thixotropic strength of the fine tailings was examined by measuring shear strength over time using a vane shear apparatus.

A difference in water chemistry during bitumen extraction was concluded to be the cause of substantial differences in particle size distributions and degree of dispersion of the comparable caustic and non-caustic fine tailings. The degree of dispersion was consistent with predictions for dispersed clays established by the sodium adsorption ratio (SAR) values for these materials. The biggest advantage of non-caustic fine tailings and treating caustic fine tailings with coagulant is an increased initial settlement rate and slightly increased hydraulic conductivity at higher void ratios. Thereafter, compressibility and hydraulic conductivity are governed by effective stress. The chemical characteristics of fine tailings (water chemistry, degree of dispersion) do not have a significant impact on their compressibility behaviour and have only a small influence at high void ratio (low effective stress). Fine tailings from a caustic based extraction process had relatively higher shear strengths than comparable non-caustic fine tailings at equivalent void ratios. However, shear strength differences were small and the overall impact on consolidation behaviour, which also depends on compressibility and hydraulic conductivity, is not expected to be significant.

ACKNOWLEDGEMENTS

The author would like to sincerely thank his supervisors, Dr. J. Don Scott and Dr. Dave C. Sego, for their guidance, encouragement, and support over the years of this research program and their understanding of the challenges faced along the way.

The unfailing help and contributions of Gilbert Wong for all his long hours in the lab without a word of complaint is gratefully acknowledged. Appreciation is also extended to the invaluable assistance and skills of Steve Gamble, Christine Hereygers and Gerry Cyre over the years.

Thank you to the members of Fine Tailings Fundamentals Consortium for providing funding, tailings materials, and reports and data relevant to the research work.

The author would also like to acknowledge the financial assistance provided by Dr. Scott and the University of Alberta.

Thank you to my parents who ensured that any opportunities pursued were met with encouragement and enthusiasm, and my brother for starting all this and his help along the way.

Finally, the author wishes to thank his wife for her unwavering support, encouragement and patience throughout.

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1. Introduction

1.1 Statement of Problem

In the oil sands industry, high temperature and addition of a caustic dispersing agent have formed the basis of the Clark Hot Water Extraction process used successfully on a commercial scale to recover bitumen from surface mined oil sands ore since 1967. Descriptions of the present day extraction and froth treatment process are provided by Cymerman and Kwong (1995); Shaw, Czarnecki, Schramm and Axelson (1994); and Shaw, Schramm and Czarnecki (1996). However, the Clark process results in the creation of extremely dispersed, high void ratio fine tailings composed primarily of silt, clay, water and residual bitumen. These caustic based fine tailings exhibit low consolidation rates and shear strengths and require considerable real estate for storage. Presently approximately 750 Mm^3 of fine tailings is being stored in tailings ponds. The conventional method for fine tailings management is a containment strategy of the fine tailings in ponds for sedimentation, consolidation, and eventually land reclamation. However, the vast quantities and slow consolidation of fine tailings raises environmental and economic questions regarding possible improvements in tailings behaviour.

Processes different from the established Clark process (high temperature and caustic) have been developed to work at a range of temperatures with or without the use of sodium hydroxide (Kasperski, 2001). One such process is the OSLO Hot Water Extraction process (Sury, Paul, Dereniwski and Schulz, 1993), a non-caustic bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the hope of improved consolidation and strength properties of the fine tailings (OSLO is an acronym for Other Six Lease Owners, the consortium of companies that piloted the process)[1]. A potential reduction in fine tailings volume and improved geoenvironmental behaviour provided an environmental and economic incentive to examine the relative differences between the properties that influence sedimentation and consolidation of the fine tailings derived from these extraction processes.

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[1] OSLO consortium: Alberta Oil Sands Equity, Canadian Occidental Petroleum Ltd., Gulf Canada Resources Limited, Petro-Canada Inc., Imperial Oil Resources Limited, Pan Canadian Petroleum Ltd.

During 1993, a joint program was initiated by Syncrude, Suncor and OSLO to test the OSLO Hot Water Extraction and the Clark Hot Water Extraction processes and compare the properties of the tailings produced. This thesis investigated the geoenvironmental engineering properties of the fine tails and the beach deposits derived from the two extraction processes. Numerous chemical and physical aspects of the tailings were examined separately by other members of the Fine Tailings Fundamentals Consortium [2]. Incorporation of these physical and chemical processes with the geotechnical engineering properties resulted in a full understanding of the behaviour of the fine tailings from a geoenvironmental perspective. Pilot plant extraction tests were carried out using Syncrude's 2 tonne per hour extraction pilot plant. Two bulk samples of oil sands, about 80 tonnes each, were obtained for the test program, one from the Syncrude mine and the other from the Suncor mine. Extraction runs were carried out during October and November 1993.

Geotechnical laboratory tests on the fine tailings runoff from the extraction tests were carried out from 1994 to 2000 including long term large strain consolidation tests and standpipe tests. Initial laboratory test results were reported to the Fine Tailings Fundamental Consortium in 1994 to 1996 and published in FTFC, 1995a, 1995b and 1995c. Complete analyses of all the laboratory tests were carried out in subsequent years and form this thesis.

1.2 Objectives of Research Program

Geoenvironmental engineering incorporates elements of geotechnical engineering, soil chemistry and the environmental sciences. Valuable insights regarding the behaviour of the fine tailings can be drawn from each of these domains to arrive at an understanding of the behaviour of the fine tailings from a geoenvironmental perspective.

The overall objective of this thesis is to evaluate the properties and processes influencing the rate and magnitude of volume decrease and strength gain for the

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[2] The Fine Tailings Fundamentals Consortium: Alberta Oil Sands Technology and Research Authority, Alberta Energy, Alberta Research Council, Energy Mines and Resources Canada (CANMET), Environment Canada, National Research Council of Canada, OSLO, Syncrude Canada Ltd., Suncor Inc.

tailings resulting from a change in bitumen extraction process (caustic versus non-caustic) and the effect of adding a coagulant to caustic fine tailings. Specific objectives include:

- Study the influence of the extraction process on the characteristics of deposits formed by hydraulically deposited oil sands tailings.
- Compare the results of flume deposition tests using caustic and non-caustic oil sand tailings with the results of numerous other flume tests summarized in the literature using a variety of other tailings material and covering a wide range of slurry concentrations and flow rates.
- Assess the influence of the caustic and non-caustic extraction process on the physical and chemical characteristics of the fine tailings in terms of index properties, mineralogy, specific surface area, water chemistry, Atterberg limits, particle size distribution, and morphology.
- Study the self-weight consolidation behaviour of the caustic and non-caustic fine tailings using large-scale equipment to model tailings pond conditions.
- Determine the compressibility and hydraulic conductivity characteristics of the fine tailings over a range of effective stresses.
- Study the thixotropic strength development of the fine tailings.
- Assess the compressibility, hydraulic conductivity and strength properties of the different fine tailings with regard to differences in physical and chemical characteristics and provide conclusions on which factors (if any) can be expected to control the rate and magnitude of volume decrease.

1.3 Scope of Thesis

For this research program seven different fine tailings derived from two types of oil sands ore were studied. The seven different fine tailings and their descriptions are summarized in Table 1.1. For each type of oil sands ore, one caustic and one non-caustic based fine tailings were investigated. Additionally, one non-caustic process using untreated river water and caustic tailings modified by the addition of 600 ppm of calcium sulphate were studied. The addition of calcium sulphate was proposed to improve the settling behaviour by causing the aggregation of clay particles.

Laboratory tests carried out and the subsequent analyses for the various fine tailings included within the scope of this thesis are summarized below:

- Flume deposition tests using tailings from both the caustic and non-caustic extraction processes;
- Physical and chemical characterization of the fine tailings derived from the flume deposition tests;
- Large-scale self-weight consolidation tests using two meter and one meter high standpipes;
- Consolidation tests using slurry consolidometers to determine compressibility and hydraulic conductivity properties of the fine tailings under applied loads; and
- Strength measurements of fine tailings to assess gain in thixotropic strength with time.

The scope of the major components of the thesis research program are described in greater detail below.

1.3.1 Flume Deposition Tests

The flume deposition tests were used as a convenient tool to study the behavior and characteristics of the oil sand tailings resulting from the deposition and beaching processes. Under laboratory conditions it is possible to control and isolate variables in a simpler and more economic manner than would be possible under field conditions.

The objective of the flume deposition tests was to hydraulically deposit oil sand tailings in order to compare the effect of the caustic (Clark) and the non-caustic (OSLO) extraction processes on the nature of the beach deposits in terms of geometry, grain size distribution, and density. In addition, the tests provided flume fine tailings runoff for subsequent testing of the geotechnical properties of the fine tailings. The characteristics of the beaches created in the flume were compared to other flume tests evaluated on a variety of tailings materials. These comparisons can be used as a guide to predict the characteristics of beaches formed in the field.

1.3.2 Characterization of Caustic and Non-Caustic Fine Tailings

A comprehensive description of the physical and chemical characteristics of the fine tailings was required to determine how the caustic and non-caustic fine tailings differ and subsequently how these fundamental properties influence the rate and magnitude of volume decrease, compressibility, hydraulic conductivity, and shear strength properties of the fine tailings. The characteristics of the fine tailings was assessed in terms of index properties, mineralogy, specific surface area, water chemistry, Atterberg limits, particle size distribution, and morphology. The differences in the fine tailings result from the type of bitumen extraction process (caustic vs. non-caustic), the choice of process water (treated vs. untreated), subsequent chemical additions to the fine tailings (caustic vs. caustic plus coagulant), and oil sand ore (Ore A vs. Ore B). The various fine tailings were evaluated based on their fundamental properties to explain differences in the engineering behaviour.

1.3.3 Self-Weight Consolidation Tests

Compressibility relationships are engineering properties that will influence the long term disposal of the fine tailings. Self-weight consolidation tests using standpipes up to 2 m high were carried out to determine the consolidation properties for the fine tailings. The consolidation in standpipes takes a relatively short period of time and stress levels reached, although small, are significant. Self-weight consolidation tests using standpipes are also advantageous because of the ease of data collection and costs, relative to field scale tests, and they model the consolidation process in tailings ponds.

The objective of the self-weight consolidation tests was to determine the influence of a change of extraction process on the rate of pore pressure dissipation (consolidation during self-weight), and the rate and magnitude of self-weight consolidation. The effect of adding a coagulant to caustic based fine tailings in terms of self-weight consolidation was also examined. Any differences in the self-weight consolidation properties between the fine tailings was explained based on the physical and chemical characteristics of the source materials.

1.3.4 Compressibility and Permeability from Consolidation Tests

Compressibility and hydraulic conductivity relationships with void ratio are engineering properties that will influence the long-term disposal of the fine tailings. These input parameters are used in large strain consolidation analyses of a storage pond to predict water release rates and changes to surface elevations that impact storage volumes and elevation of reclamation surfaces. Consolidation tests were carried out to determine these properties for the fine tailings tested. The objective of these tests was to determine the influence of a change in extraction process on the consolidation properties; compressibility and hydraulic conductivity. The effect of adding a coagulant to caustic fine tailings was also determined. Any differences in the compressibility and hydraulic conductivity properties between the fine tailings were explained based on the physical and chemical characteristics of the materials.

The consolidation tests were performed using slurry consolidometers. This type of test allows a wide range of effective stresses to be applied to the fine tailings and direct hydraulic conductivity measurements can be carried out for each effective stress.

1.3.5 Thixotropic Gain in Strength

One material property that affects the rate and magnitude of initial consolidation or settlement of oil sands fine tailings is the rapid thixotropic strength gain of the material. This thixotropic strength of fine tailings at large void ratios or low solids contents manifests itself as a bonding or gel strength which has been widely noted both in the laboratory and in the field. Development of thixotropic shear strength at large void ratios results in an overconsolidation stress which must be overcome for consolidation to take place, therefore the smaller the thixotropic strength the greater is the initial settlement. Shear strength tests were carried out to determine the overall shear strength and thixotropic gain in strength of the fine tailings. The objective of the research reported in this thesis was to determine the influence of a change of extraction process on the thixotropic strength properties of the fine tailings. The effect of adding a coagulant to caustic based fine tailings was also determined. Any differences in the thixotropic strength properties between the fine tailings was explained based on the physical and chemical characteristics of the materials.

1.4 Organization of Thesis

A description of the experimental testing, analysis, discussion, and conclusions for each of the major components of the research program are provided in the following chapters.

Flume deposition tests are described in Chapter 2. This chapter presents the flume deposition equipment and experimental procedures, the tailings materials, and the test results for the flume deposition tests.

Physical and chemical characteristics of the caustic and non-caustic fine tailings examined during the research program are summarized in Chapter 3. This includes details of testing methodology, discussion and conclusions of test results.

Chapter 4 describes the self-weight consolidation tests. The experimental equipment, specifically two meter and one meter high standpipes, and testing procedures are described and test results in terms of pore pressure dissipation, and the rate and magnitude of self-weight consolidation.

The compressibility and hydraulic conductivity and factors affecting each of these properties for the fine tailings are described in Chapter 5. The compressibilities and hydraulic conductivities of the caustic and non-caustic fine tailings are presented and discussed.

Chapter 6 explains the thixotropic behaviour of the fine tailings based on vane shear test results. The vane shear test results are compared with test results from previous research.

The final chapter summarizes the conclusions regarding the engineering properties of the caustic and non-caustic fine tailings that were discussed in the previous chapters. Recommendations for future research are also given in Chapter 7.

This thesis is presented in the "paper-format" style. Chapters 2 to 6 have previously been published in peer-reviewed journals or have been accepted for publication. References for these journal papers are provided in Section 1.5. As well, research works associated with this thesis program generated contributions to books and numerous reports and presentations which are also provided for reference in Section 1.6.

1.5 Publications, Reports and Presentations Related to Thesis Research

The following is a summary of publications, reports and presentations that have been prepared and submitted to various journals, conferences and organizations related to the research carried out for this thesis program.

1.5.1 Peer Reviewed Journals

Canadian Geotechnical Journal

Miller, W.G., Scott, J.D., & Sego, D.C. 2009. Flume Deposition Modeling of Caustic and Noncaustic Oil Sand Tailings. Canadian Geotechnical Journal, 46, 679-693.

Canadian Institute of Mining, Metallurgy and Petroleum Journal

Miller, W.G, Scott, J.D., & Sego, D.C. 2010. Influence of the Extraction Process on the Characteristics of Oil Sands Fine Tailings. CIM Journal, Vol. 1, No. 2, 93-112.

Miller, W.G, Scott, J.D., & Sego, D.C. 2010. Effect of Extraction Water Chemistry on the Consolidation of Oil Sands Fine Tailings. CIM Journal, Vol. 1, No. 2, 113-129.

Miller, W.G, Scott, J.D., & Sego, D.C. 2010. Influence of Extraction Process and Coagulant Addition on Thixotropic Strength of Oil Sands Fine Tailings. CIM Journal, Accepted for publication in: Vol. 1, No. 3, pg. pending.

Miller, W.G, Scott, J.D., & Sego, D.C. 2010. Effect of Extraction Water Chemistry on the Self-Weight Consolidation of Oil Sands Fine Tailings. CIM Journal, Accepted for publication in: Vol. 1, No. 4, pg. pending.

1.5.2 Contributions to Books

Scott, J.D. and Miller, W.G., 1995. Vol. I, Chapter 5, Geotechnical Properties of Mature Fine Tailings (MFT). In: Advances in Oil Sands Tailings Research, Fine Tailings Fundamentals Consortium, Alberta Department of Energy, Oil Sands and Research Division, Publisher, pp. 79-83.

Scott, J.D. and Miller, W.G., 1995. Vol. III, Chapter 3, Volume Reduction of Clark Hot Water Extraction Fine Tailings Utilizing Nonsegregating Tailings. In: Advances in Oil Sands Tailings Research, Fine Tailings Fundamentals Consortium, Alberta Department of Energy, Oil Sands and Research Division, Publisher, pp. 15-26.

Miller, W.G. and Scott, J.D., 1995, Vol. IV, Chapter 4.2, Geotechnical Aspects of Oslo Process Fine Tails, In: Advances in Oil Sands Tailings Research, Fine Tailings Fundamentals Consortium, Alberta Department of Energy, Oil Sands and Research Division, Publisher, pp. 48- 59.

1.5.3 Research Reports to the Fine Tailings Fundamentals Consortium

Scott, J.D., Sego, D.C., Miller, W.G. and Mazurek, K.A. 1994. Comparison of OHWE/CHWE Tailings, Flume Tests and Geotechnical Testing of Fine Tails. June, 18p.

Miller, W.G., Scott, J.D. and Sego, D.C. 1995. OHWE/CHWE Tailings Flume Tests, Final Report, January, 145p.

Mazurek, K.A., Scott, J.D., Sego, D.C. and Miller, W.G. 1995. OHWE/CHWE Fine Tailings Research Program: Accelerated Testing Program, Settlement and Consolidation of Fine Tails. January, 72p.

Miller, W.G., Scott, J.D. and Sego, D.C. 1995. OHWE/CHWE Fine Tailings Research Program, Geotechnical Properties Progress Report. March, 40p.

Miller, W.G., Scott, J.D. and Sego, D.C. 1995. Geotechnical Aspects of Oslo Process Fine Tails. May, 24p.

Mazurek, K.A., Scott, J.D., Sego, D.C. and Miller, W.G. 1995. OHWE/CHWE Fine Tailings Research Program: Hydraulic Conductivity of OHWE/CHWE Fine Tails. May, 23p.

Miller, W.G., Scott, J.D. and Sego, D.C. 1996. Comparison of Settling Behavior of Tails with Addition of Calcium Sulphate. April, 18p.

Miller, W.G. 1996. Geoenvironmental Behavior of Tailings from Two Oil Sand Extraction Processes. March, 16p.

Miller, Warren G., 2000, Laboratory Modelling of Oil Sands Tailings Disposal. Department of Civil and Environmental Engineering Report, University of Alberta, 28 p.

Miller, Warren G., 2000, Testing Procedures and Results of Flume Deposition Test, Appendix to Laboratory Modelling of Oil Sands Tailings Disposal. Department of Civil and Environmental Engineering, University of Alberta, 31 p.

Miller, Warren G., 2005, Physical and Chemical Characteristics of OHWE and CHWE Fine Tailings. Department of Civil and Environmental Engineering Report, University of Alberta, 52 p.

Miller, Warren G., 2005, Particle Size Distributions Determined by Hydrometer Tests, Appendix to Physical and Chemical Characteristics of OHWE and CHWE Fine Tailings. Department of Civil and Environmental Engineering, University of Alberta, 3 p.

1.5.4 Presentations

<u>Conferences</u>

Miller, W.G., Scott, J.D. and Sego, D.C., 1995. Geotechnical Aspects of Oslo Process Fine Tails. Poster presentation. Society of Petroleum Engineers International Heavy Oil Symposium: Heavy Oil, Oil Sands, Thermal Operations, Calgary, AB, June 19-21.

Fine Tails Fundamentals Consortium

Miller, W.G., Scott, J.D. and Sego, D.C., 1994. Presentation Contents: Beach deposit characteristics; summary of flume test results, and fine tailings dewatering status. Location: Alberta Research Council, Clover Bar Facility, Edmonton, Alberta, January.

Miller, W.G., Scott, J.D. and Sego, D.C., 1994. Presentation Contents: Two meter standpipe settlement; combined tailings composition; flume tests summary; hydrometer test program; and dispersive and nondispersive grain size distributions. Location: Alberta Research Council, Clover Bar Facility, Edmonton, Alberta, June.

Miller, W.G., Scott, J.D. and Sego, D.C., 1994. Presentation Contents: Overall project status report; preliminary vane shear results; and Atterberg limits of fine tails. Location: AOSTRA offices, Edmonton, Alberta, September.

Miller, W.G., Scott, J.D. and Sego, D.C., 1994. Presentation Contents: Update on two meter standpipe settlement; combined tailings grain size distribution; and gain in thixotropic strength results (vane and cavity expansion). Location: Alberta Research Council, Millwoods Facility, Edmonton, Alberta, December.

Miller, W.G., Scott, J.D. and Sego, D.C., 1995. Presentation Contents: Comparison of settling behavior of tails with addition of calcium sulphate. Location: Syncrude Research, Millwoods Facility, Edmonton, Alberta, December.

1.6 References

Cymerman, G.J. & Kwong, T. Improvements in the oil recovery flotation process at Syncrude Canada Ltd. 1995. In J.S. Laskowski & G.W. Poling (Eds.), Processing of Hydrophobic Minerals and Fine Coals: Proceedings of the 1st UBC-McGill Bi-Annual International Symposium on Fundamentals of Mineral Processing (pp. 319-328). Vancouver: Canadian Institute of Mining, Metallurgy and Petroleum.

FTFC (Fine Tailings Fundamentals Consortium). (1995b). "Vol. IV, Non-Clark Extraction Processes and Their Tailings Characteristics, Section 3.2". In: Advances in Oil Sands Tailings Research, Alberta Department of Energy, Oil Sands and Research Division, Publisher.

FTFC (Fine Tailings Fundamentals Consortium). (1995b). "Vol. I, Clark Hot Water Extraction Fine Tailings, Section 4.10". In: Advances in Oil Sands Tailings Research, Alberta Department of Energy, Oil Sands and Research Division, Publisher.

FTFC (Fine Tailings Fundamentals Consortium). (1995c). "Vol. III, Volume Reduction of Clark Hot Water Extraction Fine Tailings, Section 2.0". In: Advances in Oil Sands Tailings Research, Alberta Department of Energy, Oil Sands and Research Division, Publisher.

Kasperski, K. (2001). Review of research on aqueous extraction of bitumen from mined oil sands. In Division Report CWRC 01-17 (CF). CANMET-WRC, Natural Resources Canada.

Shaw, R.C., Czarnecki, J., Schramm, L.L., & Axelson, D. (1994). Bituminous froths in the hot-water flotation process. In L.L. Schramm (Ed.), Foams: Fundamentals and Applications in the Petroleum Industry (pp. 423-459). Washington, D.C.: Elsevier.

Shaw, R.C., Schramm, L.L., & Czarnecki, J. (1996). Suspensions in the hot water flotation process for Canadian oil sands. In L.L. Schramm (Ed.), Suspensions. Fundamentals and Applications in the Petroleum Industry (pp. 639-675). Washington, D.C.: American Chemical Society.

Sury, K.N., Paul, R., Dereniwski, T.M., & Schulz, D.G. 1993. Next generation oilsands technology: the new OSLO processes. In Oil Sands Conference Proceedings (pp 1-36). Edmonton: Alberta Chamber of Resources, AOSTRA, EMR Canada.

Table 1.1 Fine tailings materials included in research program.

Fine Tailings Type	Ore Designation	Ore Description (using Syncrude Geologic Facies Chart)	Extraction Process	Process Water	Coagulant Addition
1	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	None
2	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Treated Athabasca River water	None
3	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
4	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	None
5	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Non-caustic	Treated Athabasca River water	None
6	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
7	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Untreated Athabasca River water	None

CHAPTER 2. FLUME DEPOSITION MODELING OF CAUSTIC AND NONCAUSTIC OIL SAND TAILINGS

This paper was previously reviewed, accepted and published in Canadian Geotechnical Journal. It is presented as published as part of this Ph.D. thesis as Chapter 2.

Reference: Miller, W.G., Scott, J.D., & Sego, D.C. (2009). Flume deposition modeling of caustic and noncaustic oil sand tailings. *Canadian Geotechnical Journal, 46, 679-693*.

Page Numbering:

Canadian Geotechnical Journal: 679 to 693 (top right)

This thesis: 14 to 28 (bottom center)

Flume deposition modeling of caustic and noncaustic oil sand tailings

W.G. Miller, J.D. Scott, and D.C. Sego

Abstract: As part of an overall study to evaluate the properties and processes influencing the rate and magnitude of consolidation for oil sand tailings produced using different extraction processes, laboratory flume deposition tests were carried out with the objective to hydraulically deposit oil sand tailings and compare the effects of caustic and noncaustic extraction processes on the nature of beach deposits in terms of geometry, grain-size distribution, and density. The characteristics of the beaches from this research study were compared with other flume deposition test results performed using a variety of tailings materials. A good correlation exists between flume deposition test results using oil sand tailings and the various other tailings materials, especially those with appreciable fines contents with respect to parameters that govern beach slope. These comparisons show the reliability and effectiveness of flume deposition tests in terms of establishing general relationships and can serve as a guide to predict beach slopes.

Key words: oil sands, fine tailings, hydraulic deposition, flume tests, beach slope, flow rate, slurry concentration.

Résumé : Une étude globale visant à évaluer les propriétés et les procédés qui influencent le taux et la magnitude de la consolidation des résidus des sables bitumineux produits avec des méthodes d'extraction différentes a été initiée. Une partie de cette étude consiste à effectuer des essais en laboratoire de déposition en canal afin de représenter la déposition hydraulique des résidus des sables bitumineux et de comparer les effets des procédés d'extraction caustiques et non-caustiques sur la nature de la plage formée en termes de géométrie, granulométrie et densité. Les caractéristiques des plages obtenues dans cette étude ont été comparées à d'autres essais de déposition en canal effectués sur différents types de résidus. Il existe une bonne corrélation pour les essais de déposition en canal entre les résidus des sables bitumineux et d'autres matériaux résidus, particulièrement ceux dont le contenu en particules fines est élevé par rapport aux paramètres qui régissent la pente de la plage. Ces comparaisons démontrent la fiabilité et l'efficacité des essais de déposition en canal pour établir des relations générales, et peuvent aussi servir de guide pour prédire la pente des plages.

Mots-clés : sables bitumineux, résidus, résidus fins, pulpe, déposition hydraulique, essais en canal, pente de la plage, débit, concentration de pulpe, contenu en fines, taille des grains.

[Traduit par la Rédaction]

Introduction

In northern Alberta, oil sand deposits are mined and processed to recover heavy oil. The bitumen extraction process from surface mining operations result in vast amounts of tailings that are hydraulically deposited into tailings ponds for storage and densification. The sand portion of the tailings forms the pond dykes and beaches, while most of the finer-textured material remains in the liquid phase and flows into the pond in the form of a slurry. This pond material is referred to as fine tailings and presently approximately 720 million cubic meters is being stored. The conventional method for fine tailings management is a containment strategy of the fine tailings in ponds for sedimentation, consolidation, and eventually land reclamation. However, the vast quantities and slow consolidation of fine tailings raises environmental and economic questions regarding possible improvements in tailings behaviour.

High temperature and a caustic dispersing agent (NaOH) have formed the basis of the Clark hot water extraction process used successfully on a commercial scale to recover bitumen from oil sands ore. Good descriptions of the present-day extraction and froth treatment process are provided by Shaw et al. (1994 and 1996) and Cymerman and Kwong (1995). However, the Clark process results in the creation of extremely dispersed, high-void-ratio fine tailings composed primarily of silt, clay, water, and residual bitumen. These caustic-based fine tailings exhibit extremely low consolidation rates and shear strengths and require considerable vacant land for storage. Processes different from the established Clark process (high temperature and caustic) have been developed to work at a range of temperatures or without the use of sodium hydroxide (Kasperski 2001). One such process is the "other six lease owners" (OSLO, the consortium of companies that piloted the process) hot water extraction process (Sury et al. 1993), a noncaustic bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the

Received 25 October 2006. Accepted 4 February 2009. Published on the NRC Research Press Web site at cgj.nrc.ca on 12 June 2009.

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Table 1. Results of flume tests used for design of the Clark and OSLO flume deposition tests.

	Flume dimensions									Beach properties	
Test	Length (m)	Width (m)	Depth (m)	Slurry material	D_{50} (mm)	Solids content (%)	Fines content (%)	Flow rate (L/min)	Duration (min)	Slope (%)	Dry density (Mg/m^3)
TS19[a]	6.1	0.3	1.2	Syncrude tailings sand	0.178	33.9	1	4.9	180	12.0	1.46
TS35[a]	6.1	0.3	1.2	Syncrude tailings sand	0.178	35.4	1	5.1	72	12.3	1.43
TS36[a]	6.1	0.3	1.2	Syncrude tailings sand	0.178	40.2	1	5.0	78	13.5	1.41
FM1[b]	4.9	0.25	0.6	Syncrude combined tailings	—	56	15	130	1.0	1.0	1.50
10[b]	4.9	0.25	0.6	Syncrude combined tailings	—	42	21	61	1.1	3.0	1.54
3[b]	4.9	0.25	0.6	Syncrude combined tailings	—	54	18	19	4.1	6.0	1.46
P1	4.9	0.25	0.6	Suncor combined tailings	—	52	10	19	—	6.0	—
P2	4.9	0.25	0.6	Syncrude combined tailings	0.14	52.3	10.6	19	—	7.7	1.39

[a]Küpper (1991).
[b]Scott et al. (1993).

hope of improved consolidation and strength properties of the fine tailings.

A potential reduction in fine tailings volume and improved geoenvironmental behaviour provided an environmental and economic incentive to examine the relative differences between the properties that influence consolidation of the fine tailings derived from these two extraction processes. The significance of the differences in these properties, if any, will determine if there is a justification to change the extraction process based on the changes in geotechnical behaviour of the fine tailings.

Objectives

The foremost objective of this research program was to evaluate the properties and processes influencing the rate and magnitude of consolidation for the tailings produced using the OSLO and the Clark extraction processes. The influence of the physical and chemical properties of the fine tailings on consolidation and shear strength has been integrated with the engineering properties to arrive at a comprehensive understanding of the behavior of the fine tailings from a geoenvironmental perspective. The two main components of the research program were flume deposition tests and testing for geotechnical properties of the fine tailings. The fine tailings runoff from the flume deposition tests was used for the geotechnical testing program. To understand the geotechnical properties, laboratory tests determined the compressibility, hydraulic conductivity, and shear strength of the fine tailings materials.

The flume deposition tests were used as a convenient tool to study the behavior and characteristics of the sand tailings resulting from the deposition and beaching processes. Under laboratory conditions, it is possible to control and isolate variables in a simpler and more economical manner than would be possible under field conditions. Flume tests presented in published literature are consistent with field observations of hydraulic fills and natural alluvial deposits (Küpper et al. 1992*a*, 1992*b*).

The objective of the flume deposition tests was to hydraulically deposit oil sand tailings to compare the effect of the Clark and the OSLO extraction processes on the nature of the beach deposits in terms of geometry, grain-size distribution, and density. In addition, the tests provided flume fine tailings runoff for subsequent testing of the geotechnical properties of the fine tailings. The characteristics of the beaches created in the flume are compared with other flume tests evaluated on a variety of tailings materials. These comparisons serve as a guide to predict the characteristics of beaches formed in the field.

Design of the experimental study

Scale modeling is a common approach for studying hydraulic systems. However, there are numerous complications associated with scaling-down hydraulic phenomena involving sediments. Küpper et al. (1992*a*) discussed several of these complications with regard to hydraulic phenomena involving sediments, which include: decreased sediment size that introduces cohesive forces into the system; grain shape and grain surface characteristics that are difficult to scale-model, yet they exert important influences on properties such as resistance to flow, sediment transport, equilibrium slope, and deposit density; and concerns with regards to the practical limits on varying fluid density, fluid viscosity, and sediment density.

To circumvent the difficulties posed by formal scale-modeling, the approach proposed by Hooke (1968) was adopted, which is based on an informal criterion of similarity. The basic premise of applying the Hooke model is that the flume deposition test, although designed in a laboratory setting, is not considered simply a scaled-down version of a field phenomenon, but can function as an independent, integrated system in its own right, regardless of scale features. The three basic conditions for the similarity of process approach are: (*i*) gross scaling relationships are met; (*ii*) the model reproduces some morphologic characteristics of the systems being investigated; and (*iii*) the process that pro-

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Fig. 1. Flume deposition test setup.

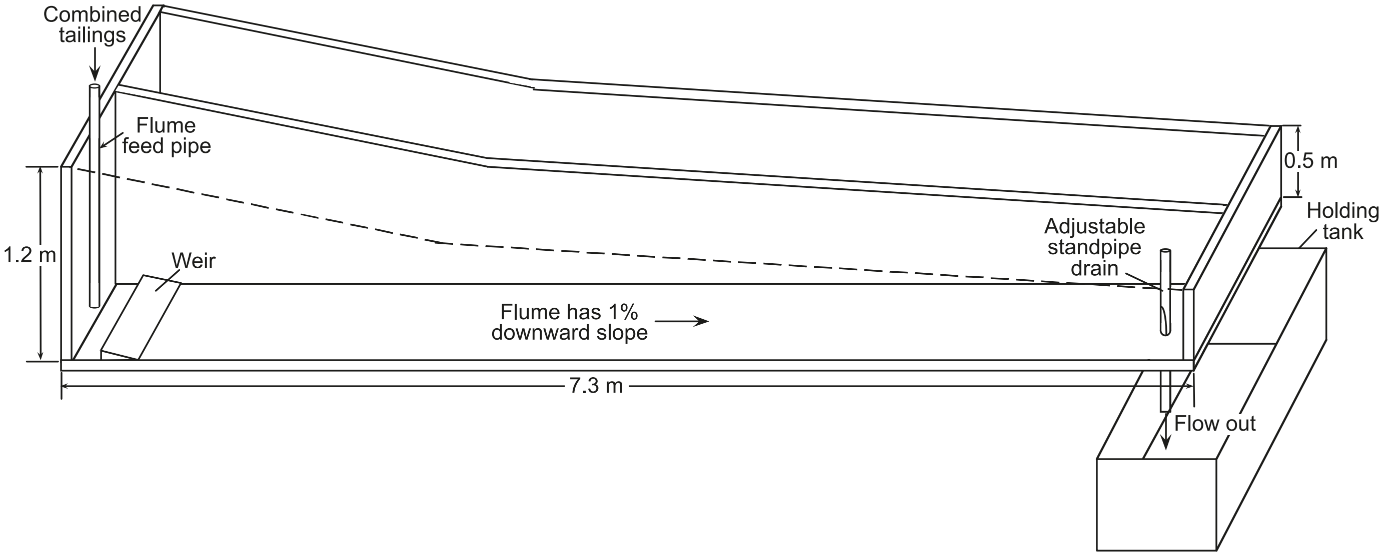


Fig. 2. The OSLO/Clark flume.

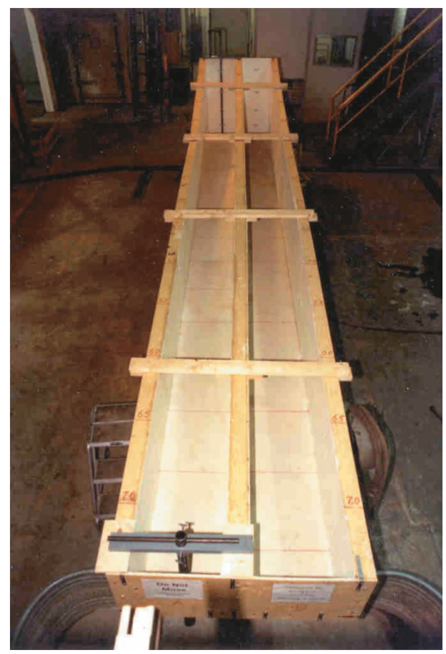
duced a certain characteristic in the laboratory system can be logically assumed to produce a similar characteristic in a full-scale system, as explained in detail by Hooke (1968) and discussed by Küpper et al. (1992*a*).

The similarity of process approach was used because it can provide an understanding of physical phenomena and aid the development of basic concepts that can be used to study real-scale situations, at least in a qualitative manner. Rather than replicating and describing field-specific phenomena at a laboratory scale, this approach is better suited for establishing general relationships, such as predicting beach slope as a function of flow rate. Several good examples of the utilization of this approach are available in published literature (Simons and Richardson 1963; Guy et al. 1966; Hooke 1967; Weaver 1984; Küpper 1991).

Flume design and construction

The Geotechnical Group at the University of Alberta designed the flume and conducted the flume tests. Five different tailings materials were produced by the pilot bitumen extraction plant, located at the Syncrude Research Centre in

Fig. 3. Overhead view of flume.



Edmonton, Alberta, and their depositional behavior was evaluated in seven large-scale flume tests.

Design parameters

The slope of a beach deposit is controlled by four parameters: (*i*) slurry flow rate; (*ii*) solids content (or slurry concentration); (*iii*) fines content of the tailings; (*iv*) grain-size distribution of the slurry solids. The solids content is defined as the mass of the tailings solids (the nonwater portion of the fine tailings consisting of bitumen and mineral solids) divided by the total mass of the tailings. The fines content is defined as the mass of the solids less than 44 µm (No. 325 sieve) divided by the total mass of the tailings solids. Combined tailings are the total waste stream created by the bitumen extraction process and are composed of several

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Fig. 4. Pilot plant extraction process flow diagram (1 foot = 0.3048 m). MIBC, methyl isobutyl carbinol.

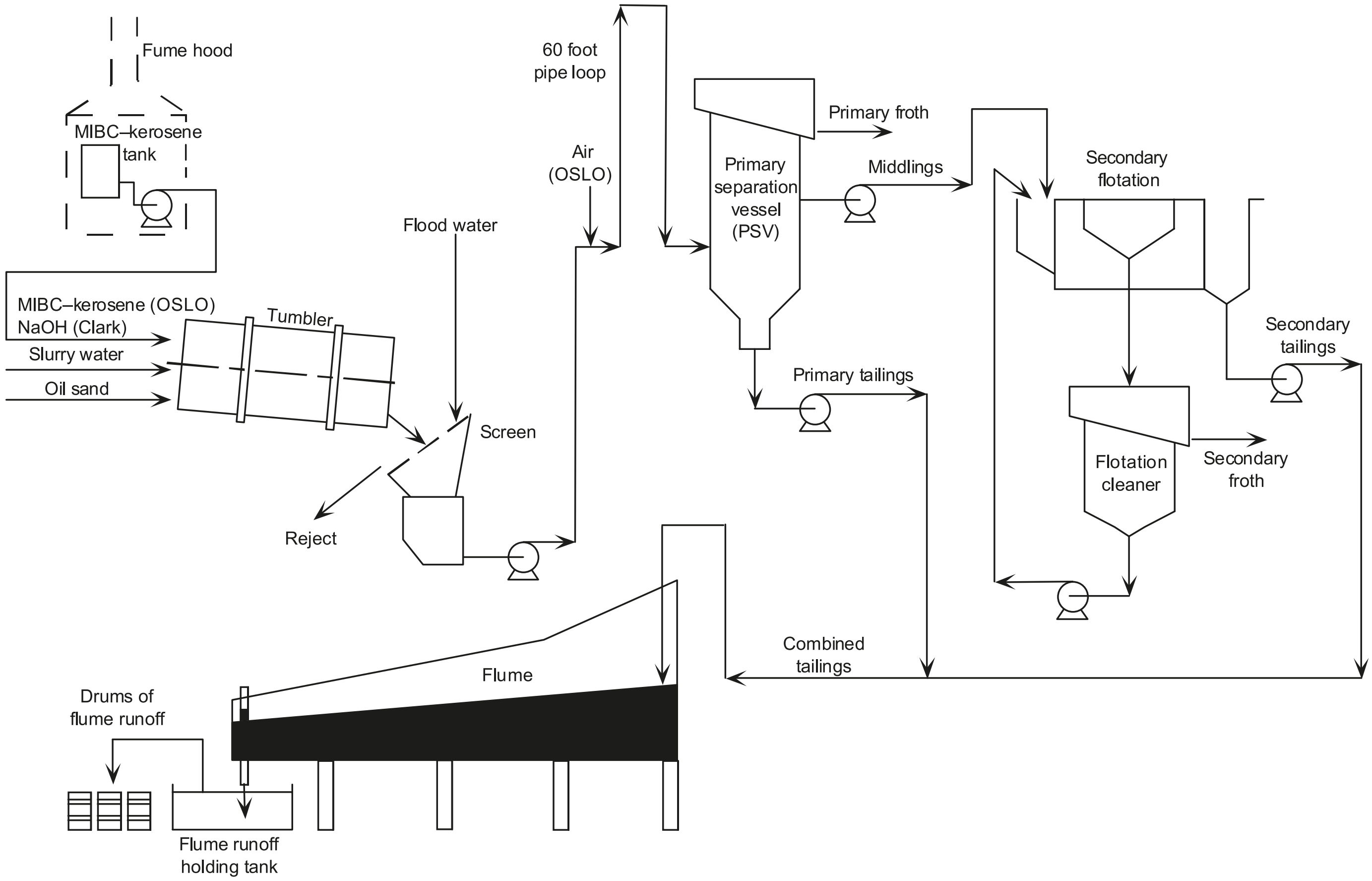

Table 2. Experimental process conditions.

Oil sand ore designation	Extraction process	Process water
A	Clark	Syncrude recycled pond water
A	OSLO	Treated Athabasca River water
A	OSLO	Untreated Athabasca River water
B	Clark	Syncrude recycled pond water
B	OSLO	Treated Athabasca River water

waste streams containing sand, fines, hot water, residual conditioning chemicals, and unextracted bitumen. Solids contents of the combined tailings typically range from 40% to 60%. The flow rate and solids content of the combined tailings deposited in the flume were determined by the bitumen extraction process and the grain-size distribution of the plant oil sand feed. The flume design was based on the anticipated values for these parameters.

Results of flume tests performed by Küpper et al. (1992*a*) with three different sands, including a tailings sand from Syncrude's tailings dyke beach, were used as preliminary guides. These tests — using a 5.5 m long, 0.31 m wide, and 1.2 m high flume — indicate that beach slope increases with increasing slurry concentration and increasing tailings particle size, and decreases with increasing flow rate. Three flume tests (FM1, 3, 10, performed by Scott et al. (1993)) with Syncrude tailings, using a 4.9 m long, 0.25 m wide, and 0.6 m high flume were also used to check the preliminary flume design. The combined tailings deposited during the Scott et al. flume tests had solids contents ranging from 42% to 56% and fines contents varying from 15% to 21%. These tests also showed that increasing flow rate results in flatter beach slopes. The Scott et al. flume tests are not consistent with Küpper's results based on solids content and particle size of the slurries. However, the higher flow rates used in the Scott et al. tests follow the trend of higher flow rates resulting in decreased beach slopes. At these higher flow rates, Küpper's correlations predict the measured beach slopes reasonably well. The major conclusion from all these tests is that flow rate is the dominant factor in determining the beach slope.

Two other flume design parameters were the solids content in the runoff stream and the required volume of flume runoff. The solids content of the flume runoff was necessary to estimate the volume of runoff required to satisfy the demands of future fine tailings testing. The required volume of runoff material dictated the required flume volume capacity to accommodate the associated beach deposit.

Design calculations

The expected rate of discharge from the extraction plant for the combined tailings was 52 L/min. For the Clark tests, the solids and fines contents of the combined tailings were estimated to be 52% and 12%, respectively. For the OSLO process, values of 52% for the solids content and 8% for the fines content were assumed as no prior testing had been carried out. Flume widths of 0.3 and 0.6 m and deposition

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Table 3. Description of oil sands ores.

Ore designation	Bitumen content (%)	Water content (%)	Solids content (%)	Fines content (%)	Location	Geology
A	12.4	20.0	83.3	13.1	Syncrude: auxiliary pit	Subtidal (channel-fill) and intertidal estuarine
B	12.3	20.5	83.0	11.3	Suncor: overburden ramp south	Lower estuarine tidal channel – tidal flat

times of 30 and 60 min were considered in the design. There were many variables to consider for the small number of tests on oil sand tailings material, so the design was mainly by inspection to obtain ranges of design parameters. The predicted beach lengths were quite long (10 to 11 m) except for a 0.6 m wide flume being filled for only 30 min (7 m). It is not necessary, however, to have the flume as long as the predicted beach. The runoff and beach slope are not affected by the length of the flume if the downstream end has a drain that can be raised during the test to keep it just above the beach.

Approximately 1600 L of flume runoff at about 6% to 8% solids content was required to meet the future fine tailings testing volume requirements. Design calculations were performed using the expected solids contents, fines contents, and discharge rate for the Clark and OSLO processes using a flume width of 0.45 m. The calculations predicted slope, volume, mass, and solids content of the beach and flume runoff; beach length; and the percent fines retained within the beach. After a 60 min filling period, the flume would contain a predicted beach volume of about 1.5 m^3 at a solids content of 78% and approximately 1600 L of flume runoff would be collected at a solids content of 7% to 8%. A beach slope of about 5% was expected with approximately 50% to 60% of the fines retained within the beach.

Two trial flume tests (P1 and P2) were performed using the flume described by Scott et al. (1993). These tests verified predictions for the beach slope and fines capture in the beach deposit. Table 1 shows the results of all the flume tests used in the design process.

Equipment and test procedure

The laboratory equipment consisted of two identical 7.3 m long plywood flumes, with each flume being 0.45 m wide separated by a dividing wall (Fig. 1). The double flume arrangement allows the performance of a test in one flume while the other flume was being sampled or prepared for a subsequent test. The flume was 1.2 m deep at the upstream end and 0.5 m deep at the downstream end, resulting in a volume capacity of 2.5 m^3. The flume had a bottom slope of 1% downstream to prevent water ponding and runoff from being buried by beach material during the initial stages of deposition. Figures 2 and 3 show the flume prior to testing.

The combined tailings being deposited into the flume were produced using Syncrude Research's experimental extraction circuit (EEC), which had an oil sand extraction rate of 2 t/h. A complete description of the pilot plant extraction operation is provided in Lowe et al. (1994). A flow diagram of this oil sand extraction pilot plant is presented in Fig. 4.

In general terms, bitumen is extracted from oil sands using a combination of hot water, steam, and conditioning chemicals. Initially, oil sand was screened through a grizzly with 10 cm openings before being fed into a tumbler where oil sand was digested and conditioned by the addition of hot water, conditioning chemicals, and steam. High slurry temperatures enhance separation by decreasing bitumen viscosity. The Clark process is typically performed at 85 °C, while the OSLO process can operate over a temperature range of 30 to 90 °C. During these tests, a temperature of 80 °C was used for both processes because for the OSLO process, bitumen recoveries were similar at slurry temperatures greater than 50 °C and a level of consistency was preferred in terms of temperature when comparing processes. Conditioning chemicals are designed to ease the separation of bitumen from the mineral solids. For the Clark tests, sodium hydroxide was added to the tumbler water and for the OSLO process tests a methyl isobutyl carbinol (MIBC)–kerosene mixture was added.

Cemented silt stones and clay band lumps that were carried through the digestion stage were removed by vibrating screens at the tumbler discharge. The slurry leaving the tumbler was passed through a double deck screen (2.5 and 0.6 cm openings) and dropped into a pump box where additional hot water (flood water) was added to dilute the slurry. Flooded slurry was pumped through a 18.3 m long section of 2.5 cm diameter pipe. The slurry had a residence time of approximately 10 s before leaving the pipe loop and entering the primary separation vessel (PSV). During OSLO runs, the slurry was aerated before entering the pipe loop (Fig. 4) to facilitate improved bitumen separation.

In the PSV (Fig. 4), the bulk of the sand-size mineral rapidly settles and is withdrawn as primary tailings. Most of the bitumen separates from the solids and floats upward to form a coherent mass known as froth. A portion of the slurry, known as middlings, is removed from the central portion of the PSV (Fig. 4) and is further processed in a secondary flotation unit to recover the fine oil droplets that remain unfloated in the primary separation process. The secondary flotation unit is an air flotation machine equipped with mechanical agitators. The waste material that settles in the secondary flotation vessel is referred to as secondary tailings. During the tests, the froth product from the PSV overflowed into a launder, then flowed into weigh tanks for rate measurements. Froth from the flotation machine flowed to a froth cleaner unit. The final secondary froth flowed from the cleaner unit to weigh tanks. The primary tailings and secondary tailings streams were combined and then pumped to the experimental flume through a 2.5 cm diameter pipe.

The combined tailings were discharged into the flume (Fig. 1) using a vertical feed pipe 2.5 cm in diameter positioned slightly above the base of the flume. The tailings were intended to be deposited in a submerged fashion

Table 4. Comparison of flume design predictions and actual test results.

