Slurry Dewatering in Pipe Jacking Industry

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Submitted in accordance with the requirements for the degree of
Doctor of Philosophy

The University of Leeds
School of Civil Engineering

December 2010

To my mother and to the memory of my father

獻給我的爸爸跟媽媽

爸爸:

你那不是很聰明的兒子做到了.他為你讀回一個博士學位.沒有你的支持,這項不可能的任務是無法完成的.相信在另一個世界的你,可以分享這份榮耀.

世澐.

Declaration

The candidate confirms that the work submitted is his own and that appropriate credit has been given where reference has been made to the work of others.

Acknowledgements

There are many people who have contributed in different ways to this research and the enjoyment of my time in Leeds and Newcastle over the last few years who I would like to acknowledge.

Firstly, I would like to express my sincere thanks to my supervisor, Professor Barry Clarke, whose constant interest and enthusiasm for this research was a never-ending source of inspiration and motivation. His technical knowledge and practical perspective have contributed in many ways and had a major influence on the direction of the work.

I have learnt much from discussions with Dr Cousens and I am indebted for the constant help and support that he generously provided. The suggestions from Dr. Poole and Dr. Chapman during the exam are also very beneficial.

My thanks are also due to the Carillion Trenchless Solutions, particularly Ian Stanley for his enthusiastic support of the research. The contribution to the work from the collaboration with Neil Phillips from Geotechnical Consulting Group has been very helpful.

Many people assisted a great help of this research, particularly academic staff: Mick Marsden, Marcia Martell, Stuart Patterson, Karen Stevens, Keith Pierre, Gary Hammersley, Bill Cragie and Donna Swan, and my colleagues: Godwin, Kenneth, Eleanor, Syazrah, Lam, Eric, Lei, Honda, and Lung-wen, Barry, Rowland and Anna from ARUP in Leeds, whose interest in the research, and their knowledge and experience contribution.

I would also like to give my thanks to the University of Leeds for financial support at the final stage.

Finally, I would like to thank my family for their constant support, love and encouragement from the other side of the world. And one final thank you to Naomi, whose love has been a constant source of motivation and happiness from the very beginning.

Abstract

Pipe jacking is a trenchless technique for installing underground pipelines, ducts and culverts. The spoil handing system plays a main role in the whole process since slurry system involves in the pipe jacking process. The solids within the slurry need to be separated out during the process. Without separation, the density of the slurry will increase, hence harder to carry out further excavation.

The main waste produced from pipe jacking industry is slurry, which is not allowed for landfill as it is a liquid waste. Therefore, Slurry must be pre-treated to become solid before being sent to landfill. In the current practice, slurry is pumped to the centrifuge to produce cake. The centrate is returned to the slurry system. However, cake may not be accepted for landfill disposal as it could be classified as liquid waste. Also, using additive in the separation process has not been defined as hazardous or non-hazardous.

This thesis presents experimental investigations of slurry dewatering by sedimentation, centrifugation and clarifier separation on slurry. The relationship between solid concentration and turbidity has been studied to assess the quality of the separated liquid.

Coagulant did not have an obvious effect on settling behaviour in most slurries, however, flocculant (polymer) did. In centrifugal separation, adding polymer into the slurry increased its liquid limit and water content. When a certain centrifugal force was supplied; the water content of cake may be lower than its liquid limit. The usage of flocculant, water content of cake and the quantity of slurry feeding to the centrifuge reduced when a clarifier was employed. There is a good relationship between turbidity and solid concentration for a given sample. The supernatant and centrate can be returned to the slurry tank to supply the water needed in the slurry system.

Keyword: pipe jacking, liquid waste, slurry dewatering, sedimentation, centrifugation, clarifier, flocculant, turbidity.

Table of contents

Declaration i

Acknowledgements ii

Abstract iii

Table of contents..iv

List of Figures.. viii

List of Tables..xv

Nomenclature xvii

Chapter 1 Introduction.. 1

- 1.1 Background and motivation for research 1
- 1.2 Aim and objectives of research 3
- 1.3 Thesis structure 4

Chapter 2 Literature review 6

- 2.1 Introduction... 6
- 2.2 The current pipe jacking process.. 6
  - 2.2.1 Overall process 6
  - 2.2.2 Pipe jacking slurry separation methods 15
    - 2.2.2.1 Hydrocyclone.. 17
    - 2.2.2.2 Centrifuge 19
  - 2.2.3 Waste products of the pipe jacking process and their disposal 25
- 2.3 European and UK legislation 25
- 2.4 Solid-liquid separation methods 33
  - 2.4.1 Introduction 33
  - 2.4.2 Flotation 36
  - 2.4.3 Gravity sedimentation 37
  - 2.4.4 Centrifugal sedimentation 42
  - 2.4.5 Force field 47
  - 2.4.6 Cake filtration 48
  - 2.4.7 Deep bed filtration.. 50

2.5 Summary of the literature review and reason for this research 51
2.5.1 Pipe jacking process 51
2.5.2 Legislation 51
2.5.3 Separation methods 54
2.5.4 Research questions 54

Chapter 3 Characterization of products from pipe jacking process 57
3.1 Introduction 57
3.2 The sample protocol 57
3.3 The testing protocol 59
3.4 Test results 65
3.4.1 Characterisation test 65
3.4.2 Pilot sedimentation test 70
3.4.3 Sedimentation test on field slurry samples 72
3.4.4 Slurry sedimentation tests on laboratory prepared samples 79
3.5 Conclusion 87

Chapter 4 Determination of solid concentration of slurry by turbidity 89
4.1 Introduction 89
4.2 Theory of turbidity 90
4.3 Clay Types 96
4.4 The testing protocol 100
4.5 Test results 102
4.5.1 Laboratory soil tests 102
4.5.2 Mixture of kaolin and bentonite 109
4.5.3 Natural soil 110
4.6 Index testing of turbidity 111
4.6.1 Particle size effect 112
4.6.2 Particle colour effect 114
4.7 Conclusion 116

Chapter 5 The effect of coagulant and flocculant on slurry sedimentation 118
5.1 Introduction........ 118
5.2 Theory of coagulation and flocculation 118
5.3 The effect of chemicals on the sedimentation process 126
5.4 The testing protocol 127
5.5 Test results 130
5.5.1 Kaolin with alum and polymer 130
5.5.2 Kaolin with ferric salt and polymer 135
5.5.3 Bentonite with alum and polymer 140
5.5.4 Bentonite and kaolin with polymer 143
5.5.5 Natural slurry with polymer........ 150
5.5.6 Mercia Mudstone with alum and polymer........ 155
5.6 Conclusion........ 157

Chapter 6 The effect of centrifuge and clarifier separation on slurry 159
6.1 Introduction........ 159
6.2 Laboratory test on centrifuge........ 160
6.2.1 The testing protocol 160
6.2.2 Laboratory test results........ 164
6.2.2.1 The effects of polymer on the output from a centrifuge 164
6.2.2.2 The effect of centrifuge conditions on cake behaviour 167
6.2.2.3 The effect of polymer on liquid limit 170
6.2.3Discussion 171
6.3 Field scale test on centrifuge and clarifier 172
6.3.1 The centrifuge and clarifier separation plant 172
6.3.1.1 Centrifuge separation 173
6.3.1.2 Clarifier separation 173
6.3.2 The testing protocol 181
6.3.2.1 Clarifier design........ 182
6.3.2.2 Scaling up a pipe flow mixer for the field from a laboratory jar test 184
6.3.3 Field scale test results........ 190

6.3.3.1 The effect of slurry flow rate on the behaviour of the cake produced by the centrifuge 190

6.3.3.2 The effect of slurry flow rate on cake behaviour after the clarifier and centrifuge 197

6.3.4 Discussion 200

6.4 Modelling of the effect of centrifuge operation on density of slurry 203

6.5 Discussion 209

6.6 Conclusion 210

Chapter 7 Summary and conclusions 212

7.1 Summary 212

7.2 Main conclusions 213

7.3 Recommendations and suggestions for further work 218

Appendix

References

List of Figures

Figure 2- 1 Pipe jacking and microtunnelling process 7

Figure 2- 2 The key elements of the pipe jacking process 8

Figure 2- 3 Pipe jacking set-up (a) shaft (b) a thrust wall are constructed with jacks and thrust ring.. 9

Figure 2- 4 Pipe jacking machine with a slurry system............................... 10

Figure 2- 5 The spoil handling process 12

Figure 2- 6 Spoil conditioning and lubrication for mechanised pipe jacking... 13

Figure 2- 7 Typical separation plants used by the pipe jacking industry..... 16

Figure 2- 8 A typical cross section of hydrocyclone and a set of six cyclones connected to a common feeding system................... 18

Figure 2- 9 Schematic representation of a typical decanting centrifuge 19

Figure 2- 10 Particle movement toward the wall through a liquid layer in a centrifugal bowl 20

Figure 2- 11 The waste hierarchy.. 27

Figure 2- 12 Wastewater treatment process 33

Figure 2- 13 Classification of solid-liquid separation processes 35

Figure 2- 14 Rectangular basin clarification 38

Figure 2- 15 Circular basin thickener 39

Figure 2- 16 Concept of projected settling area of lamella plates................. 40

Figure 2- 17 Typical lamella clarifier.. 41

Figure 2- 18 A typical nozzle discharge disc centrifuge............................... 45

Figure 2- 19 Performance of various centrifugal sedimentation equipment.. 46

Figure 2- 20 A typical plate-and-frame filter press showing operations (top) and cloth washing (bottom)... 49

Figure 3- 1 Sedimentation tank and sampling level...................................64

Figure 3- 2 The mixing tank..67

Figure 3- 3 Sedimentation test for settling behaviour of different soils 68
Figure 3- 4 The relationship between COD and turbidity of the supernatant extracted by sedimentation of different soils 69
Figure 3- 5 The relationship between COD and polymer (VP1) 70
Figure 3- 6 COD of supernatant with different concentrations of polymer .. 71
Figure 3- 7 COD of lower part of sample with different concentrations of polymer 71
Figure 3- 8 The relationship between COD and sedimentation time at a level 80% of the height of column at different pipe jacking stages 74
Figure 3- 9 The relationship between COD and sedimentation time at a level 60% of the height of column at different pipe jacking stages 75
Figure 3- 10 The relationship between COD and sedimentation time at a level 40% of the height of column at different pipe jacking stages 76
Figure 3- 11 The relationship between dry density and sedimentation time at a level 80% for different pipe jacking process stages ... 78
Figure 3- 12 The relationship between dry density and sedimentation time at a level 60% for different pipe jacking process stages ... 78
Figure 3- 13 The relationship between dry density and sedimentation time at a level 40% for different pipe jacking process stages ... 79
Figure 3- 14 CEC of the cake from the Morpeth and Murton sites 79
Figure 3- 15 Settling behaviour of floc reduction rate with different polymer content 81
Figure 3- 16 The relationship between dry density and sedimentation time at a level 80% of the column height with different polymer contents 83
Figure 3- 17 The relationship between dry density and sedimentation time at a level 60% of the column height with different polymer contents 83

