Thickening of Mature Fine Oil Sands Tailings

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Graduate Program in Civil and Environmental Engineering
A thesis submitted in partial fulfillment of the requirements for the degree in Master of Engineering Science
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THICKENING OF MATURE FINE OIL SANDS TAILINGS

(Thesis format: Monograph)

by

Shriful Islam

Graduate Program in
Civil and Environmental Engineering

A thesis submitted in partial fulfillment
of the requirements for the degree of
Master of Engineering Science

The School of Graduate and Postdoctoral Studies
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ABSTRACT

The mature fine oil sands tailings (MFT) remain suspended in tailings disposal pond for decades because of the low sedimentation/consolidation rate. This study investigates the application of coagulation and electrokinetics to thicken, i.e., to increase the solid content of the MFT suspension. At first, the optimal ferric chloride concentration is identified as 350 mg/l in jar tests, under which the best thickening result is only 6.48% from an initial of 5% after 4 hours in cylinder coagulation tests. The electrokinetic thickening under an applied voltage gradient of 219 V/m reaches the final solid content of 18.75% after 7 hours. The combined coagulation (350 mg/l ferric chloride) and electrokinetic thickening under a continuous applied voltage gradient (219 V/m) is the most effective approach, which reaches the final solid content of 23.74%. The sedimentation theories in the free settling and hindered settling stages are validated using the experimental results, which is one of the major contributions of this research. The turbidity of the supernatant ranges between 4.8 NTU and 31 NTU in all treatments. Two regression models for the electrokinetic and the combined application of coagulation and electrokinetic tests are developed to relate the final solid content and the applied voltage gradient. The models and the independent variables are statistically significant at 95% confidence level based on F-test and t-test results, respectively.

Keywords: electrophoresis, thickening, sedimentation, coagulation, mature fine oil sands tailings.
DEDICATION

Dedicated to

My Family and The Memory of My Father
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## TABLE OF CONTENTS

CERTIFICATE OF EXAMINATION ................................................................. ii

ABSTRACT .................................................................................................. iii

DEDICATION ............................................................................................. iv

ACKNOWLEDGEMENTS ....................................................................... v

TABLE OF CONTENTS .......................................................................... vi

LIST OF TABLES ....................................................................................... xi

LIST OF FIGURES ................................................................................... xiv

LIST OF SYMBOLS AND ABBREVIATIONS ....................................... xix

### CHAPTER 1 INTRODUCTION ............................................................... 1

1.1 General .............................................................................................. 1

1.2 Research Objectives .......................................................................... 2

1.3 Thesis Outline .................................................................................. 3

1.4 Original Contributions ....................................................................... 4
# CHAPTER 2 LITERATURE REVIEW

<table>
<thead>
<tr>
<th>Subsection</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1 Introduction</td>
<td>5</td>
</tr>
<tr>
<td>2.2 Basic Properties of Oil Sands Tailings</td>
<td>6</td>
</tr>
<tr>
<td>2.3 Technologies/Methods for the Treatment of Oil Sands Tailings</td>
<td>8</td>
</tr>
<tr>
<td>2.3.1 Physical/Mechanical Process</td>
<td>8</td>
</tr>
<tr>
<td>2.3.2 Natural Process</td>
<td>9</td>
</tr>
<tr>
<td>2.3.3 Chemical Treatment</td>
<td>10</td>
</tr>
<tr>
<td>2.3.4 Mixture/Co-disposal Process</td>
<td>11</td>
</tr>
<tr>
<td>2.4 Coagulation</td>
<td>11</td>
</tr>
<tr>
<td>2.5 Electrokinetics</td>
<td>12</td>
</tr>
<tr>
<td>2.5.1 Effectiveness of Electrokinetics</td>
<td>13</td>
</tr>
<tr>
<td>2.5.2 Effect of Intermittent Current in Electrokinetics</td>
<td>15</td>
</tr>
<tr>
<td>2.6 Theory of Sedimentation/Thickening</td>
<td>15</td>
</tr>
<tr>
<td>2.7 Case Study involving Combined Effect of Electrokinetics and Coagulation</td>
<td>20</td>
</tr>
<tr>
<td>2.8 Summary</td>
<td>21</td>
</tr>
</tbody>
</table>
CHAPTER 3 COAGULATION AND ELECTROKINETIC THICKENING
TESTS ON MATURE FINE OIL SANDS TAILINGS ........................................ 23

3.1 Introduction .............................................................................................. 23

3.2 Properties of Mature Fine Oil Sands Tailings ........................................ 24

3.3 Preparation of MFT Suspensions ............................................................ 26

3.4 Jar Tests for Selection of Coagulant and Optimum Dosage ...................... 27
  3.4.1 Experimental Set-up and Procedure .................................................. 27
  3.4.2 Results and Discussion ...................................................................... 28

3.5 Cylinder Coagulation Tests ...................................................................... 30
  3.5.1 Experimental Procedure .................................................................... 30
  3.5.2 Results and Discussion ...................................................................... 30
  3.5.2.1 Effect of Coagulant Dose .............................................................. 30
  3.5.2.2 Effect of pH .................................................................................. 33

3.6 Electrokinetic Thickening Tests ............................................................. 35
  3.6.1 Experimental Set-up .......................................................................... 35
  3.6.2 Testing Procedure .............................................................................. 36
  3.6.3 Results and Discussion ...................................................................... 37
  3.6.3.1 Effect of Initial Solid Content and Applied Voltage Gradient ....... 37
  3.6.3.2 Validation of Electrokinetic Sedimentation Theory ....................... 39
  3.6.3.3 Power Consumption ...................................................................... 41
3.6.3.4 Zeta Potential of Particles, Water pH, Temperature, and Turbidity after Electrokinetic Thickening ........................................................ 43

3.6.3.5 Water pH Effect on Final Solid Content ...................................................... 44

3.7 Summary .............................................................................................................. 45

CHAPTER 4 COMBINED APPLICATION OF COAGULATION AND ELECTROKINETIC THICKENING AND OPTIMIZATION OF RESULTS BY ANOVA ........................................................................................................... 79

4.1 Introduction ......................................................................................................... 79

4.2 Combined Application of Coagulation and Electrokinetic Thickening ...... 80

4.2.1 Testing Procedure ........................................................................................ 80

4.2.2 Results and Discussion ................................................................................ 81

4.2.2.1 Effect of Applied Voltage Gradient ....................................................... 81

4.2.2.2 Power consumption ................................................................................ 83

4.2.2.3 Zeta Potential of Particles and Turbidity of Supernatant after Combined Tests ................................................................................ 84

4.3 Application of Intermittent Voltage Gradient Combined with Coagulant ... 85

4.3.1 Testing Procedure ........................................................................................ 85

4.3.2 Results and Discussion ................................................................................ 86

4.4 Comparison of Thickening Effect by Coagulation, Electrokinetics and Combined Tests ........................................................................................................... 88
4.5 Response Surface Methodology for Regression Model Development 89

4.5.1 Development of Regression Model for Electrokinetic Thickening 90

4.5.2 Development of Regression Model for Combined Coagulation and Electrokinetic Thickening 92

4.6 Summary 93

CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS 113

5.1 Summary 113

5.2 Conclusions 114

5.3 Recommendations for Future Research Work 116

BIBLIOGRAPHY 118

APPENDIX 125

CURRICULUM VITAE 126
LIST OF TABLES

CHAPTER 3

Table 3.1: Properties of mature fine oil sands tailings ................................................. 48

Table 3.2: Chemical analysis of pore water of mature fine oil sands tailings .......... 48

Table 3.3: Conditions of jar experiments ........................................................................ 50

Table 3.4: Conditions of coagulation tests at cylinder ............................................... 51

Table 3.5: Conditions of electrokinetic thickening tests ........................................... 52

Table 3.6: Duration of free settling, free settling velocity, and effective treatment
time under varying applied voltage gradients for 5% MFT suspension ................. 53

Table 3.7: Location of mudline and final solid content under varying applied
voltage gradients for 5% MFT suspension ............................................................. 53

Table 3.8 Values of electrokinetic sedimentation factors and coefficient under
219 V/m applied voltage gradient .............................................................................. 54

Table 3.9: Electrical resistivity of the suspension under varying applied voltage
gradients for the MFT suspension of 5%, 10% and 15% initial solid contents ...... 54
CHAPTER 4

Table 4.1: Conditions of combined coagulation and electrokinetic thickening tests ........................................................................................................................ 96

Table 4.2: Duration of free settling, free settling velocity and effective treatment time under combined electrokinetics and coagulation tests for MFT suspension .......... 97

Table 4.3: Electrical resistivity of the MFT suspension under varying applied voltage gradient combined with ferric chloride .............................................................. 97

Table 4.4: Duration of free settling, free settling velocity and effective treatment time under combined applied voltage gradient and 350 mg/l ferric chloride for MFT suspension .......................................................................................................................... 98

Table 4.5: Comparison of thickening results by coagulation, electrokinetics and their combined application .......................................................................................... 98

Table 4.6: Factors and levels used in the full three level factorial designs in electrokinetic thickening ........................................................................................................ 99

Table 4.7: Analysis of variance for the final solid content in electrokinetic thickening .......................................................................................................................... 99

Table 4.8: Analysis of variance for the increase in solid content in electrokinetic thickening ............................................................................................................. 99

Table 4.9: Regression coefficients of full polynomial model for the final solid content (in coded units) ........................................................................................................ 100

Table 4.10: Regression coefficients of full polynomial model for the increase in solid content (in coded units) ................................................................................ 100

Table 4.11: Factors and levels used in the full three level factorial designs in combined coagulation and electrokinetic thickening ......................................................... 100
Table 4.12: Final solid content of 5% MFT at varying operational condition .......... 101

Table 4.13: Analysis of variance for the final solid content in combined tests ...... 101

Table 4.14: Regression coefficients of full polynomial model for the final solid content in combined coagulation and electrokinetic thickening .......................... 101
# LIST OF FIGURES

## CHAPTER 2

- Figure 2.1: A tailings pond in Syncrude oil sands facility ........................................ 22
- Figure 2.2: Schematic of an oil sands tailings pond (Beier and Sego 2008) .......... 22

## CHAPTER 3

- Figure 3.1: Flow chart for organization of the tests .................................................. 55
- Figure 3.2 Mature fine oil sands tailings in the lab .................................................. 55
- Figure 3.3: Grain size distribution of mature fine oil sands tailings ....................... 56
- Figure 3.4: X-ray diffraction on pulverized mature fine oil sands tailings .......... 57
- Figure 3.5: Height of mudline and final solid content vs. coagulant dosage with different coagulants for the MFT suspension of 5% initial solid content .............. 58
- Figure 3.6: Height of mudline and final solid content vs. ferric chloride dosage for the MFT suspension of 10% initial solid content .................................................. 58
- Figure 3.7: Height of mudline and final solid content vs. ferric chloride dosage for the MFT suspension of 15% initial solid content ............................................. 59
- Figure 3.8: Height of mudline and final solid content vs. pH for the MFT suspension of 5% initial solid content with 350 mg/l ferric chloride ...................... 59
- Figure 3.9: Height of mudline vs. time under varying concentrations of ferric chloride ........................................................................................................... 60
Figure 3.10: Settling velocity vs. time under varying concentrations of ferric chloride ............................................................ 61

Figure 3.11: log($v_h/v_f$) vs. log(n) for the MFT suspension of 5% initial solid content ................................................................. 62

Figure 3.12: Final solid content and increase in solid content vs. ferric chloride dosage ............................................................. 62

Figure 3.13: Turbidity of supernatant at the top of cylinder for different ferric chloride dosage ...................................................... 63

Figure 3.14: Total solids of supernatant at the top of cylinder for different ferric chloride dosage ..................................................... 63

Figure 3.15: Electric conductivity and zeta potential vs. varying dosage of ferric chloride ............................................................ 64

Figure 3.16: Height of mudline vs. time under varying pH of MFT suspension of 5% initial solid content ........................................ 65

Figure 3.17: Electric conductivity and zeta potential vs. pH of the MFT suspension of 5% initial solid content ............................. 66

Figure 3.18: Turbidity vs. pH of supernatant at the top of cylinder for 5% MFT ................................................................. 66

Figure 3.19: Schematic of Electrokinetic Thickening Column ......................... 67

Figure 3.20: Final location of mudline in an electrokinetic test with control test .. 67

Figure 3.21: Height of mudline vs. time for the MFT suspension of 5% initial solid content under varying applied voltage gradients .............................................. 68

Figure 3.22: Height of mudline vs. time for the MFT suspension of 10% initial solid content under varying applied voltage gradients ........................................ 69
Figure 3.23: Height of mudline vs. time for the MFT suspension of 15% initial solid content under varying applied voltage gradients ................................................................. 70

Figure 3.24: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 5% initial solid content .......................................................... 71

Figure 3.25: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 10% initial solid content ............................................................. 71

Figure 3.26: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 15% initial solid content ............................................................. 72

Figure 3.27: Settling velocity vs. time for the MFT suspension of 5% initial solid content under varying applied voltage gradients ................................................................. 73

Figure 3.28: Relationship between free settling velocity and applied voltage gradient for 5% MFT .................................................................................................................. 74

Figure 3.29: log(\(v_{h-ck}/v_{f-ek}\)) vs. log(\(n_{ek}\)) for 5% MFT under 219 V/m applied voltage gradient .......................................................................................................................... 74

Figure 3.30: Effective voltage gradient and voltage efficiency between anode and cathode vs. applied voltage gradient for 5% MFT ................................................................. 75

Figure 3.31: Current density vs. applied voltage gradient for 5% MFT ................. 75

Figure 3.32: Power consumption vs. applied voltage gradient for 5% MFT ........ 76

Figure 3.33: Final zeta potential of particles vs. applied voltage gradient for 5% MFT ............................................................................................................................. 76

Figure 3.34: Final water pH vs. applied voltage gradient for the MFT suspension of 5% initial solid content after 7 hours thickening ................................................................. 77

Figure 3.35: Final temperature vs. applied voltage gradient for 5% MFT ......... 77
CHAPTER 4

Figure 4.1: Height of mudline vs. time under the combined application of applied voltage gradient and ferric chloride ................................................................. 102

Figure 4.2: Final solid content and increase in solid content vs. combined applied voltage gradient and 350 mg/l ferric chloride ..................................................... 103

Figure 4.3: Settling velocity vs. time under the combined applied voltage gradient and ferric chloride ......................................................................................... 104

Figure 4.4: Effective voltage gradient and voltage efficiency between anode and cathode vs. applied voltage gradient combined with ferric chloride ....................... 105

Figure 4.5: Current density vs. applied voltage gradient combined with ferric chloride ...................................................................................................................... 105

Figure 4.6: Power consumption vs. applied voltage gradient combined with ferric chloride .......................................................................................................... 106

Figure 4.7: Final zeta potential of particles vs. applied voltage gradient under the combined application of electrokinetics and coagulation ......................................... 106

Figure 4.8: Turbidity of supernatant under varying applied voltage gradient combined with ferric chloride at the end of the tests .................................................. 107

Figure 4.9: Height of mudline vs. time under the combined application of intermittent applied voltage gradient and ferric chloride ................................................. 108
Figure 4.10: Settling velocity vs. time under the combined intermittent applied voltage gradient and ferric chloride ................................................................. 109

Figure 4.11: Final solid content and increase in solid content vs. power consumption coefficient under combined intermittent applied voltage gradient and 350 mg/l ferric chloride ................................................................................................. 110

Figure 4.12: Contour plot for the optimization of final solid content under the electrokinetic thickening .......................................................................................... 111

Figure 4.14: Contour plot for the optimization of increase in solid content under the electrokinetic thickening .................................................................................. 111

Figure 4.15: Contour plot for the optimization of solid content under the combined applied voltage gradient and 350 mg/l FeCl₃ .......................................................... 112

APPENDIX A

Figure A-1: Mastersizer analysis of mature fine oil sands tailings ...................... 125
LIST OF SYMBOLS AND ABBREVIATIONS

MFT: mature fine oil sands tailings
EK: electrokinetic
DC: direct current
XRD: X-ray diffraction
MH: elastic silt
rpm: revolution per minute
AVG: applied voltage gradient
amu: atomic mass units
NTU: nephelometric turbidity unit
DSA: dimensionally stable anode
RSM: response surface methodology
ANOVA: analysis of variance
v: suspensions thickening/settling velocity [m/s or cm/min]
u: settling velocity of one particle [m/s]
n: porosity [-]
r: sedimentation coefficient [-]
β: a factor represents average of all particles
ζ: zeta potential [MV]
ε: permittivity of water [F/m]
μ: viscosity of water [Ns/m²]
s: solid content [%]
w: water content [%]
Gs: specific gravity [-]
LL: liquid limit [%]
PL: plastic limit [%]
PI: plasticity index [%]
EC: electrical conductivity [mS/cm]
H: height of mudline [cm]
t: time [min]
U: voltage [V]
E: voltage gradient [V/m]
I: electric current [A]
A: cross-section area [m²]
j: current density [A/m²]
ρ: electrical resistivity [Ω-m]
ρₕ: density of MFT solids [kg/m³]
ρᵢ: density of MFT fluids [kg/m³]
V: volume of MFT [m³]
P: power consumption [W/m³]
T: temperature [°C]
χ: power consumption coefficient [%]
α₁/α₂/α₃: coefficient of regression models
y: response variable in regression model
x₁/x₂/x₃: independent variables in regression model
CHAPTER 1 INTRODUCTION

1.1 General

Oil sands tailings are the end by-products of oil sands processing, which are discharged as slurry containing low percentage of solids. Mine tailings have potential impacts to the environment such as water pollution, solid waste, land use and reclamation, and air pollution. After releasing to a disposal pond, the coarse solids in tailings settle quickly, and the water rises to the top. However fine solids, namely the mature fine oil sands tailings (MFT), contain clay materials and fine sands, remain suspended in water for long time. It takes a few years for some MFT to reach solids contents of 30-35% (Beier and Sego 2008, Scott 1985) by gravity alone. The oil sand industries use huge amount of water to extract bitumen from oil sands. The slow settling of fine particles and large portion of standing water in tailings are challenging to the management of containment facilities for a long time beyond the mine closure. Active researches are undertaking in an effort to increase the solid contents of mature fine oil sands tailings in the underflow and to accelerate water recycling through the overflow of the system, which is known as thickening (Concha and Burger 2003).