	Test conditions					Test results				Beach deposit	
	Solids content (%)	Fines content (%)	Water content (%)	Ave. flow rate (L/min)	Duration (min)	Beach slope (%)	Beach volume (m^3)	Runoff volume (m^3)	Total volume (m^3)	Ave. solids content (%)	Ave. fines content (%)
Design parameters											
Clark	52	12	92	52	60	5	1.49	1.63	3.12	78	—
OSLO	52	8	92	52	60	5	1.50	1.62	3.12	78	—
Flume deposition tests*											
Clark(A); A; RPW	56	10	79	39	52	7.4	1.15	0.88	2.03	76	9.9
Clark(B); A; RPW	56	10	79	40	52	6.7	1.18	0.91	2.09	75	—
OSLO; A; TRW	55	9	82	40	80	7.7	1.84	1.35	3.19	75	7.8
OSLO; A; UTRW	56	9	79	40	80	7.8	1.88	1.33	3.21	76	7.0
Clark(A); B; RPW	61	8	64	37	65	11.7	1.49	0.89	2.38	76	6.6
Clark(B); B; RPW	61	8	64	37	65	10.8	1.47	0.90	2.37	75	7.4
OSLO; B; TRW	56	8	79	42	80	10.1	1.82	1.51	3.33	76	5.2

Note: RPW, recycled Syncrude pond water; TRW, treated Athabasca River water; UTRW, untreated Athabasca River water.
*Terms in first column: process; ore designation; water.

throughout the test, and a 2.5 cm high weir was positioned just downstream to ensure prompt immersion of the feed pipe. At the downstream end of the flume, drainage was provided by a standpipe drain with adjustable height to prevent beach material from escaping the flume and to prevent the runoff pond from extending more than 1.5 m upstream. Flume runoff was collected in a holding tank and later pumped into drums (Fig. 4).

The tests were carried out by depositing combined tailings at the concentration and flow rate resulting from the pilot plant extraction process. Tailings were discharged in two stages to coincide with measurements and sampling of the EEC. For OSLO tests, the slurry was initially discharged into the empty half of the flume and subsequently onto the beach formed in the partially filled half during the first deposition stage. A modification to the testing program resulted in a twofold increase in the required volume of flume runoff from the Clark tests. To accommodate the increased volume requirements, one flume was used for each Clark deposition stage. Deposition times ranged from 40 to 65 min depending on the test being performed and the volume of runoff required for future testing. Combined tailings were sampled before and after each deposition stage. The volume of flume runoff was measured and samples were taken every 10 min during deposition. After each deposition stage, measurements of the beach deposit depth were made every 0.5 m along the length of the flume at three evenly spaced points across the width of the flume to determine the slope and profile of the beach deposit.

The beach deposit was sampled the day after deposition for solids content, fines content, bitumen content, density determination, and grain-size analysis. Sampling progressed towards the upstream end of the flume in 0.5 m intervals with samples taken along the height of the beach at 20 cm depth increments. A 5 cm diameter piston tube sampler was used because it could obtain representative beach samples (no change in water content) and minimize disturbance to neighboring sampling locations. The piston tube sampler relied on suction and friction forces to retain the samples, and visual inspections indicated it was successful at almost every sampling location. Samples were extruded from the sampler into glass jars to prevent evaporation during subsequent storage prior to testing.

Test program

In total, seven flume deposition tests under five different process conditions were performed. The process conditions are shown in Table 2. Tailings from each extraction process were generated using approximately 80 t samples of typical Syncrude ore and Suncor ore. For the remainder of this paper, oil sands ore originating from the Syncrude mine will be referred to as ore A and oil sands ore originating from the Suncor mine as ore B. Both types of oil sand ore were used because they have different physical and chemical characteristics based on their geological origins. The extraction process water was chosen based on the water source that would be used for commercial operation. The extraction process water used during the Clark process was recycled pond water from the Mildred Lake tailings pond at the Syncrude mine. The OSLO process utilized Athabasca River water (initial pH 7.4) that had been treated by slowly adding a 10% sulfuric acid solution to bring the pH to 5.0, and subsequently adding a 4% (by weight) lime slurry to increase the pH back to 7.4, resulting in 40 ppm Ca^{2+} in solution. This amendment was proposed to improve the settling behavior of the OSLO fine tailings. Another OSLO extraction run was performed using untreated river water and ore A, so that the influence of the chemical treatment of river process water could be determined.

Oil sands description

A description of the oil sands ore is presented in Table 3. A detailed characterization is provided by Cuddy (1994). The oil sand ores used for this project had similar bitumen content, water content, and solids content based on mass. Ore A, however, had a greater fines content than ore B (13.1% and 11.3%, respectively).

Summary of test results

A summary of the overall results of the flume deposition

					Flume runoff			
Ave. bitumen content (%)	Ave. water content (%)	Ave. bulk density (Mg/m^3)	Ave. dry density (Mg/m^3)	Fines capture (%)	Ave. solids content (%)	Ave. fines content (%)	Ave. bitumen content (%)	Ave. water content (%)
—	28	1.96	1.53	50	8.4	—	—	1090
—	28	1.96	1.53	60	6.9	—	—	1349
0.3	32	1.87	1.40	67	8.9	99	0.3	1024
0.3	33	1.87	1.40	67	9.3	98	0.4	975
0.4	33	1.84	1.37	63	8.4	98	0.4	1090
0.2	32	1.85	1.40	61	8.8	99	0.5	1036
0.2	32	1.88	1.44	64	8.6	99	0.5	1063
0.2	33	1.90	1.43	66	8.3	99	0.5	1104
0.2	32	1.88	1.42	54	7.5	99	0.5	1233

tests is presented here. Results of individual tests are provided by Miller et al. (1995).

Comparison of design predictions with test results

Presented in Table 4 are the assumed design parameters and the actual test conditions for the solids contents and fines contents of the combined tailings, average flow rate, and test duration. The predicted and measured values for average beach slope, beach volume, runoff volume, and total volume are also provided. For all five flume tests, the solids content of the combined tailings was greater than the assumed value of 52% (55% to 61%). The assumed fines content value of 12% for the Clark process combined tailings was greater than the actual fines content of both the ore A (10%) and ore B (8%) combined tailings. The combined tailings fines content was higher than the anticipated value of 8% for the OSLO process using ore A (9%). Average total flow rates varied between 37 to 42 L/min and were less than the assumed design value of 52 L/min. Variations in these parameters were due to changing operating conditions for the EEC to achieve optimal conditions for bitumen recovery.

In general, the measured values were comparable to predicted values taking differences in the input parameters into account. The combination of the slurry flow rate being lower than expected and solids content of the combined tailings being slightly higher than anticipated resulted in both OSLO and Clark flume tests having beach slopes greater than the predicted value of 5% (7% to 8% for ore A and 10% to 12% for ore B). These results are supported by the trends stated earlier of beach slopes becoming steeper as flow rate decreases and slurry concentration increases. The solids contents for the flume tests (55% to 61%) were somewhat similar to the design value (52%), but the flow rates (37 to 40 L/min) were considerably less than the anticipated values (52 L/min). These differences in test conditions and the resulting beach slopes show that beach slopes were mainly controlled by the flow rate.

Regardless of the extraction process, combined tailings derived from ore A were observed to have greater fines contents than ore B combined tailings (Table 4). This was due to ore A initially having more fines than ore B (Table 3). Fines contents of the combined tailings were lower than the oil sand ores because fines are removed as lumps of clay bands at the beginning of the extraction process.

Flow description

The characteristics of the flow in the flume were typical of flow conditions observed in the field. A semi-circular-shaped pool was promptly formed once deposition of the combined tailings was instituted. The pool would either overflow all around, creating sheet flow in the immediate area, or it would breach at one location, forming a channel (Fig. 5). Further down the flume, the flow would generally return to a sheet flow until the beach deposit began to form (Fig. 6). As the beach deposit began to build up, the flow tended to concentrate in a meandering channel that would migrate within the width of the flume (Fig. 7). The flow sometimes established a braided pattern formed by a channel separating and rejoining around islands of sediments (Fig. 8). Occasionally, sheet flow would be reestablished and cover most of the beach surface until a new channel was formed. However, the dynamic process of channel migration was generally continuous.

The observations of flow characteristics during the flume deposition tests satisfied the conditions of Hooke's (1968) similarity of process method. Firstly, visual inspection of the flume tests confirmed a flow above turbulent limits that met the gross scaling relationship criteria. Morphologic characteristics, such as meandering channels, braided systems, sheet flows, and islands that are found in the field, were reproduced during flume tests. Finally, the processes that produced these characteristics in the laboratory system can logically be expected to produce similar characteristics at field scale. Thus, the results of the flume test may be used to understand the physical phenomena and basic concepts and relationships that can be used to study real-scale situations, at least qualitatively.

Beach geometry

The beaches in the flume typically had a smooth and

Fig. 5. Initial channel flow.

Fig. 6. Sheet flow.

slightly concave upwards profile. Similar deposit shapes are seen in most flume and field beaches. Beach profiles of the flume tests are presented in Figs. 9 and 10. To facilitate comparison of profiles, the beach crest was always considered to be at a nominal height of 1 m. As stated earlier, results have shown that beach slope increases as the solids content (slurry concentration) increases and decreases as the flow rate increases. The results of the Clark and OSLO flume deposition tests support these findings. The Clark flume tests with ore B had a greater slurry concentration and a lower flow rate than the comparable OSLO test, resulting in a steeper beach slope (Table 4). The four ore A tests had flow rates, solids contents, and fines contents that

Fig. 7. Meandering channels.

Fig. 8. Braided pattern formed around islands of sediment.

varied by only 1% for each variable. Consequently, the beach slopes were also similar, varying by only 1.1% (Table 4). The similarity of the ore A beach deposits show that the beach building process is a controlled process and therefore beaches can be designed. Further support for this conclusion is provided by the reproducibility of the replicated Clark flume tests (Table 4).

The Clark–ore B flume tests had a higher slurry concentrations, lower flow rates, and lower fines contents, which resulted in steeper slopes than its ore A counterparts. The slurry concentrations and flow rates were only slightly dif-

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Fig. 9. Ore A beach deposit profiles.

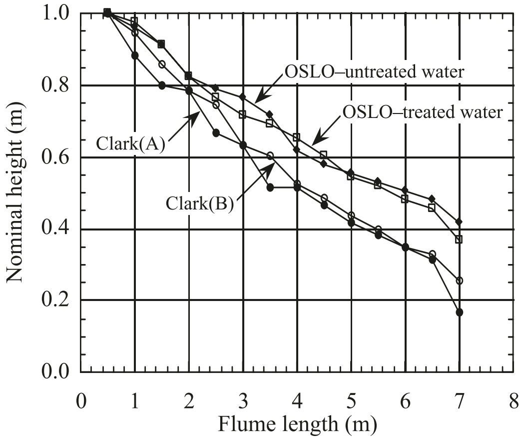
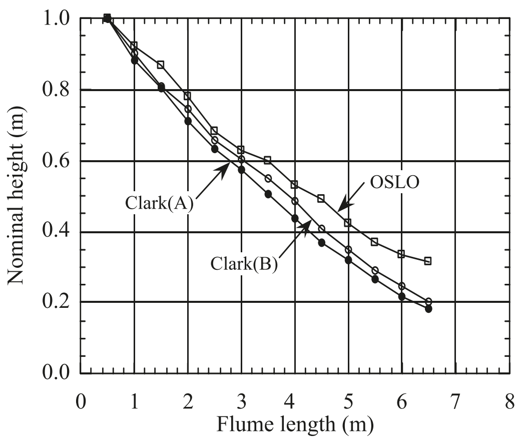


Fig. 10. Ore B beach deposit profiles.



ferent for the ore A and ore B OSLO flume tests, but the steeper beach slope of the ore B test was due to the lower fines content (Table 4).

The beach profile was measured immediately after the completion of flume deposition and on average 19 h later. Decreases in beach thickness over this period due to self-weight consolidation ranged from 0 to 0.6 mm and averaged 0.3 mm along the length of the beach over the different flume tests. In terms of percent of original beach height, an average decrease of less than 1% due to self-weight consolidation over the average 19 h period was observed.

The relatively small decrease in beach thickness indicates that minor reductions in beach volumes due to self-weight consolidation can be expected for these tailings materials. Self-weight consolidation of the beach may not have been complete after 19 h, but significant decreases in volume are not expected given the relatively small initial changes observed.

Solids contents, fines contents, and bitumen contents

The average solids contents, fines contents, and bitumen contents for the beach deposits and flume runoff are summarized in Table 4. Bitumen content is defined as the mass of the bitumen divided by the total mass of fine tailings.

Beach deposit

Profiles of solids content, water content, and fines content for the beach deposits from all the flume tests are presented in Figs. 11 to 15. No consistent change of solids content with distance was observed. Solids contents proved to be approximately constant for all tests, except for the ore A–OSLO tests where the solids content decreases slightly with distance from the discharge. No correlation was evident between solids content and the flume test parameters. However, the fines contents were observed to increase slightly with distance from the discharge point. Hydraulic sorting of the deposited materials may be responsible for this trend; that is, variation of mean grain size with distance along the flow. The increased fines contents near the downstream end of the flume are most likely due to the ponding observed in this region.

The average solids content of the beach deposits ranged between 75% and 76% (Table 4). The average fines content was generally higher in beach deposits with ore A (7.0% to 9.9%) than in beach deposits tests with ore B (5.2% to 7.4%). This was expected as ore A contained more initial fines than ore B (Table 3). Average bitumen contents by total mass were similar for all tests, ranging between 0.2% and 0.4% (Table 4).

Flume runoff

The solids content of the flume runoff for both ore A– and ore B–OSLO materials were slightly lower than the Clark tests (Table 4). The flume runoff solids were almost completely (98% to 99%) fine-sized material ranging in solids contents from 7.5% to 9.3%. Bitumen content by total mass was similar for all the tests (0.3% to 0.5%). These values may be low because bitumen skimmed off the flume runoff holding tank was not included in the calculations.

Grain-size distribution along flume

Hydraulic sorting is defined as a variation of mean grain size with distance along the flow by hydraulically deposited materials. Coarser grains are deposited first and finer grains deposited further downstream. Grain-size distributions of the beach deposit (Miller et al. 1995) indicated essentially no difference between grain sizes of beach samples at 2 and 4 m downstream. Typical grain-size distributions for the different locations are presented in Figs. 16 and 17. However, as stated earlier, there was a trend of slightly increasing fines content along the beach deposit, which indicated that while hydraulic sorting was minimal, the process was still active and had an influence on the composition of the beach deposit.

Küpper et al. (1992*a*) reported an increase in mean grain size with distance along the flow for tailings sand with little or no fines (<44 μm) due to washing out of the finer fraction of the tailings sand during the deposition process. Küpper et al. (1992*a*) concluded that the variation of grain-size parameters with distance along the beach did not seem to have any correlation with the values of slurry concentration and flow rate for the tailings sands tested. A similar conclusion may be reached for this research study over the limited flow rates and slurry concentrations used, but a more intensive study with a wider range of flow rates and slurry concentrations

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Fig. 11. Variation of solids content, fines content, water content, and dry density along beach deposits for Clark–ore A (trials A and B) flume deposition tests.

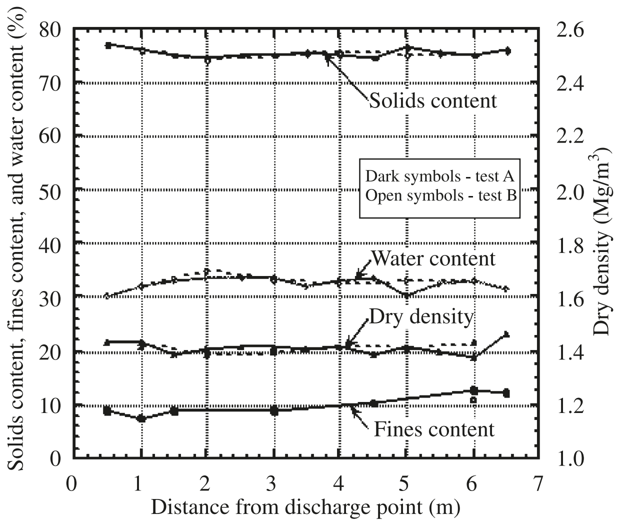


Fig. 13. Variation of solids content, fines content, water content, and dry density along beach deposits for OSLO–ore A untreated-water flume deposition tests.

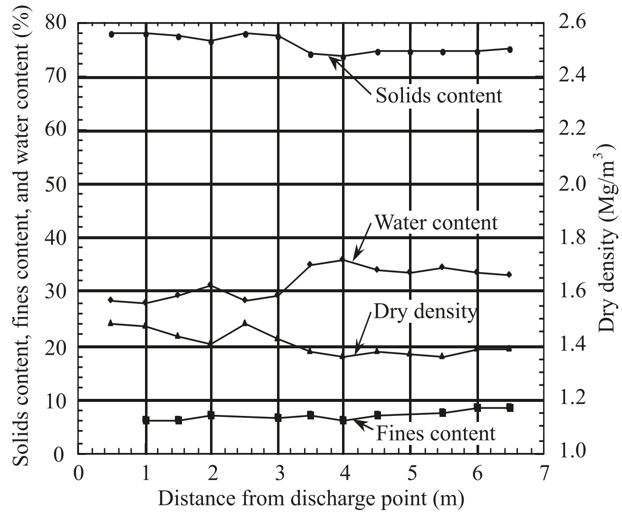


Fig. 12. Variation of solids content, fines content, water content, and dry density along beach deposits for OSLO–ore A treated-water flume deposition tests.

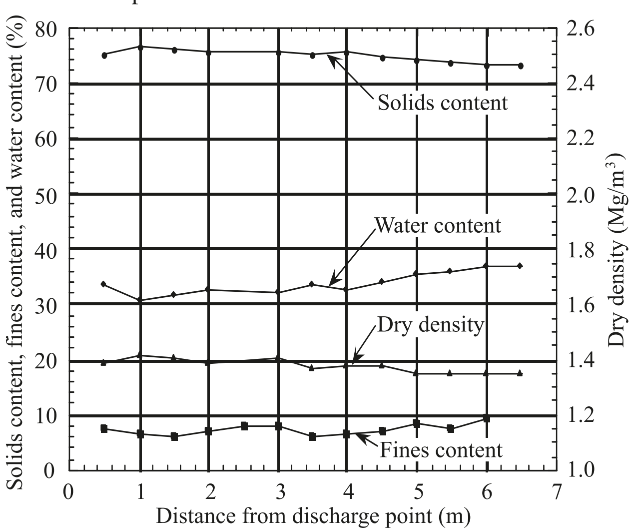
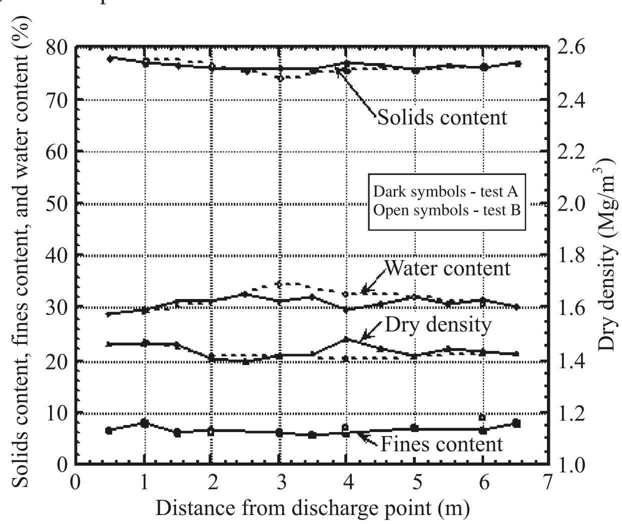


Fig. 14. Variation of solids content, fines content, water content, and dry density along beach deposits for Clark–ore B (trials A and B) flume deposition tests.



would have to be performed to more definitively reach a conclusion with regard to this issue.

Density

The density was determined at several locations along the flume assuming complete saturation. Dry density profiles are provided in Figs. 11 to 15. Dry density data in these figures was measured from samples collected from 20 to 40 cm below the beach surface unless the beach thickness was insufficient to obtain samples over these depths. In these cases, which occurred near the downstream end of the flume, samples from 0 to 20 cm or from 0 cm to maximum beach depth were used to characterize the dry density along the length of the beach.

Density profiles for both the ore A and ore B beaches were generally consistent between tests with dry density ranging from 1.35 to 1.48 Mg/m^3. There was no consistent trend of density variation with distance and any variations were not accentuated. For the ore A tests, the Clark beach had a density profile that was approximately constant with distance, whereas the OSLO beaches decreased slightly. Both the ore B tests resulted in beaches that had approximately constant density with distance. An average density (given in Table 4) was calculated for each test. Clark beach deposits were found to have greater average dry densities than the OSLO beaches, but the differences were small.

Comparison with other flume test results

The results of the OSLO and Clark flume tests and other flume tests using oil sand tailings (FM1, 3, 10, P1, P2, performed by Scott et al. (1993)) were compared with a large number of other tests using a variety of materials and covering a wide range of slurry concentrations and flow rates.

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Fig. 15. Variation of solids content, fines content, water content, and dry density along beach deposits for OSLO–ore B treated-water flume deposition tests.

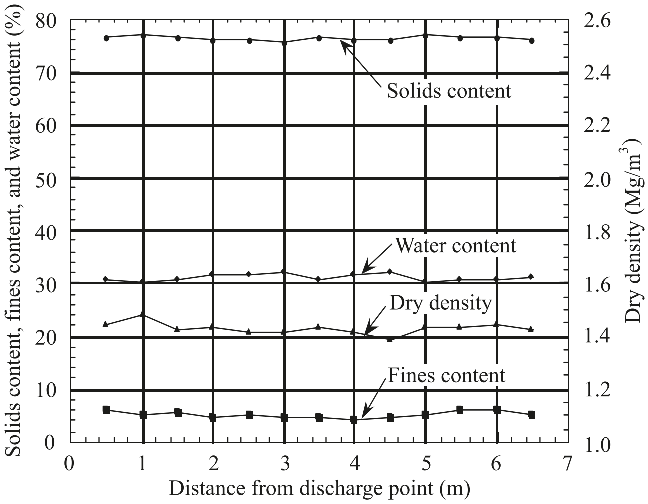
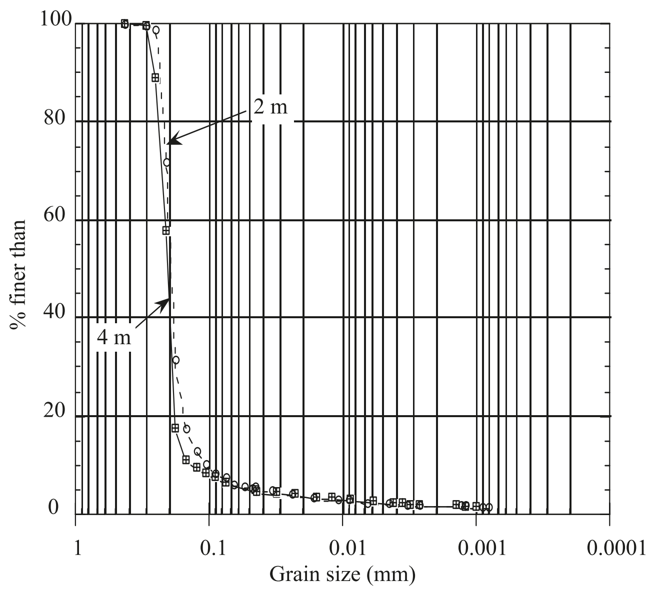


Fig. 16. Typical grain-size distributions of beach samples at 2 and 4 m downstream, Clark–ore B beach deposit.



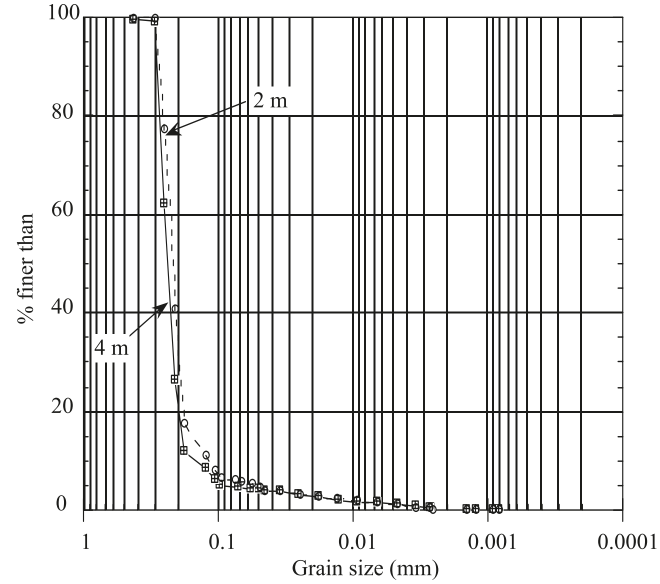
These comparisons show the reliability and effectiveness of flume tests in terms of establishing general relationships. These comparisons can serve as a guide to predict beach slopes and determine what parameters control beach slope and density for tailings materials. Data from a large number of flume tests were collected and summarized by Küpper et al. (1992*b*) from numerous publications (Ferreira et al. 1980; Blight et al. 1985; Boldt 1988; de Groot et al. 1988; Fourie 1988; Fan 1989; Winterwerp et al. 1990; Küpper 1991).

Factors influencing beach geometry

Total and specific flow rate

As seen in Figs. 18 and 19, an increase in total flow rate and specific flow rate causes the beach slopes to flatten.

Fig. 17. Typical grain-size distributions of beach samples at 2 and 4 m downstream, OSLO–ore B beach deposit.



Specific flow rate is defined as the total flow rate divided by the flume width. There is a good correlation between the results for the oil sand tailings and the various other materials. The beach slopes of the Clark and OSLO flume tests appear to be slightly steeper than the majority, but are not unreasonable with respect to the observed trend and fit best with the values derived from tests having similar high slurry concentrations.

Slurry concentration

The variation of beach slope with slurry concentration is presented in Fig. 20. The relatively large scatter in this graph is partially due to the inclusion of points corresponding to a wide range of grain sizes and flow rates. The shaded zone represents 90% of the data for sandy fills deposited at flow rates under 150 L/min and specific flow rates less than 40 $cm^3/(s \cdot cm)$. The majority of the materials in this zone had little or no fines. The beach slopes for the oil sand tailings fell outside this zone, but were in relatively good agreement with flatter beach slopes for flume tests performed with materials containing a high percentage of fines (USA and USB, fines contents of 83% and 35%, respectively). The oil sand tailings materials all contained appreciable amounts of fines (ranging from 8% to 21%).

Fines content of tailings material

In this set of high fines material with slurry concentrations ranging from 40% to 60%, beach slopes were generally observed to flatten with increasing fines content. This behavior is supported by observations of decreasing beach slopes as mean grain size decreases (Küpper 1991). Tests using high flow rates (such as FM1, USA, and USB) had flat beach slopes, regardless of fines content. Based on this limited data, for a given slurry concentration range, fines content will influence beach slope if flow rates remain fairly low. High flow rates result in flat beach slopes regardless of the fines content or slurry concentration of the tailings material.

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Fig. 18. Variation of beach slopes with total flow rate for various flume tests (adapted from Küpper et al. 1992*b*).

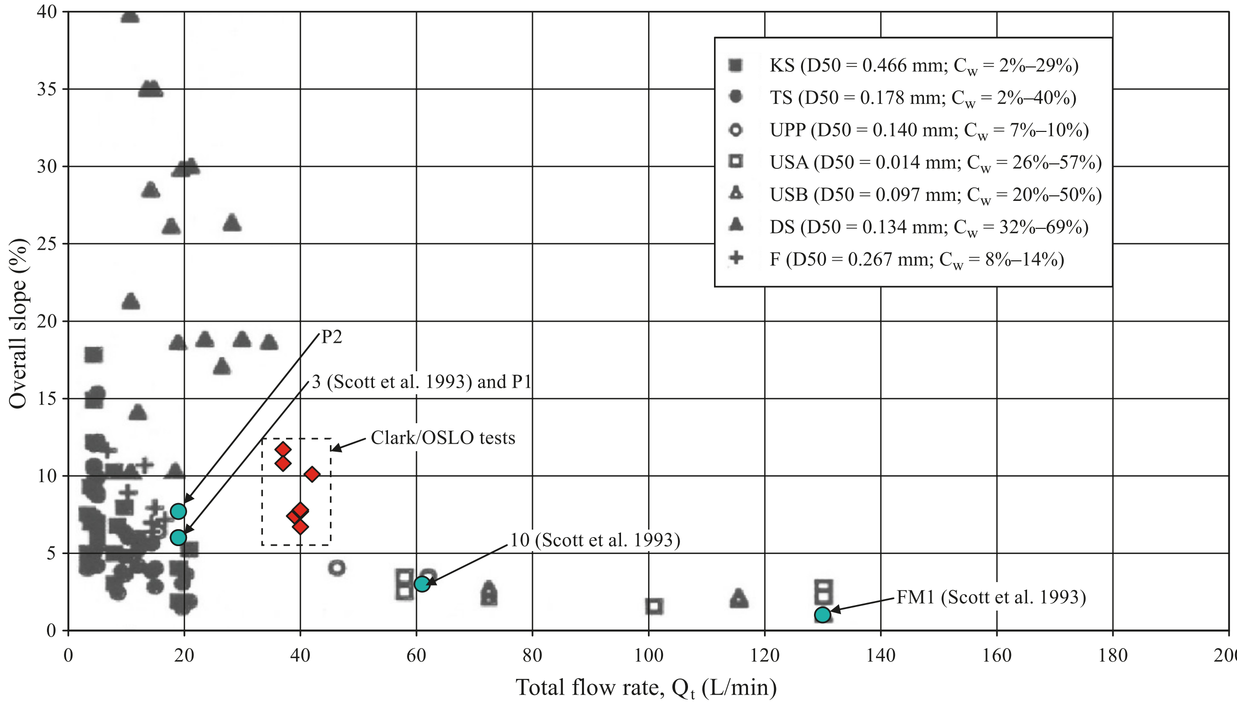
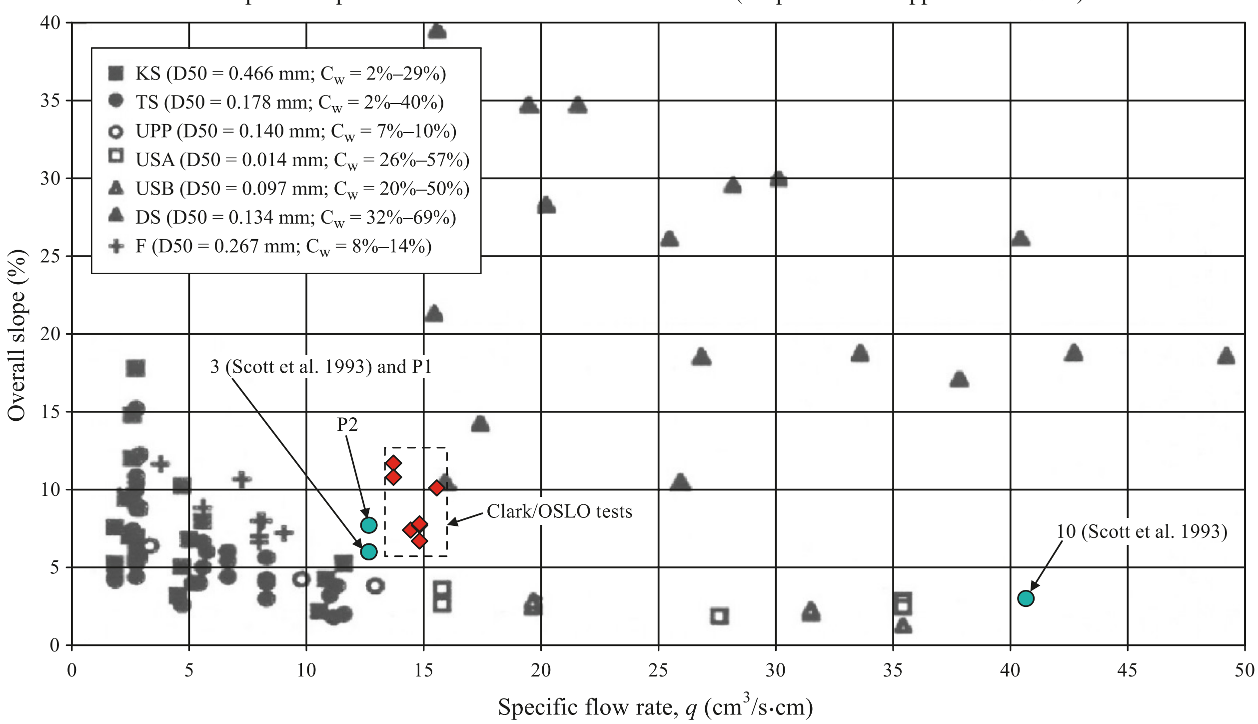


Fig. 19. Variation of beach slope with specific flow rate for various flume tests (adapted from Küpper et al. 1992*b*).



Grain-size distribution

Beach slope is also affected by grain-size distribution. Fines content is partially representative of the overall grain-size distribution. To assess the influence of overall grain-size distribution of the tailings material on beach slope angle, the parameters of flow rate and slurry concentration must remain consistent. Variation of the flume deposition parameters was limited by the time and scope of the overall research study — comparing the compressibility, hydraulic conductivity, and shear strength of the fine tailings generated from the flume deposition tests. While there are no directly comparable materials in terms of identical flow rate or slurry concentration in the data sets presented in Figs. 18 to 20, the data labeled USA provides the nearest approximation for determining the influence of overall grain-size distribution at a similar specific flow rate (15.8 $cm^3/(s{\cdot}cm)$) and

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Fig. 20. Variation of slope with slurry concentration for various flume tests (adapted from Küpper et al. 1992*b*).

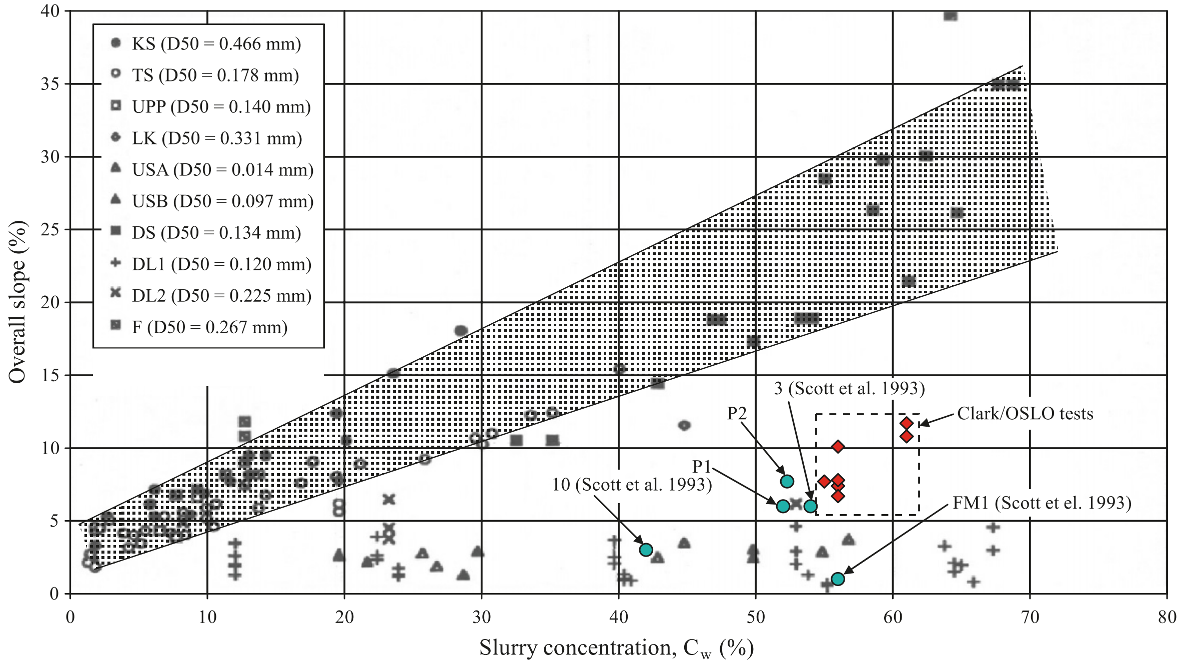
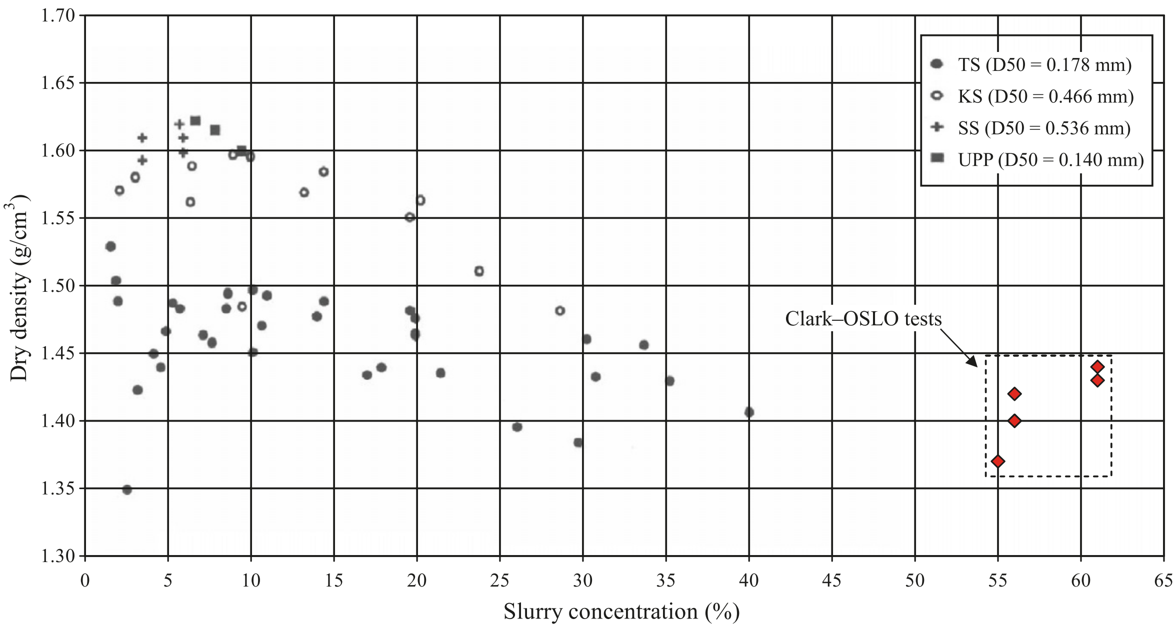


Fig. 21. Variation of density of the beach deposit with slurry concentration for various flume tests (adapted from Küpper et al. 1992*b*).



over similar slurry concentrations (26%–57%). The USA tailings had a grain diameter corresponding to 50% passing by mass, D_{50}, of 0.014 mm while the Clark and OSLO combined tailings of this research had D_{50} values raging from 0.17 to 0.18 mm. Comparing the USA tailings with these materials, beach slope increases with increasing mean grain size. Küpper et al. (1992*b*) reported similar findings by comparing tailings materials having different mean grain sizes under directly comparable flow rate and slurry concentration parameters.

These results show that flow rate is the dominant factor in determining beach slope. As well, for a given range of slurry concentrations and flow rates, beach slopes will decrease with increasing fines content of the tailings material. Beach slopes have been found to decrease with decreasing mean grain size.

Density

Figures 21 and 22 show the variation of dry density with slurry concentration and specific flow rate. Data for the Clark and OSLO materials in Figs. 21 and 22 are averages of the dry density values presented in Figs. 11 to 15. The scatter of the data in Fig. 21 is partially due to the inclusion of tests using a range of flow rates, and likewise the points in Fig. 22 correspond to different slurry concentrations (Küpper 1991). Also, scatter may be caused by density

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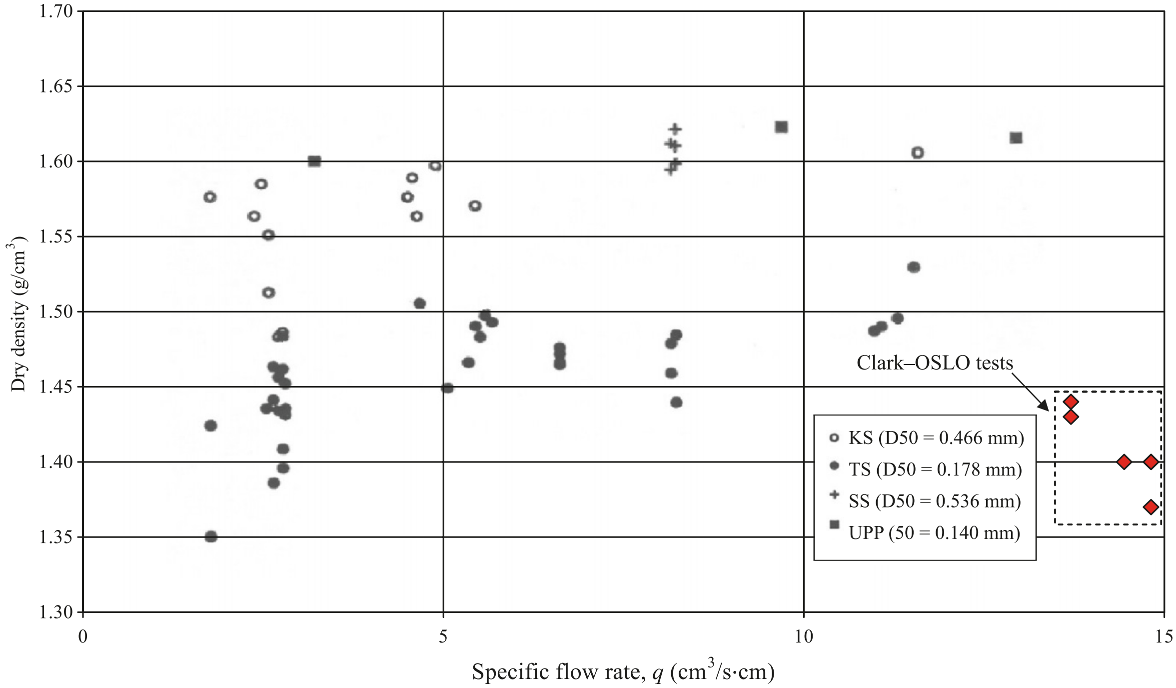
Fig. 22. Variation of density of the beach deposit with specific flow rate for various flume tests (adapted from Küpper et al. 1992*b*).



measurement accuracy problems, as well as variations in grain-size distributions, grain shape, angularity, and surface features.

Density tends to decrease with increasing slurry concentration (Fig. 21). There was a relatively good correlation between the oil sand tailings results and the other materials with regard to slurry concentration. However, no consistent change in density was found with flow rate. There is a large amount of scatter in Fig. 22 that may be due to differences in minerology, grain shape, and (or) surface features between the materials.

Conclusions

Large-scale laboratory flume tests were used to hydraulically deposit oil sand tailings and compare the effects of the combined tailings for the OSLO and the Clark extraction processes on the characteristics of the beach deposit. Flume fine tailings runoff was collected for subsequent evaluation of their geotechnical properties. Several conclusions were reached as a result of the flume deposition testing program.

- The design of the flume test was successful based on the similarity between predicted and actual test results.
- Flume tests are suitable for qualitatively modeling the hydraulic deposition of oil sand tailings, but the complex nature of the deposition process precludes quantitative extrapolation of laboratory results to the field. Field-scale deposition tests are required to determine the typical characteristics of beach deposit produced at a commercial scale.
- The reproducibility of the flume tests shows that the beach building process is a controlled process and therefore, beaches can be designed.
- Beach slopes were found to steepen with increasing slurry concentration and decrease as flow rate increased.
- For similar flow rates and slurry concentrations, beach slopes decreased with increasing fines content.
- Flow rate appears to be the dominant parameter for determining beach slope.

The results of flume tests using oil sand tailings were compared with the results of numerous other flume tests using a variety of materials and covering a wide range of slurry concentrations and flow rates. These comparisons also produced several conclusions.

- There was a good correlation between flume test results using oil sand tailings and the various other tailings materials with regard to the trend of decreasing beach slope with increasing flow rate.
- The variation of beach slope with slurry concentration resulted in one set of data for material with little or no fines and another set of data for materials with appreciable fines content, such as oil sand tailings.
- For the low fines materials, beach slope became steeper as slurry concentration increased. However, for the high fines materials, the beach slope was influenced by fines content. For a given range of slurry concentrations and flow rates, beach slopes decreased with increasing fines content of the tailings material.
- The beach density was observed to decrease with increasing slurry concentration, but no consistent change was observed for a variation in flow rate.
- The correlation between the various flume test results show the reliability and effectiveness of flume testing in terms of establishing general relationships. These comparisons can serve as a guide to predict beach slopes and determine which parameters control beach slope and density for tailings materials.

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CHAPTER 3. INFLUENCE OF THE EXTRACTION PROCESS ON THE CHARACTERISTICS OF OIL SANDS FINE TAILINGS

This paper was previously reviewed, accepted and published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal. It is presented as published as part of this Ph.D. thesis as Chapter 3.

Reference: *Influence of the extraction process on the characteristics of oil sands fine tailings*. CIM Journal, 1(2), 93-112.

Page Numbering:

CIM Journal: 93 to 112 (top right)
This thesis: 30 to 49 (bottom center)

Influence of the extraction process on the characteristics of oil sands fine tailings

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ABSTRACT An overall study was conducted to evaluate the properties and processes influencing the rate and magnitude of consolidation for oil sands fine tailings produced using different extraction processes. As part of the overall study, a comprehensive description of physical and chemical characteristics of fine tailings generated by caustic and non-caustic processes was carried out. Ultimately, the influence of these fundamental properties on the compressibility, hydraulic conductivity and shear strength properties of the fine tailings was assessed. The characteristics of the fine tailings are presented in terms of index properties, mineralogy, specific surface area, water chemistry, liquid limits, particle size distribution and structure. A difference in water chemistry was concluded to be the cause of substantial differences in particle size distributions and degree of dispersion of the comparable caustic and non-caustic fine tailings. The degree of dispersion was consistent with predictions for dispersed clays established by the sodium adsorption ratio (SAR) values for these materials. A linear variation of increasing dispersion with increasing SAR up to a SAR value of about 40 has been suggested, above which fine tailings are completely dispersed. The observed dispersed or flocculated structures (viewed using a scanning electron microscope) supported the predictions based on SAR values.

KEYWORDS Oil sands, Fine tailings, Index properties, Specific surface area, Water chemistry, Particle size distribution, Dispersion, Flocculation, Structure, Sodium adsorption ratio, Fines content, Coagulant

RÉSUMÉ Une étude détaillée a été réalisée afin d'évaluer les propriétés et les processus influençant le taux et l'ampleur de la consolidation des résidus fins de sables bitumineux produits par différents processus d'extraction. Dans le cadre de l'étude détaillée, les caractéristiques physiques et chimiques des résidus fins générés par les processus caustiques et non caustiques ont été décrites de manière très complète. De plus, l'influence de ces propriétés fondamentales sur la compressibilité, la conductivité hydraulique et la résistance en cisaillement des résidus fins a été évaluée. Les caractéristiques des résidus fins sont présentées en termes de leurs propriétés de base, de la minéralogie, de la surface spécifique, de l'hydrochimie, des limites liquides, de la granulométrie et de la structure. Il a été conclu que l'hydrochimie différente est la cause des différences significatives dans la distribution granulométrique et le degré de dispersion des résidus fins comparables, caustiques et non caustiques. Le degré de dispersion concordait avec les prédictions pour les argiles dispersées établies par les valeurs du rapport d'adsorption du sodium (SAR) pour ces matériaux. Une variation linéaire de l'augmentation de la dispersion avec une augmentation du SAR jusqu'à une valeur SAR d'environ 40 a été suggérée; au-dessus de cette valeur, les résidus fins sont complètement dispersés. Les structures dispersées ou floculées (observées au microscope électronique à balayage) supportent les prévisions basées sur les valeurs SAR.

MOTS CLÉS Sables bitumineux, Résidus fins, Propriétés caractéristiques, Surface spécifique, Hydrochimie, Granulométrie, Dispersion, Floculation, Structure, Rapport d'adsorption du sodium, Teneur en particules fines, Coagulant

INTRODUCTION

In the oil sands industry, high temperature and the addition of caustic form the basis of the caustic process used successfully to recover bitumen from surface-mined, oil sands ore. However, the caustic process results in the creation of extremely dispersed, high void ratio fine tailings, composed primarily of silt, clay, water and residual bitumen (Scott & Dusseault, 1982a). These caustic-affected fine tailings exhibit extremely low consolidation rates and shear strengths, and require considerable real estate for surface storage. Non-caustic processes are being developed to improve bitumen recovery, improve the process water chemistry and reduce the dispersion of fines during bitumen extraction (Miller, Scott, & Sego, 2009). Producing tailings with reduced fines dispersion improves the consolidation properties of the fine tailings (Miller, Scott, & Sego, 2010a). A potential reduction in fine tailings volume and improved geo-environmental behaviour provided an environmental and economic incentive to examine the relative differences between the characteristics of the fine tailings derived from a caustic and a non-caustic extraction process.

The overall objective of this research program was to evaluate the properties and processes influencing the rate and magnitude of both volume change and strength gain for the tailings produced using non-caustic and caustic extraction processes. The main components of the research program were flume deposition tests (Miller et al., 2009) and testing for geotechnical properties of the fine tailings with standpipes (Miller et al., 2010a), consolidation cells (Miller, Scott, & Sego, 2010b), and thixotropic shear strength measurements (Miller, Scott, & Sego, 2010c).