Figure 3- 18 The relationship between dry density and sedimentation time at a level 40% of the column height with different polymer contents 84

Figure 3- 19 The relationship between COD and sedimentation time at a level 80% of the column height with different polymer contents 85

Figure 3- 20 The relationship between COD and sedimentation time at a level 60% of the column height with different polymer contents 85

Figure 3- 21 The relationship between COD and sedimentation time at a level 40% of the column height with different polymer contents 86

Figure 3- 22 CEC of slurry with different content of polymer 87

Figure 4- 1 Light passing through solution to show the distribution of particles 90

Figure 4- 2 Turbidity is determined by the light scattered at an angle of 90° or transmitted light at an angle of 180° from the incident beam in nephelometric measurement. 92

Figure 4- 3 The main composition of clay materials 97

Figure 4- 4 Basic structural units of clay minerals 98

Figure 4- 5 General structures of two layer or 1:1 clay minerals (e.g. kaolin) 99

Figure 4- 6 General structures of three layer or 2:1 clay minerals (e.g. bentonite) 99

Figure 4- 7 The relationship between turbidity and solid concentration of slurry on kaolin and bentonite 103

Figure 4- 8 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for turbidity values less than 500 104

Figure 4- 9 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for FAU values between 500 and 4000 104

Figure 4- 10 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for FAU values above 4000 based on diluted samples 105

Figure 4- 11 The trend lines of turbidity and solid concentration on kaolin and bentonite slurries.. 108

Figure 4- 12 The relationship between NTU and FAU for kaolin and bentonite slurries... 108

Figure 4- 13 The relationship between turbidity and solid concentration for different mixes of kaolin and bentonite slurries 109

Figure 4- 14 The relationship between turbidity and solid concentration of natural soil sample 111

Figure 4- 15 The relationship between turbidity and solid concentration of kaolin slurry for different particle size 114

Figure 4- 16 The relationship between turbidity and colour for kaolin and bentonite 115

Figure 4- 17 The relationship between colour and solid concentration for kaolin and bentonite 116

Figure 5- 1 The interaction between two negatively charged colloidal particles with electrical double layers 121

Figure 5- 2 Polymer adsorb at a surface 125

Figure 5- 3 Mechanism of bridging flocculation 126

Figure 5- 4 Schematic diagram of sedimentation column........................ 128

Figure 5- 5 The effects of the addition of alum and polymer on dry density of kaolin slurry... 131

Figure 5- 6 The effects of the addition of alum and polymer on floc% of kaolin slurry 131

Figure 5- 7 The effects of the addition of alum and polymer on turbidity of kaolin slurry supernatant 132

Figure 5- 8 The effects of polymer and high alum dose on the dry density of kaolin slurry.. 132

Figure 5- 9 The effects of polymer and high alum dose on floc% of kaolin slurry 133

Figure 5- 10 The effects of polymer and high alum dose on turbidity of kaolin slurry supernatant 134

Figure 5- 11 The effects of the addition of ferric salt and polymer on dry density of kaolin slurry.. 135

Figure 5- 12 The effects of the addition of ferric salt and polymer on floc% of kaolin slurry 136

Figure 5- 13 The effects of the addition of ferric salt and polymer on turbidity of kaolin slurry supernatant...................................... 137

Figure 5- 14 The effects of mixing time on dry density, floc% of kaolin slurry and turbidity of kaolin slurry supernatant...................... 138

Figure 5- 15 The effects of the addition of alum and polymer on dry density, floc% of bentonite slurry and turbidity of the bentonite slurry supernatant... 141

Figure 5- 16 The effects of mixing time on dry density, floc% of bentonite slurry and turbidity of bentonite slurry supernatant 142

Figure 5- 17 The effects of different combinations of soil and polymer on dry density.. 144

Figure 5- 18 The effects of different combinations of soil and polymer on floc% 145

Figure 5- 19 The effects of different combinations of soil and polymer on turbidity of different slurries supernatant 146

Figure 5- 20 The effects of mixing time for different combinations of soil on dry density... 147

Figure 5- 21 The effects of mixing time for different combinations of soil on floc% 148

Figure 5- 22 The effects of mixing time for different combinations of soil on turbidity of supernatant.. 148

Figure 5- 23 The effects of polymer addition for natural slurries on dry density.. 151

Figure 5- 24 The effects of polymer addition for natural slurries on floc%.. 151

Figure 5- 25 The effects of polymer addition on turbidity of natural slurries supernatant 152

Figure 5- 26 The effects of mixing time on dry density, floc% of natural slurry and turbidity of natural slurry supernatant 153

Figure 5- 27 The relationship between the COD of natural slurry supernatants and sedimentation time at different sedimentation levels in the column with 20 mg/l polymer....... 154

Figure 5- 28 The effects of alum and polymer on dry density of Mercia Mudstone slurry.. 156

Figure 5- 29 The effects of alum and polymer on floc% of Mercia Mudstone slurry.. 156

Figure 5- 30 The effects of alum and polymer on turbidity of the Mercia Mudstone slurry supernatant.. 157

Figure 6- 1 The state of slurry (a) without settling and (b) with 5 minutes settling.. 162

Figure 6- 2 The effects of the addition of polymer on water content of the cakes for kaolin and the Lambeth group 165

Figure 6- 3 The effects of the addition of polymer on proportion of cakes produced for kaolin and the Lambeth group.......................... 166

Figure 6- 4 The effects of the addition of polymer on turbidity of the cakes produced for kaolin and the Lambeth group 166

Figure 6- 5 The effects of centrifugal time on water content..................... 167

Figure 6- 6 The effects of centrifugal time on the proportion of cake produced 168

Figure 6- 7 The effects of polymer dose and centrifugal time on water content 169

Figure 6- 8 The relationship between water content of the cakes and centrifugal force 170

Figure 6- 9 The relationship between cone penetration depth and water content for various doses of polymer with the kaolin slurry 171

Figure 6- 10 The effects of polymer and centrifugal force on water content in laboratory tests 172

Figure 6- 11 A diagrammatic view of a section of the clarifier 175

Figure 6- 12 Nomenclature in an up-flow lamella clarifier........................... 178

Figure 6- 13 The layout of the field scale test 181

Figure 6- 14 Pilot clarifier in the field. 183

Figure 6- 15 The field scale test separation plant...................................... 190

Figure 6- 16 The relationship between slurry flow rate, polymer dose and water content of cakes at 2500G centrifugal force 192

Figure 6- 17 The relationship between slurry flow rate and turbidity of centrate 193

Figure 6- 18 The relationship between theoretical and experimental throughput and slurry density 195

Figure 6- 19 The relationship between polymer dose and water content of cakes... 196

Figure 6- 20 The relationship between polymer dose, turbidity of centrate and water content of cakes 197

Figure 6- 21 The relationship between polymer dose, the water content of cake and the density of sludge.. 199

Figure 6- 22 The relationship between polymer dose and the turbidity of supernatant and centrate 200

Figure 6- 23 The effect of centrifuge rate on density of slurry from simulation (slurry rate at 180 m³/hr) 207

Figure 6- 24 The effect of slurry flow rate on density of slurry from simulation (centrifuge rate at 40 m³/hr) 208

Figure 6- 25 The effect of time for setup new pipe on density of slurry from simulation (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr) 208

Figure 6- 26 The effect of time of pushing one pipe on density of slurry from simulation (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr) 209

Figure 6- 27 The relationship between polymer dose and water content of cakes from laboratory and field scale tests 210

List of Tables

Table 2- 1 Some basic characteristics of decanting centrifuge 24

Table 2- 2 The waste laws relative to pipe jacking industry 28

Table 2- 3 Basic characteristics of sedimenting centrifuges...................... 43

Table 3- 1 Summary of sites information.. 58

Table 3- 2 Detail of tests on the pipe jacking product................................ 59

Table 3- 3 Protocols for characterisation test 62

Table 3- 4 Basic characterisation of products from pipe jacking process.. 65

Table 3- 5 The density and COD of the slurry at different stages of the pipe jacking process on the Morpeth site 73

Table 3- 6 The time required for COD to fall below 125 mg/l at different levels on the column 73

Table 4- 1 The guideline for the dilution factor 95

Table 4- 2 Dilution effect of turbidity on kaolin slurry................................. 96

Table 4- 3 Classification of clay minerals 98

Table 4- 4 Comparison of selected turbidity mode 102

Table 4- 5 Summary of the regression characteristics of the relationship between turbidity and solid concentration of slurry for kaolin and bentonite slurries for the three ranges of turbidity 105

Table 4- 6 Regression characteristics of the relationship between turbidity and solid concentration of slurry for kaolin and bentonite slurries with the trend lines being forced to go though the origin 106

Table 4- 7 Summary of the regression equations for turbidity and solid concentration of slurry and calibration regression on natural soil (assuming zero turbidity at zero solids concentration)..... 111

Table 4- 8 The guideline of equivalent particle size, sampling time and sampling depth.. 113

Table 5- 1 The effects of alum and polymer on dry density, flocs% and turbidity of kaolin slurry 134

Table 5- 2 The effects of ferric salt and polymer on dry density, flocs% and turbidity of kaolin slurry 139

Table 5- 3 The values of dry density, flocs% and turbidity for kaolin or bentonite slurry mixed with coagulant and polymer................ 143

Table 5- 4 The effects of adding bentonite and polymer into kaolin slurry on dry density, flocs% and turbidity 149

Table 5- 5 Typical result of different slurries on dry density, floc% and turbidity. 155

Table 5- 6 The effect of coagulant and flocculant on slurry settling behaviour 158

Table 6- 1 The controlled parameters for the field centrifuge tests 194

Table 6- 2 The theoretical effect of particle size and density on throughput and sedimentation time 196

Table 6- 3 Comparing the dewatering behaviour of the two different separation processes 202

Table 6- 4 The financial benefits of using a clarifier in the pipe jacking solid-liquid separation process 203

Table 6- 5 Assumed parameters for the simulation of pipe jacking process 206

Table 6- 6 The effect of these parameters on slurry density 207

Nomenclature

Roman symbols

A	total settling area
A_p	area of pipe
a	projected area
C	concentration
d	particle diameter
d_s	plate spacing
d_f	diameter of jar test flocculator paddle
D	hydraulic diameter of the pipe
F	frictional force
f	friction factor
G	earth's gravitational acceleration
G_v	velocity gradient
H	sampling depth
H_f	head loss
h	thickness of the liquid layer at the walls
L	length of pipe prior to the centrifuge
L_c	length of centrifuge bowl
L_m	settle particle maximum travel distance
L_p	length of the plate
M	intensity of scattered light
N	number of particles per unit volume
N_p	power number
N_r	revolutions per minute
n	refractive index
P	power dissipated in flocculator
Q	maximum slurry feed rate (throughput)
Q_p	flow rate through pipe flocculator
R	radius of rotation
RCF	relative centrifugal force
Re	Reynolds number
Re_j	Reynolds number for a laboratory stirrer configuration
Re_p	Reynolds number for a pipe flow
r_0	initially situated in the liquid surface
r_1	initial radius
r_p	particle of radius
SG	Specific Gravity
S_s	specific gravity of particle
T	retention time
t_R	minimum retention time
U_s	net settling velocity
V	volume of fluid in the flocculator pipe
V_c	volume of clarifier

V_f	upward velocity of the fluid flow
V_s	particle terminal velocity
v	mean fluid velocity
W	plate width

Greek symbols

θ	angle of plate to the horizontal
ω	angular velocity
ρ_s	density of solids
ρ	density of fluid
η	dynamic viscosity
μ	kinematic viscosity
$\frac{dr}{dt}$	velocity of the particle

Chapter 1 Introduction

1.1 Background and motivation for research

On the basis of the policies set out in the Waste Strategy for England in 2007 (Defra, 2007), levels of commercial and industrial waste landfilled are required to fall by 20% by 2010 compared to 2004. The Department for Business, Innovation and Skills (BIS) Strategy for Sustainable Construction set a target for a 50% reduction of Construction, Demolition and Excavation (CD&E) waste to landfill in 2012 compared to 2008 (BERR, 2008).