Thickening is a preliminary method to produce high solid slurries (Gladman et al. 2006), which will ease further dewatering. The operation of a sedimentation unit is categorized as thickening and clarification (Jewell and Fourie 2006). The aim of clarification is to produce an overflow of water with few or no solid particles present, while the objective of thickening is to generate an underflow with high solids concentration. Thickening by
gravity depends on the difference of densities between the solid and liquid phases. It becomes slower with time when the solid concentration of the slurry increases. Moreover, the self-weight consolidation is very slow for the fine tailings produced in the oil sands industries. So the mature fine oil sands mine tailings require additional treatment (such as coagulant, flocculants, filtration, vacuum, electrokinetics, etc.) to enhance thickening process. The filtration technology is not favorable due to presence of high percentage of fines in the tailings (Xu et al. 2008). The polymer flocculants may create environmental problem. The applicability of vacuum technology in huge oil sands fields is a concern. So in this study, coagulation, electrokinetics, and combined coagulation and electrokinetics are selected to thicken the MFT suspension to increase the solid concentration of the underflow. Coagulation-electrokinetic combined treatment is based on making larger flocs of particle in the suspensions with coagulants and then generating movement of solids by a direct current (DC). This study is limited in laboratory scale and so some real field factors such as solid content variation, effect of wind and temperature variation, flow conditions are missed out.

1.2 Research Objectives

The overall objective of this research is to thicken the mature fine oil sands tailings by combined chemical coagulants and electrokinetics. The specific objectives are:

- Measure the properties of mature fine oil sands mine tailings;
- Optimize coagulant doses in jars and study the coagulation effect in cylinders in thickening the suspension of MFT;
- Optimize the voltage gradient in achieving highest the solid content of the sediment;
- Attain the possible maximum solid content of the sediment in the combined application of coagulant and electric current;
- Study characteristics of water and solids after treatment;
- Develop regression models to determine the final solid content of MFT.

1.3 Thesis Outline

The thesis consists of five chapters. Chapter 1 contains an introduction of the thesis including the research objectives, outline and original contributions.

Chapter 2 presents a literature review related to the properties of mature fine oil sands tailings, treatment technologies of oil sands tailings, and principles and applications of electrokinetics and chemical coagulation.

Chapter 3 is comprised of geotechnical and chemical properties of mature fine oil sands tailings used in this study, optimization of coagulant and coagulant doses, testing procedures and results of coagulation and electrokinetic thickening.

Chapter 4 presents the operation, results and discussion of combined coagulant and electrokinetic thickening tests, including the development of regression models for
electrokinetic thickening, and combined application of coagulation and electrokinetic thickening.

Chapter 5 includes the summery of this study as well as conclusions and recommendations for further research.

1.4 Original Contributions

The original contributions of this study are:

- Original results of experiments on electrokinetic thickening of mature fine oil sands tailings;
- The equations of settling velocity in the free settling and hindered settling stages are validated using the experimental data;
- Original results of experiments on combined coagulation and electrokinetic thickening;
- Regression models for the final solid content generated by the electrokinetic thickening as well as by the combined coagulation and electrokinetic thickening.
CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

A review for common properties of oil sands tailings is presented and discussed in this chapter, including principles and applications of coagulation and electrokinetics. A case relevant to the present research is also assessed in brief.

The mature fine oil sands tailings have solids mostly less than 44 µm in sizes (called fines in oil sands industries). Without treatment the full consolidation of MFT may take few decades because of the low settlement or consolidation rate. It is crucial to increase the rate of thickening process for tailings disposal. Chemical coagulation and electrokinetics can be applied to accelerate the rate of thickening. Coagulants have been used in settling of river sediment (Buckland et al. 2000), waste water treatment (Genovese and Gonzalez 1998) and treatment of collected water from oil sands processing system (Pourrezaei and El-Din 2008). Research and field applications have been carried out using electrokinetics to settle, dewater and consolidate soft clays and mine tailings (Sprute and Kelsh 1980, Lockhart and Stickland 1984, Mohamedelhassan 2008, Guo and Shang 2014). Polymers are also used to flocculate the oil sands tailings to enhance the separation (Wang et al. 2010). However, the polymer flocculants have unpredictable performance due to tailings variability and may generate detrimental effects on recycle water quality (BGC 2010). Moreover, some polymer flocculants are temperature sensitive.
In open pit mining, the oil sands industries use hot water for extraction bitumen from oil sands and the extracted tailings (by product) stored in the tailings pond. About 750 million cubic metres of MFT was placed in tailings ponds as of 2008 (BGC 2010). The inventory of fine tailings is predicted to reach one billion cubic metres in 2014 and two billion in 2034 (Houlihan and Haneef 2008). A photograph of tailings pond in Syncrude oil sands facility is shown in Fig. 2.1. Eight tailings ponds in Suncor cover a total area of 3,154 hectares and depths are mostly 45.7 metres (Suncor 2010). At the end of 2009, tailings ponds cover more than 130 square kilometers in the oil sands region (Government of Alberta 2010) and it is forecasted that it will reach about 250 square kilometers by 2020. Many mine companies dispose their waste repeatedly on highly constraint areas due to their abundance of deposits. They need to compete for limited space for tailings ponds, overburden dumps, lift dewatering area, and other disposal facilities. So it is crucial to reduce the volume of oil sands tailings and environmental concern for the sustainable development of oil sands industries and economy. The electrophoresis can be applied to increase the solid content of the slurry when initial solid content of MFT is low and then further dewatering to consolidate the thickened MFT.

2.2 Basic Properties of Oil Sands Tailings

Oil sands tailings are the byproduct from the extraction of bitumen from oil sands ore. Most of the oil sands industries are situated in northern Alberta where the oil sands deposits contain approximately 1.6 trillion barrels of bitumen. According to Kasperski
oil sands tailings compositions vary considerably; however the following discussion represents an overview about it.

Athabasca oil sands, the largest oil sands reserve, are composed of 0–17 wt% bitumen, 84–86 wt% minerals (such as quartz, silts, clay) and 3–6 wt% water. Kaolinite (40–70 wt%), illite (28–45 wt%) and trace montmorillonite are the major clay minerals (Chalaturnyk et al. 2002). The oil sands tailings in northern Alberta contain water (58–62%), solids (sand and clays, 37%) and a small amount of uncovered bitumen (1–5%) (Cabrera et al. 2009). It is reported that the MFT has an average solid content of about 33%, average void ratio of 5, hydraulic conductivity from $1 \times 10^{-6}$ to $1 \times 10^{-9}$ m/s, liquid and plastic limits ranging from 40% to 75% and 10% to 20%, respectively, and the shear strength less than 1 kPa. The average particle size of MFT ranges between 5 μm and 10 μm (FTFC 1995).

The majority of clay minerals in the tailings come from the clay shale, discontinuous seams and layers since these are broken up during the mining extraction process (Scott et al. 2008). The fine tailings of Syncrude’s caustic extraction process consists of 94% fines, 76% clay minerals (55% kaolinite, 20% illite, and 1% mixed layers) and 24% rock-forming minerals (19% quartz, 3% siderite, 1% plagioclase, and 1% K-feldspar). The water pH is 8.2. The water of fine oil sands tailings mainly contains five cations and four anions which are: Na$^+$ (258 mg/l), NH$_4^+$ (8.8 mg/l), K$^+$ (7.8 mg/l), Ca$^{2+}$ (5.9 mg/l), Mg$^{2+}$ (4.1 mg/l), HCO$_3^-$ (846 mg/l), Cl$^-$ (94 mg/l), F$^-$ (8.2 mg/l), and SO$_4^{2-}$ (4.8 mg/l) (Scot et al. 2008). The coarse grained particles in the tailings settle faster than the fines and settle quickly at the edge of the tailings pond. The fines accumulate at the center of the pond, as shown in Fig. 2.2 and remain suspended for more than a decade without any treatment.
2.3 Technologies/Methods for the Treatment of Oil Sands Tailings

The major technologies that have been implemented or have the potential of application for the treatment of oil sands tailings are as follows (BGC 2010):

- Physical/Mechanical Process
- Natural Process
- Chemical Treatment
- Mixture/Co-disposal

2.3.1 Physical/Mechanical Process

Filtration is one of the conventional methods used in industries to separate solid-liquid from mixtures. In the 1990s, Alberta’s oil sands industry conducted pilot-scale tests on different bitumen extraction process (FTFC 1995). These tests were failed because coarse particles settled quickly and made a bulky permeable filter cake; however, the fines settle slowly onto the surface of this cake and blind it, and shutting off filtration. Xu et al. (2008) carried out laboratory-scale experiments and found that filtration is not realistic to filter the original tailings with more than 4% fines without using flocculant, while the mean fines content of the whole tailings stream is about 18%.
Solid-liquid separation by centrifuge applies up to thousands of times the force of gravity to extract fluid, which can increase the solid content to about 60%. Mikula et al. (2009) developed centrifuge technology at bench scale at Canada Centre for Mineral and Energy Technology (CANMET) on Athabasca oil sands fluid fine tailings. More research work is needed to evaluate this technology in field application due to their high capital and operating cost, and some knowledge gaps.

Electrical treatment applies a direct current (DC) to MFT through electrodes. The charged clay particles moves to anode (soil in water system), resulting in accelerated sedimentation and in some cases water flows from an anode to cathode in porous media (water in a soil system), resulting in dewatering and consolidation of MFT induced by a DC electric field. A detailed review of electrokinetics is presented in Section 2.5.

2.3.2 Natural Process

The freeze-thaw technology involves the MFT freezing first, then the frozen mass is permitted to thaw in the following summer (BGC 2010). A significant amount of water is released when 5 cm to 15 cm thin layers of MFT are subjected to freeze-thaw cycles (Dawson and Sego 1993). At the end of the tests, the solids content increased from 35% to 56%. But this process depends on the weather conditions of the region.

Sedimentation and consolidation use the force of gravity to separate the solids from the tailings stream. This technique has been used for 40 years in oil sands, but despite tens of
millions of dollars of research, perceptive of the basics of densification of MFT remains intangible (BGC 2010).

Dewatering by plant is another method to dewater MFT by selecting suitable plant species growing on tailings, which can dewater tailings by transpiration through their leaves and associated root systems (Silva 1999). Silva (1999) shows that appropriate plant species growing in composite tailings have the ability to take out the water through evapotranspiration that increase the undrained shear strength and bearing capacity within the root zone. The plant root system also provides fiber reinforcement and contributes to the increase in the bearing capacity of the rooted tailings. The main problem in this technique is high alkalinity and salinity of tailings pore water, which restricts the establishment of vegetation.

2.3.3 Chemical Treatment

Coagulants and flocculants are widely used in water treatment, which can efficiently settle the fine particle in tailings. When fine tailings are mixed with these chosen chemicals, the time of settling can be reduced, and comparatively high solid content can be attained (Jeeravipoolvarn 2010). The technology is still in applied research and demonstration level (BGC 2010). The process of coagulation will be reviewed in detail in the next section of this chapter.
2.3.4 Mixture/Co-disposal Process

Composite tailings (CT) process was developed at the University of Alberta (Caughill et al. 1993), which involves mixing dense extraction tailings (coarse sand) and MFT at 4:1 sand to fine ratio with an amendment (typically gypsum) to create non-segregating slurry. Syncrude implemented the CT process on a commercial basis in 2000 (Fair 2008). More works are needed to produce less energy consuming, more environment friendly, and more qualified CT.

2.4 Coagulation

Coagulation is a common technique in water and wastewater treatment to enhance sedimentation. Jar test is universally used to assess the optimum dosage for coagulation in a given medium. Various types of coagulants are used in thickening or dewatering of mine tailings. Among all $\text{Al}^{3+}$ and $\text{Fe}^{3+}$ salts are most commonly used as coagulants (Jewell and Fourie 2006) since trivalent ions are more effective than monovalent or divalent ions as coagulant.

A research was performed by Genovese and Gonzalez (1998) on solids removal from fisheries wastewaters using coagulants. The tests were executed in batch approach using 1 L flasks. The maximum removal of solid content was 30.5% with 60 mg/l ferric chloride ($\text{FeCl}_3$) as coagulant at pH 5.5. Pourrezaei and El-Din (2008) used alum ($\text{Al}_2(\text{SO}_4)_3.18\text{H}_2\text{O}$) as coagulant to treat oil sands processing water. Ferric chloride has
been used as an effective coagulant for the sedimentation of contaminated Welland River sediment (Buckland et al. 2000).

In this research three common inorganic salts, i.e. ferric chloride, aluminum sulphate and aluminum chloride, are examined as coagulants to thicken the mature fine oil sands tailings. These coagulants work well due to the high valence of Fe$^{3+}$ and Al$^{3+}$, which are attracted strongly to the particles of the suspension reducing the thickness of double layer. At higher coagulant doses (>5mg/l) the coagulant acts by making sweep-floc along with destabilization. The effectiveness of different coagulants is evaluated at different coagulant dosage and pH to find the optimal operational conditions to thicken the MFT suspensions.

2.5 Electrokinetics

Electrokinetics is the movement of ions, water or charged solid particles towards the electrodes under the influence of an electric field. The US Bureau of Mining carried out the research on electrokinetic dewatering of tailings from coal preparation and mineral processing in the 1960s (Stanczyk and Feld 1964). In the 1970s, the CSIRO of Australia started research on electrokinetic dewatering of tailings (Lockhart 1986). The principle of electrokinetic sedimentation of clay suspension is discussed by Shang (1997). The suspended solids are negatively charged in water; hence when they approach to other the negative charges on the solids causes them to repel. Since the attractive force between the particles is less than the repulsive force, the suspension remains stable without significant
settlement for a long time. When the suspension is subjected to an external electric field, the negatively charged particles move towards the positively charged anodes. This phenomenon is known as electrophoresis, which can enhance the sedimentation process. The mechanism of electrophoresis has been applied to accelerate sedimentation of river sediments (Buckland et al. 2000) and cohesive soils (Kim et al. 2008).

When a direct current is passing from anode (+Ve) to cathode (−Ve) in water, oxidation and reduction happens at anode and cathode, respectively. The electrochemical reactions in anode and cathode release oxygen and hydrogen gas, respectively (Mitchell 1993) from electrolysis of water which are:

\[
2H_2O - 4e^- \rightarrow O_2 + 4H^+ \quad \text{(at anode)}
\]

\[
4H_2O + 4e^- \rightarrow 2H_2 + 4OH^- \quad \text{(at cathode)}
\]

The electrophoresis technique will be used by applying DC electric current through the electrodes to thicken the MFT suspensions.