Fine tailings are a unique and complex material. There are many factors that influence the behaviour of these materials. A comprehensive description and explanation of their physical and chemical properties is essential for understanding their behaviour and for explaining differences between materials. However, an evaluation of the fine tailings from a single perspective is inadequate to fully understand their true nature. Geotechnical engineering, soil chemistry, and the environmental sciences all provide valuable insights regarding the attributes of fine tailings. A comprehensive geo-environmental approach that incorporates aspects from all these domains is necessary to obtain a fundamental understanding of how the characteristics of fine tailings will govern behaviour.

The specific objective of the research reported in this paper is to provide a comprehensive description of the physical and chemical characteristics of the fine tailings. How these fundamental properties influence the compressibility, hydraulic conductivity, and shear strength properties will be presented in a series of papers outlining the findings of this study. The characteristics of the fine tailings will be presented in terms of index properties, mineralogy, specific surface area, water chemistry, Atterberg limits, particle size distribution, and morphology. The differences in the fine tailings result from the type of bitumen extraction process (caustic versus non-caustic), the choice of process water (treated versus untreated), subsequent chemical additions to the fine tailings (caustic versus caustic plus coagulant), and oil sand ore (Ore A versus Ore B; Table 1). The various fine tailings will be evaluated based on their fundamental properties to explain differences in the engineering behaviour in subsequent papers.

FINE TAILINGS MATERIALS

A total of seven different fine tailings derived from extraction pilot plant operations using two different extraction processes and two different oil sands ores were investigated, as shown in Table 1. The process conditions during the flume deposition tests resulted in five fine tailings (Miller et al., 2009) and subsequent chemical additions produced two additional materials.

Fine tailings were generated from 80-tonne samples of typical Syncrude Canada Ltd. (Syncrude) and Suncor Energy Inc. (Suncor) ore that were processed using both the caustic and the non-caustic extraction methods. The tailings were collected as outlined in Miller et al. (2009). Both Syncrude and Suncor oil sands mines are located in northern Alberta, Canada, and use surface mining techniques to mine oil sands for bitumen extraction. For the remainder of this paper, oil sands ore originating from the Syncrude mine will be referred to as Ore A and oil sands ore originating from the Suncor mine as Ore B.

Table1. Fine tailings materials

Fine tailings type	Ore designation	Ore description (using Syncrude geologic facies)	Extraction process	Process water	Coagulant addition
1	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water (RPW)	None
2	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Treated Athabasca River water (TRW)	None
3	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water (RPW)	600 ppm $CaSO_4$
4	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water (RPW)	None
5	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Non-caustic	Treated Athabasca River water (TRW)	None
6	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water (RPW)	600 ppm $CaSO_4$
7	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Untreated Athabasca River water (UTRW)	None

The geology of Ore A is a marine deposit and of Ore B is a non-marine deposit. Both types of oil sand ore were used because of the difference in physical and chemical characteristics based on geological origins. The extraction process water was determined based on the water source that would be used for commercial operations. The extraction process water used during the caustic process was recycled pond water from the Mildred Lake Settling Basin at Syncrude. Sodium hydroxide was added to aid extraction; 0.05 wt % for Ore A and 0.005 wt % for Ore B. For the caustic fine tailings, pH values ranged from about 8.3 to about 8.7. The higher values were representative of some Ore A fine tailings samples. The non-caustic process utilized Athabasca river water (initial pH 7.4), which had been treated by slowly adding a 10% sulphuric acid solution to bring the pH to 5.0 and subsequently adding a 4% (by weight) lime slurry. This increased the pH of the water to be used for extraction back to a pH of 7.4 and resulted in 40 ppm Ca^{2+} in solution. The non-caustic extraction process relied on a methyl isobutyl carbonyl/kerosene mixture as a conditioning agent and physical processes, such as air injection, to encourage bitumen separation. For these non-caustic tailings, the pH values ranged between 8.0 to 8.1. Another non-caustic extraction run was performed using untreated river water (UTRW) and Ore A, so the influence of the chemical treatment of the river process water could be determined. These five fine tailings constitute the basic set of fine tailings materials. The extraction processes are fully described in the Fine Tailings Fundamentals Consortium (FTFC; 1995a) and the collection of the fine tailings is provided in Miller et al. (2009).

Two additional fine tailings materials were created by the addition of 600 ppm of $CaSO_4$ (in solution) to the caustic fine tailings. The calcium sulphate was proposed as a coagulant to improve the settling behaviour of the fine tailings due to the aggregation of clay particles. Therefore, aside from changes in salinity caused by the coagulant addition, these two fine tailings will not differ from the caustic fine tailings in the following initial characteristics: index properties, mineralogy, and specific surface area.

In Table 1, each fine tailings has been designated with a number (Type 1 to 7) to facilitate ease of presentation in figures and tables. In some cases, physical and chemical characteristics for Type 3 and Type 6 fine tailings are not available because these materials were a result of a coagulant addition to Type 1 and Type 4 fine tailings, respectively.

INDEX PROPERTIES

The index properties of the fine tailings (solids content, fines content, bitumen content, water content, specific gravity, void ratio, bulk density, and dry density) are summarized in Table 2. Solids content, fines content, and bitumen content were all measured properties, while the remaining values were calculated using mass and volume relationships.

In the oil sands industry, solids content is commonly used to express the solids-water composition of fine tailings. Solids content is defined as the mass of tailings solids (the non-water portion of the tailings consisting of bitumen and mineral solids) divided by the total mass of the tailings. Solids content was determined by oven-drying samples of fine tailings at 105° C for 24 hours. The solids content of the fine tailings flowing from the beaches in the depositional flumes varied from 7.5 to 9.1%. At the oil sand plants, fine tailings flowing from the pond dykes and beaches enter the tailings ponds with solids contents from 7 to 10% (MacKinnon, 1989).

Solids content can also be expressed in the traditional geotechnical engineering terms of water content and void ratio. Water contents ranged from 999 to 1233%. Water content is defined as the mass of water divided by the mass of tailings solids, including mass of bitumen. The void ratio for the different fine tailings varied from 25 to 30 for saturated conditions.

The fine tailings consisted almost completely of fine-sized material with fines contents ranging from 98 to 99%. The oil sands industry defines the fines content as the mass of solids less than 45 µm, divided by the total mass of tailings solids. The traditional geotechnical engineering definition designates fines as material smaller than 75 µm. Using this definition, the fine tailings were composed entirely of fine-sized particles. Fines contents were determined by wet-sieving the fine tailings through the 75 µm and 45 µm sieves, using supernatant process water corresponding to each material. Typical fine tailings contained in the commercial tailings ponds have initial fines contents of approximately 95% (Scott & Dusseault, 1982b). Fines content will

Table 2. Index properties of the fine tailings

Fine tailings type	Ore	Water	Solids content (%)	Fines content (%)	Bitumen content by total mass (%)	Bitumen content by dry mass (%)	Water content (%)	Specific gravity	Void ratio	Bulk density (Mg/m^3)	Dry density (Mg/m^3)
1	A	RPW	9.1	99	0.35	3.9	999	2.55	25	1.058	0.040
2	A	TRW	8.4	98	0.42	5.0	1090	2.51	27	1.053	0.037
4	B	RPW	8.5	99	0.50	5.9	1076	2.48	27	1.053	0.038
5	B	TRW	7.5	99	0.50	6.7	1233	2.45	30	1.046	0.034
7	A	UTRW	8.8	99	0.46	5.2	1036	2.50	26	1.056	0.039

Table 3. Minerals in fine tailings

Fine tailings type	Ore	Water	Quartz (%)	Plagioclase (%)	K-Feldspar (%)	Siderite (%)	Kaolinite (%)	Illite (%)	Mixed layer clays (%)	Smectite (%)
1	A	RPW	15	0	1	1	69	13	1	0
2	A	TRW	18	1	1	1	63	15	1	0
3*	A	RPW	15	0	1	1	69	13	1	0
4	B	RPW	19	1	1	3	55	20	1	0
5	B	TRW	19	1	1	3	55	20	1	0
6*	B	RPW	19	1	1	3	55	20	1	0
7	A	UTRW	14	0	trace	1	67	17	trace	1

*Note: Type 3 and Type 6 fine tailings consist of coagulant added to Type 1 and Type 4 fine tailings respectively.

Table 4. Minerals in clay sized fraction of fine tailings

Fine tailings type	Ore	Water	Quartz (%)	Kaolinite (%)	Illite (%)	Mixed layer clays (%)	Smectite (%)
1	A	RPW	2	81	15	2	0
2	A	TRW	2	80	15	3	0
3*	A	RPW	2	81	15	2	0
4	B	RPW	2	76	18	4	0
5	B	TRW	2	75	19	4	0
6*	B	RPW	2	76	18	4	0
7	A	UTRW	2	78	15	1	4

*Note: Type 3 and Type 6 fine tailings consist of coagulant added to Type 1 and Type 4 fine tailings respectively.

refer to the oil sands industry definition, based on 45 µm, for the remainder of this study.

Bitumen content can be expressed in terms of total mass or dry mass. Bitumen content by total mass is defined as the mass of the bitumen divided by the total mass of tailings, while bitumen content by dry mass is the bitumen mass divided by the mass of mineral solids plus bitumen. Bitumen contents were determined by the Dean-Stark extraction method (ASTM, 2010) using toluene as the solvent. Bitumen contents by total mass were consistent between the fine tailings, varying from only 0.35 to 0.50%. Similarly, in terms of dry mass, the bitumen contents ranged from 3.9 to 6.7%. At the oil sands plants, bitumen contents of the fine tailings based on total mass are slightly higher, reportedly averaging approximately 2% (MacKinnon & Sethi, 1993) and, in terms of dry mass, a value of 6.5%. This difference may be due to the more controlled conditions and smaller scale of the pilot plant operation used to produce the non-caustic and caustic fine tailings.

Specific gravities were calculated using the following relationship (provided by Scott and Dusseault, 1982a), assuming water, mineral solids, and bitumen have specific gravities of 1.00, 2.70, and 1.03, respectively:

$$G_{ss} = \frac{1 + b}{\frac{1}{G_s} + \frac{b}{G_b}} \quad (1)$$

where G_{ss} is the specific gravity of the fine tailings, b is the bitumen content by dry mass, G_s is the specific gravity of the mineral solids, and G_b is the specific gravity of the bitumen. Specific gravities of the fine tailings varied from 2.45 to 2.55. The bulk densities of the fine tailings ranged from 1.046 Mg/m^3 to 1.058 Mg/m^3, and similarly the dry density varied from 0.034 Mg/m^3 to 0.040 Mg/m^3.

In summary, little variation was seen in the index properties between the different caustic and non-caustic fine tailings. Solids content varied by only 1.6% and fines contents were essentially identical (1% difference). The bitumen contents had only small variations of 0.15 and 2.8% in terms of total and dry mass, respectively. These slight differences between fine tailings, in terms of index properties, should have little effect on their engineering behaviour. Comparisons between the caustic and non-caustic fine tailings from the pilot plant corroborated the typical properties reported for fine tailings found in the field.

MINERALOGY

The mineralogy of the fine tailings was determined using X-ray diffraction (XRD) techniques (Cuddy, 1994). Prior to testing, samples were washed with toluene to remove hydrocarbons. The clay-sized fraction (less than 2 µm) was separated from the fine tailings using an ultrasonic bath and centrifuge, and subjected to a glycol vapour bath for 24 hours to separate the clay minerals. All samples were dispersed using hexametaphosphate as a dispersing agent.

The minerals identified by the XRD analysis and the associated weight fractions for the fine tailings are summarized in Table 3. Table 4 presents the mineralogy of the clay-sized fractions. In general, little variation was seen between fine tailings originating from the same oil sand ores. For Ore A fine tailings, kaolinite was the most abundant clay mineral (63 to 69%) with lesser amounts of illite present (13 to 17%; Table 3). Ore B fine tailings had both 55% kaolinite and 20% illite. Minor amounts of mixed-layer clays (illite-smectite) were present in all the fine tailings. Ore A fine tailings contained slightly more kaolinite and less illite than Ore B fine tailings. These minor differences in the mineralogy of the fine tailings were due to the variations of the oil sands ores from which they originated.

The mineralogy of the fine tailings reflects the average clay mineralogy of the parent material, the McMurray Formation, where kaolinite and illite are the dominate clay minerals. Trace amounts of mixed-layer clays, smectite, vermiculite, and chlorite are also present (Kasperski, 1992). The mineralogy of the fine tailings from the flume deposition tests was similar to that of the fine tailings from Syncrude's tailings pond. The field fine tailings were characterized as dominantly kaolinite (55 to 65%) and illite (30 to 40%), with minute traces of mixed-layer clay minerals (Dereniwski & Mimura, 1993).

Quartz was the most abundant non-clay mineral. Minor amounts of siderite were found in all the fine tailings, while minor to trace amounts of plagioclase and K-feldspar were found in most samples.

The mineralogy of fine tailings is not affected by the type of extraction process or the process water. It is a reflection of the mineralogy of the oil sands ore used to generate the fine tailings. This conclusion is supported by the consistency between the Ore A fine tailings and, similarly, between the Ore B fine tailings. The caustic hot water extraction process does not alter the clay mineralogy in the fine tailings (Scott, Dusseault, & Carrier, 1985). Thus, mineralogy should not play a significant role when fine tailings from the same ore are compared for geotechnical engineering behaviour.

SPECIFIC SURFACE AREA

For an electrically-charged soil particle, the magnitude of the electrical charge is directly related to the particle surface area (Mitchell & Soga, 2005). Specific surface area is defined as the available surface area per unit mass and increases as the particle size decreases. It is a good indicator of the influence of electrical forces on the behaviour of the particle relative to the influence of the mass forces (the weight of the particle). A particle whose behaviour is controlled by surface-derived forces, rather than mass-derived forces, is described as a colloid. Clay particles are colloids because of their small size and irregular shape. The lower limit of the colloid range has been suggested at a specific surface area of 25 m^2/g (Lambe & Whitman, 1969). Silt-sized and larger particles have specific surface area values of less than 1 m^2/g, much lower than the lower bound for colloidal behaviour.

The specific surface area of the fine tailings was determined using ethylene glycol monoethyl ether (EGME) as the adsorbed phase (Sethi, 1994). The results are shown in Table 5. The test procedure specifies the destruction of organics by oxidation with hydrogen peroxide and subsequent air drying and grinding of the samples. The mechanical effort of a complete grinding process would render all the fine tailings to their basic clay particle components, regardless of the extraction process. Thus, these values cannot be used to interpret the dispersed natures of the fine tailings because they are, in fact, total specific surface areas.

Specific surface area is a reflection of mineralogy, so one would expect the comparable Ore A and Ore B fine tailings to have similar specific surface areas. This is indeed the case for both the Ore A and Ore B fine tailings. Fine tailings Type 1, 2, and 7 (Ore A materials) had total specific surface areas of 108 m^2/g, 108 m^2/g and 118 m^2/g, while Type 4 and Type 5 (Ore B materials) had values of 134 m^2/g and 140 m^2/g. The Ore B fine tailings had higher specific surface areas than the Ore A fine tailings. This was due to the marginally greater illite content and reduced kaolinite content of the Ore B fine tailings (Table 3).

Typical ranges of specific surface area for kaolinite, illite and smectite are also presented in Table 5. The specific surface area decreases with increasing particle size, with kaolinite having the largest particles (Mitchell & Soga, 2005). All of the minerals in the fine tailings contribute and the total specific surface area is a reflection of this combination of mineral particles.

Using the range of typical specific surface areas (Table 5) for the clay minerals present in the fine tailings (Table 3), the specific surface area accounted for by the clay minerals can be calculated. The clay minerals only account for about 18 to 36% of the measured specific surface area. The non-clay minerals (quartz, plagioclase, feldspar, and siderite) contribute very little to specific surface area. Mikula & Omotoso (2004) reported that high specific surface areas typically observed in mature fine tailings can be attributed to smectite interstratification of kaolinite and illite. Amorphous oxides may also contribute to measured specific

Table 5. Total specific surface area for fine tailings

Fine tailings type	Ore	Water	Chemical addition	Total specific surface area (m^2/g)
1	A	RPW	none	108
2	A	TRW	none	108
3	A	RPW	$CaSO_4$	83
4	B	RPW	none	134
5	B	TRW	none	140
6	B	RPW	$CaSO_4$	127
7	A	UTRW	none	118
	Typical clay minerals			
	Kaolinite			10 to 20
	Illite			65 to 100
	Smectite			700 to 840

surface area. The discrepancy between calculated and measured specific surface areas for the fine tailings may be due to interstratification of kaolinite and illite, with smectite that was not appreciated or readily apparent from the XRD analysis and was reported as simply kaolinite or illite. As well, there may have been incomplete dissolution of organics and residual bitumen during the test procedure.

The total specific surface areas of the caustic fine tailings with a coagulant added were less than the values obtained for the original fine tailings (Table 5). Type 3 fine tailings had a total specific surface area of 83 m^2/g and Type 6 had a value of 127 m^2/g. Calcium sulphate was added to these fine tailings to induce aggregation of the clay particles. However, once the samples were dried and ground during the testing procedure, any clay particle aggregates should have been eliminated and the total specific surface areas similar to the original fine tailings would be expected (108 m^2/g for Type 1 and 134 m^2/g for Type 4 fine tailings, respectively). The lower values may be a result of either incomplete grinding of the sample or the formation of aggregates due to calcium sulphate addition that are more resistant to the effort normally applied during grinding. This finding also demonstrates the variability and uncertainty that can arise when fine tailings undergo operator-sensitive procedures during testing. Cerato and Lutenegger (2002) discuss the repeatability of measuring total specific surface area for fine-grained soils using ethylene glycol monomethyl ether (EGME); the variation between the caustic fine tailings and caustic with coagulant fine tailings is near or within the range typically expected for fine grained soils, which is a standard deviation between 16 m^2/g and 22 m^2/g.

In summary, specific surface area is a reflection of mineralogy and grain size distribution, so the similarity between fine tailings derived from similar ores is not surprising, given the consistent mineralogy of the comparable fine tailings. Thus, specific surface area should have little influence when comparing geotechnical differences between these similar materials.

INITIAL WATER CHEMISTRY

The water chemistry of the fine tailings will reflect the chemical nature of the extraction processes and process water, as well as the water chemistry of the original oil sands ore. The connate water chemistry of the oil sands ore was determined in terms of major anions and cations by Syncrude Canada Ltd. (Smith, Spence, & Wong, 1994). Oil sands samples were slurried with hot (80° C), deionized water (100g) and the slurries were then stirred occasionally for 10 minutes. The aqueous phase was decanted and centrifuged (20,000 rpm for 20 minutes), and then passed through an ultrafilter using a YM3 Diaflow ultrafilter (nominal retention of 3000 MW). The ore samples were analyzed for chloride and sulphate by ion chromatography, and for bicarbonate by titration with 0.006N hydrochloric acid, using a Mettler DL 20 autotitrator. The concentrations of iron, aluminum, silicon, magnesium, sodium, calcium, and potassium were measured by inductively coupled plasma (ICP) flame emission spectroscopy. The initial water chemistry of the oil sands ores is presented in Table 6. Ore A was characterized by average concentrations of sodium (2.5 times), chloride (4.8 times) and sulphate (two times) greater than those of Ore B. This discrepancy reflects the marine origin of Ore A versus the non-marine origin of Ore B. Although the pH of the ore waters was not measured for these ores, typical pH values for medium-grade oil sands, such as these, vary between 7 and 8, with non-marine ores having the higher values.

Table 6. Water chemistry of ore connate water

Fine tailings type	Ore	Anions (mg/L)			Cations (mg/L)							SAR*
		HCO_3	Cl	SO_4	Fe	Si	Al	K	Mg	Ca	Na	
1	A	75	99.8	93.6	0	0.74	0	1.89	0	0	162.8	-
2	A	65	109.6	145.1	0.55	6.31	2.58	3.05	0	0	193.8	-
4	B	90	24.6	66.8	0	0.54	0	3.15	0	1.39	76.84	18
5	B	85	18.9	53.9	0	1.05	0	2.87	0	0.65	68.45	23
7	A	66	106.3	129.6	0.18	3.92	1.34	2.20	0	0.29	178.3	91

* SAR = sodium adsorption ratio

Table 7. Water chemistry of the fine tailings

Fine tailings type	Ore	Process water	pH	Anions (mg/L)			Cations (mg/L)							SAR*
				HCO_3	Cl	SO_4	Fe	Si	Al	K	Mg	Ca	Na	
1	A	RPW	8.7	1128	480	368	0.31	3.6	1.6	8.7	2.3	1.3	930	114
2	A	TRW	8.0	267	161	271	0.33	5.0	1.4	7.2	5.1	7.2	316	22
4	B	RPW	8.3	806	296	256	0.59	4.4	2.1	10.6	4.5	5.3	600	46
5	B	TRW	8.1	210	21	196	0.18	2.3	0.5	7.8	13	21.7	129	5
7	A	UTRW	8.0	372	161	140	0.86	3.5	0.8	6.3	3.4	3.9	308	28

* SAR = sodium adsorption ratio

The water chemistry of the fine tailings was determined in terms of major anions, cations, and pH by CanmetENERGY at the Devon Research Centre and are presented in Table 7. Sodium concentrations in the caustic fine tailings were approximately six to eight times greater than the concentrations originally measured in the ore connate water. Increasing the concentration of sodium ions in the pore water of fine grained soils is known to result in increased dispersion of clay particles (Mitchell & Soga, 2005). Thus, the caustic extraction process is expected to have a detrimental effect on ore water chemistry in terms of degree of dispersion. The impact of the extraction process on pore water chemistry and ensuing degree of dispersion should be less for the non-caustic fine tailings, as the increase in sodium concentration between ore connate water and fine tailings was only 1.6 to 1.9 times. No water chemistry data for fresh Type 3 and Type 6 fine tailings was available, as these fine tailings were produced after the initial water chemistry analysis was performed.

Ore A fine tailings

Type 1 fine tailings had a much greater sodium concentration (930 mg/L) than either of the non-caustic Type 2 and Type 7 fine tailings (316 mg/L and 308 mg/L). Bicarbonate was also found at a higher level in the Type 1 fine tailings. These results reflect the high level of sodium hydroxide (0.05 wt %) used for the caustic process with Ore A (Smith et al., 1994) and the absence of sodium hydroxide in the non-caustic process. Calcium concentrations for the Type 1 fine tailings were lower than those of the Type 2 and Type 7 materials, but none exceeded 8 mg/L.

As expected, the Type 2 fine tailings with treated water had higher levels of calcium and sulphate, but lower bicarbonate levels than the Type 7 fine tailings with untreated water. The process water was treated for the non-caustic process with sulphuric acid and lime in order to reduce the bicarbonate concentration in the water. This modification was proposed to improve the settling behaviour of the fine tailings.

Ore B fine tailings

The Ore B fine tailings followed the same trend seen for the Ore A fine tailings. Sodium concentrations were much greater for the Type 4 fine tailings (600 mg/L), relative to the Type 5 material (129 mg/L). Bicarbonate was also higher for the Type 4 fine tailings. The Type 5 fine tailings had the highest levels of calcium of all the fine tailings (21.7 mg/L), more than four times that of the caustic Type 4 fine tailings (5.3 mg/L).

Ore A versus Ore B

Type 1 fine tailings had greater levels of sodium (930 mg/L) than their Type 4 counterparts (600 mg/L). The same was true for bicarbonate concentrations. These differences may be explained by the use of a smaller amount of sodium hydroxide to achieve optimal bitumen extraction efficiency for Ore B (0.005 wt %) than was required for the Ore A (0.05 wt %; Smith et al., 1994). As well, on average, Ore A had appreciably greater sodium concentrations (178 mg/L) than Ore B (73 mg/L), which would also contribute to the differences seen in the fine tailings (Table 7).

For the non-caustic process, Type 2 and Type 7 fine tailings had sodium levels (316 mg/L and 308 mg/L) that were more than double that of the Type 5 fine tailings (129 mg/L). Because no sodium hydroxide is used in the non-caustic process, the difference is most likely due to the higher levels of sodium salts in Ore A mentioned earlier.

The water chemistry of the fine tailings varies greatly depending on the extraction process, treatment of the process water and the oil sands ore. These differences may influence the behaviour of the fine tailings, but it is uncertain to what degree. However, the variations in water chemistry for the fine tailings can be quantified by the sodium adsorption ratio. This ratio may be used as a guideline for determining whether the clays are in a dispersed or flocculated state (Dawson, Sego, & Pollock, 1999).

Sodium adsorption ratio

The sodium adsorption ratio (SAR) relates the composition of the solution phase to the composition of the adsorbed phase. That is, it provides a prediction of the adsorbed phase based on the concentrations of ions in solution. For practical purposes, SAR is defined as:

$$SAR = \frac{[Na^+]}{\sqrt{\dfrac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \tag{2}$$

where the soluble cation concentrations are in me/L.

In general when SAR values exceed a certain level specific to each material, sodium ions will occupy adsorption sites on the clay, resulting in dispersion of the clays. The SAR values for the fine tailings are presented in Table 7. All of the fine tailings had SARs in excess of 20 (22 to 114), with the exception of Type 5 fine tailings that had an SAR of 5. It has also been previously reported by Dawson et al. (1999) that SARs greater than about 7 indicate a high potential for dispersion. Based on these results, it may be expected that fine tailings with an SAR greater than 20 are likely to be in a dispersed state, while those with a SAR of 5 or less will have a less dispersed structure, approaching a flocculated structure.

Ore A fine tailings Type 1 fine tailings had the highest SAR (114), followed by Type 7 (28) and Type 2 fine tailings (22). These results indicate that the caustic materials were much more dispersed than the non-caustic. Treating the river water resulted in an improvement for Type 7 in terms of SAR value for the non-caustic fine tailings. However, all three Ore A fine tailings were well above a SAR of seven and, based on SAR, all would be expected to have been in a dispersed state.

Ore B fine tailings The Type 4 fine tailings had a much higher SAR (46) than the Type 5 fine tailings (5). Based on SAR, the caustic Type 4 fine tailings would be highly dispersed. The non-caustic Type 5 fine tailings however, were very close to the reported boundary for flocculated clays (SAR of approximately seven) and may have exhibited a less dispersed structure.

Summary

To summarize, the caustic fine tailings consistently had greater sodium and bicarbonate concentrations and lower levels of calcium than the comparable non-caustic fine tailings. Treating the river water resulted in higher calcium and sulphate concentrations, as predicted. Differences between the fine tailings have been linked to the levels of sodium hydroxide used for the extraction process and the water chemistry of the oil sands ore. Finally, SAR is a parameter that can be used to estimate the dispersed state of clays. Based on SAR, the Type 1 fine tailings were in the most dispersed state, followed by the Type 4, Type 7, Type 2 and, finally, Type 5 fine tailings.

ATTERBERG LIMITS

The liquid limits and plastic limits were determined for the fine tailings following the procedure outlined in ASTM D 4318-05 (ASTM, 2005a). From the initial solids contents (7.5 to 9.1%; Table 2), evaporation was used to lower the water content to the liquid and plastic limit ranges, as suggested in the procedure. As a result, the water chemistry of the samples (Table 7) became more concentrated than if the fine tailings were allowed to dewater naturally. Fine tailings consolidate very slowly and time restrictions prohibit preparing samples for testing in this fashion. Fine tailings are known to exhibit a very rapid thixotropic gain in strength (Kessick, 1979, Scott et al., 1985, Suthaker & Scott, 1996), so it was also important to perform the tests quickly in order to minimize the influence of thixotropy.

The liquid limits, plastic limits, and plasticity indexes are summarized in Table 8. The liquid limits varied from 49.5 to 59.6% and the plasticity indexes from 23.7 to 30.1%. All of the fine tailings would be classified as high-plasticity clays (CH). The liquid limit of field fine tailings (caustic) was reported to range from 60 to 70% and the plasticity index from 30 to 40% (Devenny, 1993). The Type 1 and Type 4 fine tailings (caustic) from this research program have similar values to recent measurements of liquid and plastic limits for Type 1 mature fine tailings (MFT; Table 8; Jeeravipoolvarn, Scott, Donahue, & Ozum, 2008) and variations may be explained due to possible differences in mineralogy and bitumen content. Note that, for liquid limit testing for fine tailings, thixotropy causes higher values if the tests are not done rapidly and may be the reason for the higher ranges reported in the literature.

The liquid limits of fine tailings are influenced by the water chemistry, clay mineralogy, and bitumen content (Scott et al., 1985). All seven fine tailings had similar bitumen contents (Table 2), thus bitumen content was not responsible for the variation in the results. The differences in liquid limits for the various fine tailings can be explained by comparing fine tailings with similar clay mineralogy and determining the influence of the water chemistry.

Ore A fine tailings

Differences in clay mineralogy of the comparable Ore A fine tailings will not influence the liquid limits of the materials because the mineralogy is essentially the same. The liquid limit of the Type 1 fine tailings (49.5%) was lower than that of the Type 2 fine tailings (59.6%). The variation was due to differences in the water chemistry. The concentration of sodium ions (Na^+) in the Type 1 fine tailings (930 mg/L) was much higher than the Type 2 material (316 mg/L). It is known that high sodium concentrations result in a decrease in the thickness of the double layer surrounding clay particles (Mitchell & Soga, 2005). This limits the adsorption capacity of the clay particles and, in turn, lowers the liquid limit, as was the case here.

The non-caustic extraction process was performed twice using Ore A: once using untreated Athabasca river water, and once with river water treated with sulphuric acid and lime to remove bicarbonate and increase calcium content in the water. The liquid limit of the Type 7 fine tailings (55.4%) was similar to that of the Type 2 fine tailings (59.6%). These fine tailings also have similar mineralogies and similar water chemistry, so the similarity of the liquid limits is not unexpected, with the sodium ion concentrations dominating the behaviour (compared with the relatively small calcium concentrations) even after the water treatment process.

The addition of 600 mg/L of $CaSO_4$ to the Type 1 fine tailings only resulted in a slightly higher liquid limit for Type 3 material (53.8%), compared with 49.5%. This small increase is probably the result of increased calcium ions in

Table 8. Atterberg limits of fine tailings

Fine tailings type	Ore	Water	Chemical additive	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)
1	A	RPW	none	49.5	25.8	23.7
2	A	TRW	none	59.6	30.5	29.1
3	A	RPW	$CaSO_4$	53.8	28.5	25.3
4	B	RPW	none	52.1	26.9	25.2
5	B	TRW	none	58.3	28.2	30.1
6	B	RPW	$CaSO_4$	58.3	29.1	29.2
7	A	UTRW	none	55.4	28.4	27.0
MFT	A	—	none	52	27	25

solution. Increasing the concentration of divalent and trivalent cations tends to increase the liquid limit of non-expansive clays, such as kaolinite (Mitchell & Soga, 2005).

Ore B fine tailings

The clay mineralogies of the comparable Ore B fine tailings were also very similar (Table 3). Again, differences in clay mineralogy did not influence the liquid limits of the materials. The Type 4 fine tailings have a lower liquid limit (52.1%) than the Type 5 fine tailings (58.3%). This follows the same pattern seen with the Ore A fine tailings. That is, high sodium ion concentrations (600 mg/L and 129 mg/L for Type 4 and Type 5 fine tailings, respectively) are responsible for decreased adsorption capacity and ultimately the lower liquid limit.

The $CaSO_4$ addition to the Type 4 fine tailings resulted in a higher measured liquid limit (52.1% and 58.3% for Type 4 and Type 6, respectively). This discrepancy, again, is the effect of more calcium ions in solution, which ultimately increases the liquid limit for non-expansive clays.

Comparison of Ore A versus Ore B

There was slightly more variation between the clay mineralogy of the comparable Ore A and Ore B fine tailings, than between fine tailings produced from the same oil sand ore. However, the clay mineralogies were still very similar and did not greatly influence the liquid limits of the materials.

Caustic fine tailings Type 1 fine tailings had a lower liquid limit (49.5%) than Type 4 (52.1%), but again this difference is explained by the greater presence of sodium in the Type 1 fine tailings and the higher concentrations of calcium in the Type 4 fine tailings, as well as the resulting behaviour of the double layer mentioned above. In addition, the greater presence of illite in the Type 4 fine tailings should result in a higher liquid limit.

Non-caustic treated fine tailings The liquid limits of these two fine tailings were very similar (59.6% and 58.3% for Type 2 and Type 5 fine tailings, respectively). One would expect the Type 2 fine tailings to have a lower liquid limit because of their higher sodium levels and lesser amounts of calcium (Table 7) and illite (Table 3). Slight delays in the testing procedure, allowing for a build up in thixotropic strength, may explain these results.

Summary

Fine tailings with similar bitumen contents and clay mineralogy were compared in terms of liquid limit. The fine tailings with higher sodium concentrations had consistently lower liquid limits. For fine tailings with similar sodium concentrations, the fine tailings with the greater calcium concentration had a higher liquid limit. The addition of $CaSO_4$ consistently increased the liquid limit of the fine tailings. All of these results have been explained by means of the double-layer theory for clay particles and the water chemistry of the fine tailings (Table 7).

From an engineering perspective, the differences between the liquid limits and plasticity indices for the fine tailings are minor. Based on these results, the deposits would tend to have about the same engineering behaviour once water contents approaching typical geotechnical ranges were achieved. Currently, the water contents of the fine tailings are much greater than the liquid limit and the fine tailings exist as slurries.

PARTICLE SIZE DISTRIBUTIONS

The fine material (less than 45 μm) in the fine tailings originated from interbedded clay bands in the oil sands formations. The extent to which these clay bands were broken up depends on the mining methods, the bitumen extraction processes and the composition of the oil sands ore. Non-dispersed and dispersed hydrometer tests were performed to determine particle size distributions and the degree of fines dispersion for both the caustic and the non-caustic fine tailings.

Test procedures

The fine tailings underwent hydrometer tests, following the procedure outlined in ASTM D 4221-99R05 (ASTM, 2005b) for determining the dispersive characteristics of clay soil by double hydrometer, in conjunction with the ASTM D 0422-63R07 procedure for the standard particle size analysis of soils (ASTM, 2007). The double-hydrometer method compares the clay-sized fraction of a standard hydrometer test with a second hydrometer test that involves no mechanical agitation or addition of dispersing agent.

It was assumed that, due to the different extraction processes, the non-caustic extraction process would produce fine tailings that would be less dispersed than the caustic fine tailings. Therefore, preservation of the as-extracted chemical and physical characteristics of the fine tailings was essential for evaluation of the particle size distributions. In order to maintain the chemistry of the fine tailings, any water added was process water. Filtration (using a 0.2 μm opening size, nylon filter) was performed to reduce the water content for tests that required a lower water content because evaporation techniques would concentrate chemicals in the tailings water. The second testing criterion was retaining the physical characteristics of the fine tailings. Bitumen could not be removed, solids could not be dried and excessive agitation that would break up particles was not allowed. Bitumen was not removed because tailings are generally dried during the process of bitumen removal. Drying the tailings modifies the chemical properties of tailings. Once dried, individual tailings particles become cemented together by heavy hydrocarbons and fine tailings would have to be broken up by grinding, blending, and sonification. This process exerts a considerable influence on the particle size distribution.

The degree of dispersion of the fine tailings was determined by comparing the non-dispersive and dispersive test results. The standard ASTM method was developed for dispersive clays subject to high shrink-swell potential and recommends using the 5 µm size as the reference point to calculate percent dispersion. The oil sands industry uses the 2 µm size as the boundary for the clay-sized fraction and, in the past, percent finer than 2 µm has been used to calculate percent dispersion. The 2-µm size was used as a reference point because it would be representative of the dispersive states of the majority of the different fine tailings. Percent dispersion (D_f) is defined as:

$$D_f = \frac{\textit{Percent finer than } 2\mu m \textit{ in nondispersed test}}{\textit{Percent finer than } 2\mu m \textit{ in dispersed test}} \times 100 \quad (3)$$

Test results for non-caustic and caustic fine tailings

The non-dispersive and dispersive particle size distributions for the five basic materials are presented on Figures 1 through 4. For easy comparison, the fines fractions (less than 45 µm), the clay-sized fractions (less than 2 µm), the percent finer than 1 µm and the percent dispersion (D_f) for the fine tailings have been summarized in Table 9. The fine tailings derived from Ore A are discussed first (Figures 1 and 2), followed by the Ore B materials (Figures 3 and 4).

Ore A fine tailings There was little difference between the particle size distributions determined from the dispersed and non-dispersed methods for Type 1 fine tailings for material coarser than approximately 1.7 µm (Figure 1). Both methods measured a clay-sized fraction of 43%, resulting in a percent dispersion of 100%. The dispersed state of the Type 1 fine tailings was expected because sodium hydroxide is added during the caustic process as a conditioning agent to disperse the clay band lumps that are introduced (as much as possible) into the extraction process to optimize the separation of bitumen from mineral solids. However, the distributions of the clay-sized fractions were somewhat different, with the non-dispersed test (19% less than 1 µm) having less finer-sized material than the dispersed test (32% less than 1 µm). These grain size distributions suggest that, while the majority of the caustic fine tailings were dispersed during the extraction process, some of the finer-sized material remained as small lumps from the original clay bands. These small clay band lumps are perhaps best described as clay particle aggregates. The more concentrated dispersive efforts of a similar sample used during the hydrometer tests resulted in their eventual dispersion, as seen in Figure 1. In summary, the Type 1 fine tailings were almost completely dispersed and the majority of the fines were present as individual particles.

The non-dispersed particle size distribution for the Type 2 fine tailings (Figure 2) definitely showed a much less dispersed material. The non-dispersed material was slightly coarser than the dispersed material, in the 45 µm to 3 µm size range. However, there was a steep decrease in the non-dispersed curve at approximately 3 µm that resulted in a significantly smaller clay-sized fraction. Clay-sized fractions of 15% and 47% were measured for the non-dispersed and dispersed tests, respectively, resulting in a percent dispersion of only 32%. Thus, the fines were less broken up during the non-caustic process and existed as small silt and clay-size particles of clay bands, instead of as individual particles. The non-caustic process relied on a methyl isobutyl carbinol/kerosene mixture as a conditioning agent and physical processes, such as air injection, to encourage

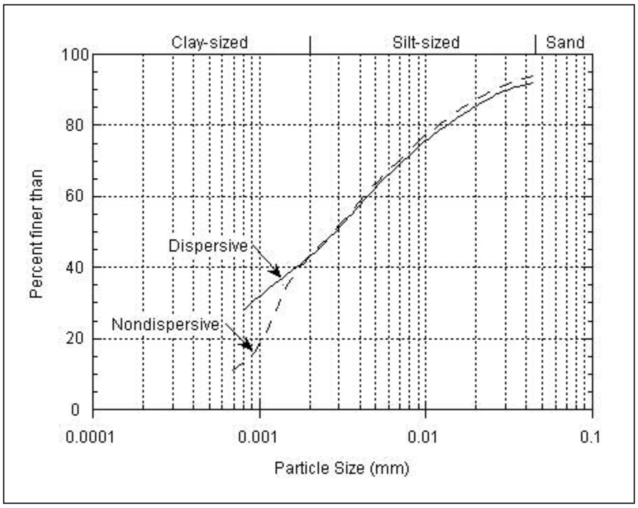

Figure 1. Particle size distribution for Type 1 fine tailings.

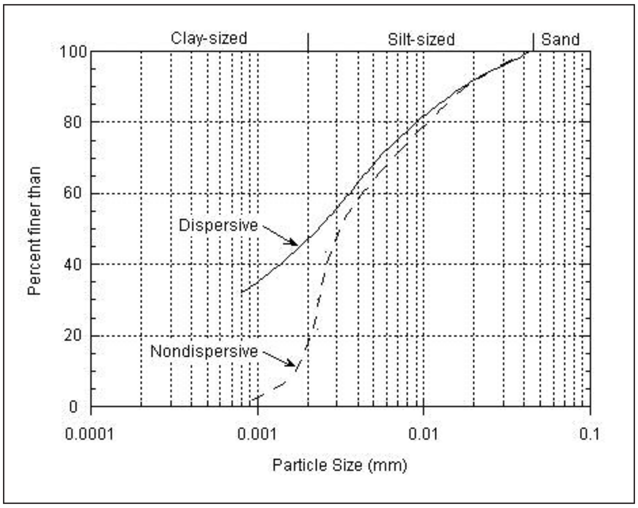

Figure 2. Particle size distribution for Type 2 fine tailings.

Table 9. Particle size distribution characteristics of fine tailings

Fine tailings type	Test method	< 45 µm (%)	< 2 µm (%)	<1 µm (%)	Percent dispersion
1	Dispersed	92	43	32	100
	Non-dispersed	94	43	19	
2	Dispersed	98	47	35	32
	Non-dispersed	99	15	2.5	
4	Dispersed	97	49	40	100
	Non-dispersed	96	49	40	
5	Dispersed	97	48	33	10
	Non-dispersed	98	5.0	1.5	
7	Dispersed	99	41	29	100
	Non-dispersed	99	41	15	

bitumen separation. The non-caustic conditioning agents were devised to be less dispersive than the sodium hydroxide used for the caustic process, and indeed, Figures 1 and 2 show that the Type 2 fine tailings were less dispersed than the Type 1 fine tailings.

Chemical treatment of the non-caustic process water also had an influence on the particle size distribution of the fine tailings. For material coarser than 2 µm, Type 7 fine tailings had similar dispersive and non-dispersive particle size distributions, and 100% dispersion (clay-sized fractions of 41% for both methods). However, the non-dispersed material had a finer distribution of the clay-sized fraction (15% and 29% less than 1 µm for the non-dispersed and dispersed tests, respectively). Therefore, while material coarser than 2 µm was completely dispersed, there was finer material present in the form of small clay band lumps or clay particle aggregates. If 1 µm was used as the reference point for percent dispersion, the Type 7 fine tailings would have a value of 52%, compared with values of 59% and 7% for Type 1 and Type 2 fine tailings, respectively. Thus, without the pre-treatment of the process water with acid and lime, the non-caustic process resulted in fine tailings that were in a slightly less dispersed state than the caustic Type 1 fine tailings, but the effects were seen in the finer-sized material (less than 2 µm). Use of the 2 µm reference point to determine percent dispersion reflects a material composed of highly dispersed fine tailings, identical to the Type 1 tailings. Treated river water with more calcium in solution would tend to result in larger clay aggregates. The less dispersed non-caustic fine tailings have been found to settle much faster than the fully dispersed caustic fine tailings (Miller et al., 2010a).

Ore B fine tailings For Type 4 fine tailings (Figure 3), the dispersive and non-dispersive curves were almost identical. This resulted in a percent dispersion of 100%, with both test methods having clay-size fractions of 49%. Thus, again as expected, the dispersive nature of the caustic extraction process resulted in fine tailings that were completely dispersed and where the fines existed as individual particles.

The particle size distributions of the Type 5 fine tailings (Figure 4) were indicative of a much less dispersed material. The non-dispersed and dispersed distributions of Type 5 fine tailings were generally similar for material coarser than approximately 4 µm, after which the non-dispersed test had substantially less finer material. The divergence of the distributions resulted in a percent dispersion of only 10% (clay-sized fractions of 5% and 48% for the non-dispersed and dispersed tests, respectively) Thus, similar to the Ore A fine tailings, the non-caustic fine tailings contained fine-sized material that existed as small silt and clay-size lumps of clay band, which were not dispersed during the extraction process.

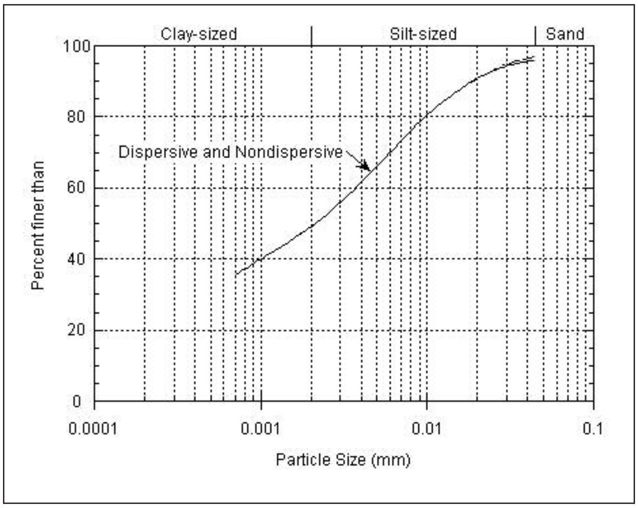

Figure 3. Particle size distribution for Type 4 fine tailings.

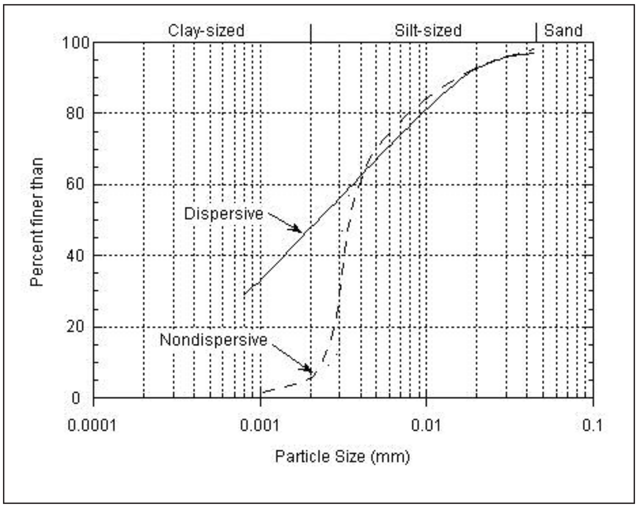

Figure 4. Particle size distribution for Type 5 fine tailings.

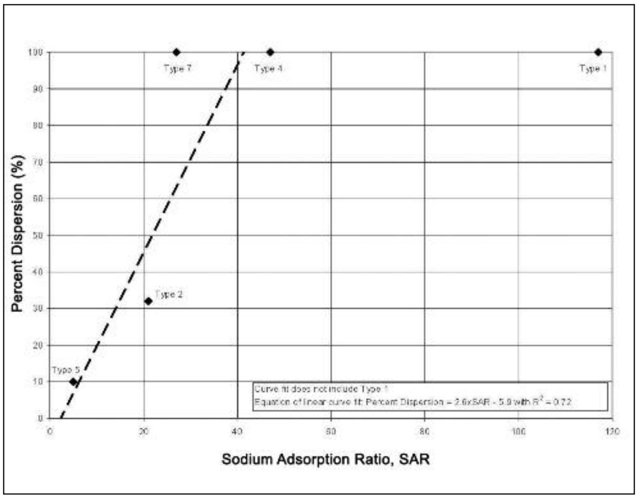

Figure 5. Percent dispersion as a function of sodium adsorption ratio (SAR).

SUMMARY

While the absolute values of the particle size distributions differ for the fine tailings, the shape and form of the non-dispersed and dispersed distributions were generally consistent. No pronounced differences were observed over the coarser particle sizes between the non-dispersed and dispersed materials. The distinguishing characteristic of the particle size distributions for the different fine tailings was the point at which the non-dispersed distribution separated from the dispersed distribution. The divergence of the distributions was consistently followed by a decrease in the amount of finer-sized material present in the non-dispersed material. This type of behaviour signifies that not all of the finer-sized material was dispersed during the extraction processes and indicates the size range of clay particle aggregates that were not dispersed. The less dispersed fine tailings can be identified by a more severe decrease of the non-dispersed distribution, occurring at larger particle sizes. The more highly dispersed fine tailings would have more gradual decreases at smaller particles sizes or no separation of the distributions at all if completely dispersed, as was the case with the Type 4 fine tailings.

Percent dispersion in relation to sodium adsorption ratio

The SAR can be used as a guideline to predict whether or not clays will be in a dispersed state. A SAR greater than 7 is indicative of dispersed clays (Dawson et al., 1999). We can infer that, as SAR values decrease toward the transition value of 7, the clays become less and less dispersed.

Ore A fine tailings Type 1 fine tailings had a SAR value of 114 (Table 7), which suggests a highly dispersed system. This hypothesis is supported by the results of the hydrometer tests (100% dispersion; Table 9). The Type 2 fine tailings had a SAR value of 22. This value is still higher than the SAR guideline of approximately 7 that is used for dispersed clays, but not as high as the Type 1 fine tailings. Therefore, the Type 2 fine tailings would have an only partially dispersed system (32% dispersion) as the SAR approaches 7. A SAR value of 28 was determined for Type 7 fine tailings, so one could expect a material with similar characteristics as the Type 2 fine tailings, but slightly greater dispersion. This was indeed the case, as greater dispersion was seen for the coarser size particles and dispersion decreased with decreasing particle size.