A key point of the Government's waste management strategy is the promotion of a waste hierarchy: reduction, re-use, recycling, recovery and disposal (Defra, 2007). The waste hierarchy defines a number of methods of waste disposal from least to most harmful to the environment. The Government is therefore increasing the landfill tax escalator to give greater financial incentives to businesses to minimise waste. In addition, it is no longer possible to dispose of liquid waste to landfill and the pre-treatment of non-hazardous waste was required from October 2007 to reduce the amount of waste and prevent leachate from landfilled waste contaminate groundwater.

Most of the construction waste is either demolition waste or material left after construction is complete. There is a further category of construction waste which is based on construction processes used as part of ground works. The majority of this is soil or rock depending on the process. This can be simply excavated material or can be in the form of slurry. The former can be disposed to landfill though is more likely to be used in construction as engineered fill. The latter is more difficult to treat since it may contain additives used to facilitate the construction process. The soil or rock can be contaminated from previous use of the land.

There are a number of construction processes that generate slurries; for example piling, tunnelling and pipe jacking. In the pipe jacking industry, slurry is used to reduce jacking forces, facilitate transportation of excavated material from the face to the surface and support excavated faces. Some additives (e.g. bentonite or polymer) may be added to the slurry or injected between a jacked pipe and soil as lubrication and as soil conditioning to improve the performance of the pipe jacking process.

The EU directive 99/31/EC on landfill classifies slurry as a liquid because of the limited solids content. Since liquid waste cannot be sent to landfill slurry must be treated before being disposed of. However, there has been little research (Phillips, 2010) in slurry separation in the pipe jacking industry. Furthermore, the majority of literature focuses on purity of supernatant rather than the water content of the solid in solid-liquid separation. Therefore, there is a need to manage slurry waste in this industry. There are three issues to be addressed. The first is to separate the solids from the slurry; the second is to ensure the liquid produced is not classified as waste; and the third is to ensure that any additives used are not contaminants. There is also the issue of the potential contamination of groundwater due to the additives used as lubrications.

1.2 Aim and objectives of research

The major aim of this research was to improve upon the current waste treatment from pipe jacking industry to comply with the new EU regulations.

The objectives of this research are:

- To identify the EU/UK legislation requirement on the waste produced from pipe jacking;
- To identify whether slurry is classified as non-hazardous or hazardous waste;
- To identify methods of treating slurry so that it can be separated into non-hazardous solid waste and recyclable liquid;
- To increase the effectiveness and efficiency of current processes in order to reduce the amount of waste;
- To reduce the costs of disposal and reduce the environmental impact.

1.3 Thesis structure

This thesis has been written in seven chapters, the outlines of which are described in the following text:

Chapter 1 - Introduction: This provides the background to the research and states the aim and objectives of the research giving a summary overview of the research work.

Chapter 2 - Literature review: This is a review of pertinent literature for the management of slurry waste from the pipe jacking industry. This chapter is divided into four sections detailing the pipe jacking process, European/UK legislation, solid-liquid separation methods and summary.

Chapter 3 - Characterization of products from pipe jacking process: This focuses on the waste produced from a slurry system in a pipe jacking process. Six sites were investigated by characterising the slurry and undertaking sedimentation tests on trial and field samples to understand the separation process. They indicated that the solids produced on site maybe not acceptable to landfill as they may still be classified as liquid waste because of their water content.

Chapter 4 - The turbidity of slurries: Turbidity is a recognised indicator of the clarity of liquid and is related to solid concentration. The theory and principle of detecting turbidity was introduced in this chapter and laboratory and natural soils were tested to show a relationship between turbidity and solid concentration as a rapid means of assessing the quality of the separated liquid.

Chapter 5 - The effect of coagulant and flocculant on slurry sedimentation: This chapter shows the effect of coagulation and flocculation on settling speeding of solids within slurry. A series of experiments have been conducted to study the effect of coagulant and flocculant on settling behaviour with variety of slurries.

Chapter 6- The effect of centrifuge and clarifier separation on slurry: It continues the results from Chapter 5 to describe the effect of a centrifuge and additive on cake dewatering behaviour in laboratory tests. Field scale tests on a clarifier and decanting centrifuge were also studied.

Chapter 7- Summary and conclusions: It discusses the findings of this research project, general conclusion and recommendations for future research. In particular, it summarises the benefits to be gained from the clarifier and the problems encountered. Finally, the chapter concludes the thesis by submitting suggestions and recommendations for waste treatment for the pipe jacking industry.

Chapter 2 Literature review

2.1 Introduction

The pipe jacking process and its waste products and their disposal and the current practice of solid-liquid separation for pipe jacking process are reviewed. The European/UK legislations on the waste produced relevant to pipe jacking industry are summarized. The principles of solid-liquid separation and a brief description of the processes are discussed.

2.2 The current pipe jacking process

2.2.1 Overall process

Pipe jacking is the trenchless technique for installing underground pipelines, ducts and culverts. The term “microtunnelling” is generally used to describe all types of pipe jacking in smaller diameter pipes, normally less than 1000 or 900 mm (Thomson, 1993; Attewell, 1995; Reeves et al., 2006). It is primarily used as an alternative to open cut excavations because of obstacles such as motorways, railways, rivers, buildings and airports in the path of pipe laying projects and to minimize the traffic disruption in urban areas.

There are other benefits for using trenchless technology: safety and environmental aspects. Health and Safety Executive guidance suggests trenchless technologies can avoid many of the hazards of open trench excavation such as collapses and falling materials when people are working in excavations. The environmental benefits to be gained by the use of pipe jacking techniques are reducing the quantities of imported fill and outgoing disposal materials (Pipe Jacking Association, no date).

The system by which pipes are thrust through the ground and the material from the face is removed through the pipeline is either mechanical or manual excavation. The pipes are introduced at a working shaft and gradually pushed forward by jacks. A boring machine leads the jacked pipes and enables the pipeline to be kept on line and level by using jacks for steering (BS6164, 2001). A mechanical pipe jacking excavation is shown in Figure 2- 1.

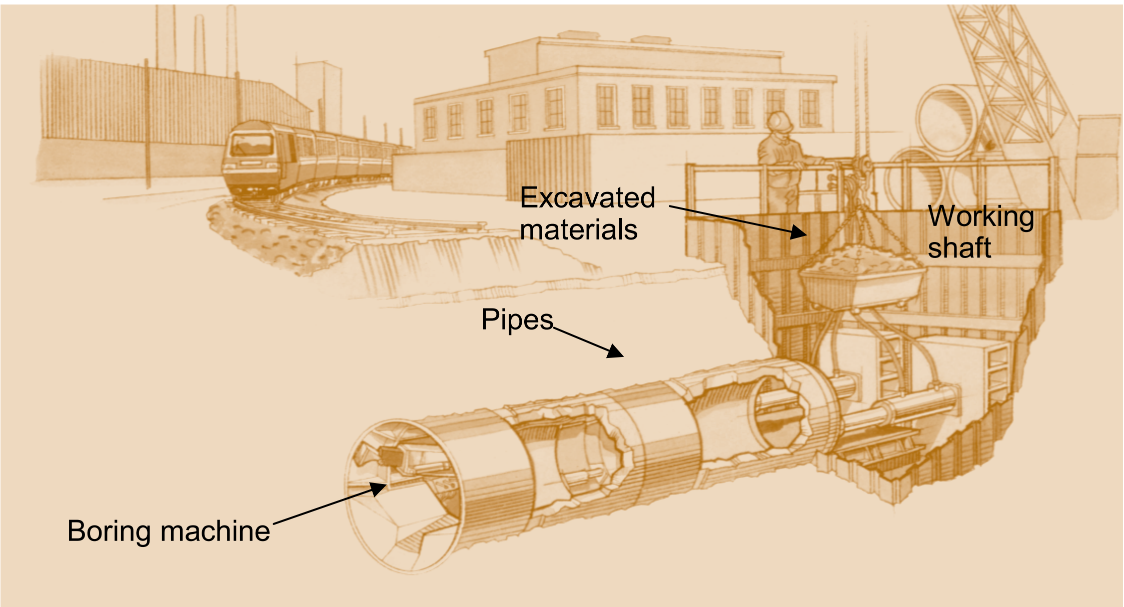


Figure 2- 1 Pipe jacking and microtunnelling process (Figure courtesy of the Pipe Jacking Association)

A shaft and a thrust wall are constructed with jacks and thrust ring (Figure 2- 2 and Figure 2- 3) to provide reaction to push the pipe through the ground. During the pipe jacking process, an anticipated contact force (frictional resistance) is produced between the ground and the pipe. A thrust wall is constructed to provide a reaction to the jacking forces. A thrust ring is used to transfer the jacking forces from the jacked pipe to the ground. Jacks are transmitting the loads from the thrust ring to the thrust wall (Thomson, 1993; Pipe Jacking Association, no date).