2.5.1 Effectiveness of Electrokinetics

Researches indicate that electrokinetics is effective in materials containing 30% or more solids finer than 2 micrometer. The effectiveness of electrokinetics changes with pH because the electrical charges of colloidal particle are pH dependent. The surface charges reverse polarity with low pH. The electrokinetic sedimentation of soil-water suspension has been successful in pH 6-8.5 (Kim et al. 2008) and pH 7.5 (Buckland et al. 2000). The
selection of electrode is another important element for the effectiveness of electrokinetic process. The common problem of using metal electrodes is the high corrosion rate at the anodes due to decrease in pH, and voltage loss at the electrodes and water interface. Corrosion of metal (steel mesh) anode has been reported in previous a study as 1.1 kg/dry tonne of coal washery tailings (Lockhart and Stickland 1984). Different combinations of anode-cathode (carbon-carbon, carbon-steel, carbon-copper, steel-steel, steel-carbon and copper-copper) have been tried in marine sediment recovery and found large voltage drop for carbon-coated electrodes (Mohamedelhassan and Shang 2001). However, Buckland et al. (2000) used graphite electrode as both anode and cathode in electrokinetic sedimentation of contaminated Welland River sediment, and found a good result in voltage efficiency (93-95%) and percentage increase (39-62%) in solid content. More recently dimensionally stable anode (DSA) mesh (made of titanium coated with iridium oxide (Ti/IrOx) has been developed, which can serve for a long time compared to other metals. Stainless steel mesh (type SS316) is found well as cathode material for its excellent resistance to natural corrosion. Guo and Shang (2014) used Ti/IrOx-SS316 anode-cathode combination in electrokinetic dewatering of oil sands tailings and got good results in terms of increment in undrained shear strength and reductions in water content of MFT. In this research Ti/IrOx and SS316 mesh electrodes are selected as anode and cathode, respectively to thicken the MFT suspensions.
2.5.2 Effect of Intermittent Current in Electrokinetics

Current intermittence is a process in which the electric current is applied periodically at predetermined time interval during the tests. The intermittent voltage (or current) reduces the power consumption, and possibly enhances the electrokinetic process as reported by Shang and Lo (1997) and Rabie et al. (1994). The contradictory results are found in different literature regarding the effectiveness of intermittent voltage to the electrokinetic processes in soil-water system. The enhanced results were found from the use of intermittent current on consolidated marine sediment by Shang and Lo (1997), whereas Buckland et al. (2000) found the best sedimentation effect with continuous electric current compared with those of intermittent current. The soil and water properties of the samples might lead to the conflicting results. The effect of intermittent applied voltage gradient combined with coagulant will be studied to examine the effect of intermittent voltage on thickening of MFT suspension.

2.6 Theory of Sedimentation/Thickening

The separation of solid particles and liquids by settling under gravity is termed as sedimentation. Many parameters (particle size and shape, specific gravity, fluid viscosity, solid concentration, and interaction between particles) can affect the settling velocity (Svarovsky 1990). The sedimentation velocity of suspensions decreases with the increase in particles interactions and solid concentrations.
The sedimentation velocity of a suspension with low solid concentration can be measured from Stokes law that follows free settling and can be written as:

$$u = \frac{g(\rho_s - \rho_f)d^2}{18\mu}$$  \hspace{1cm} (2.1)

Where $u$ is the particle settling velocity (m/s), $g$ is the gravitational acceleration (m/s$^2$), $\rho_s$ and $\rho_f$ are the densities of MFT solids and fluid (kg/m$^3$), respectively, $d$ is the diameter of particle (m), and $\mu$ is the viscosity of fluid (N.s/m$^2$).

Kynch (1952) found Stokes law is inadequate for a suspension of high concentration and developed the Hindered settling theory. According to Kynch’s theory, the sedimentation velocity decreases as the solid concentration of suspension increases. Jeeravipoolvarn (2010) studied the oil sands tailings, and showed that the sedimentation followed the Kynch’s theory with initial solid contents of 10%, 12.5% and 17.5%. Richardson and Zaki (1954) showed from experimental work that suspension velocity of particles (spherical shape) depends upon solid concentration and proposed the equation of suspension velocity which is:

$$v = u.n^r$$  \hspace{1cm} (2.2)

Where $v$ is the suspensions sedimentation velocity, $n$ represents the porosity, and $r$ is the sedimentation coefficient.

McRoberts and Nixon (1976) showed that the sedimentation velocity decreased with the increase in initial solid concentration for soil-water mixtures of varying concentration. However, a transition stage between constant velocity and consolidation was observed for
fine-grained soil. This stage is known as hindered settling stage and gave a non-linear decrease in mudline with time. The hindered settling for the slurry with fine particles are well established when the porosity of slurry well below unity. Few researchers have modified the Richardson and Zaki’s sedimentation theory by changing the function of porosity (Souslby 1997 and Dankers and Winterwerp 2007).

The theory of sedimentation developed by Richardson and Zaki (1954) is applicable for the suspension of particles size more than 100 μm. Reynolds number is also considered in many studies which characterizes the flow regime around a settling particle (Camenen and Bang 2011). In this study the experiment is started when the suspension is stable initially (without turbulence). A factor (β) is incorporated in the sedimentation equation of Richardson and Zaki (1954) relating the terminal settling velocity of particles and sedimentation velocity of the suspension which is due to the effect of flow regime and the existence of high percentage of fine particles in the slurry. So the Equation 2.2 for free settling and hindered settling (gravitational) settling stages for fine particles, following the work of Buckland et al. (2000), can be expressed as:

\[ v = \beta \cdot u \cdot n' \]  

(2.3)

Where β is a factor that relates the particle’s terminal velocity and suspensions thickening velocity. The sedimentation velocity would constant for an infinitely dilute solution, indicating the free settling stage and the equation becomes:

\[ v_f = \beta_f \cdot u \]  

(2.4)
Where the subscript \( f \) stands for free settling. When the particle interaction increased, the free settling stage disappears at the critical sedimentation point and changes to hindered settling stage, and hence, the velocity of the sediment is decreased. The sedimentation velocity during this stage can be presented as:

\[
\nu_h = \beta_h u n^r
\]  

(2.5)

Where the subscript \( h \) denotes hindered settling. As the velocity of the suspension diminished, the sedimentation velocity becomes zero, and the hindered settling is completed.

The sedimentation coefficient for gravitational settling, \( r \), can be found by combining Equations 2.4 and 2.5:

\[
\log \left( \frac{\nu_h}{\nu_f} \right) = \gamma + r \log n
\]  

(2.6)

Where \( \gamma = \log \left( \frac{\beta_h}{\beta_f} \right) \)

Shang (1997) has developed the equations for electrokinetic sedimentation velocity created by DC electric field with the arrangement of cathode at the top and anode at the bottom of the electrokinetic column. The equations for free and hindered settling stages are as follows:

\[
\nu_{f-ek} = \beta_{f-ek} u_{ek}
\]  

(2.7)

\[
\nu_{h-ek} = \beta_{h-ek} u_{ek} n_{ek}^{r_{ek}}
\]  

(2.8)
Where the subscript ek stands for electrokinetics. The individual particle velocity \( u_{ek} \) (m/s) induced by electric current is a function of the permittivity of water \( \varepsilon_w \) (F/m), zeta potential \( \zeta \) (V), voltage gradient \( E \) (V/m), viscosity of water \( \mu \) (N.s/m²) and is expressed as (Russel et al. 1989):

\[
 u_{ek} = \left( \frac{\varepsilon_w \zeta E}{\mu} \right)
\]

(2.9)

The electrokinetic sedimentation velocity becomes by replacing Equation 2.9 into Equations 2.7 and 2.8:

\[
 v_{f-ek} = \beta_{f-ek} \left( \frac{\varepsilon_w \zeta E}{\mu} \right)
\]

(2.10)

\[
 v_{h-ek} = \beta_{h-ek} \left( \frac{\varepsilon_w \zeta E}{\mu} \right) n_{ek} r_{ek}
\]

(2.11)

The electrokinetic sedimentation generated by DC electric field is a function of the applied electric field and the properties of the suspension.

The electrokinetic sedimentation coefficient, \( r_{ek} \), can be found by combining Equations 2.10 and 2.11:

\[
 \log \left( \frac{v_{h-ek}}{v_{f-ek}} \right) = \gamma_{ek} + r_{ek} \log n_{ek}
\]

(2.12)

Where \( \gamma_{ek} = \log \left( \frac{\beta_{h-ek}}{\beta_{f-ek}} \right) \)
The theories described in this section will be validated using the experimental results in the next chapter. In the experimental study it will be assumed that there is no turbulence of suspension in the column.

2.7 Case Study involving Combined Effect of Electrokinetics and Coagulation

A case on the sedimentation of Welland River sediment using coagulant enhanced electrokinetics is discussed in this section because of its relevance with the present research. Buckland et al. (2000) carried out an experimental study on the sedimentation of contaminated sediment dredged from the Welland River, Ontario, Canada. In the electrokinetic columns, the anode was placed at the bottom and cathode at the top. The electrodes (anode and cathode), made of copper, were connected with a DC power supply. The maximum electric field intensity applied was 150 V/m. The optimum electrokinetic sedimentation was found from the slurry with the initial solid concentration of 14.4% and the final solid concentration reached 51%. The maximum decrease of overall sedimentation time was about 50% compared to the control test. The best result was found for an electric field intensity of 150 V/m with a voltage efficiency of 91.3%.

From a series of jar tests, 40 mg/l ferric chloride was found to be the most effective coagulant. The electrokinetic sedimentation was more effective than that of ferric chloride in terms of increasing the final solid content. The combined action of electrokinetics and coagulant produced the best sedimentation for the Welland River
sediment. The final solid concentration reached 61% from the initial concentration of 14.4% in the combined study. The pH changes due to the application of electrokinetics were observed at the anode and cathode and were found to be above 6 and below 9.4, respectively.

2.8 Summary

A review of properties with treatment technologies of oil sands tailings are presented in this chapter. The effectiveness of coagulation and electrokinetics, and the theory of electrokinetics and applications are discussed. The materials discussed in literature/case provide encouraging background for the present study on thickening of mature fine oil sands tailings. The theory discussed in this chapter will be validated by using the experimental data found in this research. The coefficients of sedimentation will also be determined.
Figure 2.1: A tailings pond in Syncrude oil sands facility
(Source: THE CANADIAN PRESS/Jeff McIntosh, Global News)
(http://globalnews.ca/news/1696712/oilsands-tailings-ponds-emit-pollutants-into-the-air-study-confirms/)

Figure 2.2: Schematic of an oil sands tailings pond (Beier and Sego 2008)
CHAPTER 3 COAGULATION AND ELECTROKINETIC THICKENING TESTS ON MATURE FINE OIL SANDS TAILINGS

3.1 Introduction

The properties of mature fine oil sands tailings (MFT), and results of coagulation and electrokinetic tests are analyzed and presented in this chapter. Detailed discussion includes the testing procedures of coagulation and electrokinetic thickening, selection of coagulants, optimization of coagulant dosage, results, analysis and comparison of coagulation and electrokinetic thickening tests. Moreover, the theories of sedimentation velocity are validated using the experimental data.

The characterization of MFT consists of geotechnical properties of tailings (specific gravity, particle size analysis, Atterberg limits, etc.), X-ray diffraction (XRD) of solids, and chemical analysis of the pore water. The coagulation tests are carried in jars to find out the suitable coagulants and optimal dosage among alum (Al₂(SO₄)₃.18H₂O), aluminum chloride (AlCl₃) and ferric chloride (FeCl₃).

In the 2nd phase of study, coagulation tests are carried on in graduated cylinders to thicken the MFT suspension. The results are discussed in terms of the mudline (interface between solids and water) position and final solid content of the thickened tailings. The suspensions settling velocity and turbidity of the supernatant are measured.
The 3rd phase of study involves the electrokinetic thickening tests on the MFT suspension in the electrokinetic column. The results are monitored with real time in terms of the mudline position and the final solid contents. The parameters such as the effective voltage, power consumption, water pH, temperature and turbidity of supernatant are examined. The theory of electrokinetic sedimentation velocity is validated using the results of the tests.

The organization of the tests is shown in Fig. 3.1. The jar experiments are designed to select the suitable coagulant and optimal dosage for the most effective sedimentation. Then the coagulation tests in the cylinder are carried out to thicken the suspension of mature fine oil sands tailings. Finally, electrokinetic thickening tests are conducted by applying a DC electric current.

3.2 Properties of Mature Fine Oil Sands Tailings

The mature fine oil sands tailings used in this research were collected from the disposal pond in Fort McMurray, Alberta, Canada. Three barrels MFT were provided, courtesy of Syncrude Canada Ltd. and Imperial Oil Canada. The photograph of mature fine oil sands tailings in a small tray in the lab is shown in Fig. 3.2. The tailings are dark grey color with a strong odor and have a natural water content\(^1\) of 158%. The specific gravity of solids is 2.58. The amount of oil and grease in MFT is 1.67 g/l (ASTM D7575). The organic content of MFT is determined by burning the dried pulverized MFT in muffle

\(^1\) Water content (%) = (mass of water / mass of solids)\*100
furnace at 440 °C for overnight and it is 17.9%. The carbonate determined by Chittick apparatus is not significant (<1%) in dried pulverized whole MFT.

The zeta potential of MFT solids was measured by zeta potential analyzer (ZetaPlus, Brookhaven Instruments Corporation). The sample was diluted by mixing with deionized so that the light can pass through this suspension. The sample was injected in the small cell and the electrode assembly of the zeta potential analyzer was inserted into the cell filled with sample and fitted properly. This assembly was placed in the chamber of the analyzer and the chamber was closed. The zeta potential analyzer was operated for 10 times and the mode of these several runs were taken as the result. The mean zeta potential of the MFT particles was found as -52.6 mV. The value of zeta potential is suitable for electrokinetic sedimentation.

The particle size analysis was done with a laser particle size analyzer (Mastersizer 2000, Malvern Instruments Ltd., UK), and the results are shown in Fig. 3.3. The MFT contains 82.5% silt and 17.5% clay-sized solids. The properties of the tailings are summarized in Table 3.1. The MFT has the plastic and liquid limits of 36% and 54.4%, respectively and hence a plasticity index of 18.4%, which is typical of medium plasticity (Sowers 1979). The tailings can be classified as elastic silt (MH) based on the Unified Soil Classification System (USCS). Electrokinetic treatment has been reported effective on geomaterial with similar properties (Lockhart 1983b).

X-ray diffraction was conducted on MFT solids using Rigaku-MiniFlex II, powder diffractometer. The solids were first air dried for 7 days and then pulverized. The solids
for analysis were passed through #200 sieve (74 microns), and the result is shown in Fig. 3.4. As shown the mature fine oil sands tailings contain quartz, illite, and kaolinite.

The results of pore water chemical analyses are shown in Table 3.2. The pH of pore water is 8.19. At this pH electrokinetic treatment is effective for most geomaterials (Lockhart 1983a). The electrical conductivity (EC) of the pore water is 3.51 mS/cm. It is observed that the EC of the MFT suspension is a function of the initial solid content, as shown in Table 3.2. The cations present in the pore water of mature fine oil sands tailings were determined by Inductively Coupled Plasma Optical Emission Spectroscopy (ICP-OES, Varian Vista Pro), and the results are summarized in Table 3.2. The concentrations of chloride and sulphate were determined by gravimetric analysis using silver nitrate (AgNO₃) and barium chloride (BaCl₂) as reagent, respectively. The nitrate test was done using Hach DR 3900 Spectrophotometer and the result is presented in Table 3.2.

### 3.3 Preparation of MFT Suspensions

The suspensions of mature fine oil sands tailings were prepared in three large containers by mixing MFT and deionized water to solid concentrations of 5%, 10%, and 15% (mass/mass). The mixture was sealed and stored in room temperature. For every test, the MFT suspension was taken from the containers after mixing thoroughly. The suspensions’ solid contents were checked randomly to ensure they matched the predetermined values of 5%, 10%, and 15%. The results show the deviation was within
±0.05%. The pH values of the MFT suspensions of 5%, 10%, and 15% initial solid contents were 7.25, 7.47, and 7.72, respectively.

3.4 Jar Tests for Coagulant Selection and Optimum Dosage

3.4.1 Experimental Set-up and Procedure

Jar tests were carried out to select the most effective coagulant and its optimal dosage for thickening the MFT suspension. The jar tests were performed using alum (Al₂(SO₄)₃.18H₂O), aluminum chloride (AlCl₃) and ferric chloride (FeCl₃) solutions as coagulants. The conditions for jar test are summarized in Table 3.3. The mixing paddles were placed in Six 500 ml beakers. Each beaker was filled with the suspension of MFT. The prepared stock coagulant solutions (10 g/l concentration) were added by titration to the beakers to reach concentrations of 100 mg/l, 200 mg/l, 300 mg/l, 350 mg/l, and 400 mg/l, respectively. A blank sample was kept in a beaker as the control test, in which no coagulant was added. All Jar tests were performed in 3 steps, i.e. 2 min mixing at 100 rpm (revolution per minute), 20 min mixing at 20 rpm and 60 min settlement. The rapid mixing stage (100 rpm) dispersed alum solution and mixed with the particles of MFT suspension. In the slow mixing stage (20 rpm) the destabilized particles were mixed slowly and came to collide, forming larger agglomerates (floc). Finally, the flocs settled by gravity to form sediment at the bottom of the jar in the settlement phase. All the jar tests were conducted at room temperature (20 to 22°C). At the end of each jar test, the height of mudline (solids-water interface) from the bottom of the beaker and the final
solid content (average) were measured. The sediment was collected from the bottom of the beaker to test the final solid content.