Ore B fine tailings The Type 4 fine tailings had a SAR of 46, which is well above the SAR transition value of 7 and is indicative of a highly dispersed system. The results of the hydrometer tests (100% dispersion) support this prediction. The Type 5 fine tailings had a SAR value of 5, which is closest to the SAR transition value of 7 and should be the least dispersed of the fine tailings based on SAR. This was the case, with the hydrometer tests measuring only a 10% dispersion.

Percent dispersion as a function of SAR The percent dispersion of the fine tailings measured by the hydrometer tests was found to be consistent with the predictions for dispersed clays established by the SAR values for these materials. Percent dispersion is presented as a function of SAR in Figure 5. Below SARs of about 40, the percent dispersion was found to decrease with decreasing SAR values in an approximately linear fashion. Fine tailings with SARs greater than 40 were in a completely dispersed state. The Type 7 fine tailings appeared to be positioned near this upper limit, with 100% dispersion at the 2 μm size, but less dispersion with decreasing particle size. These results support the ability of the SAR to predict the dispersive nature of clays in fine tailings.

Comparison of particle size distributions between fine tailings

The degree of dispersion for the fine tailings from the different extraction processes can be assessed by taking into account the percent dispersion (Table 9) and the distributions of the finer-sized materials (Figures 1-4).

Looking at all five fine tailings, the least dispersed material was Type 5 fine tailings, followed by Type 2, Type 7, Type 1, and Type 4 fine tailings. So while Type 4 fine tailings were more dispersed than the comparable Type 1 material, the Type 5 was less dispersed than its Type 2 counterparts.

The dispersed particle size distribution for the Ore A fine tailings is presented in Figure 6. The particle size distributions and, similarly, the clay-sized fractions from the dispersed tests were similar for all three Ore A materials (43%, 47%, and 41%) and the small differences may be

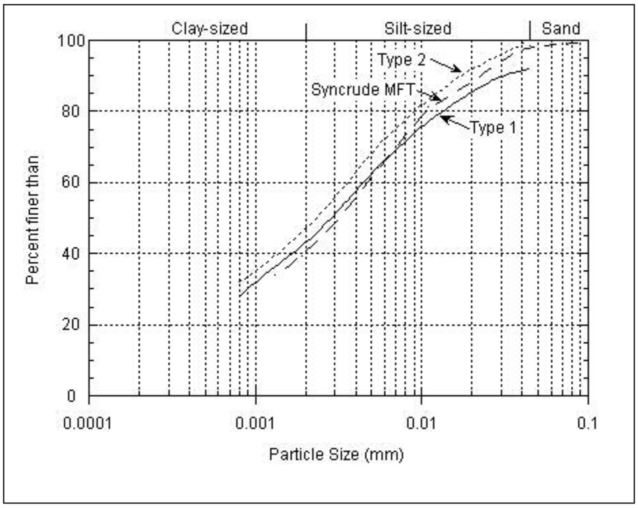

Figure 6. Dispersed particle size distributions for Ore A fine tailings.

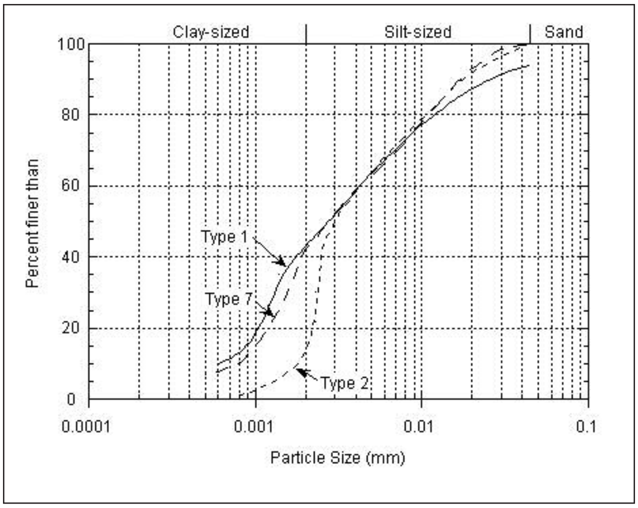

Figure 7. Non-dispersed particle size distributions for Ore A fine tailings.

explained by slight variations in the plant feed. Similarly, the Ore B fine tailings had similar dispersed clay-sized fractions (49% and 48%) and particle size distributions. There was also similarity between the dispersed values for the material less than 2 µm and 1 µm, for both the Ore A and Ore B fine tailings. These results illustrate that, because the fine tailings are derived from the same parent material, they were composed of the same fines material, irrespective of the extraction process utilized. The difference between the fine tailings was whether the fines existed in a dispersed state (individual particles) or in a non-dispersed state (larger clay band lumps), which is a reflection of extraction water chemistry.

The particle size distribution of fine tailings from Syncrude's tailings pond (Shaw, Cuddy, McKenna, & MacKinnon, 1995) is also presented in Figure 6. The depth of the fine tailings in the tailings pond has a significant influence on its composition, in that the composition becomes progressively coarser with increasing depth. The pilot plant material (comprised of Types 1 through 7) could be considered "young" fine tailings and should be more representative of the shallow fine tailings deposits in the tailings pond. The particle size distribution shown from the field is the average from the Syncrude's (Shaw et al., 1995) Non-segregating Tailings field trial, from a depth of 8 m to 10 m and a solids content of 31%.

For easy comparison between the non-caustic and the caustic materials, the non-dispersed particle size distributions of the Ore A fine tailings are presented together in Figure 7. Examining Ore A materials, Type 1 and Type 7 fine tailings had similar distributions, but both had finer distributions than Type 2 fine tailings. Ore B materials followed a similar pattern, wherein the caustic fine tailings were finer than the non-caustic fine tailings.

In summary, caustic fines are more fully dispersed during the extraction process than are non-caustic, treated water fines and exist more frequently as individual particles. As well, the chemical treatment of the non-caustic process water with acid and lime results in less dispersion of the fines. The amount of dispersion of fines in both the caustic and non-caustic processes also appears to be sensitive to the characteristics of the oil sand ore, as Ore A and Ore B had different amounts of dispersion.

It has been discussed earlier that very little variation exists between the different fine tailings in terms of solids content, bitumen content, mineralogy, and specific surface area. Thus, these properties are not responsible for the variations seen between materials in terms of particle size distribution (Figure 7) and percent dispersion (Table 9). These differences can be explained by the differences in the water chemistry of the fine tailings (Table 7). SAR is a reflection of the water chemistry and provides a good guideline for predicting the dispersive nature of the clays in the fine tailings (Figure 5).

Validity of particle size distribution curves

Due to the rapid decrease of the non-dispersed particle size distributions between 3 µm and 1 µm for the non-caustic materials, a review of the experimental procedure was required. The hydrometer analysis considers that particles involved in the sedimentation process settle according to Stokes' law, which assumes no interaction between particles during settlement. If charged particles in the suspension form larger particles as a result of interparticle attractions, Stokes' law stipulates that the larger aggregates will settle out of suspension faster, thereby altering the particle size distribution measured by the hydrometer. Dispersing agents are usually added to the suspension to prevent aggregates from forming by neutralizing the charges on the soil particles. However, a dispersing agent cannot be used during a non-dispersed test because it would eliminate the characteristic being investigated. To minimize the possibility

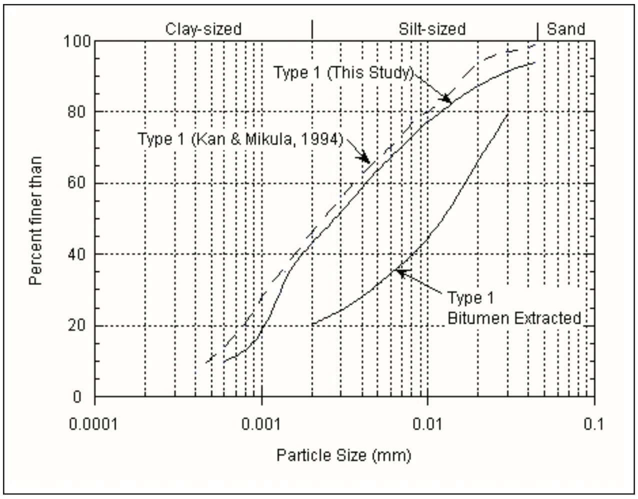

Figure 8. Non-dispersed particle size distributions for Type 1 fine tailings.

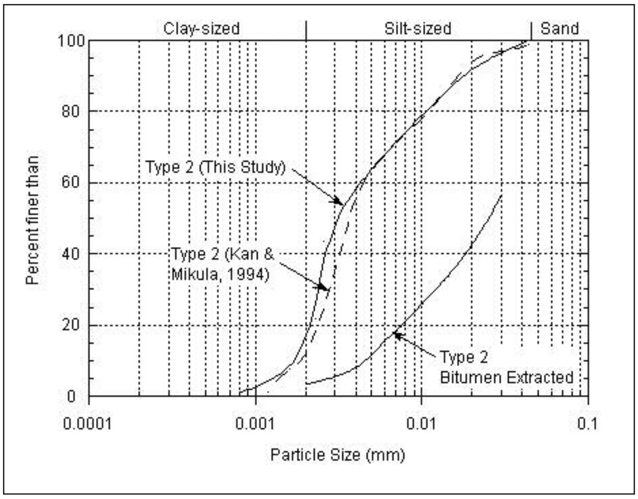

Figure 9. Non-dispersed particle size distributions for Type 2 fine tailings.

of interparticle interactions, the non-dispersed test method recommended by ASTM (2005b) proposes using a solids suspension of 2.5% by weight, instead of the normal 5%. Solids contents less than 2.5% contain very little solid material and may increase the opportunity for unrepresentative results. During the evolution of the testing procedure, non-dispersed tests were performed at a solids content of both 2.5% and 5%, and some difference was observed between the particle size distributions. For this reason, the 2.5% solids contents were used in this analysis.

Particle size distributions for the non-caustic and the caustic fine tailings were also determined by Kan and Mikula (1994), and for bitumen-extracted fine tailings by a commercial firm (Sethi, 1994). Both groups performed dispersed and non-dispersed tests using a hydrometer analysis. Typical non-dispersed test results from both sources, as well as for those of this study, are presented in Figures 8 and 9.

Similar to the procedure employed in this study, to preserve the chemical and physical characteristics of the fine tailings, Kan and Mikula (1994) used process water at all times, did not dry fine tailings prior to testing and used a solids suspension of 2.5% by weight. In general, there was a good correlation between the non-dispersed particle size distributions determined by this study and those determined by Kan and Mikula. Although there was typically greater curvature in Kan and Mikula's results, the overall characteristics of the distributions are similar in clay-sized fractions and percentages less than 1 µm.

The bitumen in the fine tailings used by the commercial firm (Sethi, 1994) was removed prior to testing using the Dean-Stark extraction method (ASTM, 2010). There is a significant difference between this firm's non-dispersed particle size distributions and those from this study and from Kan and Mikula (1994). The Dean-Stark extraction method flushes the fine tailings with toluene, which removes bitumen and water, and results in the fine tailings solids being dried out. Once dried, individual tailings particles become cemented together and the fine tailings solids have to be broken up by grinding or mixing. These processes exert a considerable influence on the particle size distribution and a return to the original state of the material is unlikely. This influence could possibly explain the differences seen in Figures 8 and 9, where fine tailings possibly subjected to bitumen extraction prior to testing were significantly coarser and bore little resemblance to fine tailings that were tested in their natural state. Similar significant differences in the dispersed particle size distributions were also seen between bitumen extracted and unaltered fine tailings.

Similar particle size results were obtained on a different non-caustic extraction process used at the Albian Sands Muskeg River mine, when the extraction plant was operating in a non-additive process mode (Jeeravipoolvarn et al., 2008). Non-dispersed hydrometer tests showed that only 7% of the fine tailings were finer than 2 µm, while dispersed hydrometer tests showed that 44% were finer than 2 µm. Mineralogy tests found that clay minerals comprised 71% of the fines, indicating that much of the clay minerals in the fines were in aggregates and booklets coarser than 2 µm.

Mikula, Omotoso, and Kasperski (2008) have suggested that both caustic and non-caustic extraction processes produce the same tailings streams. Mikula et al. state that the non-caustic extraction process still disperses the clays; it is just that, in the absence of a dispersive water chemistry, the clays behave as if they have an effectively larger particle size. Evidence for this conclusion was presented by means of testing clay suspensions for their degree of flocculation or elastic modulus. Non-caustic fine tailings were reported to show a measurable elastic modulus at much lower solids content than the same tailings from a caustic process. Mikula et al. concluded that this effect would not occur if the clays were simply still present as undispersed tactoids. However, the hydrometer tests reported here are correct for several reasons. The particle size distribution of dispersed non-caustic fine tailings was essentially the same as the caustic fine tailings (Figure 6). If the non-caustic material were finer, as Mikula et al. suggest, when fully dispersed, it should be finer than the caustic fine tailings. As well, the consistency between the degrees of dispersion determined by the hydrometer tests and the water chemistry of the fine tailings, quantified by the SAR, supports the accuracy of the particle size distributions. Finally, the observed degree of dispersion, based on the change in structures seen in the scanning electron microscope (SEM) photos, also corroborates the hydrometer test results and the water chemistry of the fine tailings.

METHYLENE BLUE TESTS

Methylene blue adsorption values were determined for both chemically dispersed and non-dispersed fine tailings solids to assess the degree of dispersion of active clays (Sethi, 1994). Methylene blue is a cationic dye that can be adsorbed on the exposed negatively charged surfaces of clays and is routinely used to measure exposed surface area of clays in soils. The quantity of exposed clay mineral in the sample, however, can be calculated using an empirical relationship developed for oil sand tailings (Morin, 2008) given below:

$$\text{Clay mineral fraction (\%)} = [(0.006)\ (\text{MB value}) + 0.04]\ /\ 0.14 \qquad (4)$$

The standard methylene blue test procedure specifies that the sample be dried, pulverized, blended and dispersed in de-ionized water, with a dispersing agent in an ultrasonic bath (ASTM, 2009). For oil sands tailings, the bitumen is extracted first by the Dean-Stark method. This method alters the chemical and physical characteristics of the fine tailings; the method's influence on the results of the non-dispersed methylene blue values will be discussed later.

Test results

The results of the methylene blue tests and the calculated clay-sized fractions for the fine tailings are summarized in Table 10. For Ore A fine tailings, the clay-sized fractions measured for the Type 1 fine tailings by the non-dispersed (43%) and dispersed (44%) tests were very similar. There was a much greater disparity between the non-caustic fine tailings. The non-dispersed tests determined clay-sized fractions of only 29% for both non-caustic fine tailings, compared with dispersed values of 48% and 46% for Type 2 and Type 7 materials, respectively.

For Ore B materials, there was also a difference between the non-dispersed (41%) and dispersed (51%) clay-sized fractions of the Type 4 fine tailings (Table 10). Type 5 fine tailings showed a greater change between the non-dispersed (30%) and dispersed (48%) clay-sized fractions.

The methylene blue test only detects clay surfaces that are exposed. So, the dispersed methylene blue test is an effective tool for determining the total amount of clay material present in a fine tailings, but does not provide any information regarding the form of the clay particles prior to dispersion (individual particles or larger clay band lumps). When completely dispersed, the clay-sized fractions for each fine tailings determined by the methylene blue tests (Table 10) and hydrometer particle size distributions (Table 9) should be similar. For easy comparison, the dispersed clay-sized fractions determined by these two methods are shown on Figure 10. As expected, there is a good correlation between the hydrometer results and the

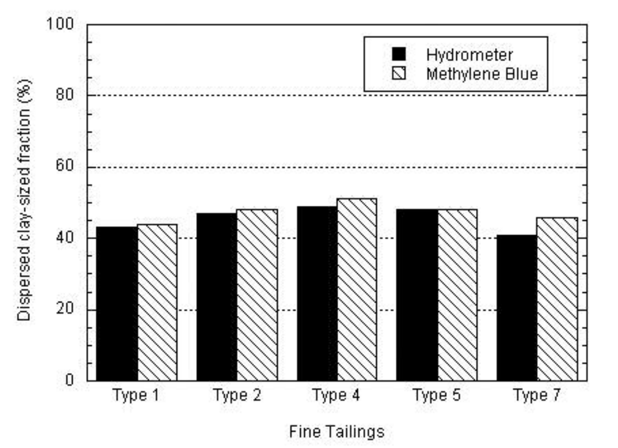

Figure 10. Dispersed clay-sized fraction determined by methylene blue and hydrometer tests.

Table 10. Clay sized fractions for the fine tailings determined by Methylene Blue tests

Fine tailings type	Ore	Water	Chemical addition	Methylene blue value (mL 0.006N/100g)		Clay sized fraction (%)	
				Non-dispersed	Dispersed	Non-dispersed	Dispersed
1	A	RPW	none	1004	1014	43	44
2	A	TRW	none	675	1108	29	48
3	A	RPW	$CaSO_4$	867	1004	37	43
4	B	RPW	none	940	1183	41	51
5	B	TRW	none	692	1122	30	48
6	B	RPW	$CaSO_4$	639	781	28	34
7	A	UTRW	none	664	1076	29	46

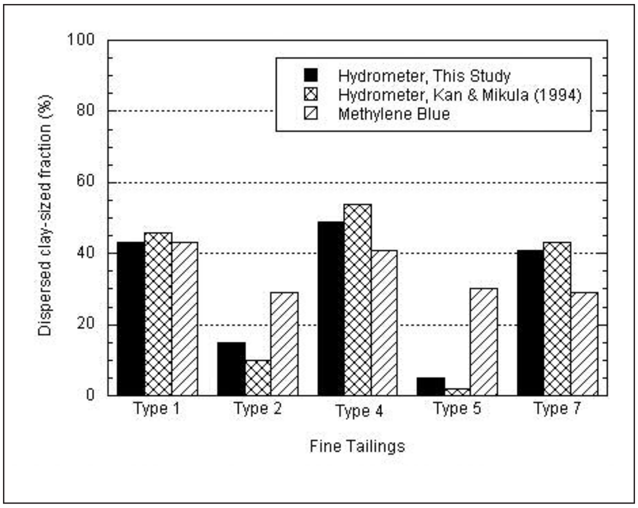

Figure 11. Non-dispersed clay sized fraction determined by methylene blue and hydrometer tests.

methylene blue results for all five fine tailings. The small difference between tests can be explained by variations between fine tailings samples themselves. Thus, both the dispersed hydrometer test and the dispersed methylene blue test are acceptable methods for determining the total amount of clay-sized material in a fine tailings.

However, the clay-sized fractions determined by the non-dispersed methylene blue tests may not be representative of the fine tailings. The non-dispersed tests were intended to measure the amount of clay in the fine tailings in its natural state. If the individual clay particles exist as part of small lumps of clay then there will be less exposed surfaces to which the methylene blue can adhere, resulting in a lower measured clay-sized fraction in the fine tailings. Figure 11 presents the non-dispersed clay-sized fractions determined from the methylene blue tests (Table 10), as well as the non-dispersed, particle size distributions of this research study and of the Kan and Mikula (1994) study. There was relatively good concordance between the results from the two hydrometer tests and the methylene blue test for the caustic fine tailings (Figure 11). However, there were substantial differences between the clay-sized fractions determined by the hydrometer and methylene blue test methods for the non-caustic fine tailings. Differences were the most pronounced for the Type 2 and Type 5 fine tailings.

The standard methylene blue test procedure specifies the use of a dried, ground mineral sample. As mentioned earlier, drying and grinding changes both the chemical and physical characteristics of the fine tailings. When dried, the mineral solids of the fine tailings become cemented together. Grinding is then required to break up the sample. The intensity and duration of the grinding determines to what degree the solids are broken apart and the proportion of clay surfaces exposed. It is unlikely that fine tailings can be consistently returned to a condition representative of fine tailings in their natural state. The variability of the results seen in Figure 11 may be evidence of this type of problem.

The methylene blue test was also used to determine the clay-sized fractions of Type 3 and Type 6 (Type 1 and Type 3 fine tailings with 600 ppm of calcium sulphate added). Type 3 and Type 6 fine tailings were also subjected to drying and grinding, so the non-dispersed clay-sized fractions may not be representative of the fine tailings in their natural state and will not be considered. The dispersed clay-sized fraction for the Type 3 fine tailings was almost

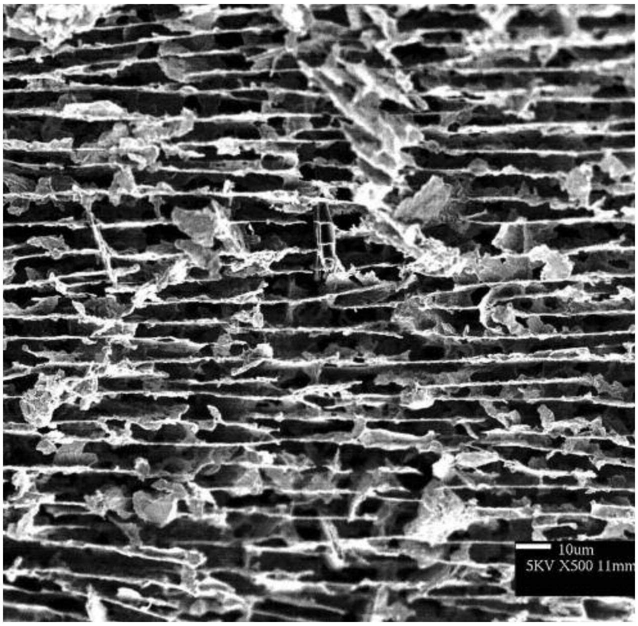

Figure 12. Structure of Type 1 fine tailings magnified 500 times.

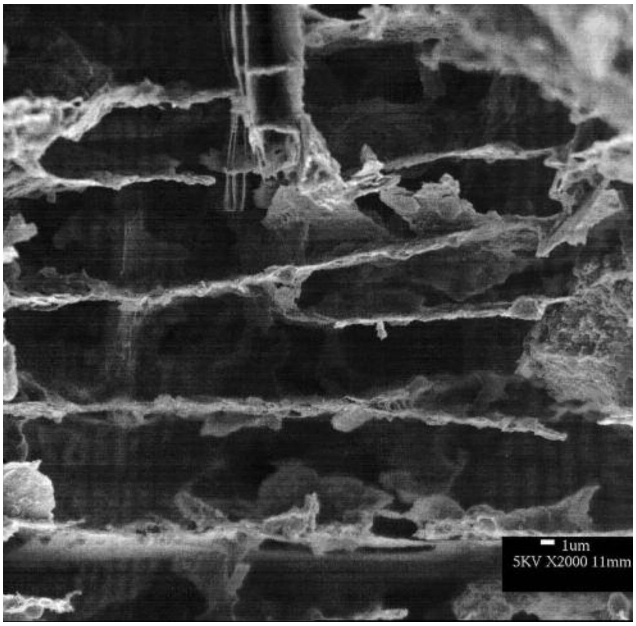

Figure 13. Structure of Type 1fine tailings magnified 2,000 times.

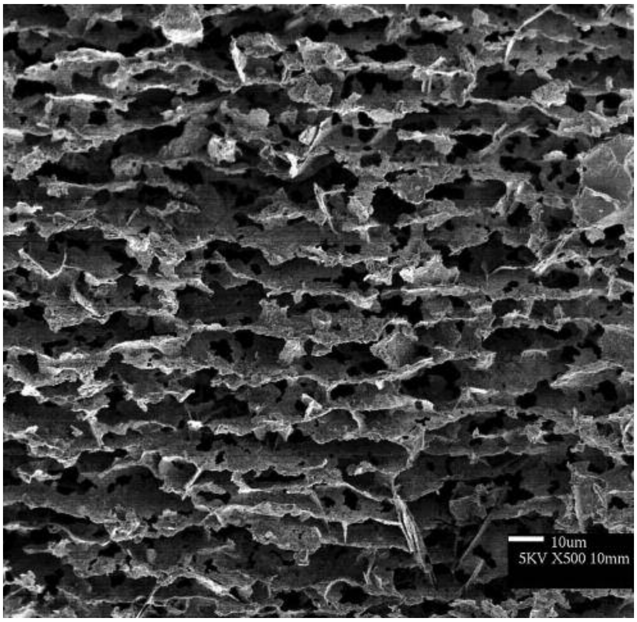

Figure 14. Structure of Type 2 fine tailings magnified 500 times.

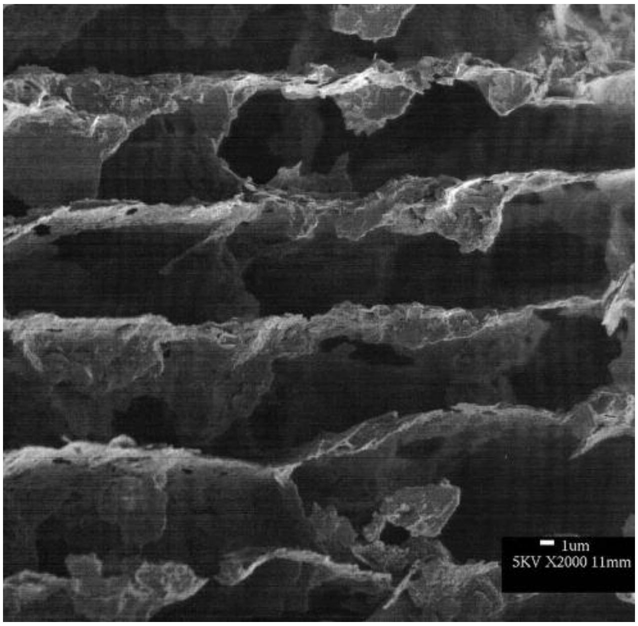

Figure 15. Structure of Type 2 fine tailings magnified 2,000 times.

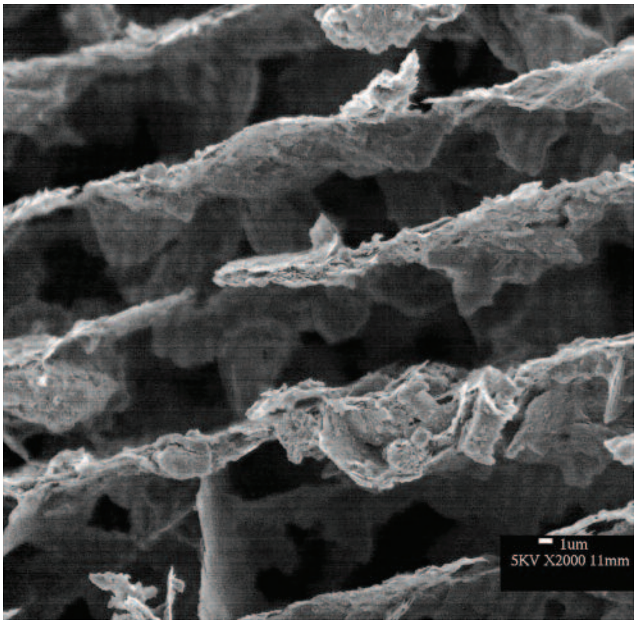

Figure 16. Structure of Type 4 fine tailings magnified 2,000 times.

the same as the original Type 1 fine tailings (43% and 44%, respectively; Table 10). The Type 6 fine tailings only had a dispersed clay fraction of 34%, well short of the 51% from the original Type 4 fine tailings. This finding suggests that, in some cases, the aggregates formed as a result of $CaSO_4$ addition to the fine tailings, possibly due to cementation, may not be easily reversed. A stronger dispersing agent or mechanical methods may be required to reduce the aggregates formed in the Type 6 fine tailings into a fully dispersed state.

FLOCCULATED AND AGGREGATE STRUCTURE OF CLAY MINERALS

An SEM was used to determine the structure of the fine tailings. The SEM procedure uses a rapid freezing of the samples to maintain the morphology or the relationship between components. The samples are frozen then fractured before being placed in the SEM chamber for observation. For these cryogenic techniques, a sufficiently high freezing rate has been identified as a consideration to minimize the creation of artefacts (FTFC, 1995b). The influence of freezing rate and other considerations for tailings materials has been discussed by Tang, Biggar, Scott, and Sego (1997). Even if the SEM may not show the actual structure in the fine tailings, a change in observed structure indicates that the actual structure is different. That is, SEM photos at the least are relative measurements and the observed structures are qualitative indicators.

Photos were taken at magnifications of 25, 50, 200, 500, and 2,000 times for all of the fine tailings. The 500-times and 2,000-times photos were considered the most descriptive of the structure of the fine tailings. Selected photos at these magnifications are presented in Figures 12 to 18.

Owing to their plate-like shape and differences in charge between the faces and edges, clays can orient themselves in a variety of ways. Face-to-face interactions are generally repulsive and face-to-edge interactions are generally attractive. Dispersed clays tend to form structures that are dominated by face-to-face orientation of the clay particles. These structures are highly ordered because the individual clay particles, due to their thicker adsorbed water layer, are free to orient themselves according to the repulsive and attractive forces determined by the water chemistry and clay

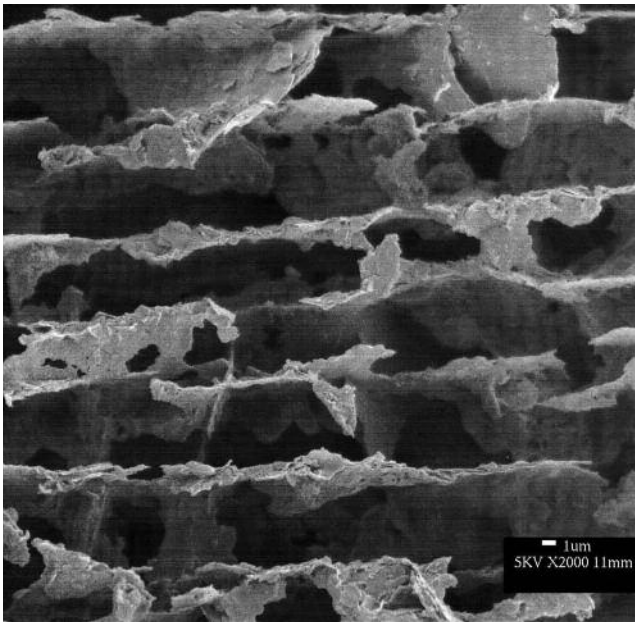

Figure 17. Structure of Type 5 fine tailings magnified 2,000 times.

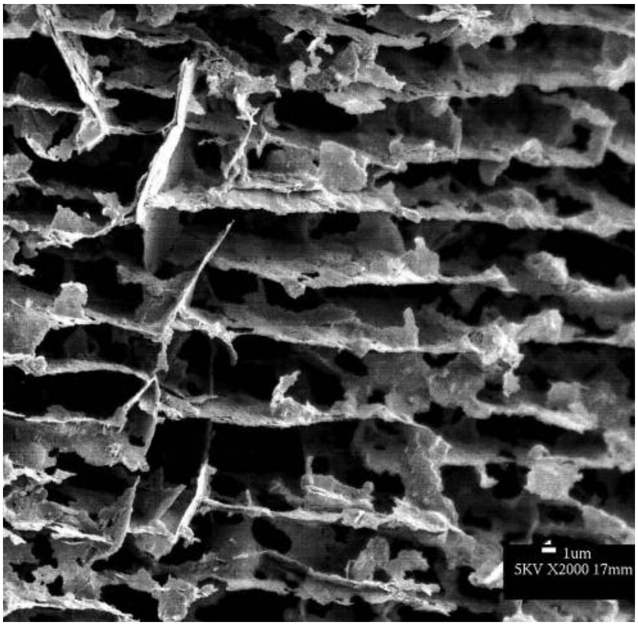

Figure 18. Structure of Type 3 fine tailings magnified 2,000 times.

mineralogy. These structures have been described as having a "card-house structure." Alternatively, flocculated clays form a more random structure, dominated by face-to-edge orientations (Mitchell & Soga, 2005).

Ore A fine tailings

Type 1 fine tailings appeared to have a highly dispersed structure (Figures 12 and 13; i.e., individual clay particles dominated by a face-to-face orientation. Other researchers have also reported this type of structure for similar caustic fine tailings (FTFC, 1995c; Jeeravipoolvarn et al., 2008; Mikula, Munoz, Lam, & Payette, 1993; Mikula, Payette, Munoz, & Lam, 1991). Type 2 fine tailings had a similar face-to-face structure (Figure 14), but the "booklets" of individual clay plates for Type 2 fine tailings (Figure 15) appeared to be thicker, relative to the Type 1 material (Figure 13). Therefore, while Type 2 fine tailings also had a dispersed clay structure, the degree of dispersion was less than that of Type 1 fine tailings.

Treating the process water for the non-caustic process had little effect on the fine tailings in terms of structure. Type 7 fine tailings had a structure quite similar to Type 2 fine tailings.

Ore B fine tailings

For Ore B fine tailings, the Type 4 material was very similar to its Type 1 counterpart, with a predominantly face-to-face orientation of individual particles (Figure 16). The only fine tailings observed to have a less dispersed structure approaching a flocculated structure was the Type 5 fine tailings (Figure 17). The observed structure was different from the other fine tailings. The clay particles were more randomly oriented and face-to-edge interactions were more prevalent, perhaps indicating a transition between a dispersed and a flocculated structure.

Influence of calcium sulphate addition

The structure of Type 3 fine tailings (caustic fine tailings with 600 ppm of calcium sulphate added) is shown in Figure 18. The addition of calcium sulphate had little influence on the structure of the fine tailings, with one exception: for Ore A materials, the spacing between the clay particles of the Type 3 fine tailings (Figure 18) was about half the distance observed in the original Type 1 fine tailings (Figure 13). No appreciable difference in spacing was observed for the comparable Ore B fine tailings, Types 4 and 6.

Tang et al. (1997) also found that the addition of laboratory-grade gypsum to MFT produces a finer and stronger clay structure for the fine tailings. Using an SEM, it was observed that the gypsum addition resulted in a more crowded, less organized and agglomerated network of particles; this effect was due to replacement of Na^{+} ions by Ca^{2+}, which reduced the double layer thickness and rendered the system to a less dispersed state.

SUMMARY

These visual observations are consistent with the degrees of dispersion (Table 9) and the SAR values (Table 7) for the fine tailings discussed earlier. Only Type 5 fine tailings had a SAR of 5, which approached the guideline value of 7 used to predict dispersed or flocculated clay system. Visual inspection of the clay mineral structure in the fine tailings indicated that it had a somewhat less dispersed structure and was possibly in a transition zone between dispersed and flocculated structures; the remainder of the fine tailings had typical dispersed structures. These findings provide further support for the reliability of the SAR to predict the dispersive nature of fine tailings.

CONCLUSIONS

Overall, the different water chemistries of the different extraction processes resulted in different amounts of dispersion of the clay-shale seams present in oil sands ore, with the non-caustic fine tailings being less dispersed. Differences in the geotechnical properties of the fine tailings are expected to be due mainly to the different grain sizes. The water chemistry of the fine tailings may have some additional effect on the geotechnical properties, but this effect is expected to be small compared to the effect of the amount of clay dispersion—and then only at large void ratios.

Based on the results of this research program, the following conclusions, specific to the physical and chemical characteristics of fine tailings, can be drawn:

- Little variation exists between the different fine tailings in terms of index properties, mineralogy, and specific surface area. Thus, these fundamental properties are not responsible for the variations seen between materials in terms of particle size distribution and percent dispersion. These differences can be explained by the differences in the water chemistry of the fine tailings. The SAR is a reflection of the water chemistry and provides a good guideline for predicting the dispersive nature of the clays in the fine tailings.
- There was strong correlation between the index properties and mineralogy of the non-caustic/caustic fine tailings and the fine tailings impounded in the tailings pond at the mine sites. Thus, the general relationships established for the non-caustic/caustic fine tailings should be applicable to commercial fine tailings, but any trends or differences in behaviour would have to be confirmed at a commercial scale.
- Differences between the liquid limits and plasticity indexes were minor for the fine tailings, and had no significant difference in terms of geotechnical engineering behaviour. Slight variations were due to differences in the pore water chemistry and have been explained by the double layer theory for clay particles.
- Substantial differences were seen in the particle size distributions and degree of dispersion of comparable non-caustic and caustic fine tailings. Caustic fine tailings were generally finer than non-caustic fine tailings due to a greater degree of dispersion. Treating the process water with acid and lime for the non-caustic process resulted in only a slightly less dispersed material.
- The degree of dispersion of the fine tailings measured by the hydrometer tests was found to be consistent with the predictions for dispersed clays established by the SAR values for these materials. A linear variation of increasing dispersion with increasing SAR, up to a SAR value of about 40, has been suggested, above which, fine tailings are completely dispersed.
- SEM was used to observe the structure of the clay minerals in the fine tailings. Only the non-caustic fine tailings generated from Ore B ore with the use of treated process water (Type 5) had an observed structure approaching the typical random structure dominated by face-to-edge particle interactions associated with less dispersed clays. The remaining fine tailings were highly structured, with face-to-face orientations predominating. These structures supported the SAR values-based predictions. Although only one of the fine tailings had a less dispersed structure, visual observations indicated the degree of dispersion decreased with decreasing SAR, in terms of the thickness of the booklets of clay plates.

Paper reviewed and approved for publication by the Oil Sands Society of CIM.

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CHAPTER 4. EFFECT OF EXTRACTION WATER CHEMISTRY ON THE SELF-WEIGHT CONSOLIDATION OF OIL SANDS FINE TAILINGS

This paper was previously reviewed, accepted and will be published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal. It is presented as per submission requirements to CIM Journal as part of this Ph.D. thesis as Chapter 4.

Reference: Effect of Extraction Water Chemistry on the Self-Weight Consolidation of Oil Sands Fine Tailings. CIM Journal, 1(4), page numbers pending.

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Page Numbering:

CIM Journal: Page numbers pending

This thesis: 51 to 83

Effect of Extraction Water Chemistry on the Self-Weight Consolidation of Oil Sands Fine Tailings

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Keywords: oil sands, fine tailings, compressibility, hydraulic conductivity, consolidation, large strain, volume decrease, void ratio, settlement, effective stress, dispersion, coagulant, sodium adsorption ratio.

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Abstract

As part of an overall study of properties and processes influencing consolidation of oil sands fine tailings resulting from different extraction processes, self-weight consolidation tests were performed. Fourteen two meter and one meter high standpipe tests were instrumented to monitor the rate and magnitude of consolidation of seven fine tailings materials. Tests provided valuable information on the variation of consolidation related to differences in fine tailings material properties resulting from a change in bitumen extraction process (caustic versus non-caustic) and the effect of adding a coagulant to caustic fine tailings. Test results are presented and discussed in terms of consolidation rate, long-term volume decrease, compressibility and downward drainage. Non-caustic fine tailings had faster initial consolidation, which is important in tailings ponds for reducing storage capacity and returning decant water at a faster rate to the extraction plant. Similar results were obtained with caustic fine tailings with a coagulant addition. However, long-term settlement of the different fine tailings appears to converge to a similar value over time as it is then governed by effective stress.

Introduction

In the oil sands industry, high temperature and addition of a caustic dispersing agent have formed the basis of the Clark Hot Water Extraction process used successfully on a commercial scale to recover bitumen from surface mined oil sands ore since 1967. Descriptions of the present day extraction and froth treatment process are provided by Cymerman and Kwong (1995); Shaw, Czarnecki, Schramm and Axelson (1994); and Shaw, Schramm and Czarnecki (1996). However, the Clark process results in the creation of extremely dispersed, high void ratio fine tailings composed primarily of silt, clay, water and residual bitumen. These caustic based fine tailings exhibit low consolidation rates and shear strengths and require considerable real estate for storage. Presently approximately 750 Mm^3 of fine tailings is being stored in tailings ponds. The conventional method for fine tailings management is a containment strategy of the fine tailings in ponds for sedimentation, consolidation, and eventually land reclamation. However, the vast quantities and slow consolidation of fine tailings raises environmental and economic questions regarding possible improvements in tailings behaviour.

Processes different from the established Clark process (high temperature and caustic) have been developed to work at a range of temperatures with or without the use of sodium hydroxide (Kasperski, 2001). One such process is the OSLO Hot Water Extraction process (Sury, Paul, Dereniwski and Schulz, 1993), a non-caustic bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the hope of improved consolidation and strength properties of the fine tailings (OSLO is an acronym for Other Six Lease Owners, the consortium of companies that piloted the process). A potential reduction in fine tailings volume and improved geo-environmental behaviour provided an environmental and economic incentive to examine the relative differences between the properties that influence consolidation of the fine tailings derived from these extraction processes.

The overall objective of this research program was to evaluate the properties and processes influencing the rate and magnitude of volume decrease and strength gain for the tailings produced using the caustic and non-caustic extraction processes. The two main components were flume deposition tests and testing for geotechnical properties of the fine tailings. The results of the flume deposition tests are provided by Miller, Scott and Sego (2009). Physical and chemical characteristics of the fine tailings derived from the flume deposition tests and examined during this geotechnical testing program are provided by Miller, Scott and Sego (2010a). Compressibility and hydraulic conductivity relationships determined from one-dimensional consolidation tests are provided by Miller, Scott and Sego (2010b) and thixotropic shear strength properties are provided by Miller, Scott and Sego (2010c). The objective of this paper is to report, analyze and discuss self-weight consolidation results derived from standpipe tests for the caustic and non-caustic fine tailings.

Compressibility relationships are engineering properties that will influence the long term disposal of the fine tailings. Self-weight consolidation tests using standpipes up to 2 m high were carried out to determine the consolidation properties for the fine tailings. The objective of this study was to determine the influence of a change of extraction process on the rate of pore pressure dissipation (consolidation during self-weight), and the rate and magnitude of self-weight consolidation. The effect of adding a coagulant to caustic based fine tailings in terms of self-weight consolidation was also examined. Any differences in the self-weight consolidation properties between the fine tailings will be explained based on the physical and chemical characteristics of the source materials.

The consolidation in standpipes takes a relatively short period of time and stress levels reached, although small, are significant. Self-weight consolidation tests using standpipes are also advantageous because of the ease of data collection and costs, relative to field scale tests, and they model the consolidation process in tailings ponds.

Experimental Program

Fine tailings from two extraction processes were used in this study. For the remainder of this paper, they will be referred to as caustic and non-caustic fine tailings.

Fine Tailings

Seven different fine tailings derived from two types of oil sands ore were studied to determine the influence of extraction process and coagulant addition on the settling and self-weight consolidation characteristics of the fine tailings. The seven different fine tailings and their descriptions are summarized in Table 1. For each type of oil sands ore, one caustic and one non-caustic based fine tailings were investigated. Additionally, one non-caustic process using untreated river water and caustic tailings modified by the addition of 600 ppm of calcium sulphate were studied. The addition of calcium sulphate was proposed to improve the settling behaviour by causing the aggregation of clay particles. In Table 1, each fine tailings has been designated with a number (1 to 7) to facilitate ease of presentation of the results in figures and tables.

Tailings from each extraction process were generated using approximately 80 tonne samples of Ore A and Ore B. The extraction process water was chosen based on the water source that would be used for commercial operation. The extraction process water used during the caustic process was recycled pond water from the Mildred Lake Settling Basin at Syncrude Canada Ltd., near Fort McMurray, Alberta, Canada. The non-caustic process utilized Athabasca River water (initial pH 7.4) that had been treated by slowly adding a 10% sulfuric acid solution to bring the pH to 5.0, and subsequently adding a 4% (by weight) lime slurry to increase the pH back to 7.4, resulting in 40 ppm Ca^{2+} in solution. A detailed description of the extraction processes and collection of the fine tailings is provided in Miller et al. (2009).

The mineralogy of the clay sized fraction of the dispersed fine tailings (Table 2) is dominated by kaolinite (75 to 81%) and illite (15 to 19%) and trace amounts of mixed layer clays. The fines larger than clay size are predominately quartz. The mineralogy of all the fine tailings derived from a particular ore will be essentially the same since the extraction process has no effect on the type and amount of clay minerals present in each fine tailings, only on how much of the clay is dispersed to be finer than 0.002 mm. Thus, mineralogy will not be a factor when comparing fine tailings derived from the same oil sands ore.

The initial water chemistry of the oil sands ore is presented in Table 3. Ore A is characterized with average concentrations of sodium (2.5 times), chloride (4.8 times), and sulphate (2 times) greater than Ore B. This reflects the marine origin of Ore A versus the non-marine origin of Ore B.

The water chemistry of the fine tailings is shown in Table 4. The pH for the fine tailings ranged between about 7 to about 8.5, with higher values being more representative of the caustic fine tailings (Smith, Spence and Wong, 1994). Of note are the high sodium concentrations of the caustic fine tailings compared to those of the non-caustic materials. This reflects the nature of the caustic extraction process which uses sodium hydroxide to aid dispersing the clay particles to enhance bitumen recovery. A combination of methyl isobutyl carbinol (MIBC) and kerosene was used as a dispersing agent for the non-caustic process.

The highly dispersed nature of the caustic tailings is evident by comparing the nondispersed and dispersed particle size distributions characteristics given in Table 5. The percent dispersion is calculated from the ratio of the percent passing 2 μm in the non-dispersed hydrometer test to that in the dispersed hydrometer test. Types 1 and 4 fine tailings were almost completely dispersed by the caustic process, whereas the non-caustic fine tailings (Types 2 and 5) were only partially dispersed. This will have an influence on the rate of self-weight consolidation of the fine tailings since a more dispersed material will have a finer grain size, that is, more individual clay particles and more opportunities for physico-chemical interactions between clay particles and a lower hydraulic conductivity.

The sodium adsorption ratio (SAR) relates the composition of the solution phase to the composition of the adsorbed phase. That is, it provides a prediction of the adsorbed phase based on the concentrations of ions in solution. For practical purposes, SAR is defined as:

$$SAR = \frac{[Na^{+}]}{\sqrt{\frac{[Ca^{2+}]+[Mg^{2+}]}{2}}} \qquad \text{(Eqn. 1)}$$

where the soluble cation concentrations are in milliequivalent per liter (me/L).

In general when SAR values exceed a certain level specific to each material, sodium ions will occupy adsorption sites on the clay, resulting in dispersion of the clays. The SAR values for the fine tailings are presented in Table 4. All of the fine tailings have SARs in excess of 20 (21 to 107) with the exception of Type 5 fine tailings which had an SAR of 6. Type 5 fine tailings has been shown to have a less dispersed structure while the other fine tailings have more dispersed structures (Miller et al., 2010a). It has also been previously reported by Dawson, Sego and Pollock (1999) that SARs greater than about 7 indicate a high potential for dispersion. Based on the dispersed and nondispersed particle size distribution results, it may be concluded that fine tailings with an SAR greater than 20 are likely to be in a dispersed state while those with a SAR of 6 or less will have a less dispersed structure.

Testing Equipment

Self-weight consolidation tests were performed using standpipe columns 2 m and 1 m in height. The experimental setup for the 2 m standpipes is presented on Figure 1. These standpipes were plexiglass cylinders with an inside diameter of 13.3 cm and a wall thickness of 0.65 cm. Each standpipe had ten manometers spaced at 20 cm intervals. The manometer ports along the inside of the plexiglass cylinder were covered with a nylon filter to prevent clogging due to fine tailings migration. The 2 m standpipes also had sampling ports spread at 20 cm intervals.

An additional set of tests was performed using 1 m standpipes to investigate the influence of standpipe height on test results. The experimental setup for the 1 m standpipes is shown on Figure 2. The inside diameter was 9.5 cm and wall thickness was 0.28 cm. The 1 m standpipes were designed for single drainage (upward only) and manometers were positioned within the fine tailings sample in the form of glass tubing.