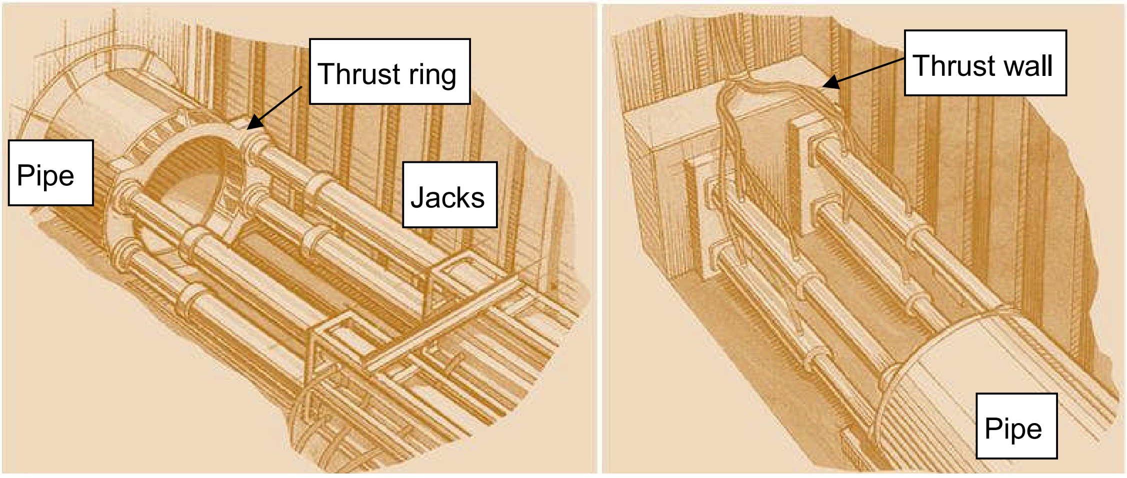
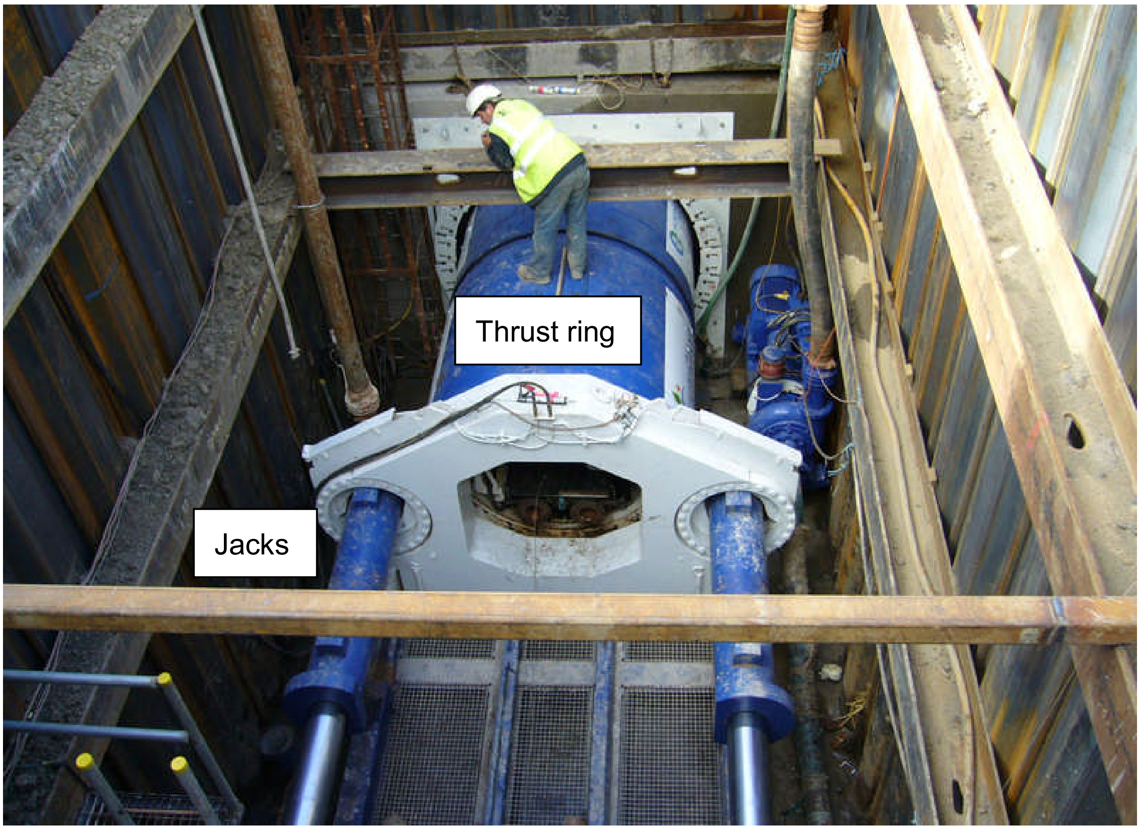
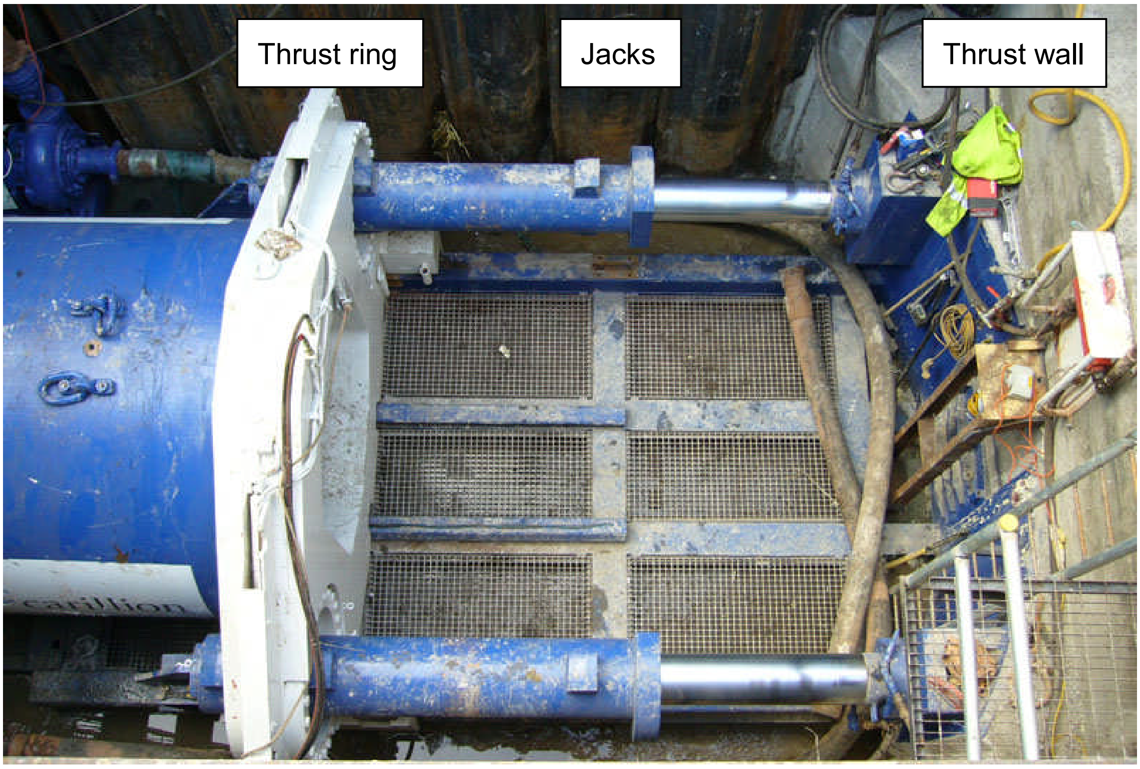


Figure 2- 2 The key elements of the pipe jacking process (Figure courtesy of the Pipe Jacking Association)

The pipe jacking processes of boring through the soil, spoil handling systems and need for supporting the face of the soil in contact with the boring machine vary depending on the ground conditions. In the pipe jacking process, the support is normally achieved by the use of slurry to prevent surface collapse in front of the boring machine. In stiff clays it is possible to excavate by hand (manual pipe jacking) or machine with an unsupported boring face (no use of slurry). Open face techniques (refer to Figure 2- 1) with the material removed with conveyors or muck cars can be used in manual pipe jacking. This technique is limited because of the soil type, the minimum diameter of tunnel and health and safety concerns. Therefore, hand excavation is being replaced by mechanised excavation with a mechanical or hydraulic spoil handling system.



(a) overview of a pipe jacking shaft



(b) a thrust wall is constructed with jacks and thrust ring

Figure 2- 3 Pipe jacking set-up (a) shaft (b) a thrust wall are constructed with jacks and thrust ring

A mechanised excavation with a hydraulic spoil handling system (slurry system) is often being used in the pipe jacking industry. This is because slurry provides some boring face support, reduces the jacking force and transports the excavated material from the face. Slurry is water based fluid containing drilling mud and excavated material. Drilling mud is a fluid which is designed to stabilize, lubricate and cool in the drilling process for pipes and ducts which reduces the friction between soil cuttings, and between the cuttings and the cutters and cutter head (Thomson, 1993; Milligan, 2000; Reeves et al., 2006). Figure 2- 4 shows the slurry system in a pipe jacking process. Excavated material is transported from the face to the surface suspended in slurry. The pressure of the slurry is used to balance the groundwater and face pressures (Pipe Jacking Association, no date).

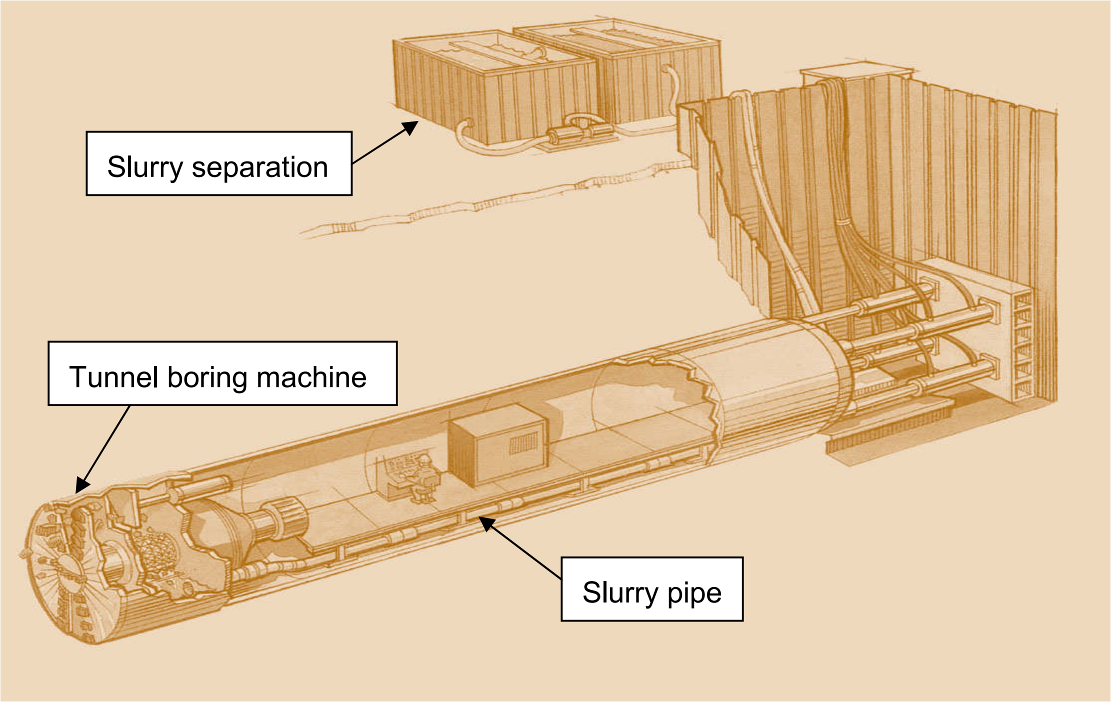


Figure 2- 4 Pipe jacking machine with a slurry system (Figure courtesy of the Pipe Jacking Association)

The boring machine usually excavates a slightly larger diameter, typically 10 to 20 mm (Reeves et al., 2006) , than the outside diameter of the pipes in order to reduce the friction on the pipes. The slurry is pumped to the face of the excavation to support the face to prevent collapse of the face. The slurry also acts as a lubricant to reduce the frictional resistance between the soil and the pipes. Some slurry is pumped into the annulus between the ground and the pipe so that the jacked pipe is effectively floating within the slurry. The liquid film around the pipe reduces the friction between the pipe and the wall thus reducing the force needed to jack the pipe (Milligan and Marshall, 1998; Milligan, 2000; Suhm, 2003; Reeves et al., 2006; Borghi, 2006; Zhou et al., 2009).