3.4.2 Results and Discussion

Fig. 3.5 shows the height of mudline and final solid content vs. coagulant dosage for the MFT suspension of 5% initial solid content with different coagulants. Without coagulant no settling is observed and the solid contents of suspensions remain constant over the testing period. Ferric chloride generates the maximum sedimentation at 350 mg/l (2.16 mM) concentration, showing a mudline of 7.6 cm from the bottom of the beaker. The final solid content is calculated from the height of mudline and volume since there is possibility of error in real solid content measurement because of very low difference in the measured value. The final solid content reaches 6.06% from an initial of 5% at the end of the test. The results show that ferric chloride works better as coagulant than alum and aluminum chloride in terms of accelerating the sedimentation of MFT suspensions. The reason behind this is the differences in the electro-negativity and atomic mass between iron (Fe) and aluminum (Al). The electro-negativity of Fe$^{3+}$ and Al$^{3+}$ is 1.83 and 1.61 (The Pauling scale), respectively, which means Fe ion attracts negatively charged clay particles more strongly than that of Al. In addition the flocs of ferric chloride compound are heavier than those of aluminum salts because the atomic mass of Fe and Al is 55.8 amu and 27 amu, respectively; hence the former settles more quickly than the later. Amokrane et al. (1997) also reported that iron (Fe) salts seem to be more efficient
than that of aluminum as coagulant on landfill leachate in removing turbidity. The result is also consistent with a previous study on the river sediment (Buckland et al. 2000). Therefore, ferric chloride is selected as the coagulant for thickening of MFT suspension.

Figs. 3.6 and 3.7 show the height of mudline and final solid content vs. ferric chloride dosage to MFT suspensions of 10% and 15% initial solid contents, respectively. It is evident from the observations that the effectiveness of chemical coagulation reduces with increasing suspension solid content.

Additional jar tests are carried out on the suspension of 5% initial solid content, using ferric chloride as coagulant under different suspensions pH. It is reported in the literature that ferric chloride works best at pH 4-7; hence the suspension pH is adjusted by titration using 0.1M HCl and 0.1M NaOH. The final solid content increases with the increase in pH from 4 to 6, attributes to the presence of sufficient hydrogen (H⁺) ions at pH 6 (slightly low acidic medium), which neutralizes the particle charge. The presence of excess hydrogen ions creates ionic clouds, which hinders the settlement of solids at very low pH. The final solid content decreases with the rise in pH when the suspension pH is more than 6. The zeta potential of particles turns more negative in this case due to presence of excess anions (OH⁻) that stabilizes the suspension and reduces the rate of settling. Fig. 3.8 shows the plot of the final mudline height and solid content vs. pH on 5% MFT suspension using the ferric chloride at dosage 350 mg/l. The plot is showing around pH 5.9 is optimum which is found from excel trends.

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2 Electro-negativity means the ability of a cations to attract oppositely charged particles or electrons
3.5 Cylinder Coagulation Tests

3.5.1 Experimental Procedure

Based on the results of jar tests, the cylinder tests were conducted using ferric chloride in the MFT suspension of 5% initial solid content. The main task of the tests was to observe the settling behavior via observation of the mudline. Seven graduated cylinders of 1 L volume (35 cm height, 6.03 cm diameter, made of borosilicate glass) were used in the tests, with conditions summarized in Table 3.4. The cylinders were filled with the suspension of MFT. The stock solutions of ferric chloride were added by titration to the cylinders in varying concentrations, as shown in Table 3.4. The tests were conducted at the room temperature (20 to 22°C). The turbidity and total solids of clear water at the top, and the final solid content of the sediment were measured at the end of the tests.

3.5.2 Results and Discussion

3.5.2.1 Effect of Coagulant Dose

Fig. 3.9 shows the height of mudline vs. time under different ferric chloride concentrations at pH 7.25 (suspension pH). No settling was observed in the control test during the test duration of 4 hours, indicating the gravitational setting is very slow, which is consistent with a previous study on MFT (Alam et al. 2014). The trend lines are similar, i.e. initially a steep straight line (free settling), followed by a parabolic shaped
line (hindered settling) and finally a flat straight line (end of settling and start of consolidation). As shown in the figure 350 mg/l of ferric chloride dosage produces the best result in the test series.

The average settling velocity is the first derivative of mudline vs. time plot and can be expressed as:

$$v = \left( \frac{dH}{dt} \right)$$

Where $v$ is the suspension's settling velocity, $H$ is the height of mudline, and $t$ is the time.

Since there is no gravitational settling registered without coagulants added over the testing period, as shown in Fig. 3.9, the measured thickening velocity is solely attributed to coagulation. Fig. 3.10 shows the plot of settling velocity vs. time for different ferric chloride concentrations. The initial flat lines are free settling followed by hindered settling stage and finally reached to a plateau of start of consolidation zone. At the beginning of two trend line (100 mg/l and 200 mg/l) having experimental issues (probably suspensions stabilization problem) goes up indicating sedimentation velocity increasing rather than constant or decreasing trend. The free settling velocity under 350 mg/l ferric chloride is 0.067 cm/min ($1.17 \times 10^{-5}$ m/s).

The mathematical expression of Stokes law (Equation 2.1) is applied to find the particle settling velocity. The following parameters are used in the calculation:

---

3 Amount of solids per unit volume of water
4 Indicates mudline decomposition velocity
\[ g = 9.81 \text{ m/s}^2, \rho_s = 2580 \text{ kg/m}^3, \rho_f = 1000 \text{ kg/m}^3, d = d_{50} = 8.03 \times 10^{-6} \text{ m}, \text{ and } \mu = 2.6 \times 10^{-3} \text{ N.s/m}^2 \]

and the particle settling velocity from the Stokes law is calculated as \(2.08 \times 10^{-4} \text{ m/s}\).

Substituting above parameters into Equation 2.4,

\[ 1.17 \times 10^{-5} = \beta_f \times 2.08 \times 10^{-4} \]

\[ \therefore \beta_f = 0.054 \]

Based on the experimental data, the free settling equation for the MFT suspension of 5% initial solid content under 350 mg/l ferric chloride can be expressed as,

\[ \nu_f = 0.054u \quad (3.2) \]

Where \( \nu_f \) is free settling velocity (m/s), and \( u \) is the particle settling velocity (m/s).

Fig. 3.11 shows the ratio of hindered settling velocity and free settling velocity in log scale, \( \log(\nu_h/\nu_f) \), vs. the porosity of the sediments in log scale, \( \log(n) \), for 5% MFT suspension under 350 mg/l ferric chloride. The value of sedimentation coefficient, \( r \) and sedimentation factor, \( \beta_h \) is found as 108 and 0.565, respectively. The hindered settling velocity can be expressed as,

\[ \nu_h = 0.565u.n^{108} \quad (3.3) \]

Where \( \nu_h \) is the hindered settling velocity (m/s), \( u \) is the particle settling velocity (m/s), \( n \) is the porosity (-).
The plot of the final solid content and increase in the solid content vs. ferric chloride concentration is shown in Fig. 3.12. With the most effective ferric chloride dose of 350 mg/l, the final solid content is 6.48% after 4- hours, indicates a 29.6% increase.

Figs. 3.13 and 3.14 show the turbidity and total solids of the supernatants after 4 hours settling tests. It shows that the sample with 350 mg/l of ferric chloride concentration yields the best results. The lower dosage could not completely destabilize the particles and didn’t create enough effective collision between particles to form flocs. The higher dosage may reverse the electrostatic charge on particles and destabilize the colloidal particles (Yukselen and Gregory 2004, and Shen 2005), and form extra clouds due to the presence of excess ions from the coagulant.

The electrical conductivity increases linearly with the increase in the concentration of ferric chloride in the MFT suspensions (Fig. 3.15), which is consistent with a study on water treatment using ferric chloride (Malakootian and Fatehizadeh 2010). This is attributed to the addition of ferric chloride that increased the ionic concentration in the suspension. On the other hand, the magnitude of zeta potential of the particles decreased proportionally with the increase in the ferric chloride dose (Fig. 3.15), which is attributed to the compressing of the double layer and charge neutralization.

3.5.2.2 Effect of pH

The effect of suspension pH is observed in cylinder tests in terms of the final mudline. The pH of the suspensions is adjusted by titration using 0.1M HCl and 0.1M NaOH. Fig.
3.16 shows the trends of mudline under the optimum ferric chloride dose of 350 mg/l. The settling curves show similar trends, i.e. starting with free settling, followed by hindered settling and beginning of consolidation. The final height of mudline decreases with the increase in pH (4 to 6). This can be attributed to the presence of hydrogen ions that neutralizes the particle charge and enhances sedimentation. Then the height of mudline increases with the rise in pH at the suspension pH above 6, which may be interpreted as the increased negative surface charge of particles. The results are consistent with Baghvand et al. (2010), who reported the optimum water pH in removing turbidity was 5-6.

The changes in the water electrical conductivity and zeta potential of the particles are monitored at the end of the tests with varying pH of the suspension. The electric conductivity decreases with increasing pH of the MFT suspensions (Fig. 3.17). On the other hand, the absolute value of zeta potential increases with increasing pH of the MFT suspensions (Fig. 3.16), which is consistent with a previous study (Guo and Shang 2014).

The turbidity of supernatant is measured at the end of 4-hour test. The lowest turbidity of water is 4.8 NTU at pH 6, as shown in Fig. 3.18. The high pH means the presence of excess hydroxide (OH\(^-\)) ions while low pH indicates the abundance of hydrogen (H\(^+\)) ions, both form extra clouds.

It is observed that thickening of the MFT suspension lasted up to 4 hours from the start. The free settling velocity of 0.067 cm/min continues only 0.75 hour with 350 mg/l ferric chloride, and the coefficient of sedimentation (Equation 3.3) is 108. The solid content reaches 6.48% from an initial of 5% under 350mg/ferric chloride without pH adjustment.
The turbidity of supernatant is 14.4 NTU, and the average zeta potential of particles is -22.6 mV at the end of the test.

3.6 Electrokinetic Thickening Tests

3.6.1 Experimental Set-up

Two identical columns are designed and constructed for electrokinetic thickening tests. A schematic of the column is shown in Fig. 3.19. The conditions of electrokinetic thickening tests are summarized in Table 3.5. The columns are made of 6 mm thick plexiglass (an electrically insulating material), 16.8 cm in height with an inside diameter of 8.9 cm. Two electrodes (anode and cathode) are used to apply the DC electric current through the MFT suspension in the column. The vertical distance between electrodes is 16 cm; the anode is kept at the bottom of the column and cathode at the top. The placement of electrodes allows the negatively charged particles to settle by gravity and electrophoresis. The anode is made of dimensionally stable (DSA) mesh (titanium coated with iridium oxide (Ti/IrOx), 0.063” in thickness and 30% in open area), whereas the cathode is made of woven wire stainless steel mesh (SS316, 0.063” in wire diameter and 30% in open area). The electrodes are connected to a DC power supply (Hewlett Packard 6545-J05). The mesh electrodes allow the hydrogen and oxygen gases formed at the cathode and anode, respectively, to escape from the system. Further, the mesh anode allows sample collection at the bottom of the column. The electrodes are arranged in
parallel to generate a uniform electric field along the axis of the column. Two voltage
cables are attached on the electrodes to measure the applied voltage by a multimeter.

3.6.2 Testing Procedure

The suspension of mature fine oil sands tailings (MFT) was poured into the testing
column. The initial solid contents of the suspension were 5%, 10%, and 15% (mass/mass)
in electrokinetic thickening tests. Table 3.5 summarizes the test conditions. At first the
effect of initial solid content was studied, and the most effective solid content was used in
all electrokinetic tests. All tests lasted for 7 hours because within this time the
sedimentation is completed in all the tests series and the system enter in consolidation
stage. The following parameters were measured with time in all tests: the solid-liquid
interface of the settling suspension (mudline), effective voltage gradient between the
anode and cathode, electric current, and temperature. At the end of each test, the water
sample was collected from the top of the column (cathode), and the sediment sample was
taken from the drainage valve at the bottom of the column (anode). The water sample was
used to measure pH and turbidity, and the sediment sample was used to measure pH, zeta
potential and final solid concentration.
3.6.3 Results and Discussion

3.6.3.1 Effect of Initial Solid Content and Applied Voltage Gradient

There is no gravitational settling observed in electrokinetic during the testing period (Fig. 3.20). The results of electrokinetic thickening tests (height of mudline vs. time plot under different applied voltage gradients) for 5%, 10%, and 15% initial solid contents are shown in Figs. 3.21, 3.22, and 3.23, respectively. For all MFT suspensions, the increase in the applied voltage gradient decreases the height of mudline from the bottom of the column. The linear initial decrease in the mudline with time at the initial stage of the test is the free settling stage. As the interaction between particles increases, the suspension enters the hindered settling stage. The hindered settling stage ends when the mudline stabilizes, which marks the beginning of self-weight consolidation. The trend lines are similar to the results of electrokinetic sedimentation of Welland river sediment (Buckland et al. 2000).

Figs. 3.24, 3.25 and 3.26 show the final solid content and increase in the solid content vs. applied voltage gradients for the suspension of 5%, 10%, and 15% initial solid contents, respectively. The final solid content reaches 18.75% from the initial of 5% after 7 hours under the applied voltage gradient of 219 V/m. When the applied voltage gradient is higher than 219 V/m, the final solid content would not further increase. The higher electric current generates excess H₂ and O₂ gases (gas bubbles), which hinder the thickening process. For MFT suspensions of 10% and 15% initial solid contents, the final
solid contents are 22% and 24.2%, respectively under the applied voltage gradient of 250 V/m. The final solid content did not further increase when the applied voltage gradients exceeding 250 V/m. The results show that electrokinetic thickening is more effective under a low solid content, similar to thickening by coagulant, and it may be attributed to increase in electrical resistivity of suspension with the increase in initial solid content.

Since there is no obvious gravitational settling registered (Fig. 3.20), it is expected that the thickening velocity measured in electrokinetic tests is attributed predominantly to electrophoresis. The average settling velocity is calculated for the 5% MFT suspension using Equation 3.1, as shown in Fig. 3.21. Fig. 3.27 shows the plot of settling velocity vs. time for the MFT of 5% initial solid content. The free settling stage (constant settling velocity), hindered settling stage (decreasing settling velocity) and the start of consolidation (velocity ≈ 0) are clearly shown.

The details of free settling velocity, duration of free settling and the time to reach the start of consolidation are summarized in Table 3.6. It shows the increase in the applied voltage gradient increases the free settling velocity and decreases the free settling duration. This is attributed to the increased particle interactions under higher voltage gradient. Moreover, consolidation of MFT suspension starts more quickly under a higher applied voltage. After the effective treatment time the efficiency of thickening became very low.

Fig. 3.21 shows when the applied voltage gradient is above 219 V/m, the height of final mudlines remains almost the same. The results are verified via the final solid contents (Fig. 3.24 and Table 3.7). Hence the threshold applied voltage gradient is identified as 219 V/m for the 5% MFT suspension.
3.6.3.2 Validation of Electrokinetic Sedimentation Theory

The relationship between applied voltage gradient and free settling velocity is linear with $R^2 = 0.995$ (Fig. 3.28, 5% initial solid content) and can be expressed as,

$$v_{f-ek} = 0.0002E + 0.0097$$

(3.4)

In which $v_{f-ek}$ is the free settling velocity for electrokinetics (cm/min), and $E$ is the applied voltage gradient (V/m).

This linear relation is in general agreement with Equation 2.10, whereas 0.0097 cm/min represents the free settling velocity by gravity. This free settling velocity without electrokinetics is not observed in the experiments, which could be attributed to the limitation of monitoring in the experiments. Equation 2.10 is used to calculate the factor, $\beta_{f-ek}$ that relates the free settling velocity and particle settling velocity under electrokinetic treatment and can be rearranged as,

$$\beta_{f-ek} = \frac{v_{f-ek}}{E \cdot \frac{\mu}{\varepsilon_\omega \cdot \zeta}}$$

(3.5)

The following parameters are used for the calculations of $\beta_{f-ek}$:

- $v_{f-ek}/E = \text{slope of } v_{f-ek} \text{ vs. } E \text{ plot} = 2 \times 10^{-4} \text{ cm-m/V-min} = 3.33 \times 10^{-8} \text{ m}^2/\text{V-s} \text{ (Fig. 3.28)}$

- $\mu = \text{viscosity of 5% MFT suspension at } 20^0\text{C} = 2.6 \times 10^{-3} \text{ N.s/m}^2$

- $\zeta = \text{absolute value of zeta potential} = 0.052 \text{ V}$
\[ \varepsilon_w = \text{permittivity of water at } 20^0\text{C at visible light} = 80.1 \text{ F/m} \]

Substituting above parameters into Equation 3.5 the value of \( \beta_{f-ek} \) is \( 2.08 \times 10^{-11} \). Based on the experimental results, the free settling equation for the MFT suspension of 5% initial solid content under electric current can be expressed as

\[
v_{f-ek} = 2.08 \times 10^{-11} \left( \frac{\varepsilon_w \zeta E}{\mu} \right)
\]

(3.6)

Where \( v_{f-ek} \) is the free settling velocity under electrokinetics (m/s), \( \varepsilon_w \) is the permittivity of water (F/m), \( \zeta \) is the absolute value of zeta potential (V), \( E \) is the applied voltage gradient (V/m), and \( \mu \) is the viscosity of the suspensions fluid (N.s/m²).

The electrokinetic sedimentation factor in the free settling stage, \( \beta_{f-ek} \), for the MFT suspension of 5%, 10%, and 15% initial solid content are presented in Table 3.8.