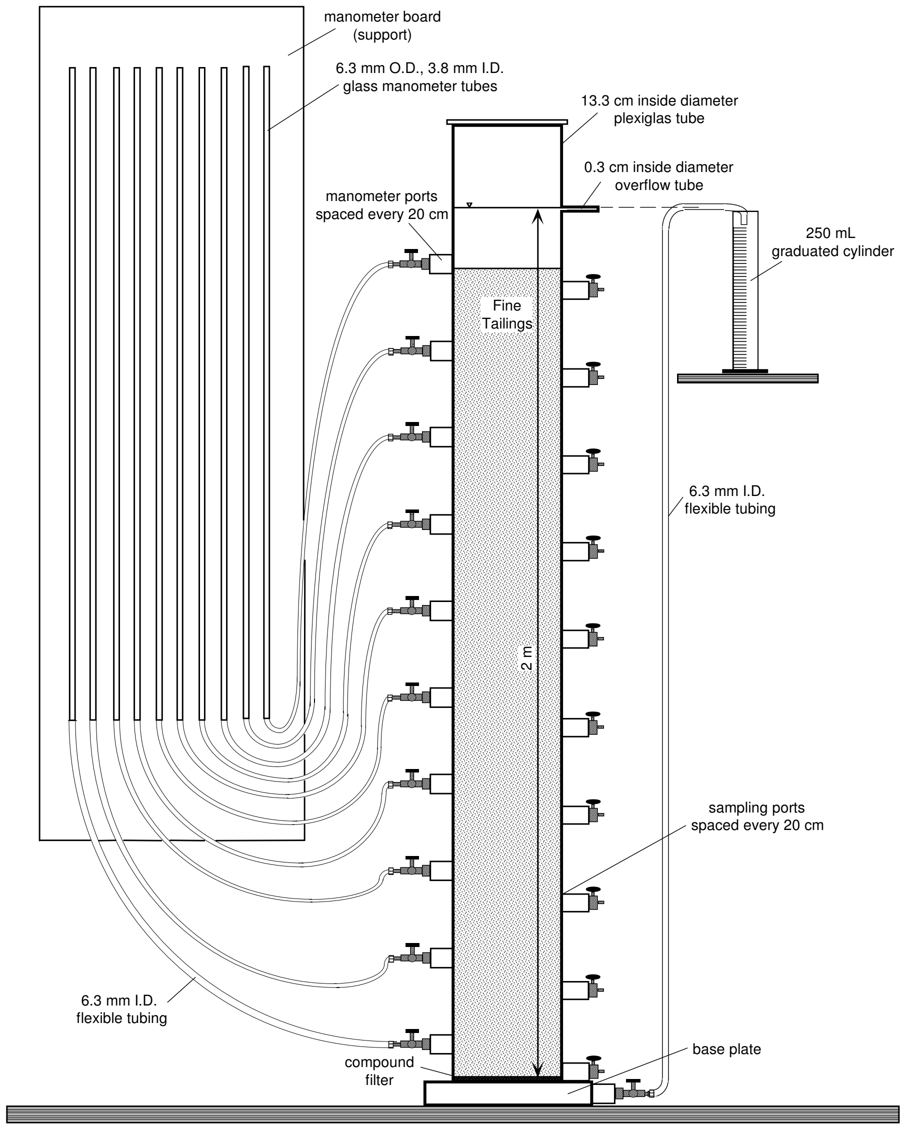


Figure 1. Experimental setup of a 2 m high standpipe.

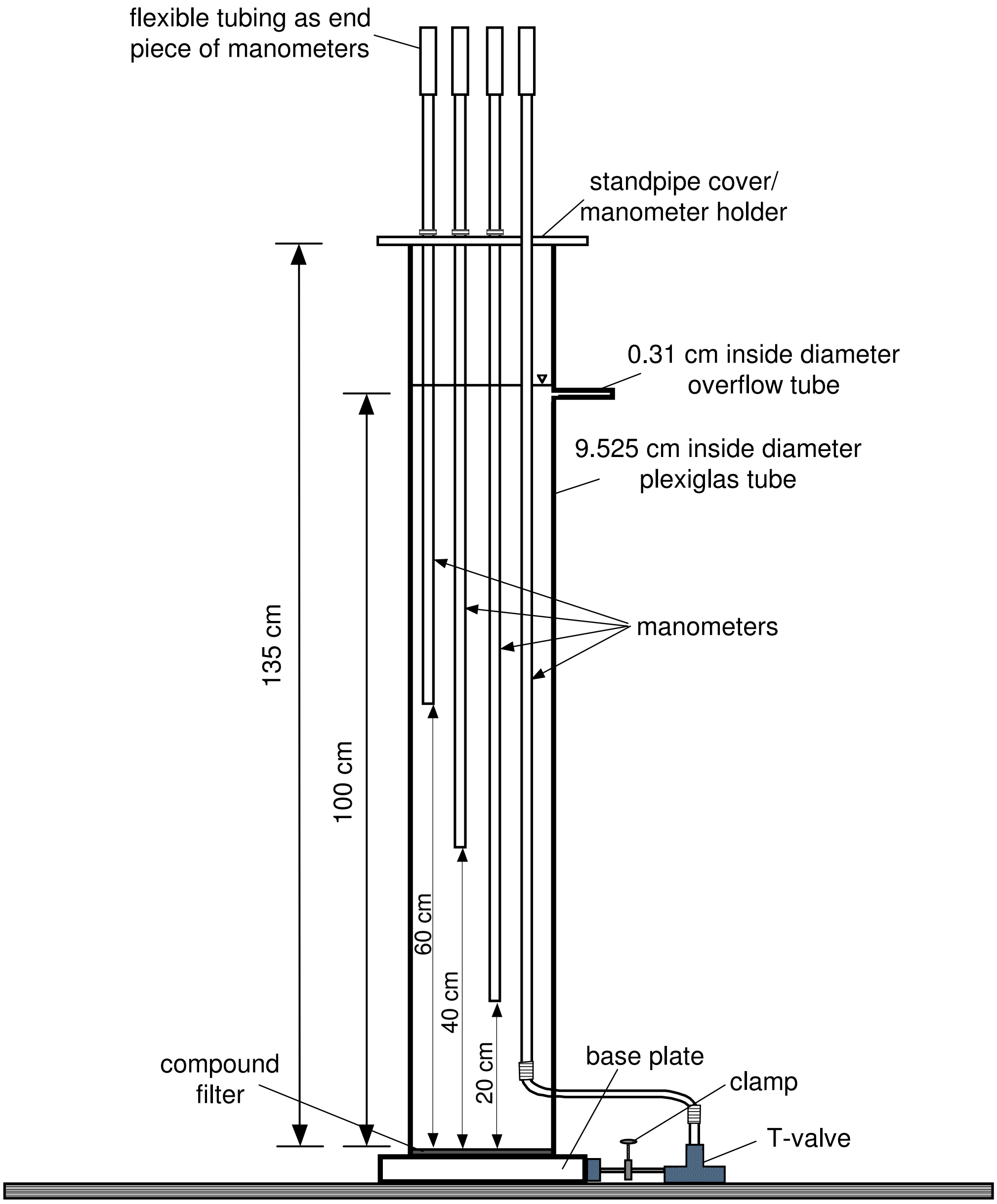


Figure 2. Experimental setup of a 1 m high standpipe.

Drainage Conditions

Two types of drainage were used in the testing program and were defined as either single drainage or double drainage. The 2 m standpipes were designed for double drainage to simulate the drainage conditions if a porous sand layer underlaid the fine tailings in a tailings pond. In this case, a drainage channel covered by a filter was opened at the base of the standpipe and both downward and upward drainage was allowed. However, it should be noted that the bottom drainage was raised and set even to the hydrostatic level of the standpipe, so no downward hydraulic gradient was imposed on the fine tailings sample. The 1 m standpipes were under single drainage conditions. That is, the base of the standpipe was sealed and only upwards drainage may occur during the test. This would simulate an impervious layer beneath the fine tailings in a tailings pond.

Test Methods and Measurements

Initial excess pore pressures were calculated assuming initially no effective stress existed and the manometers were filled to these values. The fine tailings were then deposited by gravity through a flexible hose to the base of the standpipe. The deposition point was raised as the standpipe filled so that it was always approximately 5 cm below the surface of the fine tailings until the final height was reached. This was considered to be time zero and all measurements began.

The settlement of fine tailings is characterized by the formation of an interface with supernatant water above and fine tailings below. Interface movements and pore pressures were measured throughout the duration of the self-weight consolidation tests. Self-weight consolidation tests had durations ranging from 340 to 722 days. Tests were stopped when the fine tailings had reached 100% consolidation based on pore pressure readings or at a predetermined limit of roughly 730 days (two years).

At the end of the test, standpipes were sampled to determine the solids content profile along the height of the fine tailings. Ultimately, these results were used to determine the compressibility of the different fine tailings in terms of the void ratio-effective stress relationship. In addition, the 2 m standpipes were sampled through the sampling ports at about 200 days elapsed time. A 5 mL syringe sample was collected through each port.

Initial Solids Content of Fine Tailings

The initial solids content of the fine tailings was set at 22% (void ratios from 8.9 to 9.1) because it was considered that this was the minimum value required to prevent segregation of coarser grained particles during the test. The water content was decreased (increasing solids content) by vacuum filtration to increase the dewatering rate of the fine tailings from the flume runoff which was at approximately 8% to 9% solids content.

Standpipe Self-Weight Consolidation Test Results

The initial conditions, in terms of height, solids content, void ratio, and test duration for the fine tailings are summarized in Table 6 for the 2 m and 1 m standpipe tests.

At the beginning of the 2 m standpipe test for Type 3 fine tailings, it was noted that piping channels were forming next to the wall of the standpipe and sand boils appeared on the surface. The high permeability piping channels allowed this test to consolidate quickly and the test results were not representative of a uniform material. For this reason the 2 m standpipe measurements for Type 3 fine tailings will not be included in the data analyses. No other 2 m standpipes and no 1 m standpipes showed this phenomenon.

Calculation of Percent Consolidation

For the fine tailings, self-weight consolidation was considered to be complete when excess pore pressures fully dissipated throughout the height of the sample. The excess pore pressure is defined as the total pore pressure minus the hydrostatic pore pressure. Some fine tailings were at 100% consolidation after only about 400 days while others were still in the process of consolidating after more than 700 days. Profiles of excess pore pressure provide a visual representation of the progress of consolidation along the height of the fine tailings over time. Typical excess pore pressure profiles for the fine tailings derived from Ore B (Types 4 and 5) are given on Figure 3 for the 2 m standpipes and for the same fine tailings in the 1 m standpipes on Figure 4. Excess pore pressure was zero at the base of the 2 m standpipes as a result of the double drainage design of these standpipes where the base of the standpipe was set at the hydrostatic pressure level.

The percent consolidation of the fine tailings was determined at 50, 200, 400, and end of test days (715 days for the 2 m standpipes; and 633 days (Type 4) and 446 days (Type 5) for the 1 m standpipes) by calculating the area within the measured excess pore pressure profiles at different times and relating those values to the area within the adjusted total stress profiles for each time considered. At 0 days these profiles were the same indicating no consolidation or effective stress at the beginning of the test.

The adjusted total stress is defined as the total stress minus the hydrostatic pore pressure. This stress varies as the fine tailings interface decreases in height with time. To determine the percent consolidation the adjusted total stress must be taken into consideration. Figures 3 and 4 show the adjusted total stress for each time considered. Figures 5 and 6 show the percent consolidation over time. The difference in the rate of pore pressure dissipation between the caustic fine tailings (Type 4) and the non-caustic fine tailings (Type 5) is readily seen on Figures 3 and 4.

Figure 3. Stress/pressure profiles Type 4 and Type 5 – 2 m high standpipes (a) 50 days, (b) 200 days, (c) 400 days, (d) End of test (722 days - Type 4 and 458 days - Type 5).

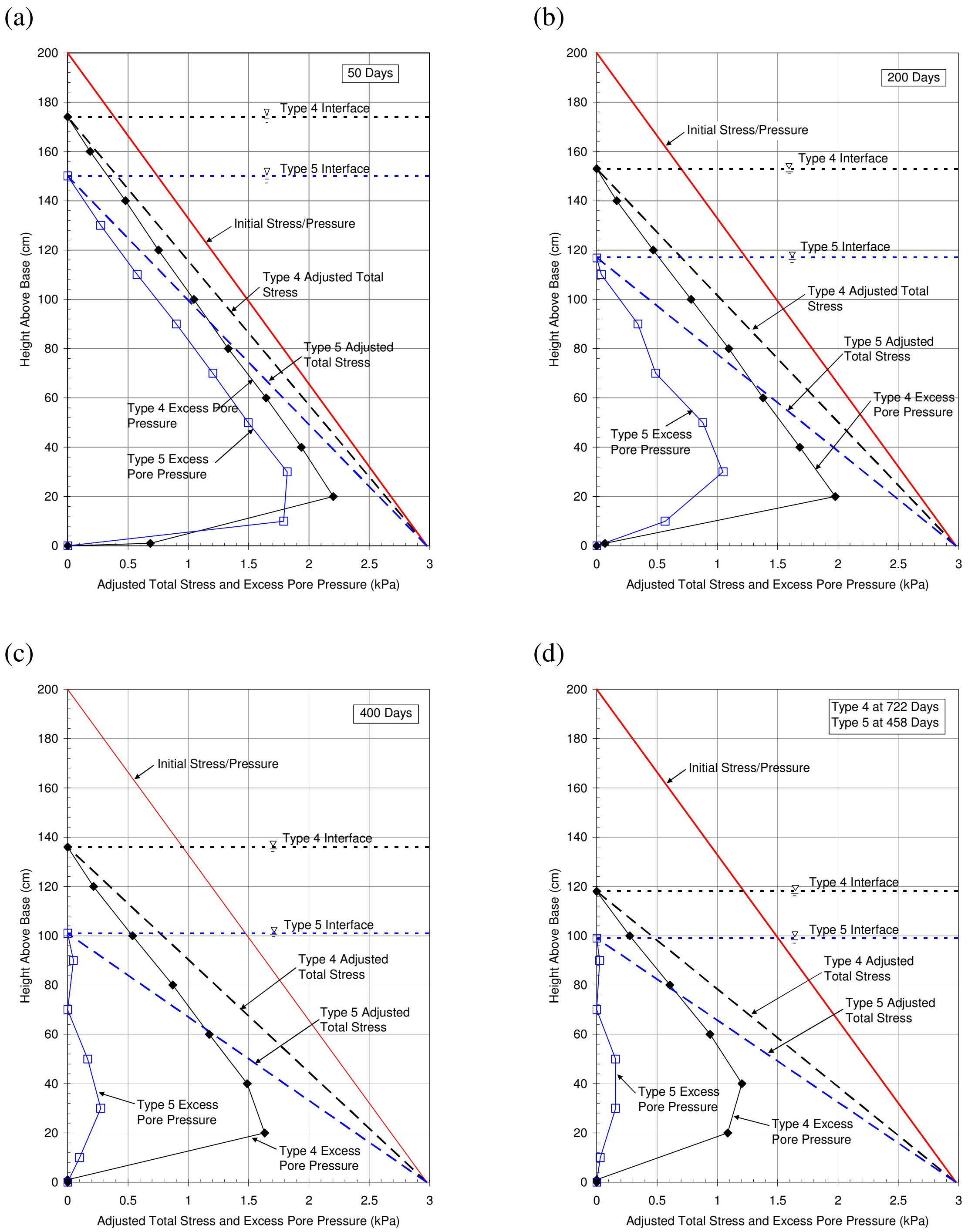
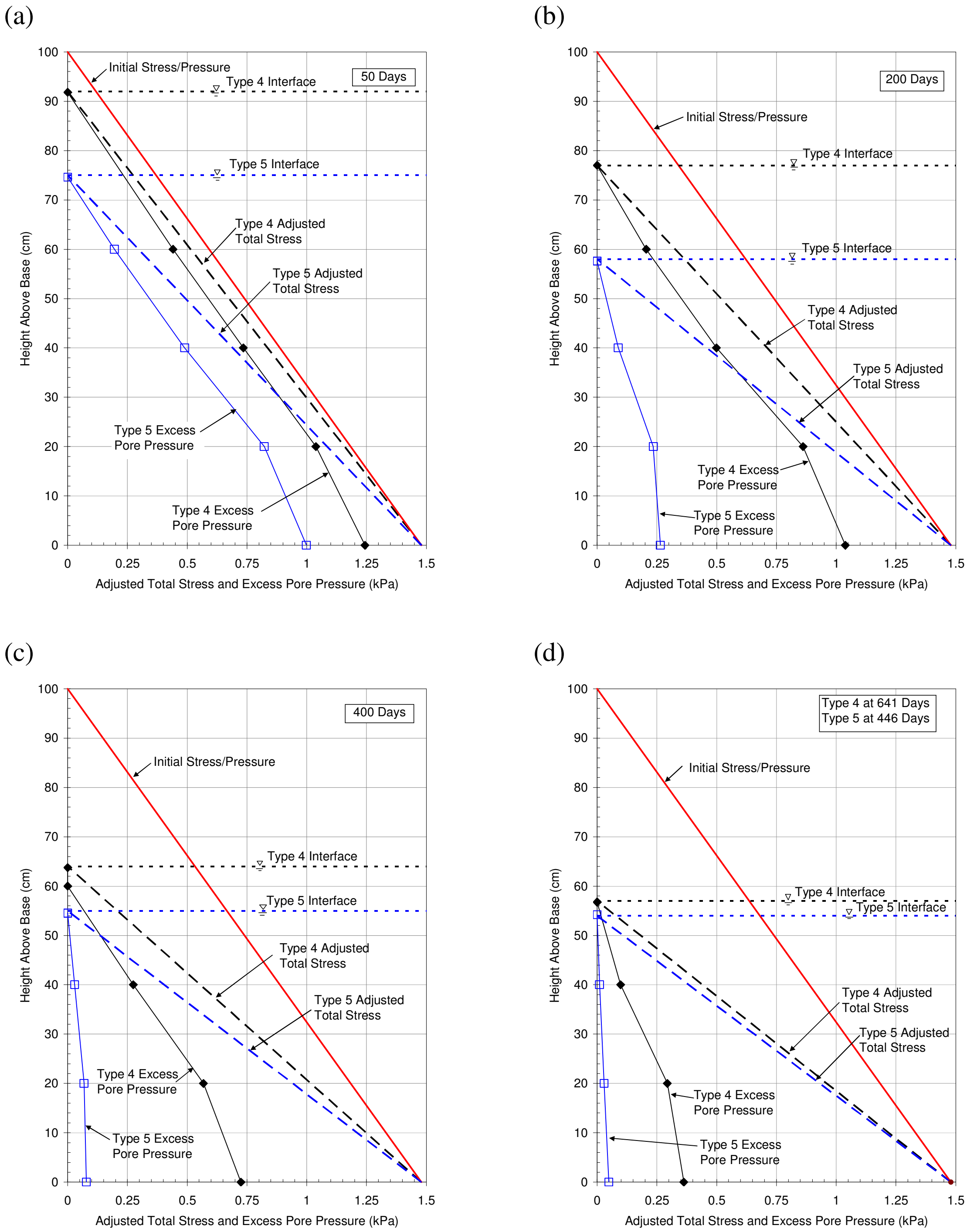


Figure 4. Stress/pressure profiles Type 4 and Type 5 – 1 m high standpipes (a) 50 days, (b) 200 days, (c) 400 days, (d) End of test (641 days - Type 4 and 446 days - Type 5).



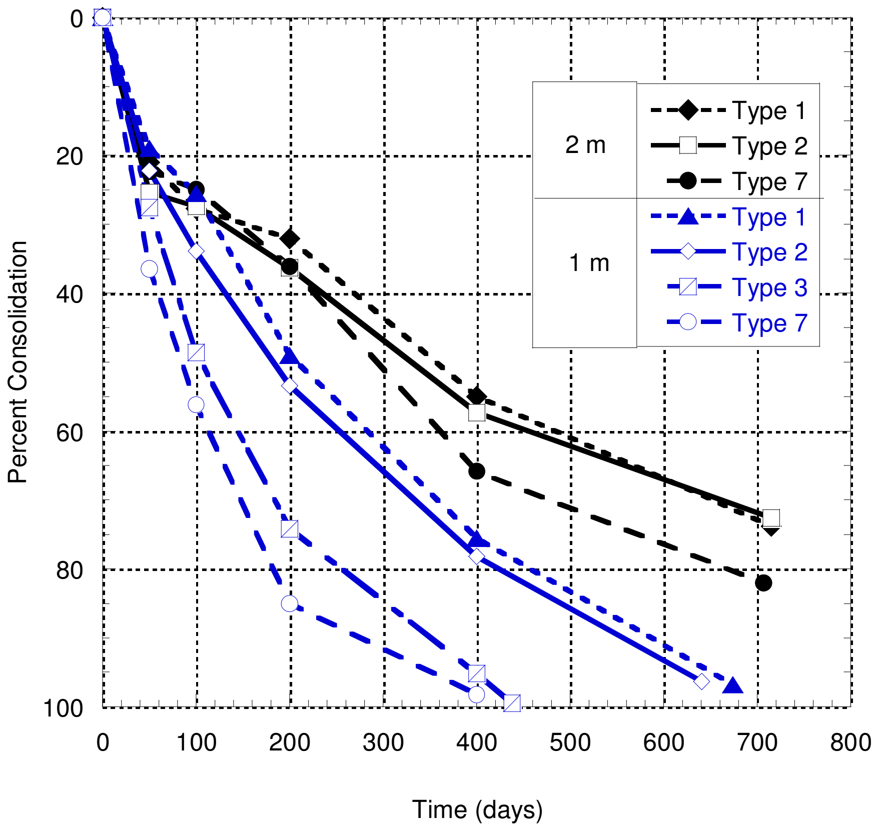


Figure 5. Rate of self-weight consolidation - Ore A fine tailings.

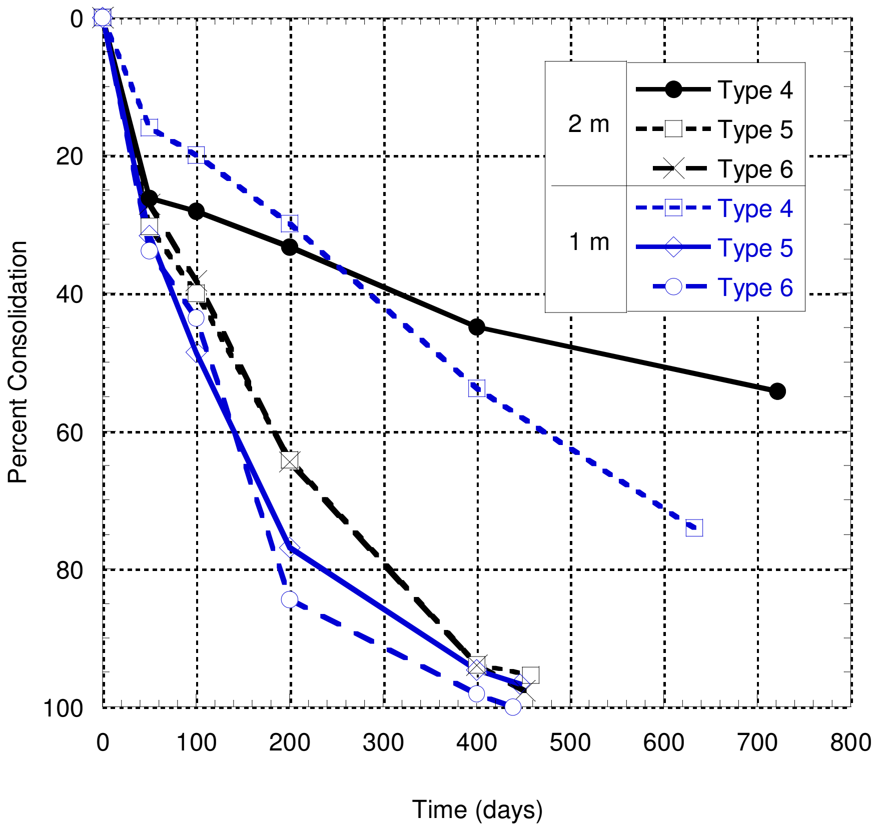


Figure 6. Rate of self-weight consolidation - Ore B fine tailings.

Rate of Self-Weight Consolidation

Summarized on Figures 5 and 6 are percent consolidation curves, derived from excess pore pressure distributions with time, for Ore A and Ore B respectively for both the 2 m and 1 m standpipes.

The rate of self-weight consolidation is controlled by the hydraulic conductivity of the fine tailings. Hydraulic conductivity decreases with smaller void ratio so the rate of self-weight consolidation was expected to slow with time as the average void ratio of the samples decreased.

For the 2 m standpipe tests, non-caustic fine tailings (Type 2) for Ore A had faster initial consolidation but decreased to approximately the same rate as caustic fine tailings (Type 1) (Figure 5). The improved consolidation rate during the early stages of settlement is due to the lesser degree of dispersion and coarser particle size distribution of the non-caustic fine tailings, resulting in a relatively higher hydraulic conductivity. The non-caustic fine tailings, Type 2, are coarser-textured than the caustic material, Type 1 (Table 5) having about 3 times less clay sized particles. This is responsible for faster initial consolidation, but after roughly 100 days the fine tailings consolidate at approximately the same rate, and reach roughly the same percent consolidation (roughly 73%) after 715 days. At this point, more and more clay particles are coming into contact with each other as the volume of the clay-water system decreases. Effective stress begins to control the consolidation of the fine tailings and particle size and degree of dispersion have diminishing importance. A similar pattern was measured for the 1 m standpipes for Types 1 and 2.

The non-caustic fine tailings (Type 5) of Ore B (Figure 6) had a greater initial rate of consolidation than the caustic material (Type 4) and continued to have a significantly greater percent consolidation up to the end of testing for the 2 m standpipe tests. At 400 days, Type 4 fine tailings had 45% consolidation compared to 94% for Type 5. Type 5 fine tailings (non-caustic) have roughly 10 times less clay sized particles than the caustic Type 4 fine tailings, compared to a ratio of only 3 for comparable Ore A fine tailings (Table 5). It should be noted that the degree of dispersion for Type 5 fine tailings is 10% (Table 5), the lowest of any of the fine tailings, and the SAR is 6% (Table 4). Clay suspensions with an SAR greater than about 7% are dispersed, however, Type 5 fine tailings are close to this limit and display a non-dispersed structure (Miller et al., 2010a). These characteristics for the Type 5 fine tailings appear to have lasting effects on improving the rate of consolidation of the fine tailings even after effective stress begins to control this process at longer times, most likely due to some of the larger flow channels present in the less dispersed fine tailings remaining open for release of fluid.

Considering the 2 m coagulant addition standpipe tests, Type 3 fine tailings were influenced by internal piping, which resulted in a very fast rate of consolidation. It is difficult to determine the effect of coagulant addition on rate of consolidation in this case. However, no evidence of piping was seen for Type 6 fine tailings, so the influence of coagulant addition is better addressed comparing Ore B materials. The coagulant addition dramatically increased the rate of consolidation for the caustic fine tailings (Figure 6) resulting in complete consolidation after only about 450 days. The reason for this improvement is the increased coarseness of Type 6 fine tailings due to aggregation of clay particles caused by the addition of the coagulant. Piping was not observed in any of the 1 m standpipe tests for the fine tailings with coagulant addition. Results were similar for the 1 m tests as those described previously with the Ore A and Ore B fine tailings with coagulant addition (Types 3 and 6) having significantly improved consolidation relative to the comparable caustic fine tailings (Types 1 and 4).

Determination of Adjusted Total Stress

Generally, in geotechnical engineering, the percent consolidation and the magnitude of the effective stress are calculated by comparing the total vertical stress and total pore pressure. In low density slurry deposits where the water surface is at or above the water-fine tailings interface, the hydrostatic water column (the hydrostatic pore pressure) makes up a high portion of the total vertical stress and total pore pressure. A clearer picture of the increase in percent consolidation and development of effective stress is shown when the hydrostatic pore pressure is subtracted from both the total stress and the total pore pressure and the adjusted total stress and excess pore pressure are compared as on Figures 5 and 6.

Pore pressures in standpipes or tailings ponds can be measured with manometers, piezometers or pore pressure probes. Total stress, on the other hand, must be determined by measuring the slurry density changes with depth by direct sampling at a number of depths or by geophysical density probes. A problem with standpipe testing therefore arises in that every time a pore pressure profile is measured a density profile should also be measured. If density samples were taken often this would seriously affect the volume of tailings in the standpipe. For this reason, density samples were only taken twice in the 2 m standpipes at about 200 days and at the end of the test. In the 1 m standpipes, density samples were only taken at the end of the test.

The adjusted total stress at other times has been approximated by taking advantage of the properties of low density slurries. At the interface the adjusted total stress is always zero and at the bottom of a standpipe it is constant at the initial value. A straight line between these two points will approximate the adjusted total stress with only a small error. This approximation is shown on Figure 7 for the 2 m standpipe Type 5 fine tailings. The actual adjusted total stress is a slightly concave upwards line because of the increase in density with depth. As the total area below the line is used to determine the percent consolidation and the magnitude of effective stress, the difference between the actual and approximated lines only results in a small error if noticeable excess pore pressure dissipation has occurred.

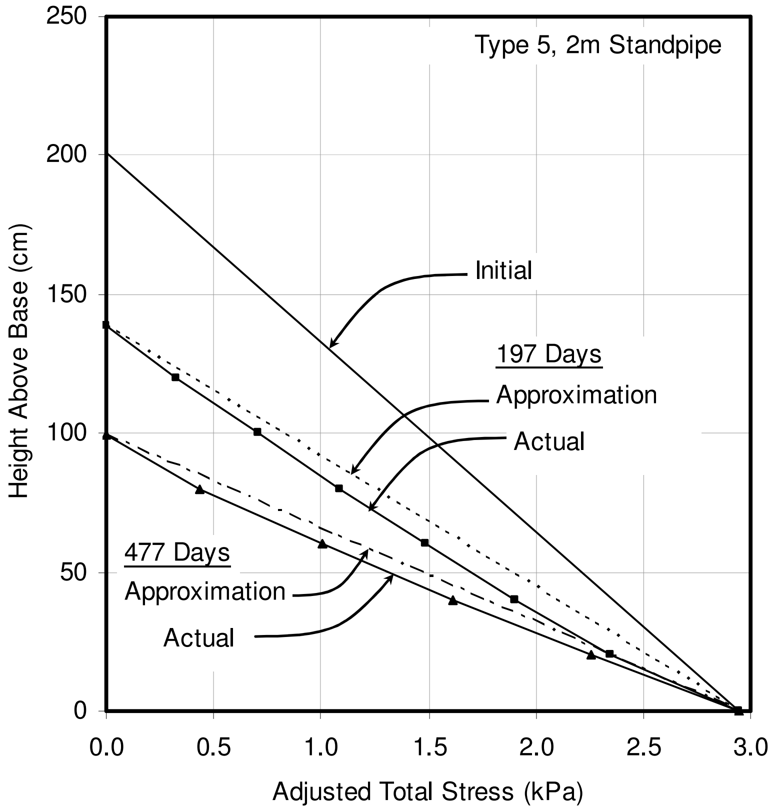


Figure 7. Approximation of adjusted total stress.

Long Term Volume Decrease

Comparisons of long term volume decrease (settlement with time) can be made using Figures 8 and 9 which present settlement of the 2 m and 1 m standpipes over a normalized height for Ore A and Ore B fine tailings respectively. Measurements of the fine tailings-water interface were recorded regularly throughout the testing program with high frequency during the initial settlement stages and decreasing frequency during the latter stages of the tests as settlement rates decreased.

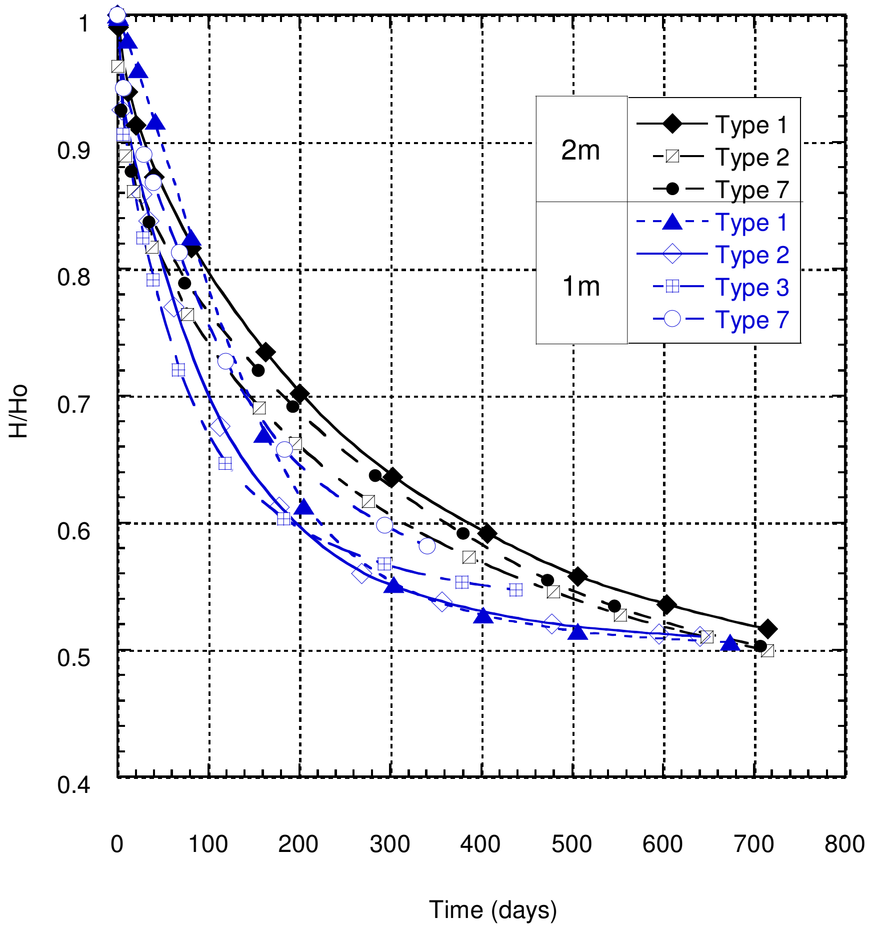


Figure 8. Settlement of the Ore A fine tailings.

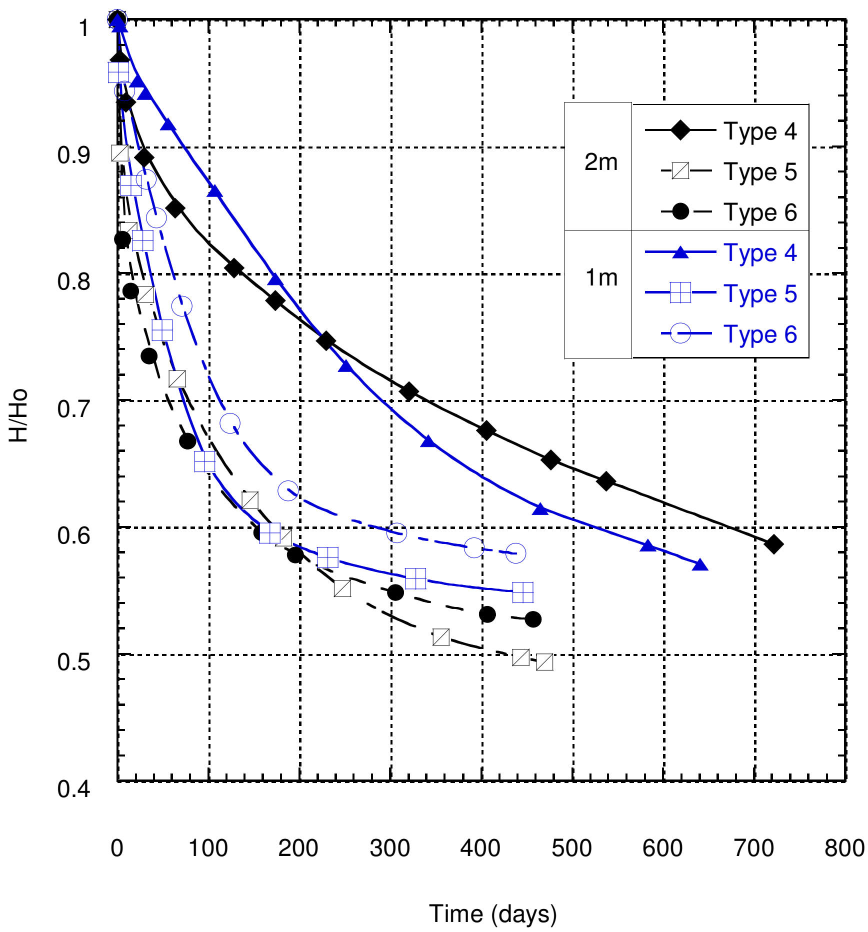


Figure 9. Settlement of the Ore B fine tailings.

Volume decrease of the fine tailings is important because it dictates the storage capacity required to retain the fine tailings. Initial volume decrease is also important because it will determine the volume of decant water available for recovery and reuse in the extraction process. Relative differences in volume decrease can be determined by comparing the interface settlement with time.

Non-caustic fine tailings had a consistently greater initial decrease in volume than the comparable caustic fine tailings. For the Ore B materials, this difference was greater than the Ore A fine tailings. The reasons for these differences are due to differences in hydraulic conductivity of the fine tailings. However, all of the fine tailings, regardless of extraction process, approach similar final volume at long times (Figures 8 and 9). Extrapolation of the curves would result in final volumes for the fine tailings that are between approximately 50% and 55% of the original volumes. Thus, even though the rate of consolidation varies, ultimately the extraction process has no observable effect on the final volumes of the fine tailings. This is due to effective stress becoming the dominant process acting on the fine tailings as the particles come into contact with each other as volumes decrease, diminishing effects of degree of dispersion and particle size distribution caused by the extraction process.

Similarly, even though the coagulant addition improved the initial rate of consolidation of the caustic fine tailings, the long term settlement appears to be converging to a similar value over time. As discussed above regarding extraction process influence, at lower volumes the effective stress controls volume decrease and the effect of coagulant addition is lessened.

Compressibility

The settlement of the fine tailings can be thought of in terms of a vertical strain caused by the application of a vertical force, which in this case is the weight of individual clay particles exerting a force on those below. Two important strain mechanisms to consider for the fine tailings are reorientation of particles and reduction of inter-particle spacing. Nondispersed clay peds in a flocculated state can be reoriented into more effective packings by the application of a vertical force. That is, the greater spacing between non-dispersed/flocculated clay particles created by the edge to face structure, decreases as particles tend to align into a parallel array as vertical force is applied. Dispersed clay particles are already in a parallel arrangement, so reorientation will have little effect.

A reduction of the spacing between clay particles can be caused by applying force or altering the water chemistry of the fine tailings. Spacing between clay particles decreases as increasing force is applied. As well, decreasing the double layer around clay particles, by increasing the valence of exchangeable ions or increasing electrolyte concentration of the pore water, will result in decreased spacing between clay particles.

Compressibility of soils is defined as the decrease in void ratio with an increase in effective stress. The effective stress in a standpipe is calculated from a profile of solids content and a profile of pore pressure. Typical solids content profiles for a caustic fine tailings, Type 4, and a non-caustic fine tailings, Type 5, are shown on Figures 10, 11 and 12.

On Figure 10, the solids content profiles are given for the 2 m standpipes at about 200 days elapsed time. The lower interface level and higher solids content for Type 5 results in it being more compressible at that time. On Figure 11, the profiles at the end of the tests are significantly different with Type 4 having a considerably lower solids content. This difference in solids contents is a result of Type 4 not being fully consolidated when the test was stopped at 722 days while Type 5 was fully consolidated when the test was stopped at 458 days (Figure 3).

On Figure 12 where typical 1 m standpipe results are reported, Type 4 was almost fully consolidated while Type 5 was fully consolidated (Figure 4). Under this condition, the solids content profiles are similar as effective stress governs the solids contents, not the water chemistry or amount of fines dispersion.

Figure 13 shows the void ratio-effective stress relationships for the fine tailings Types 4 and 5 from both the 2 m and 1 m standpipes. The compressibility curves for the 1 m standpipes and the 2 m standpipe Type 5 are essentially straight and typical of remoulded clays. The compressibility for the 2 m standpipe Type 4 caustic fine tailings is more complex. The flattening of the compressibility curve at low effective stresses is caused by the development of thixotropic strength which gives the fine tailings an overconsolidation effect (Miller et al. 2010b). This overconsolidation results in the caustic fine tailings not consolidating after a void ratio of 6.5 or solids content of approximately 28% is reached. The overconsolidation effect can be overcome by remolding or by applying an effective stress greater than 0.8 kPa. It is postulated that the 1 m Type 4 standpipe did not show an overconsolidation effect because it consolidated fast enough that thixotropic action did not have time to develop. Thixotropic strength is strength developed over time in clay deposits and occurs in caustic fine tailings due to its finer particle size distribution and high electrolyte concentration in the pore water. Similar results were obtained in the 2 m Ore A Type 1 caustic fine tailings but the thixotropic overconsolidation was less pronounced.

Figure 14 shows the void ratio-effective stress relationships for all seven of the fine tailings types in the 1 m standpipes. All seven materials were fully consolidated and plot in a narrow band. This result emphasizes that consolidation even at very low effective stresses is governed by the effective stress and not the pore water chemistry. For very long term consolidation, as in a tailings ponds, the caustic fine tailings is an exception to this finding because of the development of thixotropic strength.

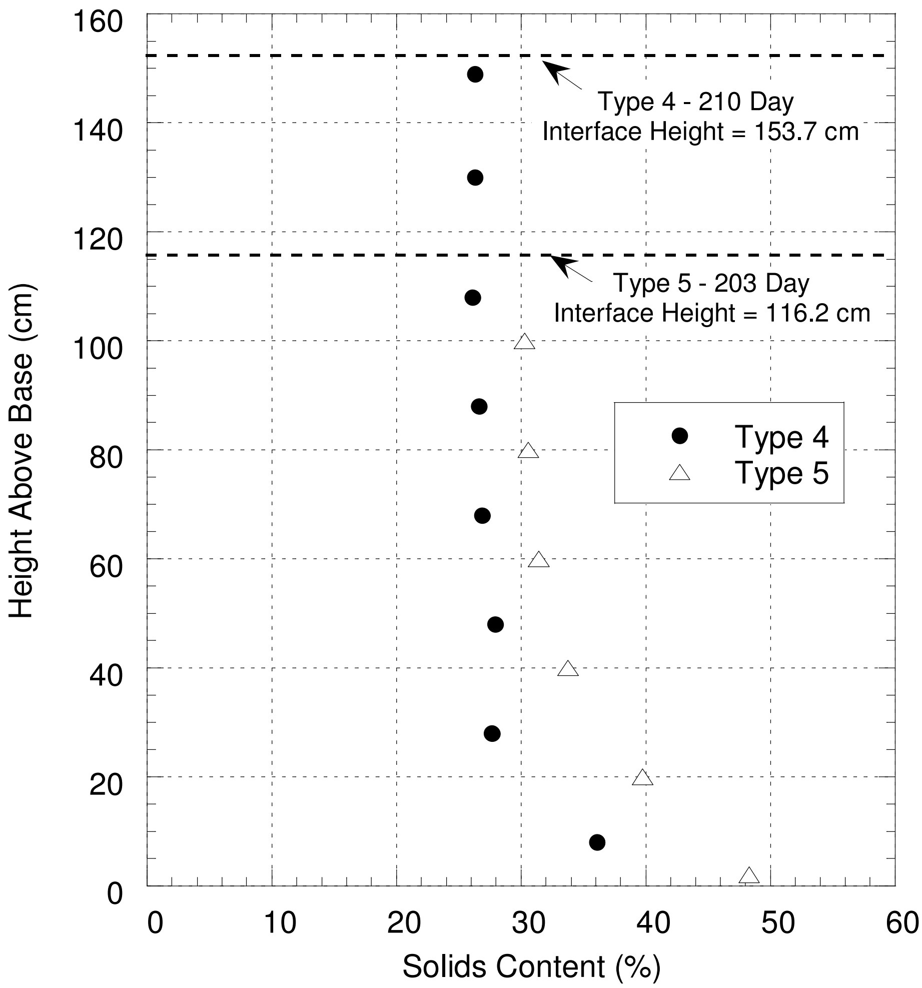


Figure 10. Solids content profiles at 200 days for 2 m high standpipe tests - Types 4 and 5 fine tailings.

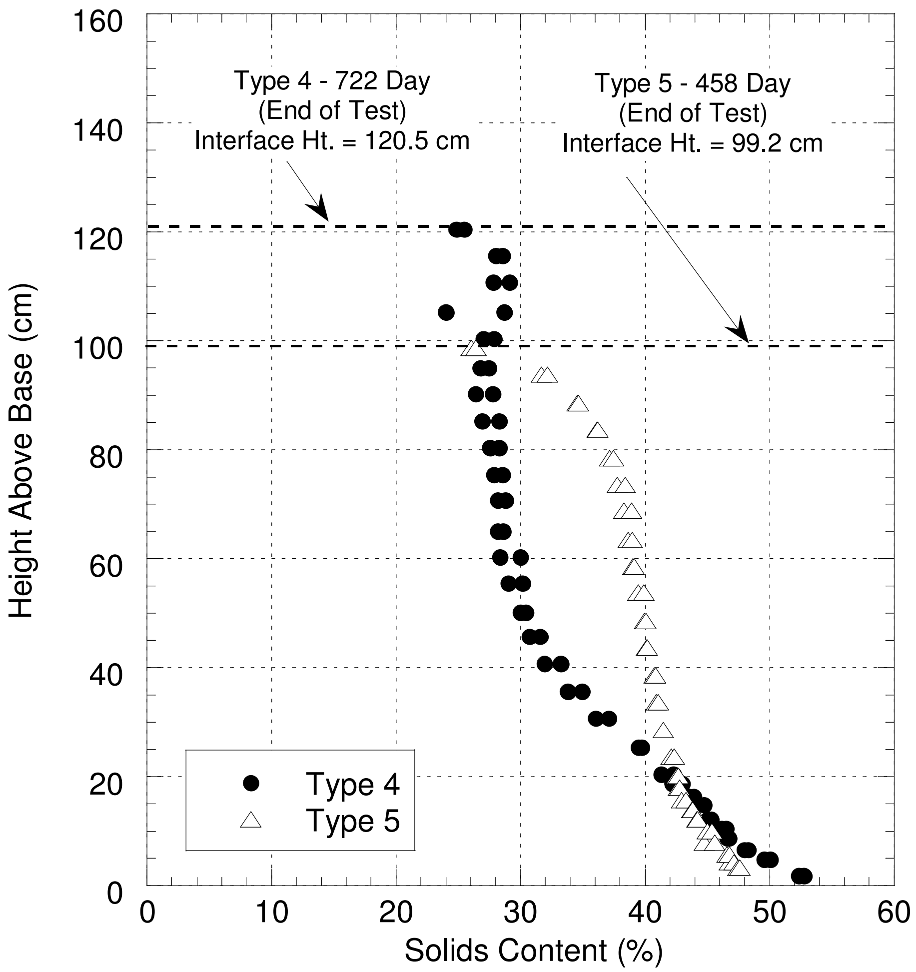


Figure 11. Solids content profiles at end of test for 2 m high standpipe tests - Types 4 and 5 fine tailings.

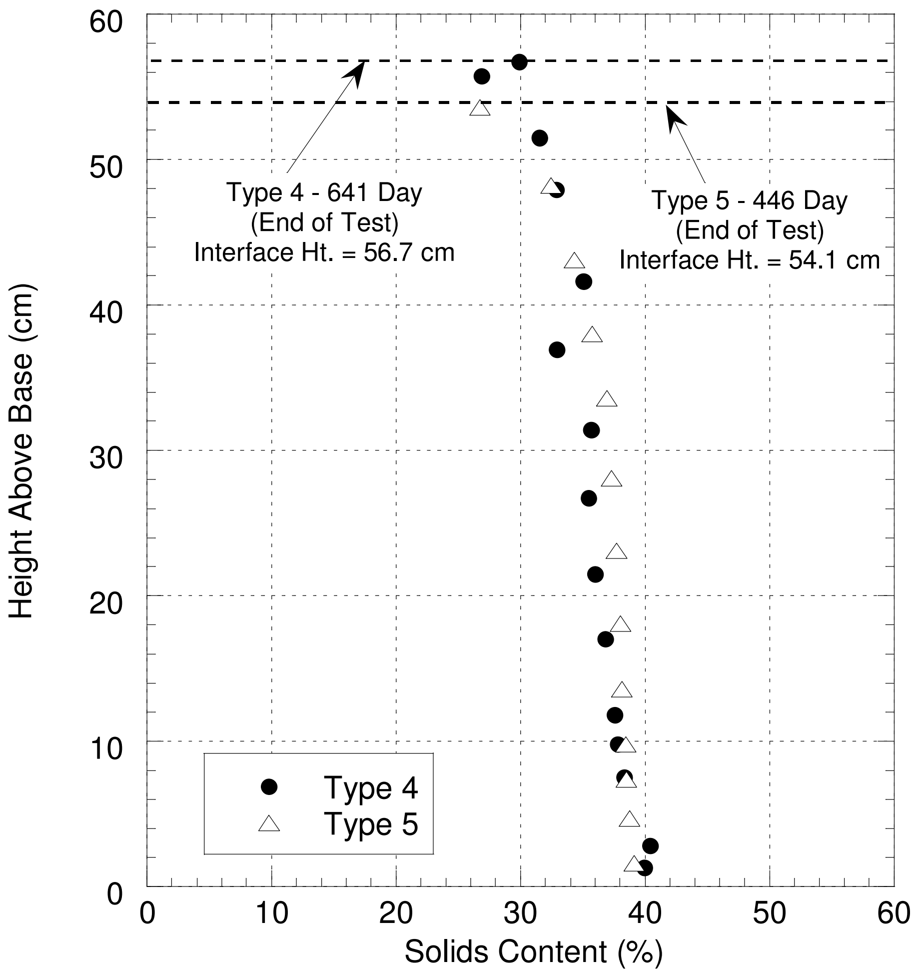


Figure 12. Solids content profiles at end of tests for 1 m high standpipe tests - Types 4 and 5 fine tailings.