A single pipe comprises a number of pipe sections. Each section is continuously pushed into the ground as the face is excavated. This excavated material is removed by the slurry which increases the density of the slurry. According to Zhou et al. (2009), high density slurry is better for reducing the jacking force, supporting the face and reducing the potential for the collapse of the surface. However, very dense slurry is more difficult to pump because of the higher pressures needed to overcome the viscous resistance within the pipes. Therefore, the additional solids have to be separated from the slurry to control the slurry density within an acceptable range. The details of slurry separation processes are described in section 2.2.2.

The slurry handling process is a cyclical process in the pipe jacking process as shown in Figure 2- 5. It links four operations: excavation, transport, separation and disposal. The slurry is pumped to the tunnelling face and then transports the excavated materials to the solid-liquid separation unit. The separated solid is sent to disposal and the liquid is returned to the slurry tank. The properties of the slurry can also change as the tunnel face advances due to the variation in ground conditions. The slurry has to remain stable over the time of the project which implies it has to be continually monitored as excavation proceeds to ensure that sufficient solids are removed to maintain the density within a range which is typically between 1.05 to 1.10 Mg/m³. This density has from experience to meet the conflicting requirements of low viscidity and acceptable density. Slurry is introduced into the process to lubricate the cutters, improve the flow of excavated material through the head chamber, assist the flow of material from the head chamber, improve the conditions of the spoil, improve the separation process and improve the properties for disposal as shown in Figure 2- 6 (Milligan, 2000).

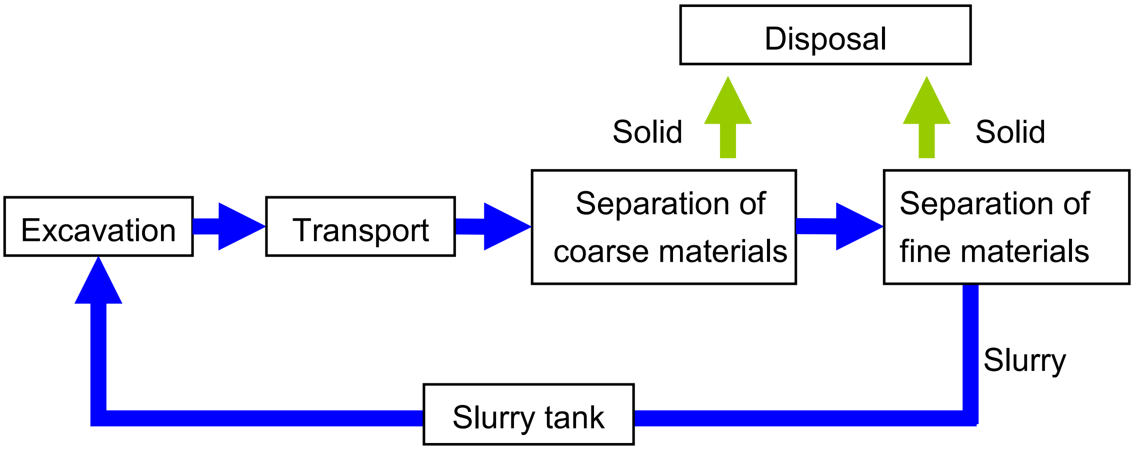


Figure 2- 5 The spoil handling process

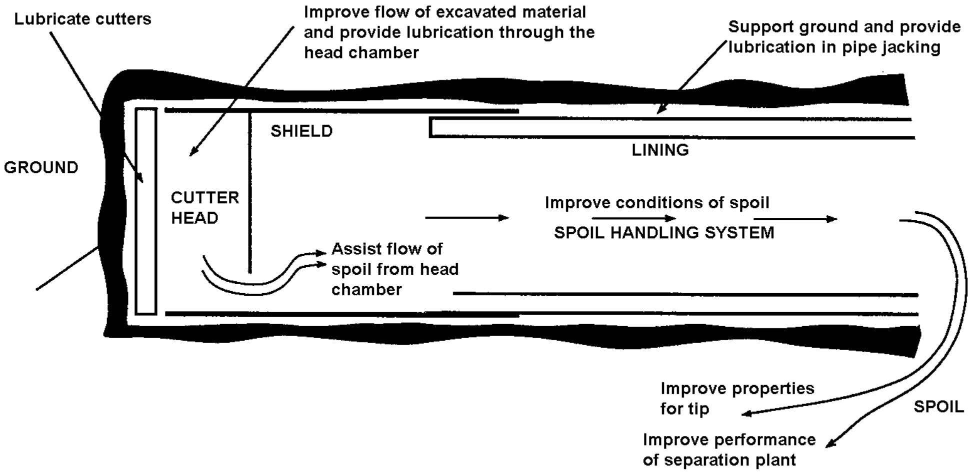


Figure 2- 6 Spoil conditioning and lubrication for mechanised pipe jacking (Milligan, 2000)

In a slurry machine the excavated material is transported from the boring face to the surface by the circulating slurry. The separation method that removes the excavated soils from the slurry is critical to the success of the pipe jacking operation. The ability of the slurry to perform satisfactorily as the excavation continues decreases with returning slurry as it becomes overloaded with excavated particles.

Since the slurry system is part of the pipe jacking process, the spoil handing system is also part of the process. The solids within the slurry need to be separated out so that the slurry can be reused. However, the finer the particle the more difficult it is to remove in the time available. Gravels and sands can be removed inline by screens and hydrocyclones respectively. Finer particles such as silts and clays remain in suspension for a long time. It is possible to remove all solids if there is sufficient time to allow the suspended solids to settle out. This will require space for settling tanks which may be limited and significant quantities of slurry to allow the pipe jacking to continue. The time for separating out the particles also affects the pipe jacking process. A longer separation time will normally result in an increased slurry density unless the total quantity of slurry in the system is increased. The increase in density is due to the excavated soil constantly being added into the slurry tank. Therefore, there is limited time to separate out particles during the process. Hence only some fines are removed. This means the condition of the slurry will change, increasing the viscosity and density which will impact on the excavation, spoil handling and separation processes.

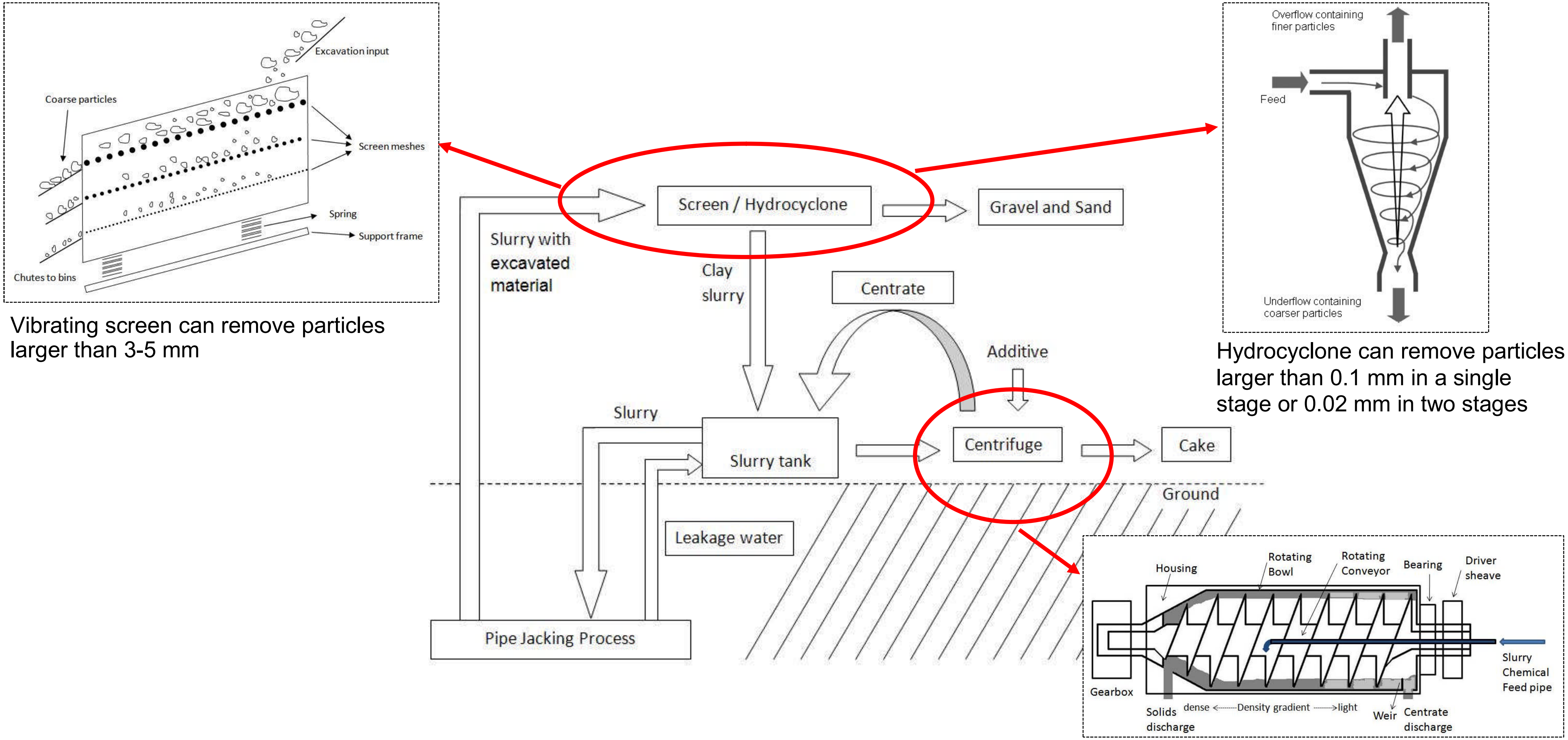
In order to start with slurry of the right density it is necessary to add bentonite or polymers. A small amount of bentonite (3-7% by weight) may be added to the slurry to support the working face for ground containing inadequate amounts of clay. It can stop cuttings falling to the bottom of the machine head chamber or sedimentation in the pipes during stoppages of fluid circulation since the soil particles remain in suspension due to the viscosity of the slurry (Milligan, 2000; Suhm, 2003; Reeves et al., 2006; Borghi, 2006).