The porosity of the sediment with time for 219 V/m applied voltage gradient is calculated from height of mudline (Fig. 3.21) and volume of suspension. Fig. 3.29 shows the ratio of hindered settling velocity and free settling velocity in log scale, \( \log(v_{h-ek}/v_{f-ek}) \), vs. the porosity of the sediments in log scale, \( \log(n_{ek}) \), for the MFT suspension of 5% initial solid content under 219 V/m applied voltage gradient. The slope of the plot is the electrokinetic sedimentation coefficient, \( r_{ek} \) (Equation 2.12), which is 39.6. From the intercept of Fig. 3.28, the value of \( \gamma_{ek} \) is 0.578 and \( \beta_{h-ek} \) is calculated as \( 7.87 \times 10^{-11} \).

Based on the experimental results, the hindered settling equation for the MFT suspension of 5% initial solid content under the optimal applied voltage gradient, 219 V/m, can be expressed as,
\[ v_{h-ek} = 7.87 \times 10^{-11} \left( \frac{E}{\mu} \right)^{39.6} \]  

(3.7)

Where \( v_{h-ek} \) is the hindered settling velocity under electric current (m/s), \( n_{ek} \) is the porosity of the sediment (unitless number), and all other notations are same as described before.

The electrokinetic sedimentation factors, \( \beta_{h-ek} \), and coefficient, \( r_{ek} \), in the hindered settling stage for the MFT suspension of 5%, 10%, and 15% initial solid content are presented in Table 3.8. As shown the value of \( r_{ek} \) increases with the increase in the initial solid content. The results of sedimentation coefficient, \( r_{ek} \), are in good agreement with Shang (1997), who reported the values of \( r_{ek} \) for the suspension of phosphatic, brown, and grey clays as 45.21, 34.65, and 18.49, respectively.

3.6.3.3 Power Consumption

The effective voltages between anode and cathode are recorded by a multimeter, which are less than the applied voltages due to the voltage loss at the electrode-soil interface. Fig. 3.30 shows the effective voltage gradient and efficiency\(^5\) between anode and cathode vs. applied voltage gradient at the end of the tests. The effective voltage gradients vary between 56.3 V/m and 270 V/m when the applied voltage gradients are between 62.5 V/m and 281 V/m, respectively. The corresponding voltage efficiency varies from 90.1% to 95.9%. The plot shows that when the applied voltage gradient is 219 V/m or higher the

\(^5\) Voltage efficiency = (Effective voltage gradient) / (Applied voltage gradient)*100
voltage efficiency is almost same. The voltage efficiency in electrokinetic sedimentation of contaminated Welland river sediment was 91% under an applied voltage gradient of 150 V/m with graphite as both anode and cathode (Buckland et al. 2000). The Ti/IrOx-SS316 anode-cathode combination performed well over the project period without any sign of deterioration.

Fig. 3.31 shows the plot of current density vs. applied voltage gradient for the MFT suspension of 5% initial solid content. The electrical resistivity, \( \rho \), of the suspensions is determined based on the Ohm’s law,

\[
\rho = \frac{E}{J}
\]  

Where \( \rho \) is the electrical resistivity (\( \Omega \cdot \text{m} \)), \( E \) is the applied voltage gradient (V/m), and \( J \) is the current density (A/m\(^2\)).

The electrical resistivity for the MFT suspension of 5%, 10% and 15% initial solid contents is presented in Table 3.9. The electrical resistivity of the suspension is almost constant for the same initial solid content. On the other hand, the electrical resistivity increases slightly with the increase in the initial solid content of MFT, which has been well reported in the literature.

The power consumption per unit volume of MFT suspension (W/m\(^3\)) in the electrokinetic thickening tests are calculated from the applied voltage, electric current and volume of the suspension during the tests using the following equation:

---

6 Electrical resistivity is the measure that quantifies how strongly a given material resists the flow of electric current.
\[
P = \frac{UI}{V}
\]  \hspace{1cm} (3.9)

Where \(U\) is the applied voltage (V), \(I\) is the electric current (A), and \(V\) is the volume of the MFT suspension (m\(^3\)).

Fig. 3.32 shows the relationship between the power consumption and applied voltage gradient for all the electrokinetic thickening tests on the suspension of MFT of 5% initial solid content for 7 hours electrokinetic thickening. The plot shows the power consumption increases with the applied voltage gradient. So it is crucial to use the threshold value of applied voltage gradient (in this case 219 V/m for 5% MFT suspension).

3.6.3.4 Zeta Potential of Particles, Water pH, Temperature, and Turbidity after Electrokinetic Thickening

The absolute value of the zeta potential of tailings solids decreases linearly with the increase in the applied voltage gradient (Fig. 3.33), which may be attributed to the compression of the double layer and neutralization of the particle charge.

The water pH at the anode decreases due to the oxidation and increases at the cathode due to reduction, as described in Chapter 2. Fig. 3.34 shows the values of final water pH vs. applied voltage gradient at anode and cathode at the end of 7 hours electrokinetic thickening tests. The initial value of water pH is 7.25. The water pH at anode decreases significantly to 4 to 3.1 with the applied voltage gradient of 62.5 V/m to 281 V/m. The
water pH is 11.5 to 12.0 at the cathode. The similar pH variations were observed in electrokinetic sedimentation of clayey soils (Kim et al. 2008). The pH change is more significant under higher applied voltage gradient due to intensified electrochemical reactions at electrodes.

Fig. 3.35 shows the final temperature vs. applied voltage gradient at the end of electrokinetic tests at anode and cathode. The final temperature at anode and cathode increases linearly with the increase in the applied voltage gradient. The higher temperature reduces the viscosity of the suspension and increase the rate of sedimentation if other parameter remains the same. In this study initial temperature is not varied, but the temperature increases with time due to electrochemical reaction at the electrodes. With time the solid content of the suspension increases and so the effect of higher temperature is not visualized in the study.

The turbidity of supernatant was tested at the end of 7-hour electrokinetic thickening and the results are presented in Fig. 3.36. The turbidity of water is mainly due to the presence of suspended particles and gas bubbles. It was noted that the generated gas bubbles disappeared with time and after 1 hour from the end of the test under the applied voltage gradient of 219 V/m the turbidity of water reduced to 30.6 NTU from 223 NTU.

3.6.3.5 Water pH Effect on Final Solid Content

A set of electrokinetic thickening tests was performed for the MFT suspension of 5% initial solid content by using the applied voltage gradient of 219 V/m with different
suspension pH. The pH of the suspensions was adjusted by titration using 0.1M HCl and 0.1M NaOH. Fig. 3.37 shows the plot of height of mudline and final solid content vs. suspension pH at the end of 7 hours testing under an applied voltage gradient of 219 V/m. At the end of the tests, the final solid content at pH 7.25 (MFT suspension pH without adjustment) was 18.75% while at pH 5 and 10.5 the solid content reached 16.79% and 19.2%, respectively. The effect of thickening is the best at higher suspensions pH, which is attributed to the higher values of zeta potential.

It is observed that thickening of the MFT suspension lasted up to 4 hours from the start and the final solid content reached 6.48% under 350 mg/l ferric chloride as the coagulant. On the other hand, thickening by electrokinetics continued up to around 7 hours, and the final solid content was 18.75% under the applied voltage gradient of 219 V/m. In conclusion the electrokinetic thickening is 3 times more effective than coagulation in terms of the final solid content of MFT.

3.7 Summary

In this chapter the mature fine oil sands tailings (MFT) is characterized for the physical, chemical and geological properties, followed by description of detailed testing procedures, as well as results and discussions of jar tests and cylinder coagulation tests. The key investigation in this chapter is the electrokinetic thickening of MFT suspension. The results of coagulation and electrokinetic thickening tests are presented, analyzed and compared. The main findings are as follows:
a) The mature fine oil sands tailings contain 82.5% silt and 17.5% clay-sized solids and have a natural water content of 158%. The plasticity index of MFT was 18.4%, and hence it is categorized as elastic silt. The major minerals in the mature fine oil sands tailings are found to be quartz, illite, and kaolinite. The pore water pH and electrical conductivity (EC) are found as 8.19 and 3.51 mS/cm, respectively.

b) In the series of jar experiments, ferric chloride at 350 mg/l generated the best coagulation effect in terms of the final position of mudline and final solid content among different coagulants studied.

c) Ferric chloride produced the best settling effect in the MFT suspensions at 350 mg/l concentration, and the final solid content was 6.48% for the MFT suspension of 5% initial solid content after 4 hours in cylinder coagulation tests.

d) In electrokinetic thickening test, the final solid content reached 18.75% from 5% initial solid content of the MFT suspension under the applied voltage gradient of 219 V/m after 7 hours. The increase in the applied voltage gradient increased the final solid content, and free settling velocity, and reduced the duration of free settling.

e) The equations of sedimentation velocity in the free settling and hindered settling stages are validated using the experimental data.

f) The voltage efficiency ranges from 90.1% to 95.9% under the applied voltage gradient of 62.5 V/m to 281 V/m, respectively, for the MFT suspension of 5% initial solid content. The power consumption in the electrokinetic tests varies from 0.271 KW/m³ to 6.15 KW/m³. The electrical resistivity of the suspension is almost constant for the same initial solid content and increases slightly with the increase in the initial solid content of the suspension.
g) The final turbidity (without pH adjustment) of the supernatant is 14.4 NTU and 30.6 NTU under coagulation and electrokinetics, respectively and the corresponding zeta potential of particles is -22.6 mV and -14.7 mV.
<table>
<thead>
<tr>
<th>Properties</th>
<th>MFT composition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water content, w (%)</td>
<td>158</td>
</tr>
<tr>
<td>Oil and grease (g/l)</td>
<td>1.67</td>
</tr>
<tr>
<td>Specific gravity, Gs</td>
<td>2.58</td>
</tr>
<tr>
<td>Zeta potential (mV)</td>
<td>-52.6</td>
</tr>
<tr>
<td>Atterberg Limits</td>
<td></td>
</tr>
<tr>
<td>Plastic limit, PL (%)</td>
<td>36</td>
</tr>
<tr>
<td>Liquid limit, LL (%)</td>
<td>54.4</td>
</tr>
<tr>
<td>Plasticity index, PI (%)</td>
<td>18.4</td>
</tr>
<tr>
<td>Organic matter (%)</td>
<td>17.9</td>
</tr>
<tr>
<td>Carbonate content (%)</td>
<td>Not significant (&lt;1)</td>
</tr>
<tr>
<td>Grain size</td>
<td></td>
</tr>
<tr>
<td>D&lt;sub&gt;10&lt;/sub&gt; (µm)</td>
<td>1.09</td>
</tr>
<tr>
<td>D&lt;sub&gt;50&lt;/sub&gt; (µm)</td>
<td>8.03</td>
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<tr>
<td>D&lt;sub&gt;90&lt;/sub&gt; (µm)</td>
<td>26.9</td>
</tr>
<tr>
<td>Sand (%)</td>
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</tr>
<tr>
<td>Silt (%)</td>
<td>82.5</td>
</tr>
<tr>
<td>Clay (%)</td>
<td>17.5</td>
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</table>
Table 3.2: Chemical analysis of pore water of mature fine oil sands tailings

<table>
<thead>
<tr>
<th>Cations</th>
<th>Concentrations (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Na</td>
<td>600</td>
</tr>
<tr>
<td>Mg</td>
<td>9.03</td>
</tr>
<tr>
<td>K</td>
<td>19.7</td>
</tr>
<tr>
<td>Ca</td>
<td>9.74</td>
</tr>
<tr>
<td>Al</td>
<td>0.04</td>
</tr>
<tr>
<td>V</td>
<td>0.01</td>
</tr>
<tr>
<td>Fe</td>
<td>0.02</td>
</tr>
<tr>
<td>Ni</td>
<td>0.01</td>
</tr>
<tr>
<td>Cu</td>
<td>0.13</td>
</tr>
<tr>
<td>Zn</td>
<td>0.01</td>
</tr>
<tr>
<td>Rb</td>
<td>0.08</td>
</tr>
<tr>
<td>Sr</td>
<td>0.35</td>
</tr>
<tr>
<td>Ba</td>
<td>0.1</td>
</tr>
<tr>
<td>Pb</td>
<td>0.01</td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>Anions</th>
<th>Concentrations (mg/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cl⁻</td>
<td>279</td>
</tr>
<tr>
<td>SO₄²⁻</td>
<td>29.1</td>
</tr>
<tr>
<td>NO₃⁻</td>
<td>2.6</td>
</tr>
<tr>
<td>OH⁻</td>
<td>0.026</td>
</tr>
</tbody>
</table>

Water pH 8.19

EC of MFT (mS/cm) 3.51

EC of MFT suspension (µS/cm):
- 5% initial solid content 511
- 10% initial solid content 751
- 15% initial solid content 997
### Table 3.3: Conditions of jar experiments

<table>
<thead>
<tr>
<th>Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>No. of beakers</td>
<td>6</td>
</tr>
<tr>
<td>Size of beakers</td>
<td>500 ml</td>
</tr>
<tr>
<td></td>
<td>9 cm height</td>
</tr>
<tr>
<td>Beaker making material</td>
<td>Borosilicate glass</td>
</tr>
<tr>
<td>No. of mixing blades</td>
<td>6</td>
</tr>
<tr>
<td>Revolution of mixing blades</td>
<td>100 rpm (rapid mixing)</td>
</tr>
<tr>
<td></td>
<td>20 rpm (slow mixing)</td>
</tr>
<tr>
<td>Mixing periods</td>
<td>2 min (rapid mixing)</td>
</tr>
<tr>
<td></td>
<td>20 min (slow mixing)</td>
</tr>
<tr>
<td>Settlement period</td>
<td>60 min</td>
</tr>
<tr>
<td>Variables in tests</td>
<td>Initial solid content</td>
</tr>
<tr>
<td></td>
<td>Coagulants</td>
</tr>
<tr>
<td></td>
<td>Coagulant dosage</td>
</tr>
<tr>
<td></td>
<td>pH</td>
</tr>
<tr>
<td>Initial solid content</td>
<td>5%, 10%, 15%</td>
</tr>
<tr>
<td>Types of coagulants</td>
<td>Alum (Al₂(SO₄)₃.18H₂O)</td>
</tr>
<tr>
<td></td>
<td>Aluminum chloride (AlCl₃)</td>
</tr>
<tr>
<td></td>
<td>Ferric chloride (FeCl₃)</td>
</tr>
<tr>
<td>Method of coagulants mixing</td>
<td>By syringe</td>
</tr>
<tr>
<td>Coagulant dosage in the suspension</td>
<td>Varies between 0 and 700 mg/l</td>
</tr>
<tr>
<td>Recorded room temperature during tests</td>
<td>20 to 22 °C</td>
</tr>
<tr>
<td>Observation tools</td>
<td>Height of mudline from the bottom of the beaker</td>
</tr>
<tr>
<td></td>
<td>Final solid content</td>
</tr>
<tr>
<td>Conditions</td>
<td>No. of cylinders</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------</td>
</tr>
<tr>
<td>Size of cylinders</td>
<td>1 L</td>
</tr>
<tr>
<td>Cylinder making material</td>
<td>Borosilicate glass</td>
</tr>
<tr>
<td>Thickening period</td>
<td>4 hr</td>
</tr>
<tr>
<td>Initial solid content</td>
<td>5%</td>
</tr>
<tr>
<td>Type of coagulant</td>
<td>Ferric chloride (FeCl₃)</td>
</tr>
<tr>
<td>Method of coagulants mixing</td>
<td>By syringe</td>
</tr>
<tr>
<td>Coagulant dosage in the suspension</td>
<td>0, 100 mg/l, 200 mg/l, 300 mg/l, 350 mg/l, 400 mg/l, and 450 mg/l</td>
</tr>
<tr>
<td>Recorded room temperature during tests</td>
<td>20 to 22 °C</td>
</tr>
<tr>
<td>Observation tools</td>
<td></td>
</tr>
<tr>
<td>Height of mudline from the bottom of the beaker</td>
<td></td>
</tr>
<tr>
<td>Turbidity of clear water at the top</td>
<td></td>
</tr>
<tr>
<td>Final solid content of the sediment at the bottom</td>
<td></td>
</tr>
<tr>
<td>Zeta potential (with varying pH only)</td>
<td></td>
</tr>
<tr>
<td>Electric conductivity (with varying pH only)</td>
<td></td>
</tr>
<tr>
<td>Conditions</td>
<td>1 L</td>
</tr>
<tr>
<td>------------------------------------------------</td>
<td>--------------------------------</td>
</tr>
<tr>
<td>Size of electrokinetic thickening column</td>
<td>16.8 cm height</td>
</tr>
<tr>
<td></td>
<td>8.9 cm inside diameter</td>
</tr>
<tr>
<td>Column making materials</td>
<td>Plexiglass</td>
</tr>
<tr>
<td>Type of electrodes</td>
<td>Anode (titanium coated with</td>
</tr>
<tr>
<td></td>
<td>iridium oxide)</td>
</tr>
<tr>
<td></td>
<td>Cathode (stainless steel mesh)</td>
</tr>
<tr>
<td></td>
<td>0.063” in thickness and 30% in</td>
</tr>
<tr>
<td></td>
<td>open area (both electrode)</td>
</tr>
<tr>
<td>Vertical distance between electrodes</td>
<td>16 cm</td>
</tr>
<tr>
<td>Power supply</td>
<td>DC power supply (Hewlett Packard</td>
</tr>
<tr>
<td></td>
<td>6545-J05)</td>
</tr>
<tr>
<td>Variables in tests</td>
<td>Initial solid content</td>
</tr>
<tr>
<td>Initial solid content</td>
<td>Applied voltage</td>
</tr>
<tr>
<td>Applied voltage</td>
<td>5%, 10%, 15%</td>
</tr>
<tr>
<td>Applied voltage</td>
<td>0, 10 V, 20 V, 30 V, 35 V, 40 V</td>
</tr>
<tr>
<td></td>
<td>45 V</td>
</tr>
<tr>
<td>Thickening period</td>
<td>7 hr</td>
</tr>
<tr>
<td>Recorded room temperature during tests</td>
<td>16.5 to 18 °C</td>
</tr>
<tr>
<td>Observation tools</td>
<td>Height of mudline from the</td>
</tr>
<tr>
<td></td>
<td>bottom of the beaker</td>
</tr>
<tr>
<td></td>
<td>Turbidity of supernatant at the</td>
</tr>
<tr>
<td></td>
<td>top</td>
</tr>
<tr>
<td></td>
<td>Final solid content of the</td>
</tr>
<tr>
<td></td>
<td>sediment at the bottom</td>
</tr>
<tr>
<td></td>
<td>Electric current</td>
</tr>
<tr>
<td></td>
<td>Change of pH at anode and</td>
</tr>
<tr>
<td></td>
<td>cathode</td>
</tr>
<tr>
<td></td>
<td>Change of temperature at anode</td>
</tr>
<tr>
<td></td>
<td>and cathode</td>
</tr>
</tbody>
</table>
Table 3.6: Duration of free settling, free settling velocity, and effective treatment time under varying applied voltage gradients for 5% MFT suspension