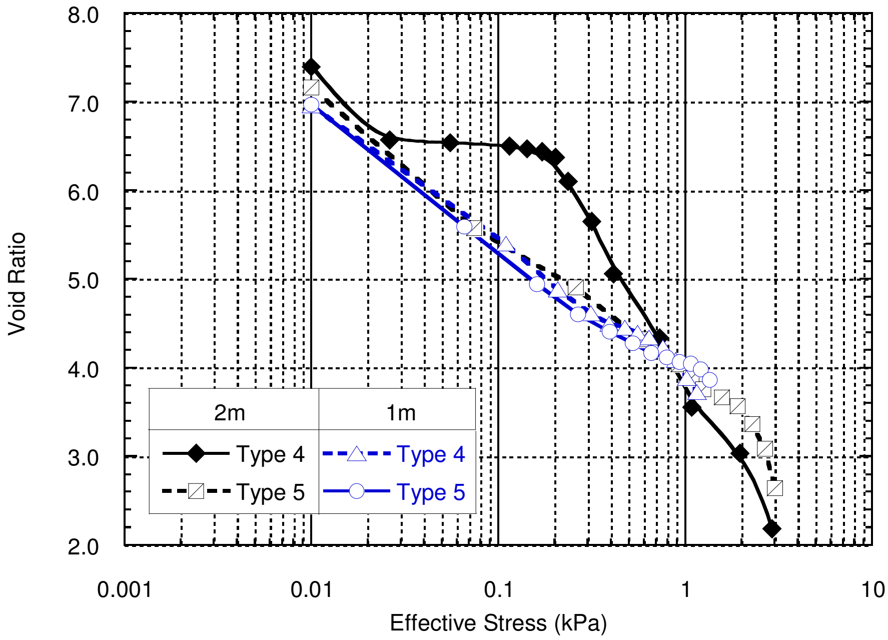


Figure 13. Compressibility of Ore B fine tailings.

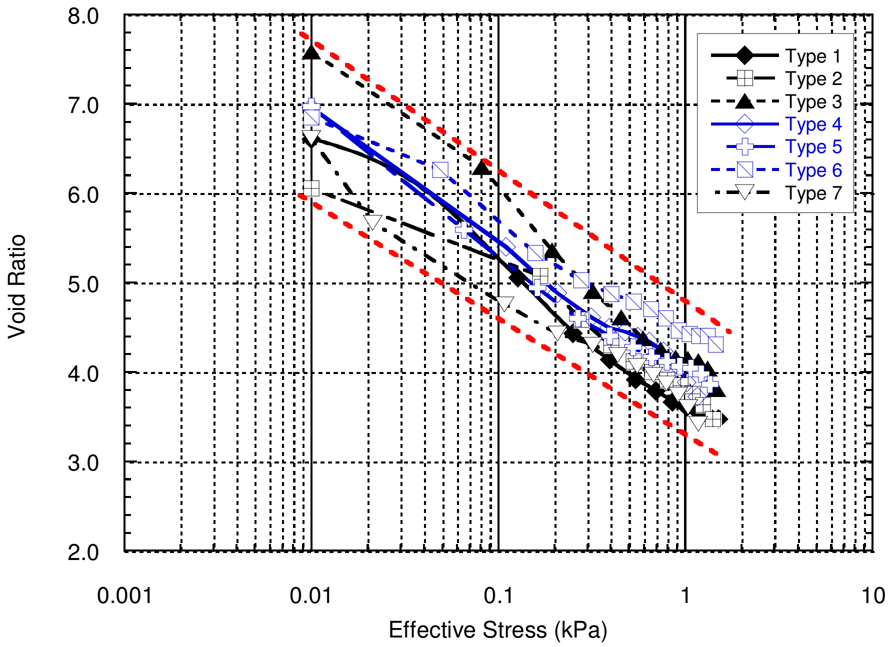


Figure 14. Compressibility of fine tailings – 1 m high standpipes.

Downward Drainage in 2 m Standpipes

The 2 m standpipes were designed to model a fine tailings pond underlain by a permeable strata such as a sand layer or a fractured bedrock. The sand layer condition exists under some of the oil sand tailings ponds. Environmental concern has been expressed about this potential leakage path of toxic tailings water to aquifers and eventually to the Athabasca River. Such leakage would be attenuated by the fairly rapid consolidation of the fine tailings immediately above the underlying permeable strata but no experimental data on this phenomenon has been reported in the literature.

To prevent rapid consolidation in the 2 m standpipes by a downward hydraulic gradient, the pore water pressure in the bottom permeable filter was kept at the hydrostatic water pressure as shown on Figure 1. The downward drainage water was continuously collected and the drainage volume with time was monitored.

Figures 10 and 11 show the increase in solids content at the bottom of the standpipes at approximately 200 days and at the end of the tests respectively for fine tailings Types 4 and 5. By 200 days the lower 20 cm of the standpipe was consolidated to a solids content of over 30% and up to 40% to 50% at the bottom. It should be realized that the height of the standpipe controls the magnitude of consolidation. A higher deposit with the same drainage conditions would consolidate to a higher solids content at the bottom.

The downward drainage volumes with time are given on Figure 15 for the 2 m standpipes fine tailings for Types 4, 5 and 6. The more rapid drainage for non-caustic Type 5 fine tailings is a reflection of its less dispersed structure. The leveling off of the downward drainage at about 300 days for this fine tailings is a result of it being close to fully consolidated at this time. The caustic Type 4 fine tailings would eventually show a similar downward drainage volume when it was fully consolidated.

Figure 16 is the downward drainage volume for the 2 m standpipes for all seven types of fine tailings at 10, 50 and 100 days plotted against the SAR of the pore water. As the SAR is an indication of the amount of fines dispersion in the tailings, the low SAR of 6 for Type 5 non-caustic fine tailings resulted in less dispersion and therefore a higher hydraulic conductivity. This resulted in the faster downward drainage volumes at an SAR of 6.

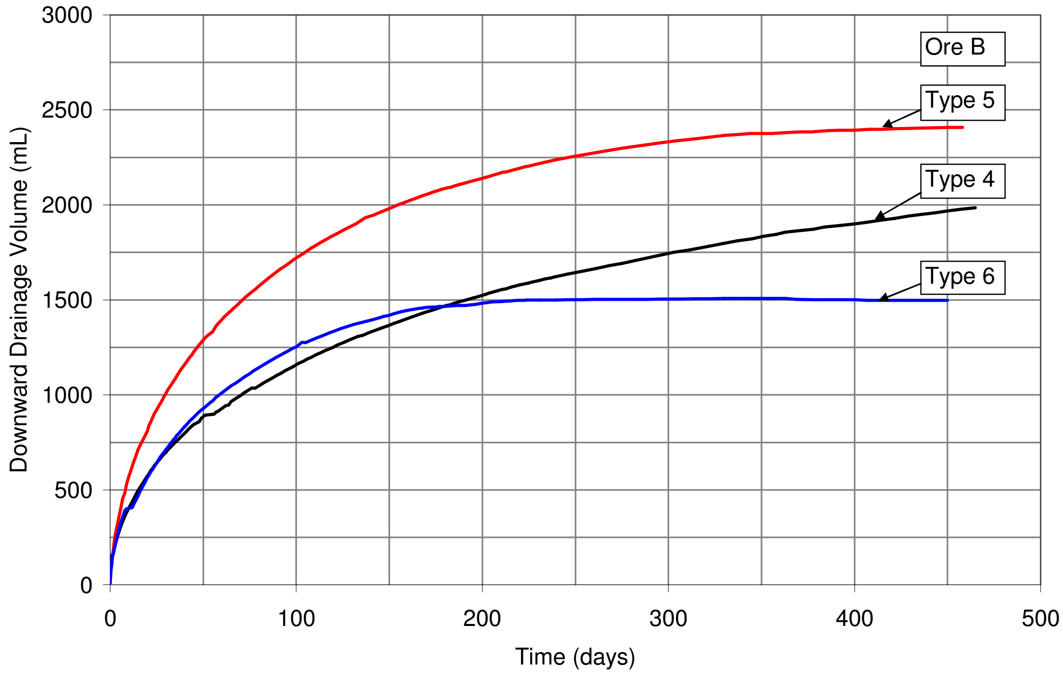


Figure 15. Comparison of downward drainage for fine tailings Types 4, 5 and 6 – 2 m standpipes.

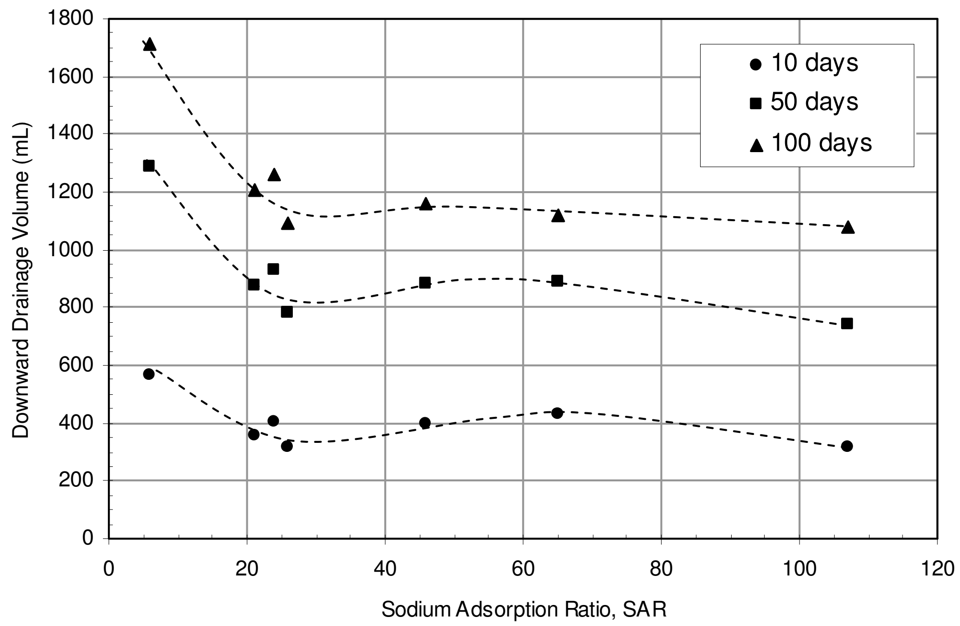


Figure 16. Relationship between downward drainage and SAR – 2 m standpipes.

Conclusions

(1) Fourteen self-weight consolidation tests on seven fine tailings materials were performed using 2 m and 1 m high standpipes fully instrumented to monitor the rate and amount of consolidation. Thirteen of the tests provided valuable information on the variation of consolidation that was related to the differences in the fine tailings pore water chemistry, particle size distribution and structure.

(2) The use of adjusted total stress and excess pore pressure instead of total stress and pore pressure provide a better visualization of the progress of consolidation.

(3) The sodium adsorption ratio (SAR) provides a prediction of the adsorbed phase based on the concentration of ions in solution. From the particle size distribution results, it was concluded that fine tailings with a SAR greater than 20 are likely to be in a dispersed state while those with a low SAR will have a less dispersed structure.

(4) Non-caustic fine tailings had faster initial consolidation which is important in tailings ponds as this fine tailings would require less storage capacity and return decant water at a faster rate to the extraction plant. Settlement of the fine tailings, or volume decrease, became similar for the caustic and non-caustic fine tailings after long periods of time. As the volume of the fine tailings decreases, and more and more clay particles come into contact with each other, effective stress will begin to control consolidation. At this point, the influence of degree of dispersion and particle size distribution will diminish.

(5) Similarly, even though the coagulant addition improved the initial rate of consolidation of the caustic fine tailings, the long term settlement appears to converge to a similar value over time and is then governed by effective stress changes.

(6) The fine tailings are highly compressible materials relative to typical clay minerals, with large changes in void ratio at low effective stresses. The long term compressibility of the non-caustic and caustic fine tailings are fairly similar, but the caustic fine tailings show an overconsolidation effect caused by the development of thixotropic strength within the mature fine tailings.

(7) The 2 m high standpipes were designed to model a fine tailings pond underlain by a permeable sand layer. The rate and amount of downward drainage was continuously monitored and the non-caustic fine tailings had more rapid downward drainage that was a reflection of its less dispersed structure and agreed with its low SAR value.

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Table 1 Fine tailings materials.

Fine Tailings Type	Ore Designation	Ore Description (using Syncrude Geologic Facies Chart)	Extraction Process	Process Water	Coagulant Addition
1	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	None
2	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Treated Athabasca River water	None
3	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
4	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	None
5	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Non-caustic	Treated Athabasca River water	None
6	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
7	A	Sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Untreated Athabasca River water	None

Table 2 Mineralogy of the clay in the fine tailings.

Fine Tailings Type	Ore Designation	Quartz (%)	Kaolinite (%)	Illite (%)	Mixed layer clays (%)	Smectite (%)
1	A	2	81	15	2	0
2	A	2	80	15	3	0
3*	A	2	81	15	2	0
4	B	2	76	18	4	0
5	B	2	75	19	4	0
6*	B	2	76	18	4	0
7	A	2	78	15	1	4

*Note: Type 3 and Type 6 fine tailings consist of coagulant added to Type 1 and Type 4 fine tailings respectively

Table 3. Water chemistry of ore connate water.

Fine Tailings Type	Ore	Anions			Cations (mg/L)							SAR
		HCO_3 (meq/L)	Cl (mg/L)	SO_4 (mg/L)	Fe	Si	Al	Mg	Na	Ca	K	
1	A	1.237	99.8	93.6	0	0.74	0	0	162.8	0	1.89	-
2	A	1.062	109.6	145.1	0.55	6.31	2.58	0	193.8	0	3.05	-
4	B	1.483	24.6	66.8	0	0.54	0	0	76.84	1.39	3.15	18
5	B	1.399	18.9	53.9	0	1.05	0	0	68.45	0.65	2.87	23
7	A	1.085	106.3	129.6	0.18	3.92	1.34	0	178.3	0.29	2.2	91

Table 4 Water chemistry of the fine tailings.

Fine Tailings Type	Ore	pH	Anions (mg/L)			Cations (mg/L)							SAR
			HCO_3	Cl	SO_4	Fe	Si	Al	K	Mg	Ca	Na	
1	A	8.9	1397	496	453	0.12	3.7	0.74	9.8	2.8	2.2	1017	107
2	A	8.2	337	174	294	0.67	6.1	2.9	7.2	6.9	10.6	350	21
3	A	8.5	1093	455	952	0.09	4.9	0.22	12.3	6.5	15.0	1197	65
4	B	8.8	860	330	323	1.6	14.4	9.2	11.8	5.8	8.2	696	46
5	B	8.1	292	49	187	0.08	2.6	0.29	8.0	15.9	29.0	150	6
6	B	8.1	623	305	822	0.08	3.0	0.52	15.1	15.2	48.4	746	24
7	A	8.3	439	190	194	0.66	6.1	2.8	6.7	4.8	7.0	363	26

Table 5 Particle size distribution characteristics.

Fine Tailings Type	Ore Designation	Test Method	< 74 µm (%)	< 44 µm (%)	< 2 µm (%)	<1 µm (%)	Percent Dispersion (%)
1	A	Dispersed Nondispersed	96 97	92 94	43 43	32 19	100
2	A	Dispersed Nondispersed	100 100	98 99	47 15	35 2.5	32
4	B	Dispersed Nondispersed	98 98	97 96	49 49	40 40	100
5	B	Dispersed Nondispersed	98 99	97 98	48 5.0	33 1.5	10
7	A	Dispersed Nondispersed	98 100	99 99	41 41	29 15	100

Table 6 Initial properties of the fine tailings - 2 m and 1m high standpipes.

	Fine Tailings Type	Ore Type	Initial Height (cm)	Initial Solids Content (%)	Initial Void Ratio	Test Limit (days)
2 m Standpipes	1	A	201	22.2	9.08	715
	2	A	201	22.0	9.00	715
	3	A	201	22.2	9.09	451
	4	B	201	22.0	8.84	722
	5	B	201	22.0	8.91	458
	6	B	201	22.0	8.98	450
	7	A	201	22.0	8.86	707
1 m Standpipes	1	A	99.3	22.2	9.03	674
	2	A	99.1	22.0	9.05	641
	3	A	99.1	21.3	9.60	438
	4	B	99.4	22.1	8.74	641
	5	B	98.8	22.1	8.88	446
	6	B	99.2	22.1	8.95	438
	7	A	99.3	22.3	8.71	340

CHAPTER 5. EFFECT OF EXTRACTION WATER CHEMISTRY ON THE CONSOLIDATION OF OIL SANDS FINE TAILINGS

This paper was previously reviewed, accepted and published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal. It is presented as published as part of this Ph.D. thesis as Chapter 5.

Reference: *Effect of extraction water chemistry on the consolidation of oil sands fine tailings*. CIM Journal, 1(2), 113-129.

Page Numbering:
CIM Journal: 113 to 129
This thesis: 85 to 101

Effect of extraction water chemistry on the consolidation of oil sands fine tailings

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ABSTRACT An overall study was conducted to evaluate the properties and processes influencing the rate and magnitude of consolidation for oil sands fine tailings produced using different extraction processes. As part of this overall study, consolidation tests using slurry consolidometers were carried out for caustic and non-caustic fine tailings. The influence of a change in bitumen extraction process (caustic versus non-caustic) on consolidation properties, namely compressibility and hydraulic conductivity, was determined, as was the effect of adding a coagulant (calcium sulphate [$CaSO_4$]) to caustic fine tailings. For fine tailings originating from two different oil sands ores (Ore A and Ore B), results were presented in terms of variation in average void ratio with time (settlement), void ratio with effective stress (compressibility), hydraulic conductivity with void ratio and coefficient of compressibility and hydraulic conductivity with sodium adsorption ratio. Findings indicated that chemical characteristics of fine tailings (water chemistry, degree of dispersion) do not have a significant impact on their compressibility behaviour and have only a small influence at high void ratio (low effective stress). The biggest advantage of non-caustic fine tailings and treating caustic fine tailings with coagulant is an increased initial settlement rate and slightly increased hydraulic conductivity at higher void ratios. Thereafter, compressibility and hydraulic conductivity is governed by effective stress.

KEYWORDS Oil sands, Fine tailings, Compressibility, Hydraulic conductivity, Consolidation, Large strain, Volume change, Void ratio, Settlement, Effective stress, Dispersion, Coagulant, Sodium adsorption ratio

RÉSUMÉ Une étude détaillée a été réalisée afin d'évaluer les propriétés et les processus influençant le taux et l'ampleur de la consolidation des résidus fins de sables bitumineux produits par différents processus d'extraction. Dans le cadre de cette étude détaillée, des essais de consolidation ont été effectués sur les boues en utilisant des oedomètres; les essais portaient sur des résidus fins caustiques et non caustiques. L'influence d'un changement dans le procédé d'extraction du bitume (caustique p/r non caustique) sur les propriétés de consolidation a été déterminée, soit la compressibilité et la conductivité hydraulique, en plus de l'effet de l'ajout d'un coagulant (sulfate de calcium [$CaSo_4$]) aux résidus caustiques fins. Pour les résidus fins provenant de deux différents minerais de sables bitumineux (minerai A et minerai B), les résultats sont présentés en termes de la variation de l'indice des vides moyen dans le temps (tassement), de l'indice des vides par rapport à la contrainte effective (compressibilité), la conductivité hydraulique par rapport à l'indice des vides et la compressibilité et la conductivité hydraulique par rapport à l'adsorption du sodium. Les résultats indiquent que les caractéristiques chimiques des résidus fins (hydrochimie, degré de dispersion) n'ont pas d'impact significatif sur le comportement en compression et n'ont qu'une petite influence à des indices des vides élevés (faible contrainte effective). Le plus grand avantage des résidus fins non caustiques et du traitement des résidus fins caustiques avec un coagulant est un accroissement du taux initial de tassement et une légère augmentation de la conductivité hydraulique à des indices des vides supérieurs. Ensuite, la compressibilité et la conductivité hydraulique sont une fonction de la contrainte effective.

MOTS CLÉS Sables bitumineux, Résidus fins, Compressibilité, Conductivité hydraulique, Consolidation, Grande contrainte, Changement de volume, Indice des vides, Tassement, Contrainte effective, Dispersion, Coagulant, Taux d'adsorption du sodium

INTRODUCTION

In the oil sands industry, high temperature with the addition of a caustic dispersing agent has formed the basis of the Clark hot water extraction process. This process has been used successfully on a commercial scale to recover bitumen from surface-mined oil sands ore since 1967. Descriptions of the present-day extraction and froth treatment process are provided by Cymerman and Kwong (1995), Shaw, Czarnecki, Schramm, and Axelson (1994), and Shaw, Schramm, and Czarnecki (1996). However, the Clark process results in the creation of extremely dispersed, high void ratio fine tailings composed primarily of silt, clay, water and residual bitumen. These caustic-based fine tailings exhibit low consolidation rates and shear strengths, and require considerable real estate for storage. At present, approximately 750 million cubic metres of fine tailings are being stored in tailings ponds (Houlihan & Mian, 2009). The conventional method for fine tailings management is a containment strategy of the fine tailings in ponds for sedimentation, consolidation and eventual land reclamation. Some fine tailings have been mixed with sand to form composite/consolidated tailings that consolidate sufficiently to allow land reclamation and this process is continuing. Another possibility for final disposal is that, at mine closure, some fine tailings can be stored in mined-out pits and water can be capped to form lakes. However, the vast quantities and slow consolidation of fine tailings raise environmental and economic questions regarding possible improvements in tailings behaviour.

Processes different from the established Clark process (high temperature and caustic) have been developed to work at a range of temperatures, with or without the use of sodium hydroxide (Kasperski, 2001). One such process is the Other Six Lease Owners (OSLO; the consortium of companies that piloted the process) hot water extraction process (Sury, Paul, Dereniwski, & Schulz, 1993). The OSLO process entails a non-caustic, bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the hope of improved consolidation and strength properties of the fine tailings. The potential reduction in fine tailings volume and improved geo-environmental behaviour provide an environmental and economic incentive to examine the relative differences between the properties that influence consolidation of fine tailings derived from such extraction processes.

The overall objective of this research program was to evaluate the extraction process influence on the rate and magnitude of consolidation for the tailings produced using the Clark and OSLO extraction processes. The two main components were flume deposition tests and testing for geotechnical properties of the fine tailings. The results of the flume deposition tests are provided by Miller, Scott, and Sego (2009). Physical and chemical characteristics of the fine tailings derived from the flume deposition tests and examined during this geotechnical testing program are provided by Miller, Scott, and Sego (2010a). Self-weight consolidation results derived from standpipe tests are provided in Miller, Scott, and Sego (2010b). Thixotropic shear strength results determined from vane shear tests are provided by Miller, Scott, and Sego (2010c).

Compressibility and hydraulic conductivity relationships with void ratio are engineering properties that will influence the long-term disposal of the fine tailings. They are used in large strain consolidation analyses of a storage pond to predict water release rates and changes to surface elevations that impact storage volumes and elevation of reclamation surfaces. Consolidation tests were carried out to determine these properties for the fine tailings tested. The objective of this study was to determine the influence of a change in extraction process on the consolidation properties, compressibility and hydraulic conductivity. The effect of adding a coagulant to caustic fine tailings was also determined. Any differences in the compressibility and hydraulic conductivity properties between the fine tailings are explained based on the physical and chemical characteristics of the materials.

Table 1. Fine tailings materials

Fine tailings fype	Ore designation	Ore description (using Syncrude geologic facies chart)	Extraction process	Process water	Coagulant addition
1	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	None
2	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Treated Athabasca River water	None
3	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
4	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	None
5	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Non-caustic	Treated Athabasca River water	None
6	B	Lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	Caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
7	A	Subtidal and intertidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	Non-caustic	Untreated Athabasca River water	None

The consolidation tests were performed using slurry consolidometers. This type of test allows a wide range of effective stresses to be applied to the fine tailings and direct hydraulic conductivity measurements can be carried out for each effective stress.

EXPERIMENTAL PROGRAM

Fine tailings from two extraction processes were used in this study. For the remainder of this paper, they are referred to as caustic and non-caustic fine tailings. The two extraction processes are described more fully in Miller et al. (2009) and in Miller et al. (2010a).

Fine tailings

Seven different fine tailings derived from two types of oil sands ore were studied to determine the influence of extraction process and coagulant addition on the compressibility and hydraulic conductivity of the fine tailings. The seven different fine tailings and their descriptions are summarized in Table 1. For each type of oil sands ore, one fine tailings from a caustic extraction process and one fine tailings from a non-caustic extraction process were investigated. Additionally one non-caustic process used untreated river water. As well, caustic tailings modified by the addition of 600 ppm of calcium sulphate were studied. The addition of calcium sulphate was proposed to improve the settling behaviour of the fine tailings by causing the aggregation of clay particles. In Table 1, each fine tailings has been designated a number (1 through 7) to facilitate ease of presentation in figures and tables.

Tailings from each extraction process were generated using approximately 80-tonne samples of Ore A and Ore B. The extraction process water was chosen based on the water source that would be used for commercial operation. The extraction process water used during the caustic process was recycled pond water from the Mildred Lake settling basin at Syncrude. Sodium hydroxide was added to aid extraction: 0.05 wt % for Ore A and 0.005 wt % for Ore B. For the causticfine tailings, pH values ranged from about 9.0 to about 9.2. The higher values were representative of some Ore A fine tailings samples. The non-caustic process utilized Athabasca river water (initial pH 7.4) that had been treated by slowly adding a 10% sulphuric acid solution to bring the pH to 5.0 and subsequently adding a 4% (by weight) lime slurry. This increased the pH of the water to be used for extraction back to a pH of 7.4 and resulted in 40 ppm Ca^{2+} in solution. The non-caustic extraction process relied on a methyl isobutyl carbonyl/kerosene mixture as a conditioning agent and physical processes, such as air injection, to encourage bitumen separation. For these non-caustic tailings, the pH values ranged from 8.4 to 8.7, with higher values for Ore A fine tailings. The extraction processes are fully described in the Fine Tailings Fundamentals Consortium (FTFC; 1995) and collection of the fine tailings is provided in Miller et al. (2009).

The mineralogy of the clay-sized fraction of the fine tailings (Table 2) is dominated by kaolinite (75 to 81%) and illite (15 to 19%), as well as trace amounts of mixed layer clays. For the fine tailings derived from Ore A, the mineralogies are essentially the same because the extraction process has no effect on the type and amount of clay minerals present in each fine tailings. This is also the case for fine tailings derived from Ore B. Thus, mineralogy is not a factor when comparing fine tailings derived from the same oil sands ore.

The water chemistry of the fine tailings is shown in Table 3. The water chemistry data was provided by

Table 2. Mineralogy of the fine tailings

Fine tailings type	Ore designation	Quartz (%)	Kaolinite (%)	Illite (%)	Mixed-layer clays (%)	Smectite (%)
1	A	2	81	15	2	0
2	A	2	80	15	3	0
3*	A	2	81	15	2	0
4	B	2	76	18	4	0
5	B	2	75	19	4	0
6*	B	2	76	18	4	0
7	A	2	78	15	1	4

*Note: Type 3 and Type 6 fine tailings consist of coagulant added to Type 1 and Type 4 fine tailings respectively.

Table 3. Water chemistry of the fine tailings

Fine tailings type	Ore designation	pH	Anions (mg/L)			Cations (mg/L)							SAR
			HCO_3	Cl	SO_4	Fe	Si	Al	K	Mg	Ca	Na	
1	A	9.2	1346	583	526	1.8	16.7	8.4	10.6	3.0	1.8	1162	124
2	A	8.7	351	185	243	0.41	12.8	1.9	6.6	8.7	11.2	353	19
3	A	9.1	917	287	1097	0.10	3.6	0.57	12.3	6.1	10.8	1212	73
4	B	9.0	860	369	380	1.6	14.2	7.7	10.8	5.9	7.4	727	49
5	B	8.4	232	44	137	0.06	8.8	0.40	6.0	15.4	24.9	105	4
6	B	8.8	483	342	952	0.15	3.8	0.91	14.1	13.9	27.0	726	28
7	A	8.8	445	188	147	1.0	8.5	4.2	6.3	4.5	5.2	327	25

SAR = Sodium adsorption ratio.

CanmetENERGY at the Devon Research Centre from tests using release water samples from the consolidation tests. The high sodium concentrations of the caustic fine tailings compared with those of the non-caustic materials are of note. This difference reflects the nature of the caustic extraction process that uses sodium hydroxide to aid with the dispersion of clay particles and to enhance bitumen recovery. A combination of methyl isobutyl carbinol and kerosene was used as a dispersing agent for the non-caustic process.

The highly dispersed nature of the caustic tailings is evident by comparing the non-dispersed and dispersed particle size distributions characteristics given in Table 4. The percent dispersion is calculated from the ratio of the percent passing 2 μm in the non-dispersed hydrometer test to that in the dispersed hydrometer test. Types 1 and 4 fine tailings were almost completely dispersed by the caustic process, whereas the non-caustic fine tailings (Types 2 and 5) were only partially dispersed. This difference in the extent of dispersion may have an influence on compressibility and hydraulic conductivity of the fine tailings because a more dispersed material will have a finer grain size (that is, more individual clay particles and more opportunities for physico-chemical interactions between clay particles).

Consolidation of fine tailings

Field consolidation of fine tailings

Large-scale laboratory standpipe tests have shown that the volume decrease of fine tailings occurs mainly by a creep process, not by an increase in effective stress (Jeeravipoolvarn, Scott, & Chalaturnyk, 2008). Although pore pressures decreased, this decrease was mainly in response to the decrease in total stress as the fine tailings settled. In slurries that undergo large, self-weight settlement, the settlement of the surface of the solids reduces the mass of solids above a point at which the total stress is reduced. Pore pressures remained close to the total stress.

Field measurements in the tailings ponds have shown similar responses. Figure 1 shows typical total stress and pore pressure profiles, with depth, in a tailings pond after more than 25 years of deposition. From the surface of the fine tailings to a depth of 20 m, the effective stress is from 0.5 to 1 kPa. From a 20 m to a 30 m depth; the effective stress gradually increases to about 5 kPa. Below 30 m, the effective stress increases to a maximum of 10 kPa.

The fine tailings enters the pond at a solids content of about 8% and sediments fairly rapidly to a solids content of 20% or a void ratio of about 9. With time, the fine tailings void ratio decreases by a creep process and by the slight increase in effective stress. Figure 2 shows the void ratio

Table 4. Particle size distribution characteristics

Fine tailings type	Ore designation	Test method	< 74 μm (%)	< 44 μm (%)	< 2 μm (%)	<1 μm (%)	Dispersion (%)
1	A	Dispersed	96	92	43	32	100
		Non-dispersed	97	94	43	19	
2	A	Dispersed	100	98	47	35	32
		Non-dispersed	100	99	15	2.5	
4	B	Dispersed	98	97	49	40	100
		Non-dispersed	98	96	49	40	
5	B	Dispersed	98	97	48	33	10
		Non-dispersed	99	98	5.0	1.5	
7	A	Dispersed	98	99	41	29	100
		Non-dispersed	100	99	41	15	

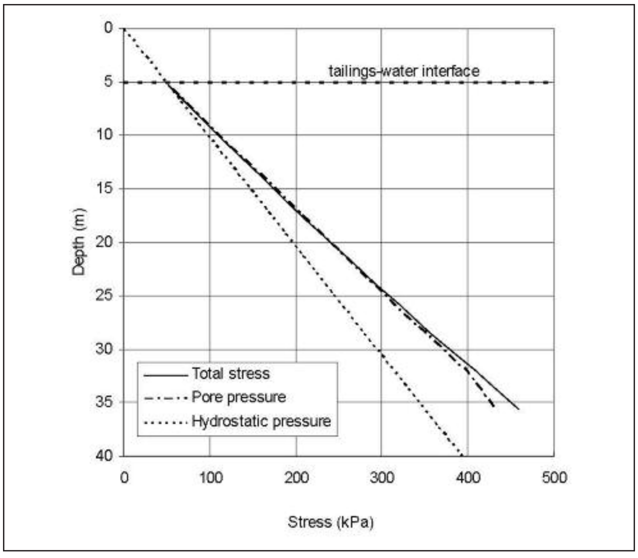

Figure 1. Typical total stress and pore pressure in fine tailings pond.

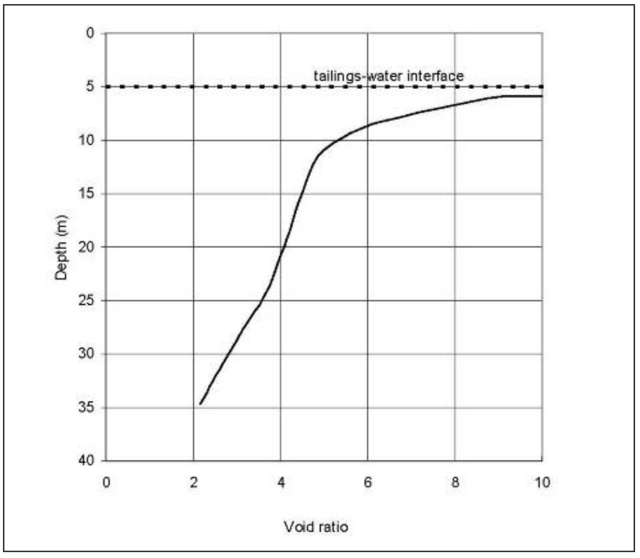

Figure 2. Typical void ratios in fine tailings pond.

profile with depth for the profiles on Figure 1. At a depth of 20 m where the effective stress is about 1 kPa, the void ratio has reduced to about 4; at 30-m depth where the effective stress is about 5 kPa, the void ratio has reduced to about 3.

Because of the low effective stresses that develop in the tailings ponds, the consolidation tests have concentrated on self-weight consolidation and on effective stresses below 10 kPa. One consolidation test on each of the seven fine tailings was carried out to an effective stress of 80 kPa, in order to model the long-term consolidation of the tailings.

Laboratory consolidation of fine tailings The infinitesimal consolidation theory (Terzaghi consolidation theory) is not valid for soft soils that undergo large amounts of volume change. A finite strain consolidation theory has been widely used for oil sands fine tailings (Jeeravipoolvarn et al., 2008; Suthaker & Scott, 1994a). The finite strain consolidation theory requires compressibility and hydraulic conductivity relationships to be obtained from a large strain consolidation test.

Infinitesimal theory does not correctly calculate the hydraulic conductivity from consolidation-time measurements and hydraulic conductivity needs to be measured directly due to the large volume changes that take place in soft soils (Jeeravipoolvarn et al., 2008). Thus, standard consolidation tests cannot be used for this purpose. Instead, a large strain consolidation testing apparatus (slurry consolidometer) was used to determine the consolidation characteristics of the fine tailings. Large strain slurry consolidometer tests provide compressibility (void ratio-effective stress relationship) and hydraulic conductivity (hydraulic conductivity–void ratio relationship). Both of these relationships are required to define the material relationships to be used in large strain consolidation numerical modelling of tailings ponds. Analytical modelling of the rate and magnitude of settlement of caustic and non-caustic fine tailings is beyond the scope of this research project. However, the compressibility and hydraulic conductivity relationships determined by the large strain consolidation tests during this research program are valid and may be applied to any future modelling of the fine tailings, assuming, of course, that the fine tailings are similar to those used in this experimental program.

Consolidation equipment At the University of Alberta, a step-loading, large strain consolidation test has been developed and used to determine consolidation characteristics of these highly compressible soils. These tests allow large deformations during consolidation and direct measurement of hydraulic conductivity. This is a step-loading test, similar to standard oedometer tests, and allows the void ratio-effective stress relationship to be measured. Between each load step, a hydraulic conductivity test was conducted to determine the hydraulic conductivity at a specific void ratio that was then used to develop the hydraulic conductivity-void ratio relationship.

Hydraulic conductivity tests The hydraulic conductivity test used for fine tailings during this research program was a constant head test utilizing upward flow through the sample. The use of this test is based on the advantages of a small hydraulic gradient to measure hydraulic conductivity during the consolidation test and the ability to observe and assess time flow effects. A large, imposed gradient usually produces a large variation of effective stress in the sample, causing it to become less homogenous (Aiban & Znidarcic, 1989). The testing equipment used for the consolidation tests was designed to allow hydraulic conductivity measurements at different void ratios after each consolidation load increment.

Test methods and measurements Consolidation tests were performed in slurry consolidometers that confine the slurried material so it can be tested at any water content. The inside diameter of the consolidometers ranged from 12.1 to 20.5 cm and the height of the cells ranged from 32 to 38 cm. Pistons ranging in thickness from 4.1 to 5.5 cm were used to apply loads to the fine tailings. The pistons had double o-rings and a porous plate attached to the bottom of the piston. At lower loading stages, dead weights were used to apply the appropriate effective stress, but, for higher loading stages, a bellofram controlled with pressurized air was employed.

Seven of the consolidometers were designed for single upward drainage and seven for double drainage. In the double-drainage case, a drainage channel covered by a filter was opened at the base of the consolidometer and both downward and upward drainage of excess pore pressures was allowed. However, it should be noted that the bottom drainage was raised and set even with the hydrostatic level of the consolidometer, so no hydraulic gradient was imposed on the fine tailings sample during consolidation.

The initial sample height of the fine tailings was 17 cm and the initial solids content was set at 22% (a void ratio of about 9.0 and a water content of 355%, depending on the bitumen content) because it was found from previous testing that this was the minimum value required to prevent segregation of coarser grained particles within the samples. As well, the initial height of the sample was chosen so that the diameter-height ratio was expected to be approximately 2.5 or greater, to minimize wall friction when effective stresses became significant above 10 kPa applied vertical stress. For these consolidation tests, diameter-height ratios at 10 kPa applied stress typically ranged between 2.4 and 3.1.

The consolidation cell was set up and the base and all lines were saturated with tailings water, including the permeability tube that was levelled at the same elevation as the outlet port. The test began with the top plate of the cell off and the fine tailings sample in the cell placed to a designated height of 17 cm. Samples of the fine tailings were taken during placement to determine initial water content (void ratio) of the fine tailings. The first loading stage was self-weight consolidation. For this stage, the sample was allowed to settle under self-weight and the settlement was monitored manually using a scale. As no external stress is applied during self-weight, the effective stress causing settlement is the submerged or buoyant mass of the sample, which varied from zero at the top to 0.26 kPa at the bottom. It was assumed that the consolidation effective stress during self-weight was the average of these or 0.13 kPa. A constant head hydraulic conductivity test with a low hydraulic gradient was performed at the end of self-weight consolidation, before the first piston load was applied.

The upward flow constant-head hydraulic conductivity test equipment consisted of a long permeability tube (inside diameter of 5 mm) with a scale, a permeability tube holder to hold and change the head difference, and a rubber tube to connect the consolidometer to the permeability tube.

Prior to testing, the system was flushed with tailings water. The outflow tube was set at the level of the outflow valve and the inflow tube was raised to the desired elevation. The vertical difference between the inflow and outflow tube is the head difference; the maximum head difference is the head that equals the total stress. A larger head would cause the sample to quick or heave. At this head, the effective stress should become zero. Under self-weight, this head is equal to 0.26 kPa or 0.026 m of water. As the effective stress increases, the maximum allowable head also increases. As a factor of safety against quicking, however, the head difference was always kept to about half the maximum allowable head and, for effective stresses over 10 kPa, it was less than 0.5 m. The hydraulic conductivity test commenced once the inflow valve was opened and the inflow water volumes and time were measured. The hydraulic conductivity test was continued until a stable flow rate was achieved, at which point the test was considered finished.

For the first applied load of 0.2 kPa, a piston and top plate was used to apply the load to the sample. The piston and its associated rod and loading plate were clamped in place immediately above the surface of the sample and a linear voltage displacement transducer (LVDT) was set up to record changes in sample height. The piston was released and the sample height was measured with time.

Once settlement was complete for each loading (the LVDT read the end of primary consolidation), a hydraulic conductivity test was performed with a designated head difference of water. Dead loads on the piston were approximately doubled to reach about 5 kPa over a total of five loading stages: self-weight consolidation (0.13 kPa) and total loads of 0.33, 0.63, 1.13, 2.63 and 5.13 kPa.

After the completion of the 5.13 kPa loading stage and the hydraulic conductivity test, the consolidation cell was transferred to a loading frame and the sample loaded with total stresses of 10.1, 20.1, 40.1, and 80.1 kPa, applied using a bellofram. Sample height was recorded with time and, after settlement was complete, a constant head hydraulic conductivity test was performed at each loading stage. At the completion of loading, the sample was taken out layer by layer to measure the variation in water content in the sample and to determine its average final water content and void ratio. The particle size distribution of each layer was not determined because previous standpipe testing proved that, at an initial solids content of 22%, the sample would not segregate, but would instead stay homogeneous (Miller et al., 2010b).

Refinement of consolidation testing for fine tailings

Advancements in current practices for consolidation testing of fine tailings and other high void ratio slurries, developed at the University of Alberta, incorporate two other tests, as well as the large strain consolidation test. Compressibility standpipe tests are used to determine the effective stress-void ratio relationship at very low effective stresses and permeability standpipe tests are used to determine the hydraulic conductivity-void ratio relationship at initial void ratios greater than 6. Results from these standpipe tests were added to results derived from slurry consolidometer tests to create complete material relationships for the slurries over the typical range of void ratios expected for field deposits.

Compressibility at high void ratio standpipe tests

Compressibility standpipe tests use a large diameter standpipe filled with tailings at the initial water content that are allowed to consolidate under self-weight and, when consolidation is complete, are sampled in layers to determine the effective stress and void ratio with depth. Standpipes used for these types of tests are typically 20 cm in diameter and filled to a height of at least 26 cm. The sample is allowed to settle under self-weight and pore pressures are monitored at the base. Consolidation is considered complete when the excess pore pressure at the base has fully dissipated. At large void ratios, the effective stress is small even after consolidation and the diameter-height ratio is satisfactory to prevent significant wall friction. Void ratios at vertical stresses from a fraction of a kilopascal up to 1 kPa can be measured with this type of test and added to the data from a slurry consolidometer test.

Permeability at high void ratio standpipe tests The relationship between hydraulic conductivity and void ratio needs to be determined over the full range of water contents or void ratios that the field tailings deposit experiences. The initial volume change of high water content tailings (void ratios greater than 4), however, is so large that this relationship cannot be measured in step load consolidation tests. As the initial volume change is a major part of the volume change during field deposition, the modelling parameters at low stresses must be determined by a different test procedure to allow field predictions to be made with confidence. A test procedure developed for this purpose involves a standpipe containing tailings at high water content. A standpipe test on a high water content slurry progresses through three stages. When the standpipe is filled with the slurry, a flocculation period or induction time may elapse during which no measurable settlement takes place. Following this period, settlement in the form of hindered sedimentation may occur for a short period of time and then long-term consolidation settlement continues until the excess pore pressures are fully dissipated. During hindered sedimentation, the tailings remain at the initial void ratio and little to no effective stress exists in the settling material. The settlement rate during this period can be used to calculate the hydraulic conductivity and therefore, a relationship between the tailings initial void ratio and hydraulic conductivity can be determined. Permeability standpipe tests for the caustic and non-caustic fine tailings of this research program was limited to the initial void ratios using 0.5 m-high standpipes. These standpipe data are included in the hydraulic conductivity-void ratio relationships, discussed below.

Effect of compressibility and hydraulic conductivity relationships on consolidation predictions

Both the effective stress-void ratio relationship and the void ratio-hydraulic conductivity relationship are necessary for large strain numerical modelling of tailings deposits to predict the settlement amount, rate and the pore pressure dissipation. As was shown by Suthaker & Scott (1994a), however, the hydraulic conductivity dominates the predicted settlement with time analysis and the effective stress relationship is not as important. Even the predicted long-term settlement amounts do not vary significantly with changes in the effective stress-void ratio relationship. Variations in the void ratio-hydraulic conductivity, however, have a strong influence on the predicted rate of settlement and predicted rate of pore pressure dissipation. Ultimate settlements are not affected by the hydraulic conductivity, but, although important, they are generally not as important during the depositional stage of an active tailings pond.

As shown below, the compressibility functions are only slightly affected at very low effective stresses by extraction water chemistry. The hydraulic conductivity functions, however, are affected at higher void ratios, leading to significantly different initial settlement rates. The compressibility function is not difficult to measure in the laboratory; however, as discussed below, the hydraulic conductivity measurements have many sources of error and inaccuracies. Both relationships, however, are affected by thixotropic strength gain and creep within the tailings.

EXPERIMENTAL RESULTS AND DISCUSSION ON COMPRESSIBILITY

Fourteen large strain consolidation tests were performed, two on each of the seven tailings materials with one test being single upward drainage and the other test being double drained. The two different tests were performed to investigate the influence of faster drainage on the creep and consolidation of the fine tailings. The initial properties of the fourteen tests are given in Table 5. The tests are numbered according to the tailings type with "s" representing single drainage and "d" representing double drainage.

Self-weight consolidation

All samples were 17-cm high initially and had a solids content of 22% or a void ratio of about 9. The effective stress at the base of the submerged sample after completion of self-weight consolidation was 0.26 kPa. As the effective

Table 5. Initial properties of fine tailings

Sample number	Solids content (%)	Bitumen content by dry mass (%)	Specific gravity	Void ratio	Water content (%)	Hydraulic conductivity from consolidation tests (cm/s 10^{-6})	Hydraulic conductivity from standpipe tests (cm/s 10^{-6})
1s	22.11	3.9	2.55	8.98	352	7.86	12.1
1d	22.06	3.9	2.55	9.01	353	—	—
2s	21.87	5.0	2.51	8.97	357	12.8	16.3
2d	22.12	5.0	2.51	8.84	352	—	—
3s	21.86	3.9	2.55	9.12	357	12.4	28.0
3d	21.70	3.9	2.55	9.20	361	—	—
4s	22.26	5.9	2.48	8.66	349	5.21	6.82
4d	22.33	5.9	2.48	8.63	348	—	—
5s	22.04	6.7	2.45	8.67	354	16.2	27.2
5d	21.92	6.7	2.45	8.73	356	—	—
6s	21.70	5.9	2.48	8.95	361	17.9	—
6d	21.72	5.9	2.48	8.94	360	—	—
7s	21.98	5.2	2.50	8.87	355	15.0	20.8
7d	22.05	5.2	2.50	8.84	354	—	—

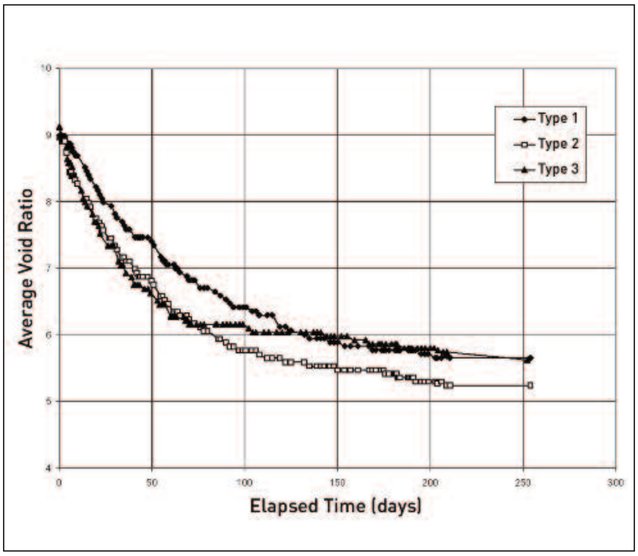

Figure 3. Variation of void ratio with time of Ore A fine tailings.

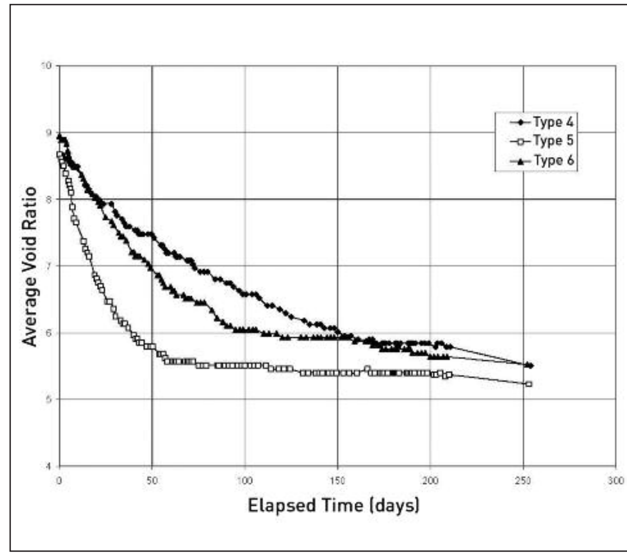

Figure 4. Variation of void ratio with time of Ore B fine tailings.

stress was zero at the top of the sample, an average effective stress of 0.13 kPa was taken as the effective stress causing self-weight consolidation.