Polymer is sometimes used in a drilling mud. Polymers are synthetic chemicals having molecular weights up to millions with varying degree of charge density (the amount of electric charge in the surface). The basic chain of polymer is often an acrylamide or amine. Polymers can be anionic, cationic or non-ionic. An example for non-ionic polymer is polyacrylamide ($-CH_2CHCONH_2-$). The neutral amide group ($-CONH_2$) may be replace by a carboxylic acid group ($-COOH$) which can ionize to give an anionic polymer, whereas replacement by an ammonium group ($-CH_2N^+R_3$) may be used to produce a cationic polymer (R represents an organic group, e.g CH3).(Barnes and Wilson, 1983; Svarovsky, 2000; Tarleton and Wakeman, 2007)

2.2.2 Pipe jacking slurry separation methods

With a slurry system, separation facilities are needed to remove the spoil from the mud. The aim is to separate the mud mix from the solids and to reuse it as the carrier fluid. Settling tanks, coarse screens, hydrocyclones, dewatering screens and centrifuges are the most common systems found on pipe jacking sites. Settling tanks offer the simplest and least expensive separation for particle sizes above 1mm, that is gravels and sands. The settling tank may not be possible on sites where space is limited because of the size of the tank and the quantity of additional slurry needed to continue pipe jacking while allowing for settling time (Stein, 1989; Thomson, 1993; Maidl et al., 1996).

The use of slurry tunnelling has increased in the pipe jacking industry over the past ten years. The slurry separation plants and their operation have been developed at the same time. Many improvements have come from the oil and gas-drilling industry and the need to satisfy the changes in waste-disposal legislation in the UK (Phillips, 2010). The most common separation plants to date include a combination of particle separation processes as shown in Figure 2- 7.



Vibrating screen can remove particles larger than 3-5 mm

Hydrocyclone can remove particles larger than 0.1 mm in a single stage or 0.02 mm in two stages

Centrifuge can remove particles larger than 5 μm

Figure 2- 7 Typical separation plants used by the pipe jacking industry

The excavated materials are delivered to a coarse screen to remove clay balls and/or coarse particles of particles sizes above 3-5 mm. A large amount of material can be screened off because many types of clay are cut and transported in lumps. The materials retained on the screen are disposed to a bin via a chute. The materials passing through the screen are sent to the primary hydrocyclone. The finer particles are passed through to the second set of hydrocyclones. The coarser particles from both primary and second hydrocyclones are passed through vibratory dewatering screens. The dewatering screen is a vibrating screen that reduces the water content further. Sand and silt (particle size down to 100 μm in a single stage or 20 μm in two stages) can be removed by hydrocyclones. The finer particles remain in suspension and are returned to the slurry tank. Most clay materials (described in section 4.3) are left in the slurry. Centrifuges with additives (flocculants) are used offline to remove particles down to 5 μm from the slurry. The centrate (liquid from a centrifuge) is returned to the slurry tank (Stein, 1989; Thomson, 1993; Maidl et al., 1996; Milligan, 2000; Reeves et al., 2006; Phillips, 2010).

The main separation processes using hydrocyclone and centrifuge are described below.

2.2.2.1 Hydrocyclone

The separation action of hydrocyclones is based on the effect of centrifugal forces. Hydrocyclones have no moving parts and the necessary vortex motion is performed by the fluid which is pumped tangentially into a cylindrical body.

A hydrocyclone consists of a cylindrical section joined to a conical section (Figure 2- 8). The slurry is injected tangentially through the inlet opening in the upper part of the cylindrical section and, as a result of the tangential entry; a strong swirling motion is developed within the cyclone. A portion of the liquid containing the fine particles is discharged through a tube fixed in the centre of the top of the cylindrical section and projecting some distance into the cyclone; this outlet tube is called the overflow pipe or vortex finder. The underflow, which carries most of the solids, leaves through the opening in the apex of the cone. Typically, particle sizes ranging from 5 to 200 μm can be removed by hydrocyclones (Stein, 1989; Thomson, 1993; Maidl et al., 1996; Milligan, 2000; Svarovsky, 2000; Richardson et al., 2002; Tarleton and Wakeman, 2007; Phillips, 2010).

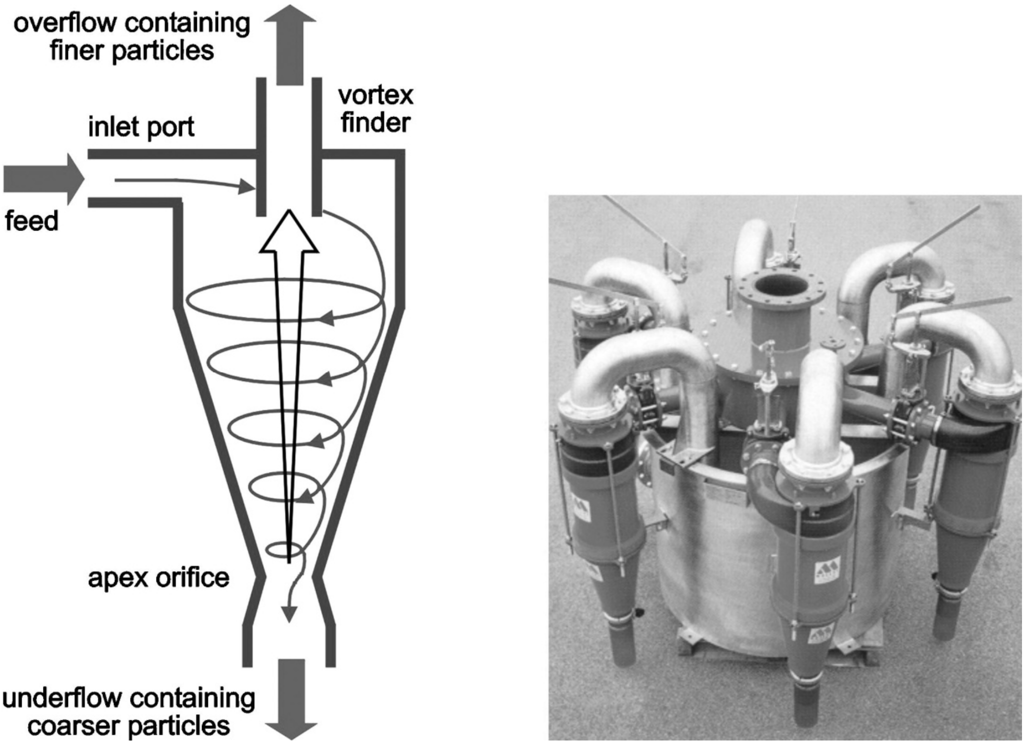


Figure 2- 8 A typical cross section of hydrocyclone and a set of six cyclones connected to a common feeding system (Tarleton and Wakeman, 2007)

2.2.2.2 Centrifuge

Centrifuges contain moving parts to create a gravitational force to cause solid separation. They may be used to remove particles down to 5 μm in a small throughput (Milligan, 2000; Reeves et al., 2006). A decanting centrifuge is often used in pipe jacking industry. The other type of centrifuge is discussed in section 2.4.4. It is based on the principle that soil particles are denser than the liquid. The centrifuge uses centrifugal force to speed up the sedimentation rate of slurry solids. In a typical decanting centrifuge (Figure 2- 9) the flocculated slurry is pumped into a horizontal bowl rotating at high speed. The liquid is removed through a skimming tube or over a weir. The solids remain in the bowl and are intermittently or continuously discharged from the bowl by a conveyor (Stein, 1989; Thomson, 1993; Maidl et al., 1996; Milligan, 2000; Svarovsky, 2000; Richardson et al., 2002; Tarleton and Wakeman, 2007; Phillips, 2010).

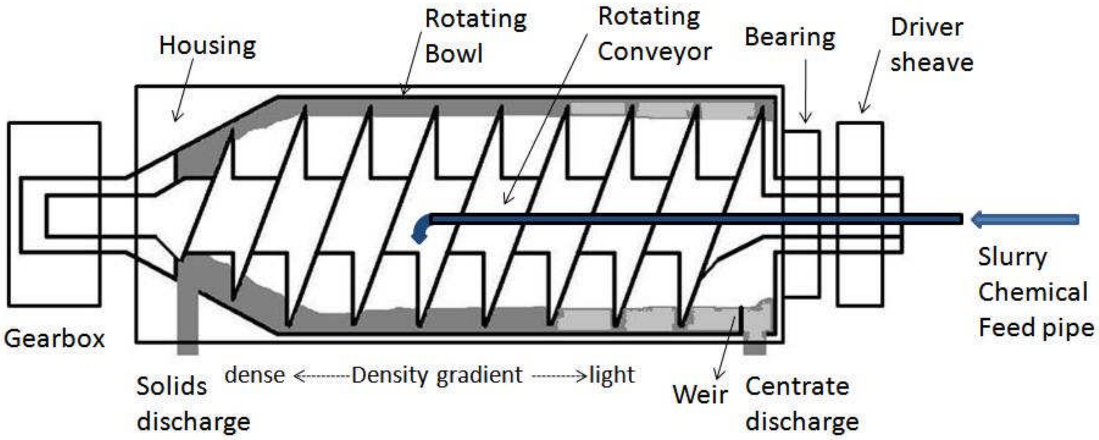


Figure 2- 9 Schematic representation of a typical decanting centrifuge

Flocculants are sometimes added to improve the sedimentation process. The theory and function of flocculation is described in section 5.1. Space is required for sedimentation. However, the pipe jacking process is usually carried out where space is limited. Therefore, a flocculant is thoroughly mixed with the slurry before being pumped into the decanting centrifuge. Excess polymer will be needed to ensure full flocculation if the mixing is not thorough and this additional polymer could be returned to the slurry tank, creating problems in the slurry pipeline due to agglomeration of particles. Records and Sutherland (2001) showed that polymer added to digested sludge in a high speed decanting centrifuge can reduce the water content of the cake. The research showed adding additional 70% of polymer in the centrifuge only reduced the water content by less than 1%. They also suggested it is necessary to admit the flocculant into a separate chamber for it to enter the pond separately and mix with the feed for the high-speed centrifuge. This suggests the location of addition of the flocculant is critical.

The movement of the particle in a decanting centrifuge is described below. The particles movement toward the wall of decanting centrifuge through a liquid layer in a centrifugal bowl is shown in Figure 2- 10.

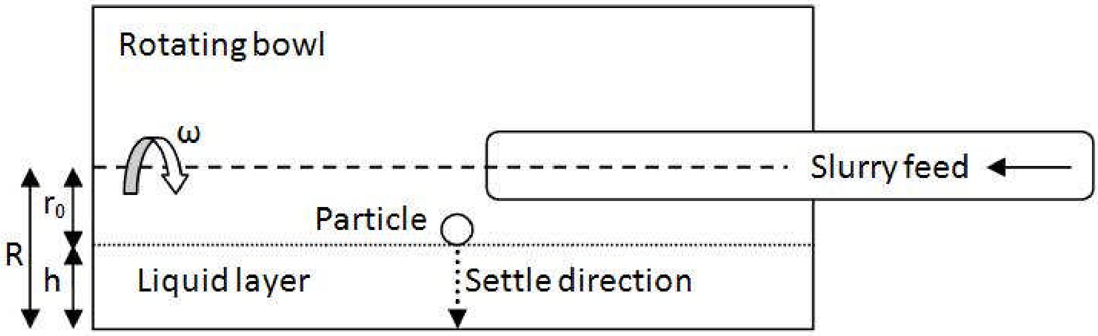


Figure 2- 10 Particle movement toward the wall through a liquid layer in a centrifugal bowl

Richardson et al. (2002) showed the instantaneous velocity ($\frac{\mathrm{dr}}{\mathrm{dt}}$) of particles in the centrifugal field using Stokes' law (the gravitational acceleration g is replaced by the centrifugal acceleration $r\omega^2$) is given by:

$$\frac{dr}{dt} = \frac{d^2(\rho_s - \rho)Rw^2}{18\eta} \tag{2- 1}$$

where d is the particle diameter (m), ρ_s is the density of solids (kg/m^3), ρ is the density of fluid (kg/m^3), R is the radius of rotation (m), ω is the angular velocity (rad/s) and η is the dynamic viscosity of the fluid (Pa·s).