<table>
<thead>
<tr>
<th>Voltage gradient (V/m)</th>
<th>Duration of free settling (min)</th>
<th>Free settling velocity (cm/min)</th>
<th>Start of consolidation/Effective treatment time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.5</td>
<td>210</td>
<td>0.02</td>
<td>390</td>
</tr>
<tr>
<td>125</td>
<td>180</td>
<td>0.032</td>
<td>375</td>
</tr>
<tr>
<td>188</td>
<td>165</td>
<td>0.04</td>
<td>345</td>
</tr>
<tr>
<td>219</td>
<td>135</td>
<td>0.047</td>
<td>315</td>
</tr>
<tr>
<td>250</td>
<td>120</td>
<td>0.053</td>
<td>285</td>
</tr>
<tr>
<td>281</td>
<td>105</td>
<td>0.057</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 3.7: Location of mudline and final solid content under varying applied voltage gradients for 5% MFT suspension

<table>
<thead>
<tr>
<th>Voltage gradient (V/m)</th>
<th>Height of mudline (cm)</th>
<th>Final solid content (%)</th>
<th>Increase in solid content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.5</td>
<td>8.9</td>
<td>9.36</td>
<td>87.2</td>
</tr>
<tr>
<td>125</td>
<td>6.7</td>
<td>12.6</td>
<td>152</td>
</tr>
<tr>
<td>188</td>
<td>5.2</td>
<td>16.5</td>
<td>229</td>
</tr>
<tr>
<td>219</td>
<td>4.6</td>
<td>18.75</td>
<td>275</td>
</tr>
<tr>
<td>250</td>
<td>4.6</td>
<td>18.77</td>
<td>275</td>
</tr>
<tr>
<td>281</td>
<td>4.6</td>
<td>18.75</td>
<td>275</td>
</tr>
</tbody>
</table>
Table 3.8: Values of electrokinetic sedimentation factors and coefficient under 219 V/m applied voltage gradient

<table>
<thead>
<tr>
<th>Initial solid content (%)</th>
<th>β_{f-ek} (for all voltage gradients)</th>
<th>β_{h-ek}</th>
<th>Sedimentation coefficient (r_{ek})</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>2.08*10^{-11}</td>
<td>7.87*10^{-11}</td>
<td>39.6</td>
</tr>
<tr>
<td>10</td>
<td>1.84*10^{-10}</td>
<td>3.9*10^{-9}</td>
<td>52.8</td>
</tr>
<tr>
<td>15</td>
<td>2.3*10^{-11}</td>
<td>2.7*10^{-9}</td>
<td>63.9</td>
</tr>
</tbody>
</table>

Table 3.9: Electrical resistivity of the suspension under varying applied voltage gradients for the MFT suspension of 5%, 10% and 15% initial solid contents

<table>
<thead>
<tr>
<th>Initial Solid Content (%)</th>
<th>Applied Voltage Gradient (V/m)</th>
<th>Electrical Resistivity (Ω·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>62.5</td>
<td>14.3</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>12.3</td>
</tr>
<tr>
<td></td>
<td>188</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>219</td>
<td>14.2</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>13.5</td>
</tr>
<tr>
<td></td>
<td>281</td>
<td>12.8</td>
</tr>
<tr>
<td>10</td>
<td>62.5</td>
<td>15.3</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>15.1</td>
</tr>
<tr>
<td></td>
<td>188</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>219</td>
<td>15.9</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>16.5</td>
</tr>
<tr>
<td></td>
<td>281</td>
<td>16.7</td>
</tr>
<tr>
<td>15</td>
<td>62.5</td>
<td>17.5</td>
</tr>
<tr>
<td></td>
<td>125</td>
<td>17.8</td>
</tr>
<tr>
<td></td>
<td>188</td>
<td>17.9</td>
</tr>
<tr>
<td></td>
<td>219</td>
<td>18.2</td>
</tr>
<tr>
<td></td>
<td>250</td>
<td>18.5</td>
</tr>
<tr>
<td></td>
<td>281</td>
<td>19.1</td>
</tr>
</tbody>
</table>
Properties of mature fine oil sands tailings

Jar experiments to select most effective coagulant and optimum dosage

Coagulation tests in cylinder to thicken the mature fine oil sands tailings

Electrokinetic tests in electrokinetic column to thicken the mature fine oil sands tailings

Analysis of results and their comparison

Figure 3.1: Flow chart for organization of the tests

Figure 3.2: Mature fine oil sands tailings in the lab
### Figure 3.3: Grain size distribution of mature fine oil sands tailings

<table>
<thead>
<tr>
<th>Clay</th>
<th>Silt</th>
<th>Sand</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Particle Size (μm)</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
<th>1000</th>
</tr>
</thead>
<tbody>
<tr>
<td>Percent Finer (%)</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

The graph shows the grain size distribution of mature fine oil sands tailings, with percentages finer for each particle size category.
Figure 3.4: X-ray diffraction on pulverized mature fine oil sands tailings
Figure 3.5: Height of mudline and final solid content vs. coagulant dosage with different coagulants for the MFT suspension of 5% initial solid content

Figure 3.6: Height of mudline and final solid content vs. ferric chloride dosage for the MFT suspension of 10% initial solid content
Figure 3.7: Height of mudline and final solid content vs. ferric chloride dosage for the MFT suspension of 15% initial solid content

Figure 3.8: Height of mudline and final solid content vs. pH for the MFT suspension of 5% initial solid content with 350 mg/l ferric chloride
Figure 3.9: Height of mudline vs. time under varying concentrations of ferric chloride
Figure 3.10: Settling velocity vs. time under varying concentrations of ferric chloride
\[ y = 108.25x + 1.0239 \]
\[ R^2 = 0.967 \]

**Figure 3.11:** log\((v_h/v_f)\) vs. log\((n)\) for the MFT suspension of 5% initial solid content

**Figure 3.12:** Final solid content and increase in solid content vs. ferric chloride dosage
Figure 3.13: Turbidity of supernatant at the top of cylinder for different ferric chloride dosage

Figure 3.14: Total solids of supernatant at the top of cylinder for different ferric chloride dosage
Figure 3.15: Electric conductivity and zeta potential vs. varying dosage of ferric chloride
Figure 3.16: Height of mudline vs. time under varying pH of MFT suspension of 5% initial solid content
Figure 3.17: Electric conductivity and zeta potential vs. pH of the MFT suspension of 5% initial solid content

Figure 3.18: Turbidity vs. pH of supernatant at the top of cylinder for 5% MFT
Figure 3.19: Schematic of Electrokinetic Thickening Column

Figure 3.20: Final location of mudline in an electrokinetic test with control test
Figure 3.21: Height of mudline vs. time for the MFT suspension of 5% initial solid content under varying applied voltage gradients
Figure 3.22: Height of mudline vs. time for the MFT suspension of 10% initial solid content under varying applied voltage gradients
Figure 3.23: Height of mudline vs. time for the MFT suspension of 15% initial solid content under varying applied voltage gradients
Figure 3.24: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 5% initial solid content

Figure 3.25: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 10% initial solid content
Figure 3.26: Final solid content and increase in solid content vs. applied voltage gradient for the MFT suspension of 15% initial solid content
Figure 3.27: Settling velocity vs. time for the MFT suspension of 5% initial solid content under varying applied voltage gradients
Figure 3.28: Relationship between free settling velocity and applied voltage gradient for 5% MFT

$y = 39.601x + 0.578$
$R^2 = 0.9899$

Figure 3.29: $\log\left(\frac{v_{h-ek}}{v_{f-ek}}\right)$ vs. $\log\left(n_{ek}\right)$ for 5% MFT under 219 V/m applied voltage gradient

$y = 39.601x + 0.578$
$R^2 = 0.9899$
Figure 3.30: Effective voltage gradient and voltage efficiency between anode and cathode vs. applied voltage gradient for 5% MFT

Figure 3.31: Current density vs. applied voltage gradient for 5% MFT
Figure 3.32: Power consumption vs. applied voltage gradient for 5% MFT

Figure 3.33: Final zeta potential of particles vs. applied voltage gradient for 5% MFT
Figure 3.34: Final water pH vs. applied voltage gradient for the MFT suspension of 5% initial solid content after 7 hours thickening

Figure 3.35: Final temperature vs. applied voltage gradient for 5% MFT
Figure 3.36: Relationship between turbidity of supernatant and applied voltage gradient for 5% MFT

Figure 3.37: Height of mudline and final solid content vs. pH of MFT suspension at the end of 7 hours thickening tests
CHAPTER 4 COMBINED APPLICATION OF COAGULATION AND ELECTROKINETIC THICKENING AND OPTIMIZATION OF RESULTS BY ANOVA

4.1 Introduction

The study on the combined effects of coagulation and electrokinetic thickening is presented in this chapter. It is found in chapter 3 that the thickening with both coagulation and electrokinetics are the most effective on the suspension of low initial solid content (5%). This combined study consists of two phases: (a) study the combined effect of a continuous electric voltage gradient and coagulant (350 mg/l ferric chloride), and (b) study the effect of an intermittent voltage in combination with ferric chloride. Finally regression models are developed to relate applied voltage gradient and final solid content for electrokinetic thickening and combined study.

The purpose of this study is to observe the effect of these parameters on increasing the final solid content of MFT. The mudline position, effective voltage gradient and voltage efficiency, power consumption, effective treatment time, the zeta potential of particles, and turbidity of supernatant are examined. The results of the combined tests are compared with that of the electrokinetic thickening. The study of the intermittent applied voltage gradient with ferric chloride focuses on the settling velocity and final solid content.
The regression models using response surface method are developed for electrokinetic thickening and combined application of coagulation and electrokinetic thickening, and their significance are examined by F-test. Moreover, the significance of independent process variables on the models is also judged using t-test values. The outcomes of the models are presented in contour plots showing the influences of independent variables on the optimization of response variables.

### 4.2 Combined Application of Coagulation and Electrokinetic Thickening

#### 4.2.1 Testing Procedure

The same columns for electrokinetic thickening described in Chapter 3 are used for combined coagulation and electrokinetic tests. The coagulation and electrophoresis are applied simultaneously to counteract the reduction of zeta potential as possible by coagulant. The conditions of combined tests are summarized in Table 4.1. The prepared MFT suspension of 5% initial solid content is used for the combined tests. Ferric chloride at 350 mg/l is found as the optimal coagulant in jar and cylinder coagulation tests (Chapter 3). Hence, the combined coagulation and electrokinetic tests are carried out using 350 mg/l ferric chloride and application of an applied voltage gradient for 7 hours. The MFT suspension is poured into the testing column. The applied voltages gradients vary between 0 and 281 V/m, as presented in Table 4.1. In all tests the location of mudline, effective voltage gradient between the anode and cathode, and electric current
are measured. The supernatant is collected at the end of 7-hour thickening tests to measure turbidity. The sediments are collected at the end of the test from the drainage valve at the bottom of the column and are used to measure the zeta potential and final solid content.

4.2.2 Results and Discussion

4.2.2.1 Effect of Applied Voltage Gradient

Fig. 4.1 shows the plot of mudline vs. time for the 5% MFT suspension under the combined applications of coagulation and electrokinetics for 7 hours. The trend lines are linear initially, become nonlinear with time, and finally reach a plateau. The initial linear decrease of the mudline with time is the free settling stage when the particles interactions are low. The hindered settling stage, shown as the nonlinear trend line, represents the hindered settling state due to increased interaction between particles. The plateau of the trend line marks the end of settling and start of self-weight consolidation. The figure indicates that the increase in the applied voltage gradient decreases the final height of mudline. When the applied voltage gradient is 219 V/m or higher the height of mudline is the same, i.e., 3.7 cm, after 7 hours.

The final solid content vs. the applied voltage gradient with the dosage of 350 mg/l ferric chloride is shown in Fig. 4.2. The final solid content after 7 hours is 23.74% under the combined applied voltage gradient of 219 V/m and 350 mg/l ferric chloride, showing 375% increase in the solid content. When the applied voltage gradient is increased to
higher than 219 V/m, the final solid contents do not further increase. The individual application of coagulation and electrokinetics reaches the final solid content of MFT suspension to 6.48% and 18.75%, respectively, from an initial of 5% (discussed in Chapter 3). The combined application of electrokinetics and coagulation produces 1.3 times and 3.7 times more concentrated sediments than that of the individual application of electrokinetics and coagulation, respectively. The results are consistent with the results of Buckland et al. (2000) who reported the combined application of 150 V/m applied voltage gradient and 40 mg/l ferric chloride yielded 1.2 times and 1.3 times more concentrated sediment than those of their individual effect.

The average settling velocity is calculated using Equation 3.1 in Fig. 4.1. Fig. 4.3 shows the settling velocity vs. time under the combined coagulation and electrokinetic thickening. The settling velocity is constant in the free settling stage, and the zero settling velocity at the end indicates the start of self weight consolidation. The details of free settling velocity are summarized in Table 4.2. The free settling velocity increases with the increase in the applied voltage gradient. On the other hand, an increase in the applied voltage gradient reduces the time of free settling, leading to the earlier start of the self-weight consolidation. The average free settling velocity of the suspension under the ferric chloride only (control test) is 0.02 cm/min, while with the applied voltage gradient of 219 V/m, the free settling velocity is 0.06 cm/min. The increase in free settling velocity is attributed to the applied voltage gradient. The similar result of electrokinetic thickening velocity (0.047 cm/min) was found in Chapter 3 under the electric current only. The effective treatment time for different applied voltage gradients combined with 350 mg/l of ferric chloride is presented in Table 4.2, and the effective thickening time decreases
with the increase in the applied voltage gradient. The settling under combined application is more rapid comparing to that of the lone effect of electrophoresis. In conclusion, electrokinetic thickening combined with coagulation can reduce the treatment time, which saves energy.

4.2.2.2 Power Consumption

The effective voltage gradients between the anode and cathode are recorded from the multimeter. The plot of the effective voltage gradient and voltage efficiency vs. the applied voltage gradient is shown in Fig. 4.4. The effective voltage gradient increases linearly with the rise in applied voltage gradient. The voltage efficiency increases with increasing the applied voltage gradients (up to 219 V/m) combined with 350 mg/l ferric chloride, ranging from 92.4% to 97%. The voltage efficiency varied between 90.1% and 95.9% under the application of applied voltage gradient only, discussed in Chapter 3, which demonstrates that the Ti/IrOx-SS316 anode-cathode combination performs well in the presence of ferric chloride. It is also noticed from the plot that the voltage efficiency is almost constant when the applied voltage gradient is 219 V/m or higher.

The electric current through the MFT suspension is recorded. The current density varies linearly with the change in applied voltage gradient and the results are plotted in Fig. 4.5. The electrical resistivity, $\rho$ of the suspensions containing 5% initial solid content under different applied voltage gradients combined with ferric chloride is determined from applied voltage gradient, $E$ and current density, $J$ using Equation 3.2 and the results are
summarized in Table 4.3. It shows the suspensions electrical resistivity is almost constant with varying applied voltage gradient. The electrical resistivity of the suspension is 13.6 \( \Omega \)-m, which is marginally lower than that suspension without coagulant (14.16 \( \Omega \)-m).