The time-versus-void ratio plots of the single upward drainage tests under self-weight consolidation are shown, as they represent the consolidation process in the tailings ponds with no or little under-drainage. The decrease in void ratio under self-weight was monitored for approximately 250 days. For some specimens, the decrease in void ratio was still continuing at this elapsed time, but, at such a slow rate, a piston load was applied to increase the stress at mid-height of the specimens to 0.33 kPa.

Figure 3 shows the decrease in void ratio with time for Ore A, Types 1, 2, and 3. The non-caustic and $CaSO_4$ coagulant tailings settled more rapidly than the caustic tailings initially, indicating a higher initial hydraulic conductivity. The initial hydraulic conductivity values are summarized in Table 5. In the long-term, the slopes of all the plots became similar, but Type 2 non-caustic tailings consolidated the most. All specimens decreased in void ratio from about 9 to between 5 and 6.

Figure 4 shows the decrease in void ratio for Ore B, Types 4, 5, and 6. The non-caustic tailings settled at a much higher rate than the other two tailings, indicating a much higher hydraulic conductivity. The $CaSO_4$ coagulant tailings initially settled more rapidly than the caustic tailings, but eventually slowed down to finish at the same void ratio. For this ore, all specimens also decreased in void ratio from about 9 to between 5 and 6, with the Type 5 non-caustic tailings consolidating the most. It is postulated that the greater settlement of the non-caustic fine tailings is due to creep.

Non-caustic fine tailings had a consistently greater initial decrease in volume than the comparable caustic fine tailings due to differences in the initial hydraulic conductivity of the fine tailings. The larger initial hydraulic conductivity of the non-caustic tailings was the result of less dispersed clay fines. Similar results were observed in 2-m- and 1-m-high standpipe tests (Miller at al., 2010b); however, in these larger self-weight consolidation tests, all of the fine tailings, regardless of extraction process, approach similar final volumes at long times.

Figure 5 compares the decrease in void ratio with time for the two Ore A, non-caustic tailings Types 2 and 7. Both-extraction processes used Athabasca River water, treated and untreated respectively. The settlement plots were similar, indicating the difference in extraction water chemistry had little effect on the initial hydraulic conductivity or ultimate self-weight settlement.

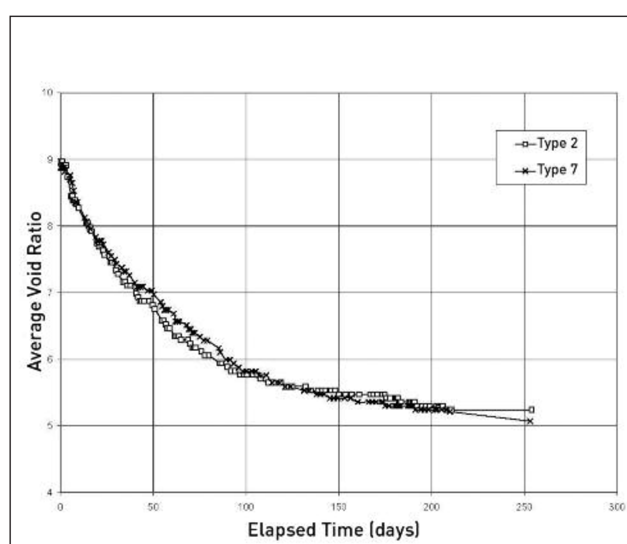

Figure 5. Effect of water treatment on variation of void ratio with time under self-weight loading of Ore A non-caustic fine tailings.

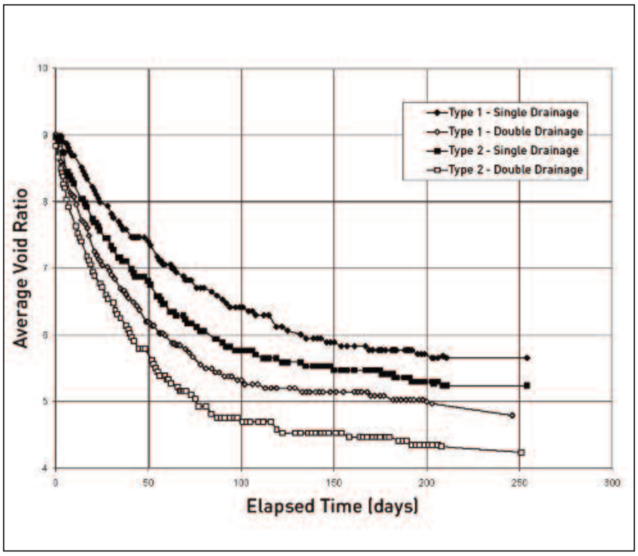

Figure 6. Effect of drainage conditions on variation in void ratio with time under self-weight loading.

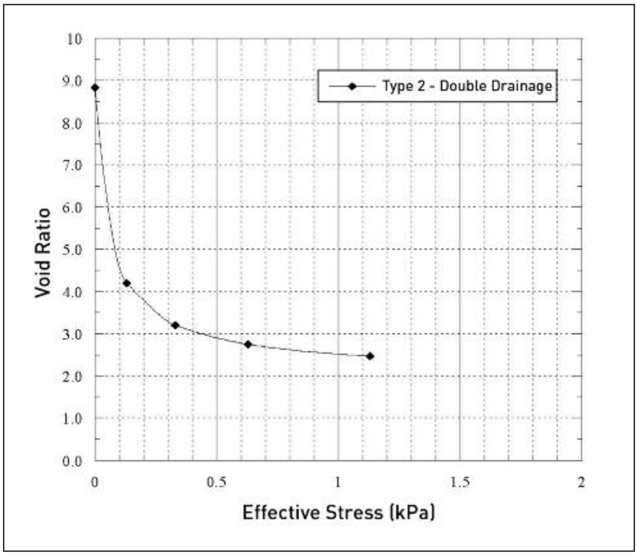

Figure 7. Typical arithmetic plot of compressibility for low effective stress range.

All double-drainage consolidation tests had more rapid settlement than their respective single-drainage tests, which was to be expected. However, all double-drainage tests also had greater long-term settlement than their respective single-drainage tests. Figure 6 shows typical results using Type 1 caustic tailings and Type 2 non-caustic tailings. The differences in long-term settlements are significant, although all specimens were consolidated under the same effective stress of 0.13 kPa. It is postulated that creep settlements had a greater influence on the double-drainage tests because their excess pore pressures dissipated more rapidly. It appears that the creep rate increases with an increase in effective stress in these high void ratio tailings.

Compressibility with effective stress

Plotting initial void ratio Approximately half of the volume decrease of the consolidation specimens from initial void ratio to the void ratio at an effective stress of 80 kPa occurred during self-weight consolidation. It is important, therefore, to include this change in void ratio in the log effective stress-versus-void ratio relationship for the fine tailings. The procedure used to do this entailed plotting the initial void ratio and the first four applied effective stresses, 0.13, 0.33, 0.63, and 1.13 kPa, on an arithmetic effective stress-void ratio plot and drawing a smooth curve through the data. An example of this plot is given in Figure 7 for Type 2 fine tailings.

This smooth curve was then transposed onto a log effective stress-versus-void ratio plot. Figure 8 shows the full log effective stress-versus-void ratio relationship for the Type 2 tailings used on Figure 7. The log-cycle minimum effective stress was chosen at 0.01 kPa in these plots because most of the self-weight consolidation data occurred at effective stresses from 0.01 to 0.13 kPa.

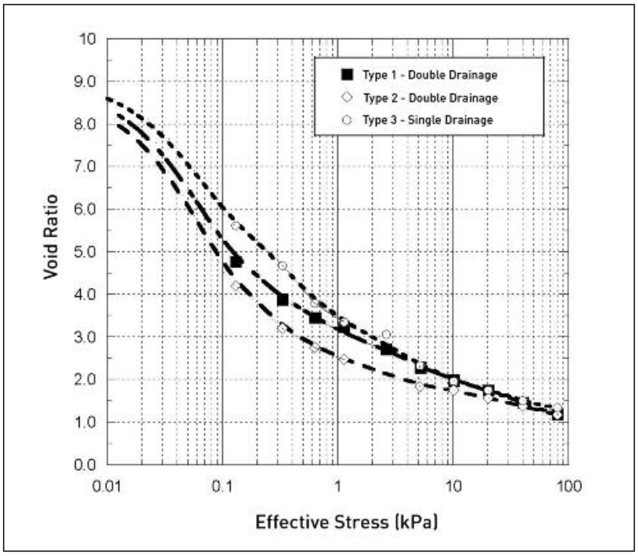

Figure 8. Compressibility of Ore A fine tailings.

Effect of extraction water chemistry The log effective stress-void ratio plots for Ore A, Types 1, 2, and 3 are given in Figure 8. The shape of all three consolidation plots are similar, but the Type 2, non-caustic tailings had the greatest volume change, followed by the Type 1, caustic tailings; the Type 3, $CaSO_4$ tailings had the smallest volume change. Above 10 kPa effective stress, the magnitudes of the consolidation for all the Types was similar.

Figure 9 illustrates similar plots for Ore B, Types 4, 5, and 6. Types 4 and 5, caustic and non-caustic tailings, respectively, had similar volume changes, with the $CaSO_4$ tailings again displaying the smallest volume change.

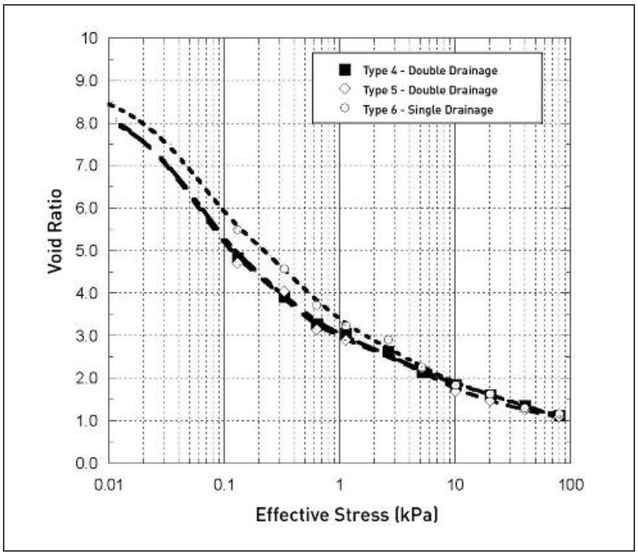

Figure 9. Compressibility of Ore B fine tailings.

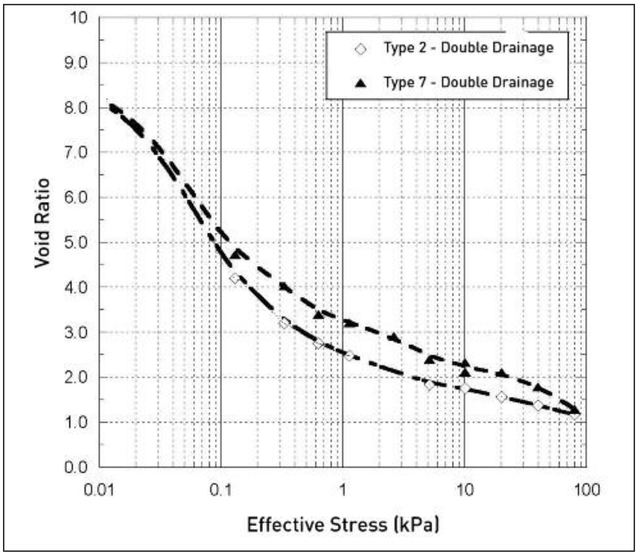

Figure 10. Effect of water treatment on compressibility of Ore A non-caustic fine tailings.

Above 10 kPa effective stress, the amounts of consolidation were again similar for all Types for this ore.

The consolidation plots for the two Ore A, non-caustic tailings Types 2 and 7 are compared in Figure 10. The extraction treated water Type 2 tailings had a greater volume change than the extraction untreated water Type 7 tailings.

Comparison of compressibilities for all types To compare the compressibilities of these highly non-linear consolidation plots the coefficient of compressibility, a_v, the change in void ratio divided by the change in effective stress, has been calculated for three effective stress ranges. These values of coefficient of compressibility are given in Table 6 for effective stress ranges of 0.01 to 0.13 kPa, 0.13 to 10.1 kPa, and 10.1 to 80.1 kPa.

Overconsolidation stress due to thixotropy

Thixotropy is defined as an isothermal, reversible time-dependent process occurring under conditions of constant composition and volume whereby material stiffens while at rest and softens or liquefies by remoulding (Mitchell & Soga, 2005). For geotechnical engineering, the thixotropic phenomenon can be generally described as a continuous decrease in shear strength or softening caused by remoulding, followed by a time-dependent return to the original harder state at a constant water content and constant porosity. Most clay-water systems exhibit this phenomenon. Because the process of consolidation in clays is time-dependent and thixotropy is a time-dependent effect, Mitchell (1960) argued that thixotropic effects during consolidation would result in less volume change. Thixotropic gain in strength retards the consolidation process by building up bond strength and not allowing the soil to compress to release water.

In general, kaolinite has minor thixotropic behaviour compared with bentonite and illite. However, the fine tailings in which kaolinite is the predominant mineral (Table 2), exhibits a very high thixotropic gain in strength (Suthaker & Scott, 1997). Mineralogy is not the major factor for the thixotropic phenomenon, but it is postulated that the addition of sodium hydroxide as a dispersing agent during the caustic oil sands extraction process and the presence of bicarbonates and organic matter (bitumen) give the material its thixotropic behaviour.

Thixotropic strength measurements on mature fine tailings from Syncrude's tailings pond are shown on Figure 11 (Suthaker & Scott, 1997). Fine tailings from the tailings pond were mixed at five different void ratios from 2.5 to 10 and undrained strength measurements were made by the cavity expansion method for a period of 450 days.

Table 6. Coefficient of compressibility by effective stress for fine tailings

Fine tailings type	Process	Ore	Coagulant addition	Coefficient of compressibility, a_v (1/kPa)		
				Effective stress range (kPa)		
				0.01 to 0.13	0.13 to 10.1	10.1 to 80.1
1	Caustic	A	None	28.5	0.29	0.012
2	Non-caustic	A	None	31.5	0.26	0.008
3	Caustic	A	$CaSO_4$	24.0	0.37	0.010
4	Caustic	B	None	26.0	0.31	0.011
5	Non-caustic	B	None	27.3	0.31	0.009
6	Caustic	B	$CaSO_4$	23.8	0.37	0.011
7	Non-caustic	A	None	27.7	0.26	0.014

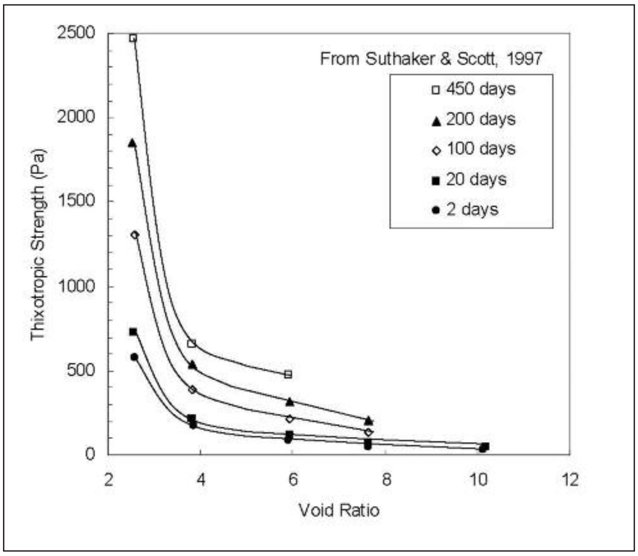

Figure 11. Thixotropic strength of a Type 1 fine tailings (MFT from tailings ponds).

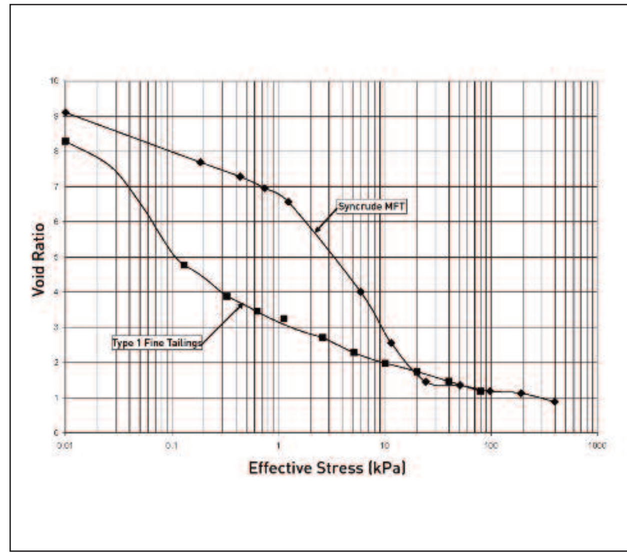

Figure 12. Comparison of consolidation of aged MFT with young Type 1 fine tailings.

Settlement of the higher void ratio specimens limited their testing periods to shorter times. Syncrude fine tailings are similar to Type 1 fine tailings, but exhibit longer-term aging effects in contrast to the young fine tails from the pilot plant tested in this study.

Suthaker and Scott (1994b) performed a large strain consolidation test on the aged fine tailings from the Syncrude pond, with an initial void ratio of about 9 that is similar to the consolidation tests performed in this study. Figure 12 compares the consolidation of the aged fine tailings from the tailings pond with the consolidation of the young Type 1 fine tailings. The aged fine tailings show significant overconsolidation behaviour, while the young fine tailings have minor over-consolidation behaviour. The value of the overconsolidation stress can be estimated by the graphical construction in Terzaghi, Peck, and Mesri (1996).

Thixotropy is responsible for the overconsolidation behaviour exhibited by the fine tailings during consolidation. Thixotropy is directly related to the physiochemcial effect produced by the repulsive-attractive forces in a clay-water system, R-A, where R is repulsive force and A is attractive force (Chatterji & Morgenstern, 1990). The R and A forces are the direct result of pore water ionic chemistry and clay mineralogy. The equation for true effective stress is

$$\sigma'_i = \sigma - u - (R\text{-}A) \tag{1}$$

where σ'_i = true inter-granular stress or true effective stress, σ = total stress, u = pore water pressure and (R-A) = repulsive and attractive stresses.

The more commonly used equation in engineering practice is

$$\sigma' = \sigma - u \tag{2}$$

where σ' = apparent effective stress or, when R-A forces are small enough to be neglected, it is simply referred to as effective stress.

In natural deposits of sedimentary clays, the undrained shear strength has been found to increase with time (Bjerrum, 1967). It has also been found that the undrained shear strength is proportional to the over-consolidation stress. The fines-water structure has gone through the same process and, therefore, can be treated similarly. Terzaghi et al. (1996) show the following relationship:

$$\tau_f/\sigma'_p = 0.22 \tag{3}$$

where τ_f = undrained shear strength and σ'_p = overconsolidation stress.

This empirical relationship, based on laboratory undrained shear strength data, was found to be the same for field in situ vane strengths and field settlements, and is independent of the plasticity index of the material tested.

Overconsolidation stress is usually associated with a previous loading on a clay deposit that has subsequently been eroded, leaving the clay overconsolidated with respect to its present vertical effective stress. Thixotropic changes in structure and improved interparticle bonding through chemical changes also contributes to the magnitude of the overconsolidation stress (Terzaghi et al., 1996). A vertical effective stress greater than the overconsolidation stress must be applied to the deposit to cause the breakdown of interparticle bonds which would then result in consolidation settlement.

Using the above relationship for the aged fine tailings in Figure 12 and the thixotropic strength measurements in Figure 11, the overconsolidation stress in the aged fine

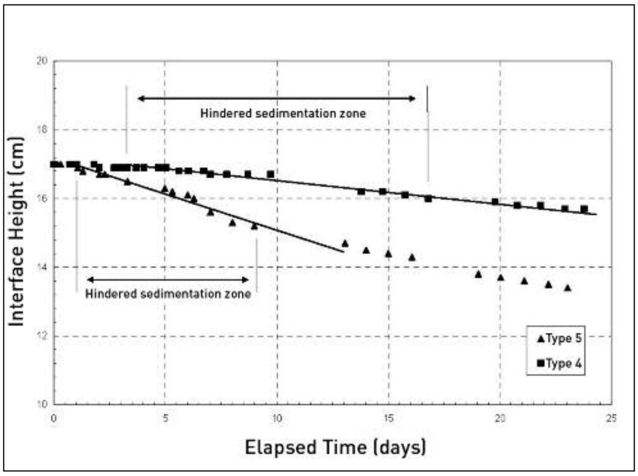

Figure 13. Typical determination of initial hydraulic conductivity.

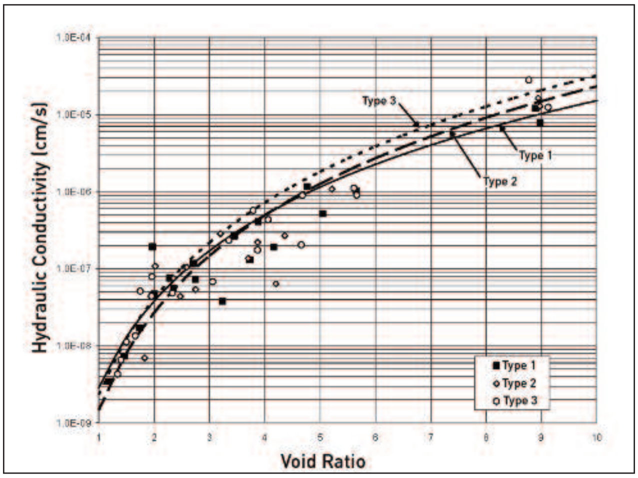

Figure 14. Hydraulic conductivity of Ore A fine tailings.

tailings can be estimated. At a void ratio of about 6, the long-term thixotropic strength from Figure 11 is about 500 Pa or 0.5 kPa. The overconsolidation stress, σ'_p is then

$$\sigma'_p = \tau_f/0.22 = 0.5/0.22 = 2.3\ kPa \qquad (4)$$

This value of overconsolidation stress corresponds well with the consolidation plot for the aged fine tailings, where significant volume decrease starts at an effective stress of about 2 kPa. Therefore, fine tailings deposits at a void ratio of about 6 must have vertical effective stresses greater than 2 kPa for significant virgin consolidation to occur. Volume decreases that take place at lower effective stresses must be mainly caused by creep mechanisms. As the void ratio decreases, the thixotropic strength rapidly increases (Figure 11), with a similar increase in the overconsolidation stress. As the pore pressure dissipation and the increase in the effective stress in the fine tailings are so slow while the increase in thixotropy and in the overconsolidation stress are so rapid, it may be that the virgin consolidation condition is never reached because the vertical effective stress is always lower than the over-consolidation stress.

EXPERIMENTAL RESULTS AND DISCUSSION ON HYDRAULIC CONDUCTIVITY

Determination of the initial hydraulic conductivity

The initial hydraulic conductivity of the fine tailings can be determined by using the rate of interface settlement during the hindered settlement phase. Pane and Schiffman (1997) present an experimental determination of hydraulic conductivity for clay-water suspensions based on sedimentation and fluidization. For a transient sedimentation test on a uniform dispersion of a given void ratio, the initial hydraulic conductivity can be determined from the initial settling velocity of the suspension, according to

$$k(e) = \frac{v_{si}\,(1+e)}{(\gamma_s - \gamma_w)/\gamma_w} \qquad (5)$$

where k is the hydraulic conductivity of the suspension at a given void ratio (e); v_{si} is the initial settling velocity of the solids; and γ_s and γ_w are the unit weights of the solids and water, respectively. The equation is valid only as long as the suspension has the initial porosity at the sediment-water interface (that is, as long as the surface settling velocity is constant). Pane and Schiffman (1997) determined that only the early stages of settling are of interest. After an induction period, the settling velocity of the interface approaches a fairly constant value v_{si}. It is during this range that the initial hydraulic conductivity of the suspension may be calculated for the initial void ratio of the material. It was in this manner that the initial hydraulic conductivities were determined for the fine tailings.

Typical examples of the constant rate of interface settlement for two of the 17 cm-high consolidation specimens are shown in Figure 13.

For all seven single, upward-drainage consolidation specimens, the hindered settlement phase continued for eight to 15 days, allowing a good measurement of the initial settling velocity. The calculated initial hydraulic conductivities are listed in Table 5 and plotted in Figures 14 to 16.

Upward-drainage standpipe tests, 0.5-m-high, were also conducted on all seven fine tailings materials at initial void ratios of about 9. These standpipe tests were monitored similarly to the 17-cm-high consolidation tests and initial hydraulic conductivities were similarly calculated. These hydraulic conductivities are also listed in Table 5 and plotted in Figures 14 to 16.

Initial hydraulic conductivities cannot be calculated from the initial settling velocities of the double-drainage

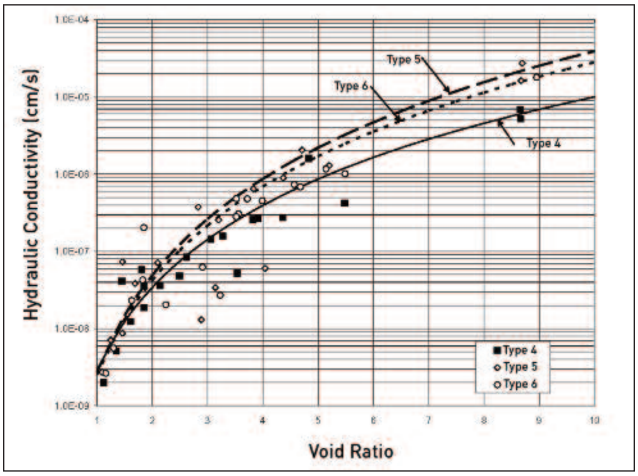

Figure. 15. Hydraulic conductivity of Ore B fine tailings.

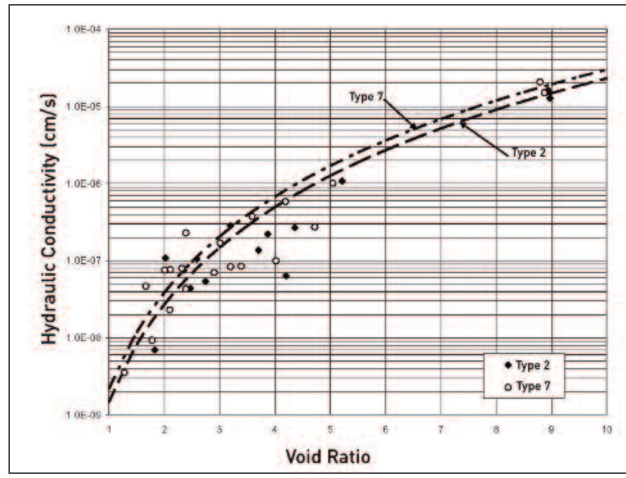

Figure 16. Effect of water treatment on hydraulic conductivity of Ore A non-caustic fine tailings.

consolidation tests or standpipe tests because these interface settlements are a combination of surface-hindered settlement and bottom drainage.

Hydraulic conductivity with void ratio

The results of the hydraulic conductivity testing on the fine tailings during consolidation testing resulted in data with some scatter. This scatter was due to the sensitivity of the testing method and the variability of the oil sands fine tailings. The data do, however, establish trends that can aid in discussing the variability of hydraulic conductivity of the different fine tailings.

The relationship between void ratio and hydraulic conductivity for a particular fine tailings was drawn with a best-fit curve, starting at the average of its two initial hydraulic conductivities. Seven of the consolidation tests were conducted to an effective stress of 80.1 kPa, one for each of the fine tailings types. Generally, these seven tests were double-drainage tests, but single-drainage tests were continued to 80.1 kPa for two of the fine tailings where the consolidation apparatus was performing best. The other seven consolidation tests were terminated after the 10.1 kPa effective stress loading. After the 0.33 kPa effective stress loading, the single-and double-drainage tests had similar void ratios for each load step. To provide additional hydraulic conductivity results, the data from all 14 tests have been included in the plots.

Effect of extraction water chemistry The relationship between void ratio and hydraulic conductivity for the fine tailings Ore A, Types 1, 2, and 3 are given in Figure 14. The non-caustic and $CaSO_4$ coagulant tailings initially had a greater hydraulic conductivity than the caustic tailings, but all three fine tailings had similar hydraulic conductivities below a void ratio of about 3.

Figure 15 contains similar plots for Ore B, Types 4, 5, and 6. The non-caustic and $CaSO_4$ coagulant tailings from this ore also initially had a greater hydraulic conductivity than the caustic fine tailings. Below a void ratio of about 4, all three fine tailings had similar hydraulic conductivities.

The void ratio-hydraulic conductivity relationships for the two Ore A, non-caustic tailings Types 2 and 7 are compared in Figure 16. The extraction untreated water Type 7 tailings had a higher hydraulic conductivity over the full range of void ratios than did the extension treated water Type 2 tailings.

Comparison of hydraulic conductivities for all types To compare the hydraulic conductivities of these non-linear void ratio-hydraulic conductivity relationships, the average hydraulic conductivity was calculated for five void ratios. The hydraulic conductivities are given in Table 7 for void ratios of 9, 7, 5, 3, and 1.

Table 7. Hydraulic conductivity by void ratio for fine tailings

Fine tailings type	Process	Ore	Coagulant addition	Bitumen content (by dry mass, %)	Hydraulic conductivity of fine tailings at selected void ratios ($cm/s \times 10^{-6}$) Void ratio: 9	7	5	3	1
1	Caustic	A	None	3.9	10.2	4.0	1.2	0.17	0.0029
2	Non-caustic	A	None	5.0	14.9	5.2	1.3	0.15	0.0015
3	Caustic	A	$CaSO_4$	3.9	20.7	7.3	1.8	0.22	0.0023
4	Caustic	B	None	5.9	6.9	2.8	0.87	0.14	0.0029
5	Non-caustic	B	None	6.7	25.2	8.9	2.2	0.26	0.0027
6	Caustic	B	$CaSO_4$	5.9	18.3	6.6	1.7	0.22	0.0026
7	Non-caustic	A	None	5.2	19.4	6.9	1.7	0.21	0.0022

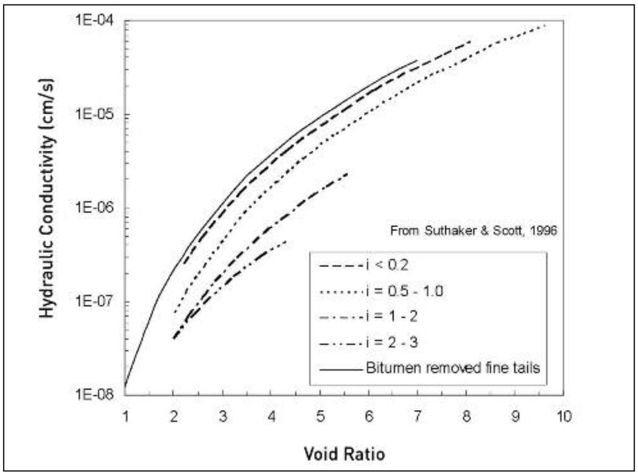

Figure 17. Variation of permeability with bitumen content and hydraulic gradient for MFT from Syncrude tailings pond.

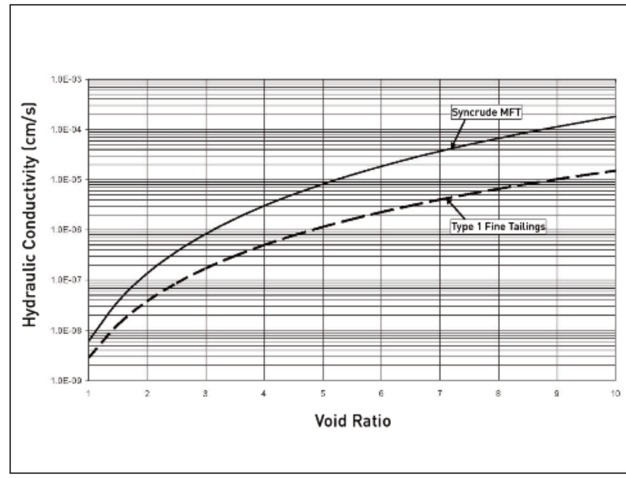

Figure 18. Comparison of hydraulic conductivity of aged MFT with young Type 1 fine tailings.

Effect of hydraulic gradient and bitumen content on hydraulic conductivity Suthaker and Scott (1996) studied the effect of hydraulic gradient on hydraulic conductivity of Syncrude fine tailings, a Type 1 fine tailings, by performing permeability tests during consolidation tests at different hydraulic gradients at each void ratio (Figure 17). As the gradient increases, the permeability of fine tails decreases at any given void ratio. However, when tested under hydraulic gradients less than 0.2, all permeability tests gave similar values for hydraulic conductivity. In contrast to Darcy's law, it can be concluded that the permeability of the fine tails depends on the hydraulic gradient.

The influence of hydraulic gradient may be due to (a) deformation of bitumen into pore throats within the soil skeleton in response to the flow of water, or (b) fines migration under the applied gradient into pore throats. It was noted that the permeability at low gradients was the same before and after a higher gradient was applied on the sample. This indicates a recoverable mechanism in flow through fine tails. The bitumen can deform when the hydraulic gradient is applied and, when the gradient is removed, it can relax back to the original position. If fines collect in the pore throats, the recoverable mechanism will not occur.

The deformation of bitumen should be directly related to the applied hydraulic gradient. The higher the gradient, the larger the deformation of the bitumen and the smaller the permeability. At small hydraulic gradients ($i < 0.2$), the deformation of bitumen should be small and the effect of hydraulic gradient on the permeability measurements should be negligible. Hydraulic conductivity of fine tails is about two to three times lower when the hydraulic gradient is increased from 0.2 to 1. Due to the influence of hydraulic gradient on permeability, it is necessary to perform permeability tests at the field hydraulic gradient (measured or expected) in order to obtain permeability values for field predictions.

Large strain consolidation tests were also performed on bitumen-removed fine tails in order to evaluate the effect of the bitumen on the consolidation properties. Bitumen was removed by treating the sample with hydrogen peroxide, which vaporizes the bitumen. It was found that hydraulic conductivity of the bitumen-removed fine tailings was independent of the hydraulic gradient and obeyed Darcy's law. Figure 17 shows that the permeability of the bitumen-removed fine tails is somewhat greater, but similar to the permeability of fine tails at a low hydraulic gradient.

These tests also indicate that the hydraulic conductivity of the fine tailings should decrease with an increase in bitumen content. When more bitumen is present in the voids of the fine tailings, more deformation of the bitumen into pore throats can take place, even under low hydraulic gradients.

When evaluating or comparing hydraulic conductivity test results, the bitumen content of the fine tailings must be taken into account. In this study, the bitumen content of all seven fine tailings types was similar, but may be responsible for some of the variation in these test results (Table 5).

Comparison of hydraulic conductivities of Syncrude fine tailings and Type 1 fine tailings Figure 18 shows the variation in hydraulic conductivity with void ratio for mature fine tailings (MFT) from the Syncrude tailings pond, which had a similar particle size distribution as Type 1 fine tailings (Suthaker & Scott, 1996). MFT had a greater hydraulic conductivity at a given void ratio than Type 1 fine tailings. One explanation for the difference between hydraulic conductivity for these comparable caustic fine tailings is related to water chemistry. MFT has been reported

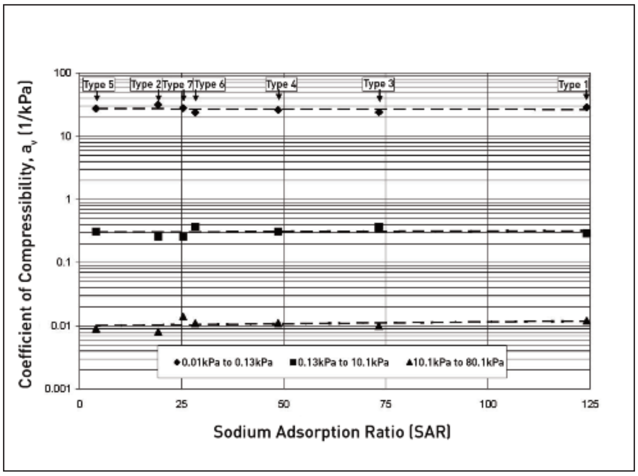

Figure 19. Variation of coefficient of compressibility with SAR.

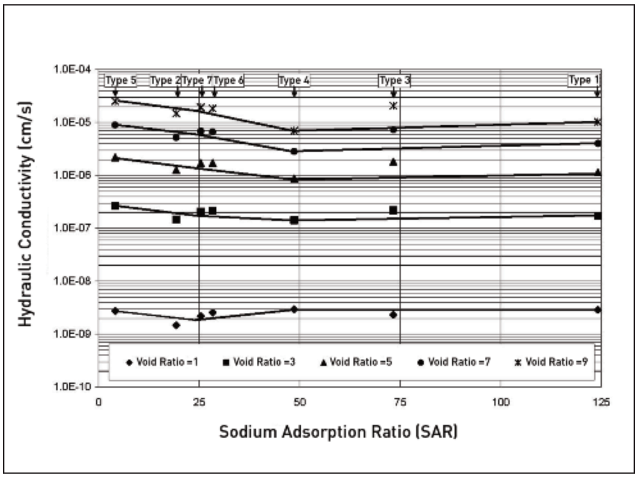

Figure 20. Variation of hydraulic conductivity with SAR.

to have a sodium adsorption ratio value of approximately 33 (Allen, 2008) which is considerably lower than the comparable Type 1 fine tailings (SAR = 117). As shown below, as SAR decreases, the hydraulic conductivity increases.

As well, the history of these fine tailings differs for old (MFT) and young (Type 1) fine tailings. The history is complex and there is uncertainty surrounding how aging of fine tailings impacts hydraulic conductivity.

SODIUM ADSORPTION RATIO

The sodium adsorption ratio (SAR) relates the composition of the solution phase to the composition of the adsorbed phase. That is, it provides a prediction of the adsorbed phase based on the concentrations of ions in solution. For practical purposes, SAR is defined as

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \qquad (6)$$

where the soluble cation concentrations are in me/L.

In general, when SAR values exceed a certain level specific to each material, sodium ions will occupy adsorption sites on the clay, resulting in dispersion of the clays. The SAR values for the fine tailings are presented in Table 3. All of the fine tailings have SARs in excess of 20 (21 to 117), with the exception of Type 5 fine tailings that had a SAR of 5. Type 5 fine tailings has been shown to have a less dispersed structure, while the other fine tailings have more dispersed structures (Miller et al., 2010a). It has also been previously reported by Dawson, Sego and Pollock (1999) that SARs greater than about 7 indicate a high potential for dispersion. Based on these results, it may be concluded that fine tailings with a SAR greater than 20 are likely to be in a dispersed state, while those with a SAR of 5 or less have a less dispersed structure.

Variation of compressibility with SAR

The variation in compressibility with respect to SAR of the different fine tailings over three different effective stress ranges is presented in Figure 19. Compressibility of the fine tailings is presented in terms of the coefficient of compressibility (a_v). The coefficient of compressibility is defined as the change in void ratio over a specified range of effective stress.

The compressibility of the fine tailings is unaffected by SAR for the various fine tailings for all three stress ranges (0.01 to 0.13 kPa, 0.13 to 10.1 kPa, and 10.1 to 80.1 kPa). Across these effective stress ranges, variations in water chemistry represented by the SAR values do not affect the compressibility of the fine tailings materials. The compressibility of the fine tailings at effective stresses as low as 0.01 kPa appears to be dominated by effective stresses.

Compressibility controls the magnitude of settlement during consolidation. Based on the results of this research program, ultimate settlement values for the fine tailings are similar for the various caustic and non-caustic fine tailings.

Variation of hydraulic conductivity with SAR

The variation of hydraulic conductivity of the different fine tailings with SAR at five different void ratios is presented in Figure 20. General trend lines showing variation of hydraulic conductivity with SAR are included in the figure. These trend lines do not included data points for Type 3 and Type 6 fine tailings because the SAR of these fine tailings was altered subsequent to the extraction process by the addition of 600 ppm of $CaSO_4$.

SAR was found to have an influence on the hydraulic conductivity of the fine tailings at a void ratio of 3 and above. There was a trend of increasing hydraulic conductivity with decreasing SAR at SARs less than approximately 50. At a void ratio of 1, SAR was found to have little or no effect on hydraulic conductivity.

The SAR of Type 3 and Type 6 fine tailings was altered after extraction was completed. A coagulant addition of 600 ppm $CaSO_4$ was added to Type 1 fine tailings and the resulting fine tailings was labelled Type 3. $CaSO_4$ addition has the affect of decreasing SAR by increasing the proportion of adsorbed calcium ions on clay particle surfaces. Replacing sodium ions on clay particles results in a decrease in the thickness of the diffuse double layer, causing clay particles to flocculate together. The flocculation of clay particles should have the effect of increasing hydraulic conductivity of the fine tailings on a macro scale because the size of channels between agglomerated clay particles will increase. This theory is supported by the results shown in Figure 20, where Type 3 fine tailings had a slightly higher hydraulic conductivity than Type 1 fine tailings at void ratios of 3 and above. At a void ratio of 1, there was only a small difference between the hydraulic conductivity of Type 1 and Type 3 fine tailings. At the lower void ratio, effective stress dominated and the effect of water chemistry had no impact on hydraulic conductivity. The same relationship of increasing hydraulic conductivity due to decreased SAR resulting from $CaSO_4$ addition was seen between Type 6 and Type 4 fine tailings.

Hydraulic conductivity controls the rate of settlement during consolidation. At void ratios of 3 and above, fine tailings with low SAR values (less than approximately 50) are expected to be less dispersed and settle faster than high SAR fine tailings. Non-caustic fine tailings have lower SARs than caustic fine tailings and, thus, are expected to settle at a faster rate. However, as discussed earlier, SAR appears to have little or no effect on the compressibility of the fine tailings, so, although the non-caustic fine tailings may initially settle at a faster rate, the final settled fine tailings volume will be similar between caustic and non-caustic fine tailings.

CONCLUSIONS

Using slurry consolidometers, consolidation tests were carried out for caustic and non-caustic fine tailings to determine the influence of a change in extraction process on the consolidation properties, namely compressibility and hydraulic conductivity. The effect of adding a coagulant to caustic fine tailings was also determined.

Overall, the different water chemistries of the different extraction processes resulted in different amounts of dispersion of the clay-shale seams present in oil sands ore, with less dispersed non-caustic fine tailings. The differences in the geotechnical properties, including compressibility and hydraulic conductivity of the tailings, were mainly due to the different grain sizes. The water chemistry of the fine tailings may have had some additional effect on the geotechnical properties, but this effect was small compared with the effect of the amount of clay dispersion—and then only at large void ratios.

Based on the results of this research program, the following conclusions specific to compressibility and hydraulic conductivity can be drawn.

Self-weight consolidation

- Non-caustic and $CaSO_4$ coagulant tailings had a faster initial settlement rate versus the caustic tailings for both Ore A and Ore B. This indicated a higher initial hydraulic conductivity in these materials. For the non-caustic tailings, this higher hydraulic conductivity was mainly due to less dispersed clay fines, while, for the coagulated tailings, it was due to the fines being flocculated. At a void ratio of 9, Ore A non-caustic tailings had a hydraulic conductivity nearly twice that of the caustic tailings; for Ore B, the non-caustic tailings had a hydraulic conductivity nearly four times that of the caustic tailings. These higher hydraulic conductivities should result in much faster initial settlement in a tailings pond and in the release of recycle water.
- Under self-weight, all tailings decreased in void ratio from about 9 to between 5 and 6. Approximately half of the volume decrease of the tailings from its initial void ratio to the void ratio at an effective stress confining pressure of 80 kPa occurred during self-weight consolidation.

Effect of water chemistry on compressibility volume change

- The volume changes of all materials were similar, but, in Ore A, the non-caustic tailings had the greatest volume change. In Ore B, the volume change of the two tailings types was similar.
- The $CaSO_4$ tailings from both ores had the smallest volume changes, probably due to the cementation effect of coagulation.

Over-consolidation stress

- Aged caustic fine tailings from the Syncrude tailings pond showed significant overconsolidation behaviour, while the young caustic fine tailings in this study showed minor overconsolidation behaviour. This difference is probably caused by differences in thixotropy arising from the differences in pore water chemistry and by the length of time for thixotropic strength to develop.

Effect of water chemistry on hydraulic conductivity

- For both ore types, the non-caustic fine tailings and the $CaSO_4$ coagulant tailings had a greater hydraulic conductivity than the caustic tailings for void ratios in excess of 3, where the effects of less fines dispersion and flocculation predominated.
- Below a void ratio of about 3, all fine tailings had similar hydraulic conductivities. Consolidation to this void ratio overcame the effects of fines dispersion and flocculation.

- As discussed, hydraulic conductivity dominated these large void ratio tailings' rate of settlement, while compressibility had little effect on the rate of settlement. In active tailings ponds, the rate of settlement at large void ratios is more important because faster settlement results in smaller tailings ponds and faster release of recycle water.

Sodium adsorption ratio

- Over the effective stress range from 0.01 to 80.1 kPa, variations in water chemistry represented by the SAR values did not affect the compressibility of the fine tailings materials. The compressibility of the fine tailings appears to have been dominated by effective stresses.
- There was a trend of increasing hydraulic conductivity with decreasing SAR at SAR values less than approximately 50 for samples with void ratios greater than three. At SARs greater than about 50, increasing SAR had little influence on hydraulic conductivity.

Paper reviewed and approved for publication by the Oil Sands Society of CIM.

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CHAPTER 6. INFLUENCE OF EXTRACTION PROCESS AND COAGULANT ADDITION ON THIXOTROPIC STRENGTH OF OIL SANDS FINE TAILINGS

This paper was previously reviewed, accepted and published in Canadian Institute of Mining, Metallurgy and Petroleum (CIM) Journal. It is presented as submitted and accepted by CIM Journal as part of this Ph.D. thesis as Chapter 6.

Reference: *Influence of Extraction Process and Coagulant Addition on Thixotropic Strength of Oil Sands Fine Tailings*. CIM Journal, 1(3), page numbers pending.

Page Numbering:

CIM Journal: Page number pending

This thesis: 103 to 126

Influence of extraction process and coagulant addition on thixotropic strength of oil sands fine tailings

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ABSTRACT The influence of using different extraction processes (caustic versus non-caustic) on the thixotropic strength of oil sands fine tailings is examined, as is the influence of adding a coagulant to caustic fine tailings. The thixotropic strength of fine tailings at large void ratios manifests itself as a bonding or gel strength that has been widely noted both in the laboratory and in the field. This gel strength has a significant influence on preventing the initial consolidation or settlement of fine tailings. Differences between the fine tailings' thixotropic strength development are explained based on their physical and chemical characteristics.

KEYWORDS Oil sands, Tailings, Fine tailings, Caustic, Non-caustic, Coagulant, Shear strength, Vane shear, Thixotropy, Thixotropic strength

RÉSUMÉ ~~The influence of using different extraction processes (caustic versus non-caustic) on the thixotropic strength of oil sands fine tailings is examined, as is the influence of adding a coagulant to caustic fine tailings. The thixotropic strength of fine tailings at large void ratios manifests itself as a bonding or gel strength that has been widely noted both in the laboratory and in the field. This gel strength has a significant influence on preventing the initial consolidation or settlement of fine tailings. Differences between the fine tailings' thixotropic strength development are explained based on their physical and chemical characteristics.~~

MOTS CLÉS

INTRODUCTION

In the oil sands industry, high temperature with the addition of a caustic dispersing agent has formed the basis of the Clark hot water extraction (CHWE) process, used successfully on a commercial scale to recover bitumen from surface mined oil sands ore. Descriptions of the present-day extraction and froth treatment process are provided by Shaw, Czarnecki, Schramm, and Axelson (1994), Shaw, Schramm and Czarnecki (1996), and Cymerman and Kwong (1995). However, the Clark process results in the creation of well dispersed, high void ratio fine tailings composed primarily of silt, clay, water, and residual bitumen (Miller, Scott, & Sego, 2010a). These caustic-based fine tailings exhibit low consolidation rates and shear strengths, and require considerable real estate for storage. Presently approximately 750 million cubic meters of fine tailings are being stored in tailings ponds (Houlihan & Mian, 2009). The conventional method for fine tailings management is a containment strategy of the fine tailings in ponds for sedimentation, consolidation, and eventual land reclamation. Some fine tailings have been mixed with sand to form composite/consolidated tailings that consolidate sufficiently to allow land reclamation and this process is continuing. Another possibility for final disposal is that, at mine closure, some fine tailings could be stored in mined-out pits and water could be capped to form lakes. However, the vast quantities and slow consolidation of fine tailings raise environmental and economic questions regarding possible improvements in tailings behaviour.