The time taken for a particle to move to a radius R from an initial radius r_1 is given by:

$$t = \frac{18\eta}{d^2 w^2(\rho_s - \rho)} \ln\frac{R}{r_1} \tag{2- 2}$$

For a suspension feed to a centrifuge, the time taken for a particle initially at the surface of the liquid ($r_1 = r_0$) to reach the wall of the bowl (R) is given by:

$$\mathrm{t} = \frac{18\eta}{\mathrm{d}^2 \mathrm{w}^2(\rho_s - \rho)} \ln\frac{\mathrm{R}}{\mathrm{r}_0} \tag{2- 3}$$

If h (=R-r_0) is the thickness of the liquid layer at the walls, then,

$$\ln\frac{R}{r_0} = \ln\frac{R}{R-h} = \ln\left(\frac{R-h}{R}\right)^{-1} = -\ln\left(\frac{R-h}{R}\right) = -\ln\left(1 - \frac{h}{R}\right) \tag{2- 4}$$

From the Mercator series in mathematics,

$$\ln(1+x) = x - \frac{x^2}{2} + \frac{x^3}{3} - \frac{x^4}{4} + \cdots \tag{2- 5}$$

Thus,

$$\ln(1-\frac{\mathrm{h}}{\mathrm{R}}) = -\frac{\mathrm{h}}{\mathrm{R}}+\frac{1}{2}(\frac{\mathrm{h}}{\mathrm{R}})^2-\frac{1}{3}(\frac{\mathrm{h}}{\mathrm{R}})^3+\frac{1}{4}(\frac{\mathrm{h}}{\mathrm{R}})^4-\cdots \qquad (2\text{- }6)$$

Therefore,

$$\ln\frac{R}{r_0} = -\ \ln(1-\frac{h}{R}) = \frac{h}{R}-\frac{1}{2}(\frac{h}{R})^2+\frac{1}{3}(\frac{h}{R})^3-\frac{1}{4}(\frac{h}{R})^4+\cdots \qquad (2\text{- }7)$$

If h is small compared with R, then equation (2- 7) can be presented as:

$$\ln\frac{R}{r_0} \approx \ \ln\frac{h}{R}$$

The minimum retention time (t_R) required for all particles of size greater than “d” to settle through the distance “h” at a velocity given by equation (2- 1) is given by:

$$\mathrm{t_R} = \frac{18\eta h}{d^2w^2(\rho_s-\rho)R} \qquad (2\text{- }8)$$

V_L is the volume of liquid in the bowl.

$$V_L = \ \pi(\mathrm{R}^2-\mathrm{r}_0^2)\,L_c \qquad (2\text{- }9)$$

where L_c is length of centrifuge bowl (m)

The maximum slurry feed rate (throughput) Q (m^3/s) at which all particles larger than “d” will be retained is given by substituting t_R in equation (2- 8) and substituting V_L in equation (2- 9). Therefore,

$$Q= \frac{V_L}{t_R} = \frac{\mathrm{d}^2\mathrm{w}^2(\rho_\mathrm{s}-\rho)\mathrm{R}}{18\eta\mathrm{h}}\,\pi(\mathrm{R}^2-\mathrm{r}_0^2)\,L_c \qquad (2\text{- }10)$$

The throughput of the commercially available decanting centrifuge is usually up to 60 m^3/h. However, in practice the slurry flow rate is 180 m^3/h or more. It is not possible to run a decanting centrifuge inline. This theoretical calculation leads to the conclusion that all particles larger than a certain size “d” can be removed by the centrifuge. Increasing the angular velocity (ω) or particle size (d) will increase the maximum throughput Q. The effects of the density of fluid (ρ), the radius of rotation (R), the thickness of the liquid layer at the walls (h) and the dynamic viscosity of the fluid (η) on the maximum throughput Q is complex due to the fact that the relationships between these factors are interrelated. For example, ρ is directly proportional to η and r_0 and h are directly dependent on R.

The most common design of a decanting centrifuge is one in which slurry is introduced into the bowl by appropriate mixing with the feed point being well away from the liquid discharge point. The separation process takes place inside the cylindrical section of the bowl. The solids are pushed co-currently along the walls of the bowl by the relative velocity of the scroll and moved through the narrower conical end of the centrifuge to discharge.

As the feed is continuous a liquid level is established in the bowl following a cylindrical surface that constitutes the internal surface of the liquid ring. The solids passed out of the liquid ring are drained out by the ejector. The clarified liquid is collected at the other end of the bowl by flowing over the weir. The liquid phase, which may not always be clear due to the presence of fines, leaves the centrifuge via a weir or ports at the broader end of the bowl.

Some characteristics of decanting centrifuges are summarized in Table 2- 1. The machine size, target particle size and solid feed concentration for commercial decanting centrifuges are acceptable for pipe jacking operations. Due to the limit of throughput, a decanting centrifuge can only be used off-line in the pipe jacking industry. Otherwise, multiple centrifuges are needed to achieve the flow rates, which is too expensive.

Table 2- 1 Some basic characteristics of decanting centrifuge (Records and Sutherland, 2001; Richardson et al., 2002; Tarleton and Wakeman, 2007)

Characteristics	Values
Diameters (cm)	10–200
Length	1.5–5 times of the diameter
Centrifugal force (g)	2000-6000
Throughputs (m^3/h)	0.4-60, in extreme cases can up to 100
Particle size (μm)	1–5000
Feed concentration (w/w %)	4–40

In practice, little knowledge is available for slurry separation in the pipe jacking industry. The guidelines and research papers do not cover the slurry separation. Furthermore, the majority of literature, found in literature on water treatment, focuses on purity of supernatant rather than the water content of the solid. The slurry separation system can affect the disposal of the waste and the pipe jacking process. Firstly, the cake must be not classified as liquid waste. Secondly, the water content of the cake will affect the disposal cost due to the fact that the landfill tax is charged by weight. Thirdly, a poor separation operation can affect the success of pipe jacking process. The main problems can be (Phillips, 2010):

- Over-flocculation: the flocculant contaminates the slurry, which may settle in the slurry tank resulting in particles becoming harder to remove through the centrifuge in subsequent cycles;
- Failure to remove the finest particles: producing a fine, rich slurry with an increased mud weight and viscosity;
- Inefficient running: not running the centrifuge to full capacity to keep up with the pipe jacking production rates.

2.2.3 Waste products of the pipe jacking process and their disposal

The wastes from the pipe jacking process with a mechanical hydraulic spoil handling system are mainly coarse materials, fine materials and slurries. The coarse fractions, mostly gravel, sands and balls of clay, from separation plants cause no problems in disposal because they can be considered as solids. The finer materials, cakes produced from the centrifuge, may be not accepted for landfill disposal due to the residual water content of the cake being too high and the undefined hazardous character of any additive used in the separation plants. The slurry retained in the slurry tank at the end of a project will contain a mixture of water and fine particles. This remnant is usually drained to a sewer. The restrictions of sewer disposal are described in next section.

2.3 European and UK legislation

As mentioned above, pipe jacking is a safer method of working than open trench construction but it produces a different type of waste. The main waste produced from the pipe jacking industry is cake through the site operations and slurry at the end of the site operations. Basically, the cake is not supposed to be reused as an engineered fill as it may contain chemicals which may contaminate groundwater. Ideally the cake should be taken to landfill. The additives in lubricating the pipe and preventing the ground collapsing onto the pipe may contaminate groundwater.

The EC regime and UK government policy aim at reducing the waste impact on the environment and human health by implementing a waste hierarchy management and the polluter pays principle. The waste hierarchy (Figure 2- 11) defines a number of methods of waste disposal from least to most harmful to the environment. The priority is prevention, reduce, reuse, recycling, recovery and disposal.

- Prevention: prevent producing waste is the best solution to waste management.
- Reduce: minimise the amount of waste.
- Reuse: use resources again without changing their form.
- Recycle: reprocess (such as compost) of used materials to make new and useful products.
- Recovery: convert waste into energy resources (such as electricity, heat and fuel) through thermal or biological techniques.
- Disposal: disposal is the last operation (such as landfill) to manage waste.

The pipe jacking process produces waste because a void is being created in the ground hence prevention cannot be avoided. However, the amount of waste produced can be minimised. It is therefore necessary to assess the possibilities of reusing, recycling and recovering of the waste before the final disposal operation.

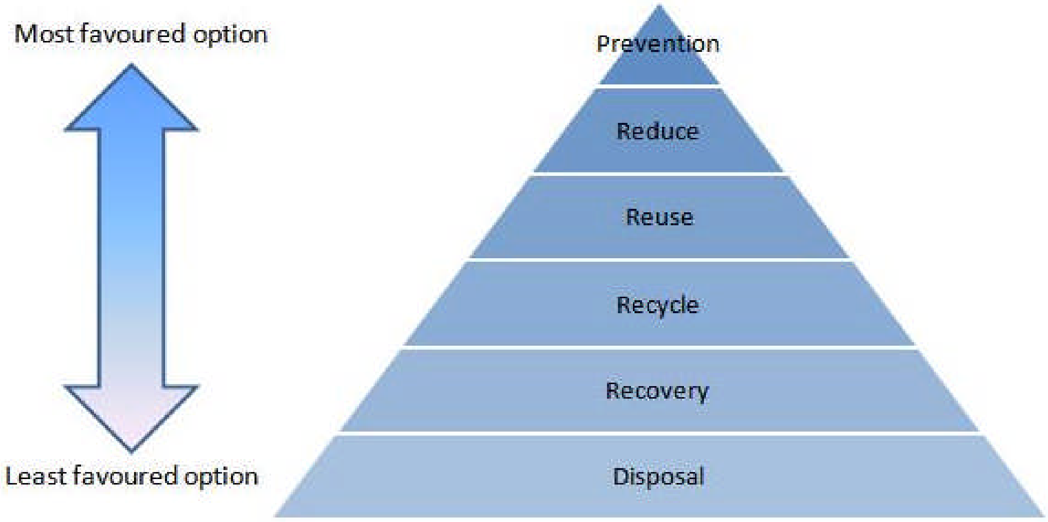


Figure 2- 11 The waste hierarchy

The European Union adopts legislation in the form of directives and regulations. European Directives require member states to implement their provisions nationally for the benefit of Europe. Regulations directly implement EU policy in member states without the need for member states to enact their own legislation. The EU and UK waste legislation are divided into three main categories: general waste framework, treatment and disposal facilities, and others related legislation. The waste laws relevant to the pipe jacking industry are summarized in Table 2- 2.