The power consumption (W/m\(^3\)) of the combined coagulation and electrokinetic thickening tests are calculated from the volume of MFT suspension (m\(^3\)), applied voltage (V) and electric current (A) during the tests using Equation 3.9. The plot of power consumption vs. applied voltage gradient combined with 350 mg/l ferric chloride for 7 hours electrokinetic thickening is shown in Fig. 4.6. The power consumption increases with the increase in applied voltage gradient. The power consumption in the combined coagulation electrokinetic thickening is higher than that of electrokinetics only. The increased electrical conductivity due to the addition of ferric chloride increases the flow of electric current and the power consumption is proportional to the electric flow. At the end of 7 hours thickening test the lone application of 219 V/m applied voltage gradient reaches the final solid of 18.75% with the power consumption of 3.36 KW/m\(^3\). On the other hand the solid content reaches 23.74% consuming a power of 3.51 KW/m\(^3\) under the combined application.

4.2.2.3 Zeta Potential of Particles and Turbidity of Supernatant after Combined Tests

The negative value of zeta potential decreases linearly with the increase in the applied voltage gradient combined with 350 mg/l ferric chloride (Fig. 4.7). The zeta potential of particles is –14.7 mV under the applied voltage gradient of 219 V/m in combination with
ferric chloride dose of 350 mg/l at the end of 7 hours tests. The original zeta potential of the particle in the suspension is –52.6 mV. The zeta potential of the particles in the sediment under the individual application of electrokinetics and coagulant was –16.3 mV and –22.7, respectively.

The turbidity of supernatant is tested at the end of 7 hours combined tests. The water turbidity at different applied voltage gradients combined with ferric chloride dosage of 350 mg/l is shown in Fig. 4.8. With the applied voltage gradient of 219 V/m combined with 350 mg/l ferric chloride the turbidity of water is 203 NTU just after the end of the test. It is noticed that the turbidity of water decreases to 22.7 NTU after 1 hour from the end of the test, which was 30.6 NTU under same applied voltage gradient only (Chapter 3). The combined application of electrokinetics and coagulant produces better quality water in terms of final turbidity than that of electrokinetics only.

4.3 Application of Intermittent Voltage Gradient Combined with Coagulant

4.3.1 Testing Procedure

The intermittent current is applied through the electrodes of the electrokinetic column (described in Chapter 3) in combination with 350 mg/l ferric chloride. The prepared 5% MFT suspension is used, and the combined coagulation and intermittent electrokinetic tests are done under 350 mg/l ferric chloride and 219 V/m applied voltage gradient with
varying power consumption coefficients ($\chi$). However, some experiments are executed with applied voltage gradient of 94 V/m and 156 V/m combined with ferric chloride for regression model development. The other tests conditions of combined intermittent applied voltage gradient and 350 mg/l ferric chloride are same as that of Table 4.1. Seven series of tests are carried out to observe the effect of intermittent applied voltage gradient: one with 350 mg/l ferric chloride only (Control, without applied voltage gradient, $\chi = 0$), five tests with intermittent current ($\chi = 50\%, 60\%, 70\%, 80\%, \text{ and } 90\%$) and another with continuous applied voltage gradient ($\chi = 100\%$) combined with 350 mg/l ferric chloride. In five intermittent electrokinetic tests the power on time is kept as 10 min (constant) and power off time are 10 min, 6.67 min, 4.29 min, 2.5 min, and 1.11 min to maintain the predetermined power consumption coefficient of 50\%, 60\%, 70\%, 80\%, and 90\%, respectively. There is no power off time in case of continuous applied voltage gradient ($\chi = 100\%$) and no power on time when only ferric chloride is applied ($\chi = 0$). The combined tests under intermittent applied voltage gradient of 219 V/m and coagulant are carried out for 7 hours. The height of mudline from the bottom of the column throughout the testing period, and final solid content of the sediments at anode are tested.

4.3.2 Results and Discussion

The mudline vs. time plot for seven tests, i.e. only 350 mg/l ferric chloride (Control), six tests under 219 V/m applied voltage gradient with varying power consumption coefficient, are presented in Fig. 4.9. Within the tests subjected to intermittent applied voltage gradient ($\chi = 50\% \text{ to } 90\%$) the height of mudline decreases with the increase in
the power consumption coefficient. The continuous applied voltage gradient ($\chi = 100\%$) generates better thickening effect than the tests using intermittent current for the same applied voltage gradient combined with 350 mg/l ferric chloride. The results are consistent with a previous study on the river sediment (Buckland et al. (2000)).

The average settling velocity of the suspension is evaluated using Equation 3.1 in Fig. 4.9 for the combined intermittent applied voltage gradient and 350 mg/l ferric chloride. The plot of settling velocity vs. time under the combined intermittent applied voltage gradient and 350 mg/l ferric chloride is shown in Fig. 4.10. The trend lines are similar to that of thickening by coagulation in cylinder, electrokinetic thickening, and combined applications of continuous applied voltage gradient and coagulant. The details of free settling velocity are summarized in Table 4.4. The free settling velocity increases with the increase in power consumption coefficient though the ferric chloride dose and applied voltage gradient remain unchanged. With higher power consumption coefficient the consolidation of particles began more quickly, which reduces effective treatment time.

The final solid content vs. power consumption coefficient to the applied voltage of 219 V/m combined with 350 mg/l ferric chloride is shown in Fig. 4.11. The final solid content increases with the increase in power consumption coefficient. The percentage increase in final solid content varies between 289% and 375% for the power consumption coefficient of 50% to 100% under the applied voltage of 219 V/m combined with 350 mg/l ferric chloride. The continuous applied voltage gradient shows the best thickening effect though power consumption is high. In the economic perspective the intermittent current with 60% power consumption coefficient produces an acceptable result of final solid content (20.8%) which saves the power consumption by 40%.
4.4 Comparison of Thickening Effect by Coagulation, Electrokinetics and Combined Tests

The comparison of optimum thickening effect by coagulation, electrokinetics and combined application of coagulation and electrophoresis (both continuous and intermittent current) are tabulated in Table 4.5. It is observed that thickening of the MFT suspension lasted up to 4 hours from the start and the final solid content reached 6.48% under 350 mg/l ferric chloride as the coagulant. On the other hand, thickening by electrokinetics continued up to around 7 hours, and the final solid content was 18.75% under the applied voltage gradient of 219 V/m. After 7 hr combined tests, the final solid content was 23.75% and 21.57% under continuous (χ = 100%) and intermittent (χ = 70%), respectively. It is evident that electrokinetic thickening works more effectively than coagulants, while the combined continuous mode provides the best sedimentation result. The intermittent electric current with ferric chloride generates an acceptable final solid content of MFT with 30% save in power consumption compared with continuous current. The duration of free settling under coagulation and electrokinetic thickening are 0.75 hour and 2 hours, respectively, however the free settling velocity was highest for coagulation; this is because of long (35 cm) cylinder used in cylinder coagulation tests. The final turbidity of supernatant was 14.4 NTU, 30.6 NTU and 22.7 under thickening by coagulation, electrokinetics, and combined application, respectively, while the corresponding zeta potentials of particles were -22.6 mV, -14.7 mV, and -16.3 mV without suspensions pH adjustment.
4.5 Response Surface Methodology for Regression Model Development

Response Surface Methodology (RSM) explores the relationships between explanatory (independent) variable and response (dependent) variable. This method is used for the modeling of experimental responses (Box and Draper 1987) and analysis of problems in which a response depends on more than one variable. The RSM is applied to see the significance of two most influencing factors of electrokinetic thickening, i.e. the initial solid content (%) and applied voltage gradient (V/m), based on the response of final solid content (%) and increase in solid content of MFT in electrokinetic thickening. Among different factorials level, a full three-level factorial design is carried out as shown in Table 4.6.

The response variable is a function of independent process variables according to response surface quadratic model (Montgomery 2001) and can be expressed as,

$$y = \alpha_0 + \alpha_1 x_1 + \alpha_2 x_2 + \alpha_{12} x_1 x_2 + \alpha_{11} x_1^2 + \alpha_{22} x_2^2$$ (4.1)

Where, y is the response variable, $x_1$ and $x_2$ are the independent variables, and $\alpha_0$, $\alpha_1$, $\alpha_2$, $\alpha_{12}$, $\alpha_{11}$, and $\alpha_2$ are the regression coefficients for the model.

The regression analysis of the model is carried out by using the statistical software MINITAB 15. Analysis of variance (ANOVA) (F-test and P-values) is employed to check the significance of influencing factors of the quadratic equation based on the response variables with 95% confidence level.
4.5.1 Development of Regression Model for Electrokinetic Thickening

The final solid content (%) and increase in solid content (%) are correlated with the most important factors of the electrokinetic thickening process, i.e. the initial solid content and applied voltage gradient, using Equation 4.1. The experimental conditions of ANOVA are shown in Table 4.6. From the experimental results plotted in Fig. 3.22, 3.23, and 3.24, the following regression models can be obtained.

Final Solid Content (%) = 21.5 + 3.85x_1 + 1.62x_2 - 1.36x_1^2 - 0.545x_2^2 (in coded units) or, - 8.55 + 2.58x_1 + 0.116x_2 - 0.004x_1x_2 - 0.054x_1^2 - 0.0001x_2^2 (in uncoded units) (4.2)

(R-Sq = 99.1%, R-Sq (adj) = 97.7%)

Increase in Solid Content (%) = 117 - 80.6x_1 + 25.7x_2 - 28.6x_1x_2 - 26.7x_1^2 - 7.57x_2^2 (in coded units) or, 67.3 - 20.3x_1 + 2.06x_2 - 0.091x_1x_2 - 1.07x_1^2 - 0.002x_2^2 (in uncoded units) (4.3)

(R-Sq = 98.5%, R-Sq (adj) = 95.9%)

Where x_1 is the initial solid content (%), and x_2 is the applied voltage gradient (V/m).

Since the R-Sq (adj) values are 97.7% and 95.9% for the final solid content and increase in solid content, the data fit well in the regression models. These models are analyzed by Fisher’s test (F-test) for ANOVA. The ANOVA results for the final solid content and increase in solid content are shown in Table 4.7 and 4.8. A model is considered to be
statistically significant when P-value is lower than 0.05 (Jaikumar and Ramamurthi 2009). Tables 4.7 and 4.8 indicate the regression models of the final solid content and increase in solid content are significant at 95% confidence level as the P-values are less than 0.05.

The relative significance of initial solid content and applied voltage gradient is analyzed by Student’s t-test results. The t-test results shown in Table 4.9 and 4.10 reveal that both the initial solid content and applied voltage gradient have a strong effect on the responses of final solid content and increase in solid content as the P-value is less than 0.05. The interaction effects of these two variables are also significant. However, P-values of the coefficients in the quadratic term for the initial solid content are less than that for the applied voltage gradient, and the former has more effect on the outcome of the response variables.

Fig. 4.12 and 4.13 show the contour plots for optimization of response variables based on the developed models to illustrate the influence of initial solid content and applied voltage gradient. Fig. 4.12 shows that the final solid content increases with increasing initial solid content and/or applied voltage gradient and maximum final solid content has been obtained with high initial solid content and high applied voltage gradient. Fig. 4.13 depicts that both the initial solid content and applied voltage gradient have effect on increase in final solid content, but the low initial solid content has much more strong effect on increase in solid content, and higher initial solid content has a diminishing effect on increase in solid content of MFT. The highest increase in solid content (275%) was found in low initial solid content (5%).
4.5.2 Development of Regression Model for Combined Coagulation and Electrokinetic Thickening

In the combined application of coagulation and electrokinetic thickening of MFT, the final solid content is correlated with the applied voltage gradient and power consumption coefficient keeping the ferric chloride dose as constant (350 mg/l). Using the experimental conditions of ANOVA shown in Table 4.11 and experimental results tabulated in Table 4.12, the following regression model is obtained.

Final Solid Content (%) = 17.4 + 5.06x_2 + 1.13x_3 - 0.318x_2x_3 - 0.002x_2^2 - 0.153x_3^2

(in coded units) or, 0.917 + 0.061x_2 + 0.078x_3 + 0.0003x_2x_3 - 0.0004x_3^2

(in uncoded units)  

(R-Sq = 100%, R-Sq (adj) = 99.9%)

Where x_2 is the applied voltage gradient (V/m), and x_3 is the power consumption coefficient (%).

The data fit well in the regression model for the final solid content as R-Sq (adj) value is 99.9%. The analysis of variance is done using F-test to judge the statistical significance of the model and the results are presented in Table 4.13. The quadratic regression model of the final solid content is statistically significant at 95% confidence level since the P-value is less than 0.05.

The t-test is carried out to analyze the relative significance of applied voltage gradient and power consumption coefficient for the optimization of final solid content in combined coagulation and electrokinetic thickening test. The t-test results are presented
in Table 4.14 which shows that the applied voltage gradient and power consumption coefficient are equally statistically significant as the P-value is 0 (<0.05).

The contour plot based on the model developed are shown in Fig. 4.14 to illustrate the influence of applied voltage gradient and power consumption coefficient on the final solid content in the combined test. The final solid content increases with the increase applied voltage gradient and/or power consumption coefficient. The highest final solid content is observed with high applied voltage gradient and high power consumption coefficient (continuous applied voltage gradient).

4.6 Summary

The combined coagulation and electrokinetic thickening tests are conducted, and the results are analyzed in this chapter. The electric current and coagulant are applied together to accelerate sedimentation. The electric current is applied in two modes: continuous applied voltage gradient and intermittent applied voltage gradient. The main results and conclusions are summarized as follows:

a) The final solid content after 7 hours is 23.74% from an initial of 5% under the combined applied voltage gradient of 219 V/m and 350 mg/l ferric chloride which shows 375% increase in the solid content compared to initial solid content.

b) The combined application of applied voltage gradient and coagulant generates higher free settling velocity compared to electrokinetics only. The effective treatment time before the start of consolidation is lower under the combined application than that of
electrokinetics. The addition of coagulant leads to slight decrease the electrical resistivity of suspensions.

c) The zeta potential of the particles in the thickened MFT after combined application is the lowest. The turbidity of the supernatant is 22.7 NTU under the combined application of 219 V/m applied voltage gradient and 350 mg/l ferric chloride when the gas bubbles disappear after 1 hour from the end of the test.

d) Within the tests subject to combined intermittent applied voltage gradient and coagulant the thickening rate increases with the increase in the power consumption coefficient, and the continuous applied voltage gradient generates the best thickening effect. The final solid content due to the application of intermittent applied voltage gradient combined with 350 mg/l ferric chloride increases with the increase in power consumption coefficient.

e) The developed regression models to relate the final solid content and increase in the solid content based on experimental data of the initial solid content and applied voltage gradient under the electrokinetic thickening are statistically significant at 95% confidence level, and fit well. The initial solid content and applied voltage gradient have strong influence on the final solid content, but the low initial solid content has stronger responses on the increase in solid content.

f) The regression model that correlates the final solid content with the applied voltage gradient and power consumption coefficient under combined application of coagulation and electrokinetic thickening fits well with the experimental data. The
maximum final solid content is observed with the high applied voltage gradient and high power consumption coefficient.
Table 4.1: Conditions of combined coagulation and electrokinetic thickening tests

<table>
<thead>
<tr>
<th>Conditions</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Size of electrokinetic thickening column</td>
<td>1 L</td>
</tr>
<tr>
<td></td>
<td>16.8 cm height</td>
</tr>
<tr>
<td></td>
<td>8.9 cm inside diameter</td>
</tr>
<tr>
<td>Column making material</td>
<td>Plexiglass</td>
</tr>
<tr>
<td>Type of electrodes:</td>
<td></td>
</tr>
<tr>
<td>Anode</td>
<td>Titanium coated with iridium oxide</td>
</tr>
<tr>
<td>Cathode</td>
<td>Stainless steel mesh</td>
</tr>
<tr>
<td>Vertical distance between electrodes</td>
<td>16 cm</td>
</tr>
<tr>
<td>Power supply</td>
<td>DC power supply (Hewlett Packard 6545-J05)</td>
</tr>
<tr>
<td>Initial solid content</td>
<td>5%</td>
</tr>
<tr>
<td>Applied voltage</td>
<td>0, 10 V, 15 V, 20 V, 25 V, 30 V, 35 V, 40 V, 45 V</td>
</tr>
<tr>
<td>Coagulant dosage</td>
<td>350 mg/l ferric chloride</td>
</tr>
<tr>
<td>Thickening period</td>
<td>7 hr</td>
</tr>
<tr>
<td>Recorded room temperature during tests</td>
<td>16.5 to 18 °C</td>
</tr>
<tr>
<td>Observation tools</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Height of mudline from the bottom of the beaker</td>
</tr>
<tr>
<td></td>
<td>Final solid content of thickened MFT suspension</td>
</tr>
<tr>
<td></td>
<td>Turbidity of clear water at the top</td>
</tr>
</tbody>
</table>
### Table 4.2: Duration of free settling, free settling velocity and effective treatment time under combined electrokinetics and coagulation for MFT suspension