Processes different from the established Clark process (high temperature and caustic) have been developed to work at a range of temperatures or without the use of sodium hydroxide (Kasperski, 2001). One such process is the Other Six Lease Owners (OSLO, the consortium of companies that piloted the process) hot water extraction process (OHWE; Sury, Paul, Dereniwski, & Schultz, 1993).

This process entails a non-caustic bitumen extraction technique developed to improve bitumen recovery and produce tailings with reduced fines dispersion, in the hope of improved consolidation and strength properties of the fine tailings. Fine tailings from the CHWE and OHWE processws were used in this study and are referred to in the remainder of this paper as caustic and non-caustic fine tailings, respectively. A potential reduction in fine tailings volume and improved geo-environmental behaviour provided an environmental and economic incentive to examine the relative differences between the properties that influence consolidation of the fine tailings derived from these extraction processes.

The overall objective of this research program was to evaluate the properties and process influencing the rate and magnitude of volume change and the strength gain for tailings produced using the caustic and non-caustic extraction processes. The two main components were flume deposition tests and testing for geotechnical properties of the fine tailings. The results of the flume deposition tests are provided by Miller, Scott, and Sego (2009). Physical and chemical characteristics of the fine tailings derived from the flume deposition tests and examined during this geotechnical testing program are provided by Miller et al. (2010a). Self-weight consolidation results derived from standpipe tests are provided in Miller, Scott, and Sego (2010b). Compressibility and hydraulic conductivity relationships determined from one-dimensional consolidation tests are provided by Miller, Scott, and Sego (2010c).

One material property that affects the rate and magnitude of initial consolidation or settlement of oil sands fine tailings is the rapid thixotropic strength gain of the material. This thixotropic strength of fine tailings at large void ratios or low solids contents manifests itself as a bonding or gel strength that has been widely noted both in the laboratory and in the field. Development of thixotropic shear strength at large void ratios results in an over-consolidation stress that must be overcome for consolidation to take place; therefore, the smaller the thixotropic strength, the greater the initial settlement. Shear strength tests were carried out to determine the overall shear strength and thixotropic gain in strength of the fine tailings. The objective of the research reported in this paper was to determine the influence of a change of extraction process on the thixotropic strength properties of the fine tailings. The effect of adding a coagulant to caustic-based fine tailings was also determined. Any differences in the thixotropic strength properties between the fine tailings are explained based on the physical and chemical characteristics of the materials.

THIXOTROPY

From a geotechnical point of view, thixotropy can be defined as a process of weakening caused by remolding, followed by a time-dependent return to the original, stronger state at a constant water content and constant porosity (Mitchell, 1960). Thixotropy is of interest to geotechnical engineers because studies suggest that this phenomenon generally occurs in the majority of clay-water systems. With regard to fine tailings, as the shear strength increases over time (due to thixotropic effects), there is a negative impact on dewatering due to decreased compressibility and slowed consolidation of the fine tailings. Suthaker and Scott (1997) summarized several factors that affect thixotropic behaviour, such as mineralogy of the clay, water content, and rate of loading.

In terms of clay mineralogy, oil sands fine tailings are generally composed of 80 % kaolinite, 15 % illite, 1.5 % montmorillonite, 1.5 % chlorite, and 2 % mixed-layer clays (Fine Tailings Fundamentals Consortium [FTFC], 1995a). Oil sands fine tailings are not expected to be thixotropic because kaolinite has been found to exhibit almost no thixotropy and illite shows only a moderate regain in strength (Skempton & Northey, 1952). However, kaolinite can be made thixotropic by using a dispersing agent to reduce the degree of flocculation present in the natural material (Mitchell, 1960). The addition of sodium hydroxide (as a dispersing agent) and organic matter (in the form of residual bitumen) are important factors in the thixotropic nature of fine tailings material.

Table 1. Fine tailings materials

Fine Tailings Type	Ore Designation	Ore Description (using Syncrude Geologic Facies Chart)	Extraction Process	Process Water	Coagulant Addition
1	A	sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	caustic	Syncrude recycled pond water	none
2	A	sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	non-caustic	treated Athabasca river water	none
3	A	sub-tidal and inter-tidal estuarine, Facies 7 with interbeds of Facies 10, 21 and 22, Syncrude site	caustic	Syncrude recycled pond water	600 ppm $CaSO_4$
4	B	lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	caustic	Syncrude recycled pond water	none
5	B	lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	non-caustic	treated Athabasca river water	none
6	B	lower estuarine tidal channel – tidal flat, mostly Facies 7, Suncor site	caustic	Syncrude recycled pond water	600 ppm $CaSO_4$

Table 2. Mineralogy of the fine tailings

Fine Tailings Type	Ore	Quartz (%)	Kaolinite (%)	Illite (%)	Mixed Layer Clays (%)	Smectite (%)
1	A	2	81	15	2	0
2	A	2	80	15	3	0
3*	A	2	81	15	2	0
4	B	2	76	18	4	0
5	B	2	75	19	4	0
6*	B	2	76	18	4	0

* Note: Type 3 and Type 6 fine tailings consist of coagulant added to Type 1 and Type 4 fine tailings respectively

EXPERIMENTAL PROGRAM

Fine tailings from two extraction processes were used in this study. For the remainder of this paper, they will be referred to as simply caustic and non-caustic fine tailings, respectively.

Fine tailings

Six different fine tailings derived from two types of oil sands ore were studied to determine the influence of extraction process and coagulant addition on the thixotropic gain in strength of fine tailings. The six different fine tailings and their descriptions are summarized in Table 1. For each type of oil sands ore, one caustic and one non-caustic-based fine tailings were investigated. As well, caustic tailings modified by the addition of 600 ppm of calcium sulphate ($CaSO_4 \bullet ½H_20$) were studied. The addition of calcium sulphate was proposed to improve the settling behaviour of the fine tailings by causing the aggregation of clay particles. In Table 1, each fine tailings has been designated with a number (1 to 6) to facilitate ease of presentation in figures and tables.

Tailings from each extraction process were generated using approximately 80 tonne samples of Ore A and Ore B. The extraction process water was chosen based on the water source that would be used for commercial operation. The extraction process water used during the caustic process was recycled pond water from the Mildred Lake Settling Basin at Syncrude. Sodium hydroxide was added to aid extraction; 0.05 wt % for Ore A and 0.005 wt % for Ore B. For the caustic fine tailings, pH values ranged from about 9.0 to about 9.2. The higher values were representative of some Ore A fine tailings samples. The non-caustic process utilized Athabasca river water (initial pH 7.4) that had been treated by slowly adding a 10 % sulphuric acid solution to bring the pH to 5.0 and, subsequently, adding a 4 % (by weight) lime slurry. This increased the pH of the water to be used for extraction back to a pH of 7.4 and resulted in a 40 ppm Ca^{2+} in solution. The non-caustic extraction process relied on a methyl isobutyl carbonyl/kerosene mixture as a conditioning agent and physical processes, such as air injection, to encourage bitumen separation. For these non-caustic tailings, the pH values ranged between 8.4 and 8.7, with higher values for Ore A fine tailings. The extraction processes are fully described in FTFC (1995b) and the collection of the fine tailings is provided in Miller et al. (2009).

The mineralogy of the clay-sized fraction of the fine tailings (Table 2) is dominated by kaolinite (75 to 81 %), and illite (15 to 19 %), and there are trace amounts of mixed layer clays. For the fine tailings derived from Ore A, the mineralogies are essentially the same because the extraction process has no effect on the type and amount of clay minerals present in each fine tailings. This lack of effect on clay minerals is also the case for fine tailings derived from Ore B. Thus, mineralogy is not a significant factor when comparing fine tailings derived from the same oil sands ore.

The water chemistry of the fine tailings is shown in Table 3. The water chemistry data was provided by CanmetENERGY at the Devon Research Centre from tests using release water samples from one-dimensional consolidation tests (Miller et al., 2010c). Fine tailings used in both the shear strength tests and the consolidation tests were obtained from the same original fine tailings material. Of note are the high sodium concentrations of the caustic fine tailings compared with those of the non-caustic materials. This difference reflects the nature of the caustic extraction process, which uses sodium hydroxide to aid dispersing the clay particles and enhance bitumen recovery. A combination of methyl isobutyl carbinol and kerosene was used as a dispersing agent for the non-caustic process.

The highly dispersed nature of the caustic tailings is evident by comparing the non-dispersed and dispersed particle

Table 3. Water chemistry of the fine tailings

Fine Tailings Type	Ore Designation	pH	Anions (mg/L)				Cations (mg/L)						SAR
			HCO_3	Cl	SO_4	Fe	Si	Al	K	Mg	Ca	Na	
1	A	9.2	1346	583	526	1.8	16.7	8.4	10.6	3.0	1.8	1162	124
2	A	8.7	351	185	243	0.41	12.8	1.9	6.6	8.7	11.2	353	19
3	A	9.1	917	287	1097	0.10	3.6	0.57	12.3	6.1	10.8	1212	73
4	B	9.0	860	369	380	1.6	14.2	7.7	10.8	5.9	7.4	727	49
5	B	8.4	232	44	137	0.06	8.8	0.40	6.0	15.4	24.9	105	4
6	B	8.8	483	342	952	0.15	3.8	0.91	14.1	13.9	27.0	726	28

Table 4. Particle size distribution characteristics

Fine Tailings Type	Ore Designation	Test Method	< 74 µm (%)	< 44 µm (%) (%)	< 2 µm (%) (%)	<1 µm (%) (%)	Percent Dispersion (%)
1	A	dispersed	96	92	43	32	100
		non-dispersed	97	94	43	19	
2	A	dispersed	100	98	47	35	32
		non-dispersed	100	99	15	2.5	
4	B	dispersed	98	97	49	40	100
		non-dispersed	98	96	49	40	
5	B	dispersed	98	97	48	33	10
		non-dispersed	99	98	5.0	1.5	

size distributions characteristics given in Table 4. Type 1 and 4 fine tailings were almost completely dispersed by the caustic process, whereas the non-caustic fine tailings (Types 2 and 5) were only partially dispersed. This difference may have an influence on the shear strength and thixotropic behaviour of the fine tailings because a more dispersed material has a finer grain size (i.e., more individual clay particles and more opportunities for physico-chemical interactions between clay particles; Mitchell & Soga, 2005).

Testing program

Shear strength tests were performed at two different initial water contents for each fine tailings. The varying water contents were selected to represent the fine tailings at different ages during long-term consolidation. The first set of water contents ranged from 194 to 257 %. These were the predicted water contents after one year of settling and consolidation, based on the results of two metre-high, self-weight consolidation tests (Miller et al., 2010b). The second water content for all the fine tailings was set at 150 % to represent mature fine tailings that has undergone greater consolidation. It takes about two years for the fine tailings in the pond to consolidate to a water content of 233 % (30 % solids content). Fine tailings at this point are considered mature (Scott & Dusseault, 1982).

Due to the thixotropic nature of the fine tailings, an important variable in this testing was the age of the fine tailings. Age was defined as the elapsed time from the moment when the process of remolding or physical agitation ceased to the time of strength testing. Tests were performed for each set of water contents at the following times: zero, two, and six hours, as well as one, two, five, 10, 20, 40, 80, 160, and 365 days.

Testing methods

Fine tailings are slurries with very high water contents that make measurement of shear strength difficult. The vane shear test is one of the most widely used methods to measure un-drained shear strength in soils that are too soft to sample for triaxial testing. The vane shear test was modified for very high water content slurries and successfully applied to fine tailings by Banas (1991). The shear strengths of the six fine tailings investigated in this study were measured using the equipment and procedures developed and described in detail by Banas (1991).

A modified Wykeham-Farrance miniature vane shear apparatus was used for testing the samples. To provide a constant vane rotational speed, the hand-operated drive mechanism of the conventional vane shear apparatus was replaced with an electric motor. Two belt-driven gears connected the electric motor to the drive mechanism, allowing constant vane rotational speeds anywhere between zero and 120 degrees per minute. A rigid transducer replaced the conventional torque-measuring spring. Three custom-made vanes were used for the strength testing of fine tails. Two of them had four blades each, height-to-diameter ratios of two, and diameters of 20 mm and 60 mm, respectively. The third vane had six blades, a diameter of 80 mm, and a height-to-diameter ratio of one. Vane rotational speeds were determined according to an angular velocity of 0.17 mm/s. The testing procedure was in accordance with the ASTM Standard D4648-05 (ASTM, 2005).

RESULTS AND DISCUSSION

The standard bitumen extraction process used by commercial oil sands operations is the caustic-based CHWE process. Other experimental processes are being used, but not on commercial projects. These caustic fine tailings were taken as the norm and all other fine tailings were compared with them.

The purpose of this study was to determine the influence of extraction process on the thixotropic strength of the fine tailings, which is most effectively carried out by comparing materials derived from the same oil sands ore. No comparisons were made between Ore A and Ore B fine tailings because they are inherently different materials, as evidenced by their different mineralogies (Table 2), water chemistries (Table 3), and grain size distributions (Table 4).

Consolidation effects

As shown by the variation of water content with the age of the fine tailings, the strength developed during the test period was not caused by thixotropy alone, but was also

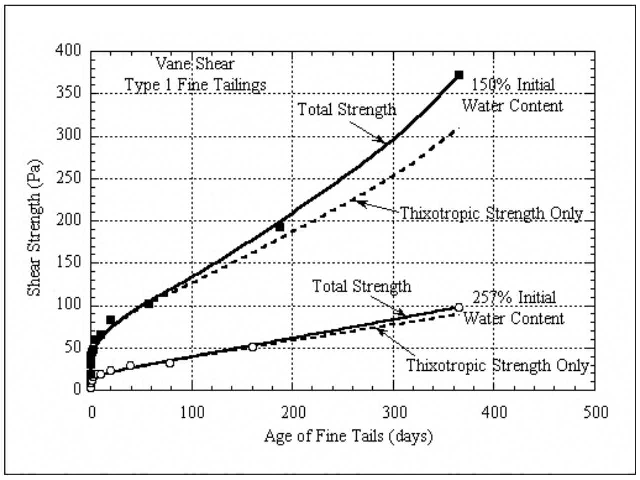

Fig. 1. Shear strength of a typical fine tailings and correction for consolidation.

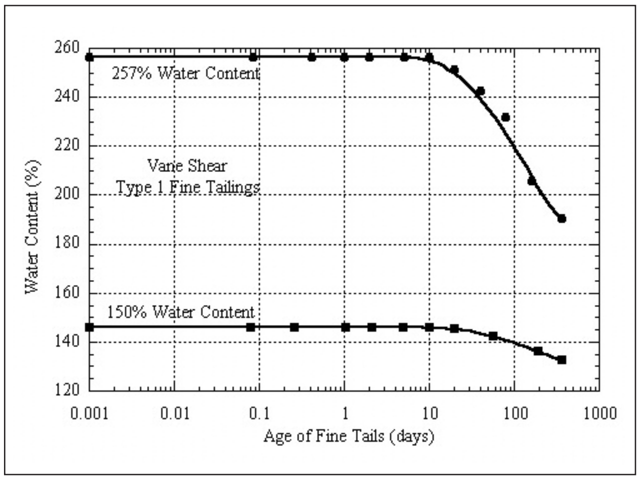

Fig. 2. Self-weight consolidation of a typical fine tailings.

due to a decrease in water content associated with self-weight consolidation. A typical example of the gain in strength with time is shown in Figure 1 and the associated decrease in water content is shown on Figure 2. Strength gain caused by consolidation had to be determined to assess the actual thixotropic strength gain.

Following the technique developed by Suthaker and Scott (1997), corrections for consolidation effects were included by interpolating between the water contents for each sample, taking into consideration the initial, un-drained shear strengths. Initially, the water content was constant, but consolidation effects started to appear once the water content began to decrease. In the case shown in Figure 2, corrections for consolidation only began after about 10 days; prior to this time, the strength developed was due solely to thixotropy. Figure 1 shows both the total strength of the fine tailings (which includes both thixotropic and strength gain through decrease of moisture content—consolidation) and the corrected strength (due to thixotropy) alone.

Thixotropic strength of the caustic and non-caustic fine tailings

The thixotropic strengths of the fine tailings were influenced by variations in the water chemistry of the different materials. These results can best be explained in terms of how variations in water chemistry influenced the diffuse double-layer surrounding the clay particles.

The basic theory of the diffuse double-layer on charged colloid surfaces was developed by Guoy and Chapman in the early 1900s and has been described in detail by many sources, such as Mitchell and Soga (2005) and Bohn, McNeal, and O'Connor (1985). The negative charge on the surface of the clay particle and distributed charge within the adjacent phase are together termed the diffuse double-layer. The thickness of the diffuse double-layer is loosely defined as the distance over which the solution concentration is affected by the particle charge on the clay surface. In general, the thicker the double-layer, the smaller the tendency for particles in suspension to flocculate.

Inter-particle repulsive force depends on the amount of overlap or interaction between adjacent double-layers. Thus, one can estimate the probable influences on behaviour that result from differences in the system variables, such as electrolyte concentration and cation valence. Increasing electrolyte concentration causes the double-layer thickness to decrease. This effectively lowers the surface charge (reducing the repulsive forces between clay particles) and allows attractive forces to bond the particles together. These attractive forces are the van der Waals forces, which are independent of the characteristics of the fluid between particles. Thus, interactions extend to lesser particle spacings for a high electrolyte concentration system and should result in higher thixotropic strengths.

As cation valence increases, double-layer thickness decreases, leading to a decrease in repulsive forces between clay particles. Clays preferentially adsorb multivalent ions, which means that di- or tri-valent cations can have a significant influence on physical , relative to clay-water-monovalent electrolyte systems.

Discussion of results

In general terms, thickness of the double-layer decreases with increasing electrolyte concentration and cation valence. This effect leads to a decrease in the repulsive forces between clay particles, allowing attractive forces (mainly van der Waals forces) to create more bonding between clay particles and resulting in a higher un-drained shear strength of the fine tailings.

For the fine tailings of this study, an important factor influencing the shear strength of the fine tailings was the concentration of sodium ions in the pore water. Concentrations of sodium ions were substantially greater than any other cation present (Table 3). The relatively small number

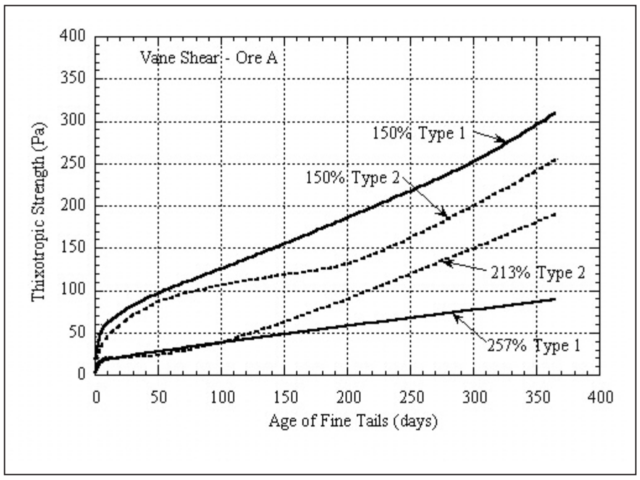

Fig. 3. Influence of extraction process on thixotropic strength of Ore A fine tailings.

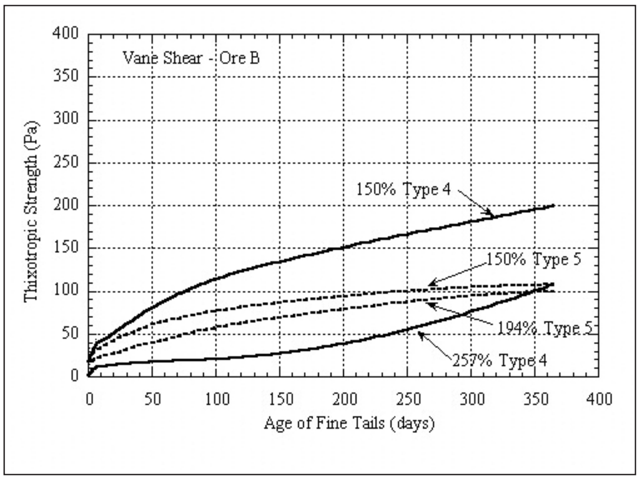

Fig. 4. Influence of extraction process on thixotropic strength of Ore B fine tailings.

of divalent cations present in pore water not treated with calcium sulphate had a negligible effect on the clay particles and the double-layer. Differences in double-layer thickness resulted from the variation in electrolyte concentration of the pore water, leading to differences in shear strength. The calcium sulphate modified fine tailings also had the aggregation of clay particles, which contributed to the shear strength.

Influence of extraction process

It was expected that the caustic fine tailings (Types 1 and 4) would have higher thixotropic shear strengths than the comparable non-caustic material (Types 2 and 5), based on the large concentrations of sodium ions in the caustic pore water compared with the non-caustic pore water (Table 3). This increase in caustic tailings' thixotropic shear strengths is shown in the sodium adsorption ratio (SAR) given in Table 3, which reflects the dominance of sodium with regard to adsorbed ions. SAR relates the composition of the solution phase to the composition of the adsorbed phase (i.e., it provides a prediction of the adsorbed phased based on the concentrations of ions in solution). For practical purposes, SAR is defined as:

$$SAR = \frac{[Na^+]}{\sqrt{\frac{[Ca^{2+}] + [Mg^{2+}]}{2}}} \quad (1)$$

where the soluble cation concentrations are in milliequivalents per litre (me/L).

In general, when SAR values exceed a certain level specific to each material, sodium ions occupy adsorption sites on the clay, resulting in dispersion of the clays. It has been previously reported by Dawson, Sego, and Pollock (1999) that SARs greater than about seven indicate a high potential for dispersion. Based on the SARs for the fine tailings used in this testing program, it was concluded that fine tailings with a SAR greater than 20 were likely to be in a dispersed state, while those with a SAR of five or less had a flocculated structure (Miller et al., 2010a). While the non-caustic pore waters contain slightly greater concentrations of calcium ions than the caustic pore water (Table 3), the relatively small number of divalent cations present have a negligible effect on the clay particle and the double-layer. Hence, relative differences in water chemistry were dominated by the sodium concentrations and should result in a thinner double-layer for the caustic clay particles, decreased repulsive forces between clay particles and, ultimately, a greater thixotropic strength relative to comparable non-caustic materials.

For Ore A materials that had the same initial water content (150 %), the Type 1 fine tailings had a higher thixotropic strength than did the Type 2 material (Figure 3). This difference is an expected result based on the relative sodium concentrations and SARs of the two materials, as mentioned earlier. Consequently, Type 1 clay particles had relatively thinner double-layers than their Type 2 counterparts and, ultimately, greater strength. The Ore B materials also followed this pattern (Figure 4).

In terms of initial shear strength, little difference was seen between the caustic and non-caustic fine tailings (Table 5). For the Ore A materials, the Type 1 fine tailings had a greater initial shear strength than Type 2, but the difference was only 4.5 Pa. The difference was also small between Ore B fine tailings (4.0 Pa), but, in this case, the non-caustic Type 5 fine tailings had a higher strength. This higher strength was a short-lived phenomenon because the Type 4 fine tailings had the same shear strength as the non-caustic tailings after two hours and exceeded Type 5 in shear strength after one day.

Influence of coagulant addition

The addition of calcium ions, in the form of calcium sulphate, to the fine tailings should result in a decrease in the

Table 5. Initial and final shear strengths from vane shear tests

Fine Tailings Type	Ore Designation	Coagulant Addition	Initial Water Content	Zero Time Shear Strength (%)	Shear Strength after 365 Days (Pa)	Thixotropic Ratio after 365 Days (Pa)
1	A	none	257	2.8	89	31.8
2	A	none	213	9.0	190	21.1
3	A	$CaSO_4$	257	7.2	149	20.7
4	B	none	257	1.7	107	62.9
5	B	none	194	14.0	100	7.1
6	B	$CaSO_4$	257	4.8	111	23.1
1	A	none	150	19.6	310	15.8
2	A	none	150	15.1	254	16.8
3	A	$CaSO_4$	150	33.9	300	8.8
4	B	none	150	17.3	200	11.6
5	B	none	150	21.3	107	5.0
6	B	$CaSO_4$	150	26.7	218	8.2

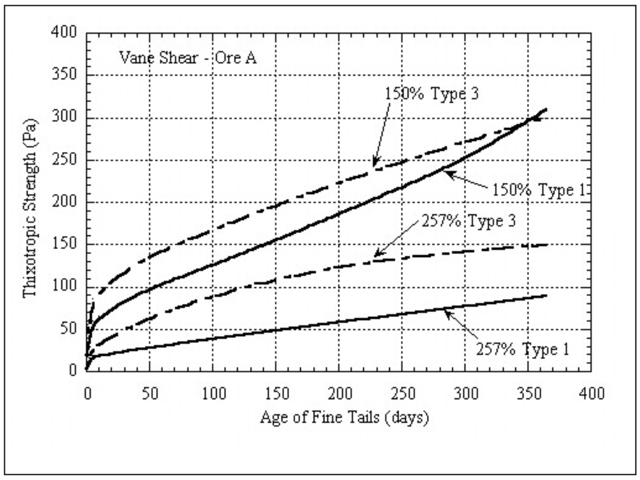

Fig. 5. Influence of coagulant addition on thixotropic strength of Ore A fine tailings.

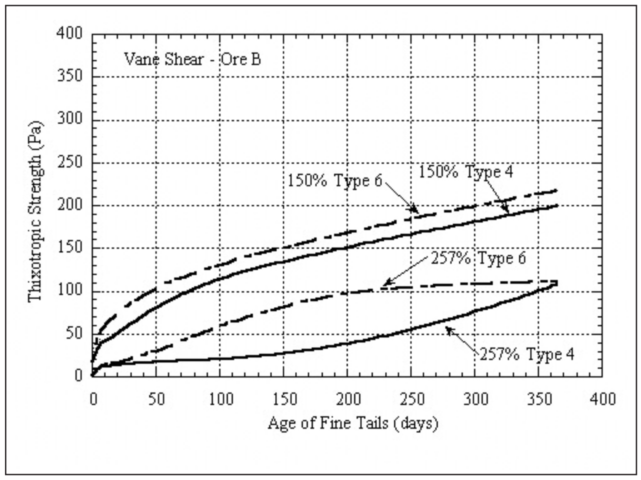

Fig. 6. Influence of coagulant addition on thixotropic strength of Ore B fine tailings.

double-layer surrounding the clay particles due to the preferential adsorption of divalent cations by clays. Thus, the repulsive forces are reduced and the attractive forces are allowed to bond the particles together, resulting in higher thixotropic strengths. This effect was evidenced for both the Ore A (Figure 5) and Ore B (Figure 6) fine tailings with similar initial water contents (150 % and 257 %). Caustic fine tailings with calcium sulphate had consistently higher thixotropic strengths and differences in thixotropic strength were greater at higher water contents.

For both the Ore A and Ore B fine tailings, the caustic fine tailings with calcium sulphate had greater initial shear strengths than did the normal caustic materials (Table 5). The higher strengths of the materials were a reflection of the agglomeration of clay particles caused by the coagulant, resulting in a coarser material and, ultimately, a higher shear strength. Tang, Biggar, Scott, and Sego (1997) reported similar results for mature fine tailings after the addition of laboratory grade gypsum. Using scanning electron microscopy, Tang et al. reported that the clay structure of the fine tailings was a more crowded, less organized, and agglomerated network of clay particles that, consequently, produced a finer and stronger clay structure in mature fine tails.

The influence of the coagulant addition was more pronounced for those fine tailings with higher initial water contents (257 %). For both the Ore A and Ore B fine tailings, the ratio of initial shear strength averaged 2.7 times greater for the 257 % water content and 1.6 times greater for the 150 % water content materials (Table 5). Calcium sulphate had a greater effect on the higher water contents materials because there was more space for the particles to re-orient themselves and create larger agglomerations, which produced higher shear strengths.

Influence of initial water content

Comparisons between caustic and non-caustic fine tailings that had different initial water contents (213 % and 257 % in Figure 3; 194 % and 257 % in Figure 4) always resulted in the material with the lower water content (i.e., non-caustic fine tailings) having a higher shear strength. This trend held true for both Ore A and Ore B fine tailings. Suthaker and Scott (1997) showed that thixotropic strength decreased with an increase in water content at any given age of the fine tailings. Therefore, even though the caustic fine tailings may have had a greater thixotropic strength (as discussed above), the influence of initial water content was more significant.

The influence of decreasing initial water content is better shown by comparing similar fine tailings at different initial water contents. Using the Ore A fine tailings in Figure 3 as an example, the shear strength decreased with increasing water content for both the caustic and non-caustic fine tailings.

Comparison of fine tailings thixotropy for other research

Thixotropic strength of Type 1 fine tailings measured during this research study and results from previous vane shear testing on fine tailings (Banas, 1991) is provided on Figure 7. The results from Banas are for fine tailings obtained from the Syncrude tailings pond, generated by the commercial caustic process, and comparable to the fine tailings designated here as Type 1.

Thixotropic strength measured by the vane shear tests was reasonably similar for the two sets of data. Higher thixotropic strengths were measured by Banas (1991), but, after 365 days, the strengths were similar. Differences in strength may be attributed to differences in the fine tailings materials used.

A similar trend can be seen when Banas' results (1991) for Type 1 fine tailings (which had an initial water content of 233 %) are compared with the results for Type 1 fine tailings from this study (which had an initial water content of 257 %). While there is a difference in initial water contents, the similar test methods resulted in the same trend, with reasonable similarity between the two sets of vane shear results.

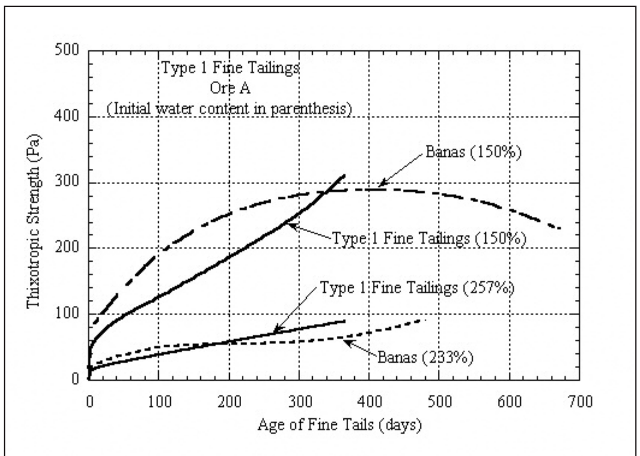

Fig. 7. Comparison of thixotropic strength measurements for Type 1 fine tailings: 150 % initial water content.

CONCLUSIONS

Overall, the different water chemistries of the different extraction processes resulted in different amounts of dispersion of the clay-shale seams present in oil sands ore, with less dispersed non-caustic fine tailings. The differences in the geotechnical properties, including the shear strength of the tailings, were mainly due to the different grain sizes. The water chemistry of the fine tailings may have had some additional effect on the geotechnical properties, but this effect was generally small for most of the geotechnical properties compared with the effect of the amount of clay dispersion—and then only at large void ratios. For thixotropic strength or gel strength, however, water chemistry controlled development.

Based on the results of this research program, the following conclusions, specific to shear strength, can be made:

@Enumeration:Fine tailings derived from a caustic-based extraction process had relatively higher shear strengths than comparable non-caustic based fine tailings. The difference in strength between fine tailings was explained using the diffuse double-layer theory for clay particles and attributed mainly to the varying concentrations of sodium ions in the fine tailings pore water. Support for this theory was evidenced in the sodium adsorption ratio (SAR), which reflected the dominance of sodium with regard to adsorbed ions.

The addition of a chemical coagulant in the form of calcium sulphate resulted in increased shear strengths for the caustic-based fine tailings. The increase in shear strength was explained in terms of the addition of higher valence cations into the pore water of the fine tailings, which affected the diffuse double-layer. The higher strengths of the coagulant modified fine tailings resulted from the coagulant, which caused agglomeration of clay particles and resulted in a coarser material, and, ultimately, in a higher shear strength.

The difference in pH between the caustic and non-caustic fine tailings was not large (varying from 8.4 to 8.7 for non-caustic fine tailings and from 9.0 to 9.2 for caustic fine tailings). These differences should not have a significant influence on the development of thixotropic shear strength.

Development of thixotropic shear strength at large void ratios resulted in an over-consolidation stress, which would have to be overcome in order for consolidation to take place. Therefore, non-caustic fine tailings showed better consolidation behaviour than caustic fine tailings at high void ratios. However, differences in shear strength were small and the overall impact on consolidation behaviour, which also depends on compressibility and hydraulic conductivity, should not be significant (Miller et al., 2010c).

Similarly, the addition of the coagulant of calcium sulphate to the caustic fine tailings should have a negative effect in terms of consolidation behaviour, but the overall impact is expected to be small and overwhelmed by the greater hydraulic conductivity of the coagulated fine tailings.

The gel strength of caustic fine tailings (which results in consolidation difficulty past a solids content of 30 %) can be duplicated in non-caustic fine tailings. However, the greater hydraulic conductivity of non-caustic, less dispersed, fine tailings results in faster consolidation (Miller et al., 2010c).

Paper reviewed and approved for publication by the Oil Sands Society of CIM.

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David C. Sego joined the University of Alberta in 1977 and worked on permafrost and cold region engineering topics. Since 1990, his research is directed at oil sands tailings and mine waste issues in permafrost regions.

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7. Conclusions and Recommendations

The overall objective of this thesis is to evaluate the properties and processes influencing the rate and magnitude of volume decrease and strength gain for the tailings resulting from a change in bitumen extraction process (caustic versus non-caustic) and the effect of adding a coagulant to caustic fine tailings. Specific objectives include:

- Study the influence of the extraction process on the characteristics of deposits formed by hydraulically deposited oil sands tailings.
- Compare the results of flume deposition tests using caustic and non-caustic oil sand tailings with the results of numerous other flume tests summarized in the literature using a variety of other tailings material and covering a wide range of slurry concentrations and flow rates.
- Assess the influence of the caustic and non-caustic extraction process on the physical and chemical characteristics of the fine tailings in terms of index properties, mineralogy, specific surface area, water chemistry, Atterberg limits, particle size distribution, and morphology.
- Study the self-weight consolidation behaviour of the caustic and non-caustic fine tailings using large-scale equipment to model tailings pond conditions.
- Determine the compressibility and hydraulic conductivity characteristics of the fine tailings over a range of effective stresses.
- Study the thixotropic strength development of the fine tailings.
- Assess the compressibility, hydraulic conductivity and strength properties of the different fine tailings with regard to differences in physical and chemical characteristics and provide conclusions on which factors (if any) can be expected to control the consolidation process.

7.1 Conclusions

7.1.1 Flume Deposition Modeling

<u>Large Scale Flume Deposition Tests</u>

Large scale laboratory flume tests were used to hydraulically deposit oil sand tailings and compare the effects of the combined tailings for the OSLO and the Clark extraction processes on the characteristics of the beach deposit. Flume fine tailings runoff was collected for subsequent evaluation of their geotechnical properties. Several conclusions were reached as a result of the flume deposition testing program.

- The design of the flume test was successful based on the similarity between predicted and actual test results.
- Flume tests are suitable for qualitatively modeling the hydraulic deposition of oil sand tailings, but the complex nature of the deposition process precludes quantitative extrapolation of laboratory results to the field. Field scale deposition tests are required to determine the typical characteristics of beach deposit produced at a commercial scale.
- The reproducibility of the flume tests shows that the beach building process is a controlled process and therefore beaches can be designed.
- Beach slopes were found to steepen with increasing slurry concentration and decrease as flow rate increased.
- For similar flow rates and slurry concentrations, beach slopes decreased with increasing fines content.
- Flow rate appears to be the dominant parameter for determining beach slope.

<u>Comparison Between Oil Sands Tailings and Other Materials</u>

The results of flume tests using oil sand tailings were compared to the results of numerous other flume tests using a variety of materials and covering a wide range of slurry concentrations and flow rates. These comparisons also produced several conclusions.

- There was a good correlation between flume tests results using oil sand tailings and the various other tailings materials with regard to the trend of decreasing beach slope with increasing flow rate.
- The variation of beach slope with slurry concentration resulted in one set of data for material with little or no fines, and another set of data for materials with appreciable fines contents, such as oil sand tailings.
- For the low fines materials, beach slope became steeper as slurry concentration increased. However for the high fines materials, the beach slope was influenced by fines content. For a given range of slurry concentrations and flow rates, beach slopes decreased with increasing fines content of the tailings material.

- The beach density was observed to decrease with increasing slurry concentration, but no consistent change was observed for a variation in flow rate.
- The correlation between the various flume test results show the reliability and effectiveness of flume testing in terms of establishing general relationships. These comparisons can serve as a guide to predict beach slopes and determine what parameters control beach slope and density for tailings materials.

7.1.2 Extraction Process Influence on the Characteristics of Oil Sands Fine Tailings

Based on the results of this research program, the following conclusions specific to physical and chemical characteristics of the fine tailings can be made:

- Little variation exists between the different fine tailings, in terms of index properties, mineralogy, and specific surface area. Thus, these fundamental properties are not responsible for the variations seen between materials in terms of particle size distribution and percent dispersion. These differences can be explained by the differences in the water chemistry of the fine tailings. The SAR is a reflection of the water chemistry and provides a good guideline for predicting the dispersive nature of the clays in the fine tailings.
- There was good correlation between the index properties and mineralogy of the non-caustic/caustic fine tailings and fine tailings impounded in the tailings pond at the mine sites. Thus, the general relationships established for the non-caustic/caustic fine tailings should be applicable to the commercial fine tailings, but any trends or differences in behaviour would have to be confirmed at a commercial scale.
- Differences between the liquid limits and plasticity indexes were minor for the fine tailings, and will have no significant difference in terms of geotechnical engineering behaviour. Slight variations were due to differences in the pore water chemistry and have been explained by the double layer theory for clay particles.
- Substantial differences were seen in the particle size distributions and degree of dispersion of the comparable non-caustic and caustic fine tailings. Caustic fine tailings were generally finer than non-caustic fine tailings due to a greater degree of dispersion. Treating the process water with acid and lime for the non-caustic process resulted in only a slightly less dispersed material.

- The degree of dispersion of the fine tailings measured by the hydrometer tests was found to be consistent with the predictions for dispersed clays established by the SAR values for these materials. A linear variation of increasing dispersion with increasing SAR up to a SAR value of about 40 has been suggested, above which, fine tailings are completely dispersed.
- A scanning electron microscope was used to observe the structure of the clay minerals in the fine tailings. Only the non-caustic fine tailings generated from Ore B ore with the use of treated process water (Type 5) had an observed structure approaching the typical random structure dominated by face-to-edge particle interactions associated with less dispersed clays. The remaining fine tailings were highly structured with face-to-face orientations predominating. These structures supported the predictions based on the SAR values. Although only one of the fine tailings had a less dispersed structure, visual observations indicated the degree of dispersion decreased with decreasing SAR, in terms of the thickness of the booklets of clay plates.

7.1.3 Self-Weight Consolidation

Based on the results of this research program using large scale standpipe tests, the following conclusions specific to self-weight consolidation can be made:

- Fourteen self-weight consolidation tests on seven fine tailings materials were performed using 2 m and 1 m high standpipes fully instrumented to monitor the rate and amount of consolidation. Thirteen of the tests provided valuable information on the variation of consolidation that was related to the differences in the fine tailings pore water chemistry, particle size distribution and structure.
- The use of adjusted total stress and excess pore pressure instead of total stress and pore pressure provide a better visualization of the progress of consolidation.
- The sodium adsorption ratio (SAR) provides a prediction of the adsorbed phase based on the concentration of ions in solution. Based on the particle size distribution results, it was concluded that fine tailings with a SAR greater than 20 are likely to be in a dispersed state while those with a low SAR will have a less dispersed structure.

- Non-caustic fine tailings had faster initial consolidation which is important in tailings ponds as these fine tailings would require less storage capacity and return decant water at a faster rate to the extraction plant. Settlement of the fine tailings, or volume decrease, became similar for the caustic and non-caustic fine tailings after long periods of time. As the volume of the fine tailings decreases, and more and more clay particles come into contact with each other, effective stress will begin to control consolidation. At this point, the influence of degree of dispersion and particle size distribution will diminish.
- Similarly, even though the coagulant addition improved the initial rate of consolidation of the caustic fine tailings, the long term settlement appears to converge to a similar value over time and is then governed by effective stress changes.
- The fine tailings are highly compressible materials relative to typical clay minerals, with large changes in void ratio at low effective stresses. The long term compressibility of the non-caustic and caustic fine tailings are fairly similar, but the caustic fine tailings show an overconsolidation effect caused by the development of thixotropic strength within the mature fine tailings.
- The 2 m high standpipes were designed to model a fine tailings pond underlain by a permeable sand layer. The rate and amount of downward drainage was continuously monitored and the non-caustic fine tailings had more rapid downward drainage that was a reflection of its less dispersed structure and agreed with its low SAR value.

7.1.4 Compressibility and Hydraulic Conductivity

Based on the results of this research program using slurry consolidometers, the following conclusions specific to compressibility and hydraulic conductivity can be made:

<u>Self-Weight Consolidation</u>

- Non-caustic and $CaSO_4$ coagulant tailings had a faster initial settlement rate versus the caustic tailings for both Ore A and Ore B. This indicated a higher initial hydraulic conductivity in these materials. For the non-caustic tailings this higher hydraulic conductivity was mainly due to less dispersed clay fines while for the coagulated tailings it was due to the fines being flocculated. At a void ratio of 9, Ore A non-caustic tailings had a hydraulic conductivity nearly twice that of the caustic tailings while for Ore B, the non-caustic tailings had a hydraulic conductivity nearly four times that of the caustic tailings. These higher hydraulic conductivities would result in much faster initial settlement in a tailings pond and release of recycle water.

- Under self-weight, all tailings decreased in void ratio from about 9 to between 5 and 6. Approximately one-half of the volume decrease of the tailings from its initial void ratio to the void ratio at an effective stress confining pressure of 80 kPa occurred during self-weight consolidation.

Effect of Water Chemistry on Compressibility Volume Decrease

- The volume decreases of all materials were similar, but in Ore A the non-caustic tailings had the greatest volume decrease. In Ore B the volume decrease of the two tailings types was similar.
- The $CaSO_4$ tailings from both ores had the smallest volume decreases probably due to the cementation effect of coagulation.

Overconsolidation Stress

- Aged caustic fine tailings from the Syncrude tailings pond show significant overconsolidation behaviour while the young caustic fine tailings in this study have minor overconsolidation behaviour. This difference is probably caused by differences in thixotropy arising from the differences in pore water chemistry and by the length of time for thixotropic strength to develop.

Effect of Water Chemistry on Hydraulic Conductivity

- For both ore types, the non-caustic fine tailings and the $CaSO_4$ coagulant tailings have a greater hydraulic conductivity than the caustic tailings for void ratios in excess of 3 where the effects of less fines dispersion and flocculation predominate.
- Below a void ratio of about 3, all fine tailings have similar hydraulic conductivities. Consolidation to this void ratio overcomes the effects of fines dispersion and flocculation.
- As discussed, the hydraulic conductivity dominates the settlement with time of these large void ratio tailings while the compressibility has little effect on the rate of settlement. In active tailings ponds the rate of settlement at large void ratios is more

important as faster settlement results in smaller tailings ponds and faster release of recycle water.

Sodium Adsorption Ratio

- Over the effective stress range from 0.01 kPa to 80.1 kPa, variations in water chemistry represented by the SAR values do not affect the compressibility of the fine tailings materials. The compressibility of the fine tailings appears to be dominated by effective stresses.
- There was a trend of increasing hydraulic conductivity with decreasing SAR at SAR values less than approximately 50 for samples with void ratios greater than 3. At SARs greater than about 50, increasing SAR had little influence on hydraulic conductivity.

7.1.5 Thixotropic Strength

Based on the results of this research program, the following conclusions specific to shear strength can be made:

- Fine tailings derived from a caustic based extraction process had relatively higher shear strengths than comparable non-caustic based fine tailings. The difference in strength between fine tailings was explained using the diffuse double layer theory for clay particles and attributed mainly to the varying concentrations of sodium ions in the fine tailings pore water. This is reflected in the sodium adsorption ratio (SAR) that reflects the dominance of sodium with regard to adsorbed ions.
- The addition of a chemical coagulant in the form of calcium sulphate resulted in increased shear strengths for the caustic based fine tailings. The increase in shear strength was discussed in terms of the effect of adding higher valence cations into the pore water of the fine tailings and its effect on the diffuse double layer. The higher strengths of the coagulant modified fine tailings are a reflection of the coagulant causing agglomeration of clay particles, resulting in a coarser material and ultimately a higher shear strength.
- The difference in pH between the caustic and non-caustic fine tailings was not large; varying from 8.4 to 8.7 for non-caustic fine tailings and varying from 9.0 to 9.2 for caustic fine tailings. These differences are not expected to have a significant influence on the development of thixotropic shear strength.

- Development of thixotropic shear strength at large void ratios results in an overconsolidation stress which must be overcome for consolidation to take place. Therefore, non-caustic fine tailings show better consolidation behaviour than caustic fine tailings at high void ratios. However, differences in shear strength were small and the overall impact on consolidation behaviour, which also depends on compressibility and hydraulic conductivity, is not expected to be significant.
- Similarly, the addition of the coagulant of calcium sulphate to the caustic fine tailings will have a negative effect in terms of consolidation behaviour, but the overall impact is expected to be small and will be overwhelmed by the greater hydraulic conductivity of the coagulated fine tailings.
- The gel strength of the caustic fine tailings which results in the fine tailings having difficulty in consolidating past a solids content of 30% may be duplicated in the non-caustic fine tailings. The greater hydraulic conductivity of the non-caustic, less dispersed, fine tailings will, however, result in faster consolidation.

7.2 Recommendations

- Data from any future flume tests using oil sands tailings should be collected and added to the current database to increase reliability and confidence in the general relationships established to serve as a guide for field designers to predict beach slopes and determine what parameters control beach slope and density for tailings materials on a commercial scale.
- Further advances in the understanding of the characteristics of fine tailings require continued measurements of geotechnical and physico-chemical properties of fine tailings. Measurements of characteristics of fine tailings from the existing ponds and any fine tailings produced from non-caustic or alternative extraction methods on a commercial level is recommended. Measurements of sodium adsorption ratio (SAR) in particular may prove useful in predicting the dispersive or flocculated state of the fine tailings and provide insight on expected consolidation behaviour of the material in question. Geotechnical and physico-chemical data from oil sands fine tailings should be collected and added to the current database to increase reliability and confidence in the general relationships established.

- Standardized test procedures for the testing of particle size distribution and other physico-chemical characteristics of fine tailings should be established for the oil sands industry to ensure that physical and chemical characteristics of the fine tailings are not destroyed or altered during the testing process. Recognised testing standards may not be sufficient for specialised soils such as fine tailings to preserve physical and material characteristics that are highly sensitive to drying, mechanical grinding and chemical addition.
- Compressibility and hydraulic conductivity relationships with void ratio determined by large strain consolidation tests during this research program are valid and may be applied to any future modeling of the fine tailings assuming, of course, that the fine tailings are similar to those used in this experimental program. These engineering properties will influence the long-term disposal of the fine tailings. Both of these relationships are required to define the material relationships to be used in large strain consolidation numerical modeling of a storage pond to predict water release rates and changes to surface elevations that impact storage volumes and elevation of reclamation surfaces. Compressibility and hydraulic conductivity relationships determined during this research program should be applied to a suitable large strain consolidation numerical model and used to predict the consolidation behaviour of the fine tailings on a commercial scale. This would provide a valuable assessment of potential commercial benefits of pursuing a change in extraction methodology to improve fine tailings management.
- Comparisons of shear strength of the fine tailings measured by different types of equipment other than the vane shear test should be made. Equipment that is robust and reliable to measure shear strength of the fine tailings in field conditions should be developed and an in-situ testing program should be carried out to confirm laboratory results.
- A research program focused on the impact on standpipe height and filling rate should be performed to determine the impact of these parameters on self-weight consolidation of fine tailings. Assessment of these parameters on a laboratory scale may provide conclusions and implications for commercial fine tailings management.
- Although gas bubbles were not present in the fine tailings produced and tested in this research program, most field deposits of fine tailings are now showing the presence of gas in bubbles and in solution. The presence of gas bubbles increases the complexity of determining the settlement and consolidation properties of the fine tailings.

Measurements of fine tailings properties with depth in the field should not only include solids and fines content, water chemistry, shear strength and pore pressure but also bitumen content (which has an effect on hydraulic conductivity), free gas content (under in situ pore pressure), temperature (has a great effect on gas and bitumen properties) and gas producing microbial type and content. Future research programs should be developed which examine the effect of all these factors on the settlement and consolidation of fine tailings.