<table>
<thead>
<tr>
<th>Voltage gradient (V/m)</th>
<th>Ferric chloride dose (mg/l)</th>
<th>Duration of free settling (min)</th>
<th>Free settling velocity (cm/min)</th>
<th>Start of consolidation/Effective treatment time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>350</td>
<td>225</td>
<td>0.02</td>
<td>390</td>
</tr>
<tr>
<td>62.5</td>
<td>350</td>
<td>285</td>
<td>0.023</td>
<td>345</td>
</tr>
<tr>
<td>94</td>
<td>350</td>
<td>270</td>
<td>0.03</td>
<td>345</td>
</tr>
<tr>
<td>125</td>
<td>350</td>
<td>240</td>
<td>0.033</td>
<td>375</td>
</tr>
<tr>
<td>156</td>
<td>350</td>
<td>210</td>
<td>0.04</td>
<td>330</td>
</tr>
<tr>
<td>188</td>
<td>350</td>
<td>180</td>
<td>0.047</td>
<td>285</td>
</tr>
<tr>
<td>219</td>
<td>350</td>
<td>120</td>
<td>0.06</td>
<td>255</td>
</tr>
<tr>
<td>250</td>
<td>350</td>
<td>105</td>
<td>0.067</td>
<td>240</td>
</tr>
<tr>
<td>281</td>
<td>350</td>
<td>105</td>
<td>0.073</td>
<td>225</td>
</tr>
</tbody>
</table>

### Table 4.3: Electrical resistivity of the MFT suspension under varying applied voltage gradient combined with ferric chloride

<table>
<thead>
<tr>
<th>Applied Voltage Gradient (V/m)</th>
<th>Electrical Resistivity (Ω·m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>62.5</td>
<td>13.5</td>
</tr>
<tr>
<td>94</td>
<td>12.2</td>
</tr>
<tr>
<td>125</td>
<td>12.4</td>
</tr>
<tr>
<td>156</td>
<td>13</td>
</tr>
<tr>
<td>188</td>
<td>13.6</td>
</tr>
<tr>
<td>219</td>
<td>13.6</td>
</tr>
<tr>
<td>250</td>
<td>13.2</td>
</tr>
<tr>
<td>281</td>
<td>12.6</td>
</tr>
</tbody>
</table>
Table 4.4: Duration of free settling, free settling velocity and effective treatment time under the combined intermittent applied voltage gradient and 350 mg/l ferric chloride for MFT

<table>
<thead>
<tr>
<th>Power consumption coefficient, $\chi$ (%)</th>
<th>Ferric chloride dose (mg/l)</th>
<th>Duration of free settling (min)</th>
<th>Free settling velocity (cm/min)</th>
<th>Start of consolidation/ Effective treatment time (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>350</td>
<td>225</td>
<td>0.02</td>
<td>390</td>
</tr>
<tr>
<td>50</td>
<td>350</td>
<td>135</td>
<td>0.04</td>
<td>390</td>
</tr>
<tr>
<td>60</td>
<td>350</td>
<td>120</td>
<td>0.044</td>
<td>390</td>
</tr>
<tr>
<td>70</td>
<td>350</td>
<td>105</td>
<td>0.051</td>
<td>375</td>
</tr>
<tr>
<td>80</td>
<td>350</td>
<td>90</td>
<td>0.055</td>
<td>345</td>
</tr>
<tr>
<td>90</td>
<td>350</td>
<td>90</td>
<td>0.058</td>
<td>285</td>
</tr>
<tr>
<td>100</td>
<td>350</td>
<td>120</td>
<td>0.06</td>
<td>255</td>
</tr>
</tbody>
</table>

Table 4.5: Comparison of thickening results by coagulation, electrokinetics and their combined application

<table>
<thead>
<tr>
<th>Properties to be compared</th>
<th>Coagulation (350 mg/l FC)</th>
<th>EK (219 V/m)</th>
<th>Combined application (cont.)</th>
<th>Combined application (int.)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial solid content (%)</td>
<td>5</td>
<td>5</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>Final solid content (%)</td>
<td>6.48</td>
<td>18.75</td>
<td>23.75</td>
<td>21.57</td>
</tr>
<tr>
<td>Total treatment time (hour)</td>
<td>4</td>
<td>7</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>Free settling velocity (cm/min)</td>
<td>0.067</td>
<td>0.047</td>
<td>0.06</td>
<td>0.05</td>
</tr>
<tr>
<td>Duration of free settling (hour)</td>
<td>0.75</td>
<td>2</td>
<td>2</td>
<td>1.5</td>
</tr>
<tr>
<td>Sedimentation coefficient, $r$</td>
<td>108</td>
<td>39.6</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Zeta potential of particles (mV)</td>
<td>-22.67</td>
<td>-14.7</td>
<td>-16.3</td>
<td>-</td>
</tr>
<tr>
<td>Turbidity of Supernatant (NTU)</td>
<td>14.4</td>
<td>30.6</td>
<td>22.7</td>
<td>-</td>
</tr>
</tbody>
</table>

FC = ferric chloride, EK = electrokinetics, cont. = continuous electric current, int. = intermittent electric current with $\chi = 70\%$
Table 4.6: Factors and levels used in the full three level factorial designs in electrokinetic thickening

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low (-1)</th>
<th>Medium (0)</th>
<th>High (+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Solid Content (%), $x_1$</td>
<td>5</td>
<td>10</td>
<td>15</td>
</tr>
<tr>
<td>Applied Voltage Gradient (V/m), $x_2$</td>
<td>125</td>
<td>188</td>
<td>250</td>
</tr>
</tbody>
</table>

Table 4.7: Analysis of variance for the final solid content in electrokinetic thickening

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>114</td>
<td>22.9</td>
<td>68.2</td>
<td>0.003</td>
</tr>
<tr>
<td>Residual error</td>
<td>3</td>
<td>1.01</td>
<td>0.336</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total error</td>
<td>8</td>
<td>115</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.8: Analysis of variance for the increase in solid content in electrokinetic thickening

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>47700</td>
<td>9540</td>
<td>38.2</td>
<td>0.006</td>
</tr>
<tr>
<td>Residual error</td>
<td>3</td>
<td>749</td>
<td>245</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total error</td>
<td>8</td>
<td>48449</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
### Table 4.9: Regression coefficients of full polynomial model for the final solid content (in coded units)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Parameter estimate</th>
<th>Standard error of parameter</th>
<th>T-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>21.5</td>
<td>0.432</td>
<td>49.8</td>
<td>0</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>3.85</td>
<td>0.237</td>
<td>16.3</td>
<td>0.001</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>1.62</td>
<td>0.237</td>
<td>6.82</td>
<td>0.006</td>
</tr>
<tr>
<td>$\alpha_{12}$</td>
<td>-1.2</td>
<td>0.29</td>
<td>-4.12</td>
<td>0.026</td>
</tr>
<tr>
<td>$\alpha_{11}$</td>
<td>-1.36</td>
<td>0.41</td>
<td>-3.32</td>
<td>0.045</td>
</tr>
<tr>
<td>$\alpha_{22}$</td>
<td>-0.545</td>
<td>0.41</td>
<td>-1.33</td>
<td>0.276</td>
</tr>
</tbody>
</table>

### Table 4.10: Regression coefficients of full polynomial model for the increase in solid content (in coded units)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Parameter estimate</th>
<th>Standard error of parameter</th>
<th>t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha_0$</td>
<td>117</td>
<td>11.8</td>
<td>9.9</td>
<td>0.002</td>
</tr>
<tr>
<td>$\alpha_1$</td>
<td>-80.6</td>
<td>6.45</td>
<td>-12.5</td>
<td>0.001</td>
</tr>
<tr>
<td>$\alpha_2$</td>
<td>25.7</td>
<td>6.45</td>
<td>3.98</td>
<td>0.028</td>
</tr>
<tr>
<td>$\alpha_{12}$</td>
<td>-28.6</td>
<td>7.9</td>
<td>-3.62</td>
<td>0.036</td>
</tr>
<tr>
<td>$\alpha_{11}$</td>
<td>26.7</td>
<td>11.2</td>
<td>2.39</td>
<td>0.097</td>
</tr>
<tr>
<td>$\alpha_{22}$</td>
<td>-7.6</td>
<td>11.2</td>
<td>-0.684</td>
<td>0.543</td>
</tr>
</tbody>
</table>

### Table 4.11: Factors and levels used in the full three level factorial designs in combined coagulation and electrokinetic thickening

<table>
<thead>
<tr>
<th>Variable</th>
<th>Low (-1)</th>
<th>Medium (0)</th>
<th>High (+1)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Applied Voltage Gradient (V/m), $x_2$</td>
<td>94</td>
<td>156</td>
<td>219</td>
</tr>
<tr>
<td>Power Consumption Coefficient (%), $x_3$</td>
<td>60</td>
<td>80</td>
<td>100</td>
</tr>
</tbody>
</table>
Table 4.12: Final solid content of 5% MFT under varying operational conditions

<table>
<thead>
<tr>
<th>Applied voltage gradient (V/m) combined with 350 mg/l ferric chloride</th>
<th>Power consumption coefficient (%)</th>
<th>Final solid content (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>60</td>
<td>11.4</td>
<td></td>
</tr>
<tr>
<td>94</td>
<td>80</td>
<td>12.3</td>
</tr>
<tr>
<td>100</td>
<td>13</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>16.1</td>
<td></td>
</tr>
<tr>
<td>156</td>
<td>80</td>
<td>17.4</td>
</tr>
<tr>
<td>100</td>
<td>18.3</td>
<td></td>
</tr>
<tr>
<td>60</td>
<td>20.8</td>
<td></td>
</tr>
<tr>
<td>219</td>
<td>80</td>
<td>22.4</td>
</tr>
<tr>
<td>100</td>
<td>23.7</td>
<td></td>
</tr>
</tbody>
</table>

Table 4.13: Analysis of variance for the final solid content in combined tests

<table>
<thead>
<tr>
<th>Source of variation</th>
<th>Degree of freedom</th>
<th>Sum of squares</th>
<th>Mean square</th>
<th>F-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regression</td>
<td>5</td>
<td>162</td>
<td>32.4</td>
<td>18100</td>
<td>0</td>
</tr>
<tr>
<td>Residual error</td>
<td>3</td>
<td>0.005</td>
<td>0.002</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Total error</td>
<td>8</td>
<td>162</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 4.14: Regression coefficients of full polynomial model for the final solid content in the combined coagulation and electrokinetic thickening (in coded units)

<table>
<thead>
<tr>
<th>Coefficient</th>
<th>Parameter estimate</th>
<th>Standard error of parameter</th>
<th>t-value</th>
<th>P-value</th>
</tr>
</thead>
<tbody>
<tr>
<td>α₀</td>
<td>17.4</td>
<td>0.0315</td>
<td>552</td>
<td>0</td>
</tr>
<tr>
<td>α₂</td>
<td>5.06</td>
<td>0.0172</td>
<td>294</td>
<td>0</td>
</tr>
<tr>
<td>α₃</td>
<td>1.13</td>
<td>0.0172</td>
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Figure 4.1: Height of mudline vs. time under the combined application of applied voltage gradient and ferric chloride
Figure 4.2: Final solid content and increase in solid content vs. combined applied voltage gradient and 350 mg/l ferric chloride
Figure 4.3: Settling velocity vs. time under the combined applied voltage gradient and ferric chloride
Figure 4.4: Effective voltage gradient and voltage efficiency between anode and cathode vs. applied voltage gradient combined with ferric chloride

\[ y = 8 \times 10^{-6} x + 9 \times 10^{-6} \]

\[ R^2 = 0.992 \]

Figure 4.5: Current density vs. applied voltage gradient combined with ferric chloride
Figure 4.6: Power consumption vs. applied voltage gradient combined with ferric chloride

Figure 4.7: Final zeta potential of particles vs. applied voltage gradient under the combined application of electrokinetics and coagulation
Figure 4.8: Turbidity of supernatant under varying applied voltage gradient combined with ferric chloride at the end of the tests
Figure 4.9: Height of mudline vs. time under the combined application of intermittent applied voltage gradient and ferric chloride
Figure 4.10: Settling velocity vs. time under the combined intermittent applied voltage gradient and ferric chloride
Figure 4.11: Final solid content and increase in solid content vs. power consumption coefficient under the combined intermittent applied voltage gradient and 350 mg/l ferric chloride
Figure 4.12: Contour plot for the optimization of final solid content under the electrokinetic thickening

Figure 4.13: Contour plot for the optimization of increase in solid content under the electrokinetic thickening
Figure 4.14: Contour plot for the optimization of solid content under the combined AVG and 350 mg/l FeCl₃ (AVG = applied voltage gradient)
CHAPTER 5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Summary

A broad study on thickening of mature fine oil sands tailings by coagulation and electrokinetics was conducted in this thesis. The geotechnical and mineralogical properties of the solids and chemical properties of the pore water of MFT were examined before the thickening tests on MFT suspensions. The study was divided basically into two parts: (a) thickening of MFT suspensions by coagulation and electrokinetics separately, and (b) combined application of coagulation and electrokinetics to thicken the MFT suspensions. Coagulation tests were conducted into jar apparatus to find out the optimum coagulant and coagulant dosage by observing the location of mudline and final solid content of MFT. The coagulation tests in graduated cylinder were carried out to thicken the MFT suspension and the results are examined in terms of the mudline position, thickening velocity, final solid content of MFT and turbidity of supernatant after settling. In electrokinetic thickening tests the most effective initial solid content was determined first and then the final solid content of the sediments, thickening velocity, power consumption, and turbidity of the supernatant during and/or at the of the tests were measured on the MFT suspensions of 5% initial solid content. The combined thickening tests contained two phases which are: (a) the combined effect of the electric voltage gradient and 350 mg/l ferric chloride, and (b) the combined effect of intermittent current in providing the threshold applied voltage gradient of 219 V/m and 350 mg/l ferric chloride as coagulant.
5.2 Conclusions

This study concluded that electrokinetic thickening, and combined coagulation and electrokinetic thickening are technically feasible to increase the solid concentrations of MFT suspension. The major findings of the research are summarized as follows:

a) The mature fine oil sands tailings tested in this study have a natural water content of 158% (solid content of 38.2%), fine particles (82.5% silt and 17.5% clay) and the specific gravity of 2.58. The MFTs are classified as elastic silt and average zeta potential of the particles is -52.6 mV. The major minerals present in the tailing are quartz, illite, and kaolinite. The tailings water pH and electrical conductivity are 8.19 and 3.51 mS/cm, respectively.

b) In the study of chemical thickening, ferric chloride at 350 mg/l concentration produces the best settling effect among different coagulants investigated in the MFT suspensions in both jar and cylinder coagulation tests. The jar tests results reveal that the effectiveness of coagulation decreases with the increase in the initial solid content of MFT suspension. The thickening tests in cylinder show the solid content of MFT reaches 6.48% from an initial of 5% after 4 hours; the thickening velocity is insignificant after 4 hours.

c) In the study of electrokinetics, it is observed that the electrokinetic thickening is more effective under a low initial solid content (5%) in terms of the final solid content. The results show the solid content of MFT reached 18.75% from an initial of 5% after 7
hours treatment under the applied voltage gradient of 219 V/m, which is significantly better than the chemical coagulation.

d) The theory of sedimentation velocity in the free settling and hindered settling stages was validated using the results of this research.

e) The final solid content of MFT after 7 hours of thickening is 23.74% from the initial of 5% under the voltage gradient of 219 V/m and 350 mg/l ferric chloride, further enhances thickening results. The intermittent application of electric current decreases the final solid content of MFT compared to the treatment with continuous electric current.

f) Under the optimized treatment of combined application, the zeta potential of the tailings particles after the thickening test is the lowest in all treatments, including coagulation, electrokinetics, and combined application. The corresponding turbidity of the supernatant is 14.4 NTU, 30.6 NTU, and 22.7 NTU after 1 hour from the end of the tests.

g) The developed regression models for electrokinetic thickening and combined application of coagulation and electrokinetic thickening fit well with the experimental data and statistically significant.
5.3 Recommendations for Future Research Work

The results of this research reveal that coagulant assisted electrokinetic thickening of mature fine oil sands tailings is effective. With knowledge gained from this research, a number of recommendations could be made for future studies:

- In this study the vertical distance between electrodes was constant and voltage gradient was varied by changing the applied voltage. The vertical distance should be a key variable in further study. The vertical distance may also be changed by using movable cathode.

- The viscosity of tailings water may have strong effect on thickening of oil sands tailings. It is recommended to examine the efficiency of electrokinetic thickening by reducing the viscosity of water at higher temperature.

- The opening (aperture size) of electrodes should be optimized in future study to thicken MFT suspension.

- The property of MFT solids might be changed due to electrochemical reaction at anode. So the tailings solids property should be analyzed whether it meet the regulatory standards for dumping.

- A field scale tests on thickening of MFT should be developed to further investigate the effects of combined coagulation and electrokinetic thickening, including the development of a detailed field scale implementation scheme.
• The current study did not focus on the technical issues and so cost-benefit analysis of this technology should be carried out to provide more practical information to the owner.
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APPENDIX A: GRAIN SIZE ANALYSIS
(MASTERSIZER 2000)

Figure A-1: Mastersizer analysis of mature fine oil sands tailings
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