Table 2- 2 The waste laws relative to pipe jacking industry

Sub-categories	EU/UK directives and regulations	Relevant context
General waste framework	2006/12/EC* on Waste 2000/532/EC on Waste list	Minimize the amount or harmfulness of waste and pollution hazards, and polluter pays. Drilling muds and other drilling wastes containing dangerous substances are "Mirror entries" in the European Waste Catalogue (EWC).
	91/689/ EEC* on Hazardous waste The Hazardous Waste (England and Wales) Regulations 2005	A list of hazardous wastes.
	2008/98/EC on Waste	A waste management principle such as the polluter pays principle and waste hierarchy.
Treatment and disposal facilities	1999/31/ EC on Landfill The Landfill (England and Wales) Regulations 2002 The Landfill (England and Wales) (Amendment) Regulations 2004 The Landfill (England and Wales) (Amendment) Regulations 2005	Liquid waste is not accepted in a landfill. Hazardous waste with a total organic carbon (TOC) content of more than 6% is unacceptable to landfill.
Others related legislation	80/68/EEC on the protection of groundwater against pollution caused by certain dangerous substances Groundwater Daughter Directive 2006/118/EC Groundwater (England and Wales) Regulations 2009	Protection of groundwater against pollution caused by certain dangerous substances.
	Water Industry Act 1991 Environmental Protection Act 1990 Water Framework Directive 2000/60/EC Freshwater Fish Directive 2006/44/EC The Environmental Permitting (England and Wales) Regulations 2010 91/271/EEC on Urban waste-water treatment The Urban Waste Water Treatment (England and Wales) Regulations 1994	Discharge to sewer - a trade effluent consent is needed. Requirements for discharges from urban waste water treatment plants: • Chemical Oxygen Demand (COD) 125 mg/l • Total Suspended Solids (TSS) 35 mg/l
Notes	*This Directive is repealed by Directive 2008/98/EC with effect from 12 December 2010.	

The wastes produced from a pipe jacking separation plant are classified as “drilling muds and other drilling wastes containing dangerous substances” in the European Waste Catalogue (EWC). These wastes are a “Mirror entries”. This means that waste may be classified as either hazardous or non-hazardous depending on the concentrations of “dangerous substances” in the waste. If it is a hazardous waste, it must be treated under the hazardous waste regulation. In addition, the cake produced from pipe jacking separation plant is formed from the solids separated from the slurry as it passes though a centrifuge and solids removed from the screens and hydrocyclones. There may be some chemicals in the waste due to ground contamination or additives used in the centrifuge process. There is a need to check the composition of the additives. A flowchart in Appendix I shows the steps involved in finding out if waste is hazardous or not. Hazardous waste list is showed in Appendix II.

If the additives are deemed to be dangerous substances, then the hazardous properties in the Approved Supply List (ASL) will be examined. The ASL prescribes hazard classifications for many common chemicals. The concentration of the chemical in the waste with the “Classifications, Risk Phrases, Hazards and Hazardous Waste Threshold Limits” (Appendix III) could display the hazardous property.

According to the Landfill (England and Wales) Regulations 2005, liquid wastes whether non-hazardous or hazardous must not be accepted in landfills. However, sludges can, and therefore it is important to be clear about the difference between the sludges and liquid wastes. The Government consulted on a definition of liquid waste as it was not defined elsewhere in UK legislation. They concluded that liquid waste is:

- A waste that instantaneously flows into a void created in its surface.
- Or the quantity of free liquid in a load is more than 250 litres, or more than 10% of the load volume. Free liquid is the liquid that rises to the surface of waste which contains liquid. This may occur as the waste is transported to the disposal site.

To distinguish between liquids and sludges, a waste that flows only slowly rather than immediately into an indentation in its surface (such as made by a stick or spatula) is a sludge and therefore not prohibited (Environment Agency, 2006).

Landfill tax is based on the polluter pays principle. Landfill tax was introduced in October 1996 in the U.K. It is paid to the HM Revenue and Customs for each tonne of waste sent to landfill. The tax is chargeable by weight and there are two rates:

- The lower rate for inactive (or inert) waste, such as rocks and soil.
- The standard rate applies to active waste, such as biodegradable waste.

The landfill tax was set at £2 and £7 per tonne for lower rate and standard rate wastes, respectively, in October 1996. The rates vary from year to year. The landfill tax was increased to £2.5 and £48 per tonne for lower rate and standard rate wastes in 2010. The government has stated that the landfill tax will increase gradually and the standard tax rate will continue to escalate by £8 per year until at least 2014/2015, when it will reach £80 per tonne.

According to the UK Water Industry Act 1991, if industrial wastewater is sent to a sewer a Trade Effluent Consent is needed and there will also be a Trade Effluent Charge. This is calculated and collected by the receiving water company to recover the cost of carriage to and treatment in their treatment plants. The charges for most trade effluents are based on the Mogden Formula Tool. This tool uses an average effluent factor, in terms of Chemical Oxygen Demand (COD) and Suspended Solids (SS) to calculate costs. Moreover, the Trade Effluent Consent typically is maximum instantaneous flow rate, maximum daily volume, composition of wastewater (chemical composition, solids concentration and pH), temperature and pre-treatment requirement.

The requirements and standards for the acceptability of wastewater discharged to the sewer are not identical from one sewer to another because the sewers are privately owned and each one will have a unique treatment plant. The limits which are set out when a permit for discharge is granted includes what substances the effluent contains and water quality issues on that specific watercourse. An important criteria is that it should not contain rapidly settling solids. Some companies may accept wastewater contain settling solids. Typically, rapidly settling solids mean solids with a settling velocity of at least 3 m/hr; settling solids mean solids with a settling velocity of at least 0.25 m/hr. From Stokes' law (Equation 2-1), particle sizes above 30 μm and 9 μm can be considered rapidly settling solids and settling solids, respectively, by assuming the density of particle is 2650 kg/m^3 and viscosity is 1.002×10^{-3} Pa·s at 20°C. It means the solid particle size greater than 9 μm in slurry will not be accepted in sewage.

If the wastewater from pipe jacking consented to discharge to river, it would be subject to the same legislation as a Waste Water Treatment Works (WwTW). The Freshwater Fish Directive (FFD) and Water Framework Directive (WFD) legislation look at the catchment size, the flow of the receiving watercourse and quality standard being applied (salmonid, cyprinid waters etc), then based upon a model mass balance, consented parameters based on Suspended Solids, Organic content (COD etc), Nitrogen (Ammonia – FFD and Total Nitrogen – WFD) and Phosphorous (WFD) is applied.

According to the Groundwater (England and Wales) Regulations 2009, the composition of lubricating agent between pipes and ground during the tunnelling process need to be checked to prevent the pollution of groundwater caused by hazardous substances (see Appendix IV). The non-hazardous pollutants need to limit the input to the groundwater so as to ensure that such inputs do not cause pollution in the groundwater. The composition of flocculant used in the centrifuge also needs to be checked as slurry with certain flocculant may contaminate soil if the slurry is over-flocculated.

2.4 Solid-liquid separation methods

2.4.1 Introduction

Before describing the solid-liquid separation methods, it is necessary to understand the wastewater treatment process. Treatment processes for wastewater can be classified in three ways (primary, secondary and tertiary) which are shown in Figure 2- 12. The choice of separation techniques depends on the type of wastewater to be treated and the requirement of the final sludge/cake. A brief description of the separation processes are given in the following sections.

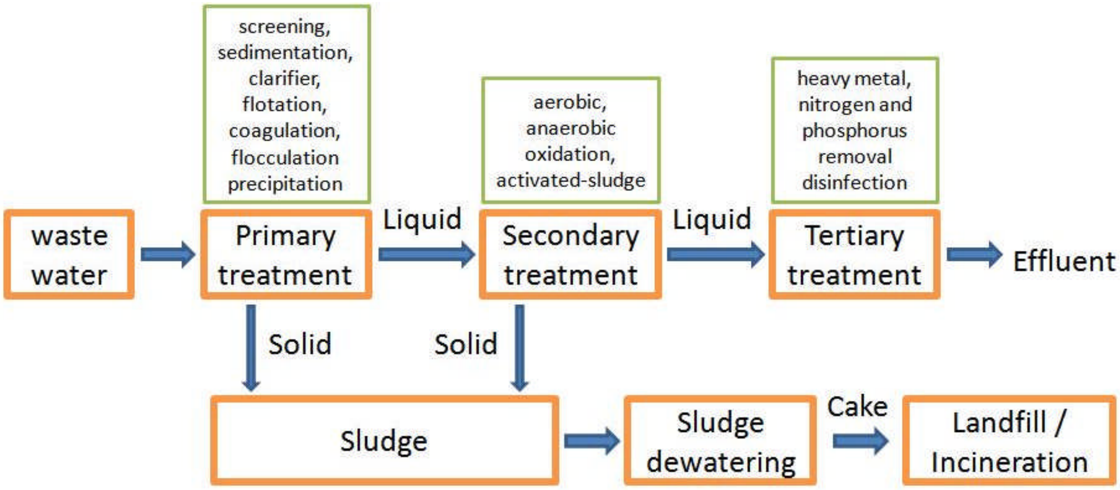


Figure 2- 12 Wastewater treatment process

Typically, the primary treatment is a physical/chemical process, which may include screening, sedimentation, clarification, flotation, coagulation, flocculation and precipitation to remove suspended solids from liquid. This covers the processes used in the majority of pipe jacking projects. It is necessary to proceed to the secondary treatment for organic contaminated wastewaters. The secondary treatment is a biological process, which may be including aerobic, anaerobic oxidation and activated-sludge process to remove the soluble and colloidal organics that escape the primary treatment and to provide further removal of suspended solids. It is unlikely that secondary treatment will be used in the pipe jacking process as there is normally little organic contamination. The tertiary treatment is to provide a final treatment to raise the effluent quality before it is discharged to the receiving environment (sea, river, lake, ground etc), which may be including removal of heavy metals, nitrogen, phosphorus and disinfectants. During these treatment processes, organic or inorganic sludge with high water content may be produced. The choice of the dewatering process depends on the water content requirement of the final disposal (landfill, incineration) and land availability. Mechanical dewatering systems, such as filters and centrifuges, are generally selected where land is not available. It may be possible to produce a cake with 50-75% water content by filter press, 65-85% on vacuum filters and 65-85% from decanting centrifuges (Schroeder, 1977; Tebbutt, 1998; Qasim, 1999; Akers, 1975).

There are two groups of solid separation – sedimentation and filtration. They differ in the way the solid particles are collected. Figure 2- 13 gives the general classification of methods and principles of solid-liquid separation.

In the sedimentation group, the liquid and solids are separated by forces (flotation, gravity sedimentation, centrifugal and force field) acting on the particles. If gravity or centrifugal fields are used, a density difference must exist between the solids and the suspending liquid for the separation to take place.

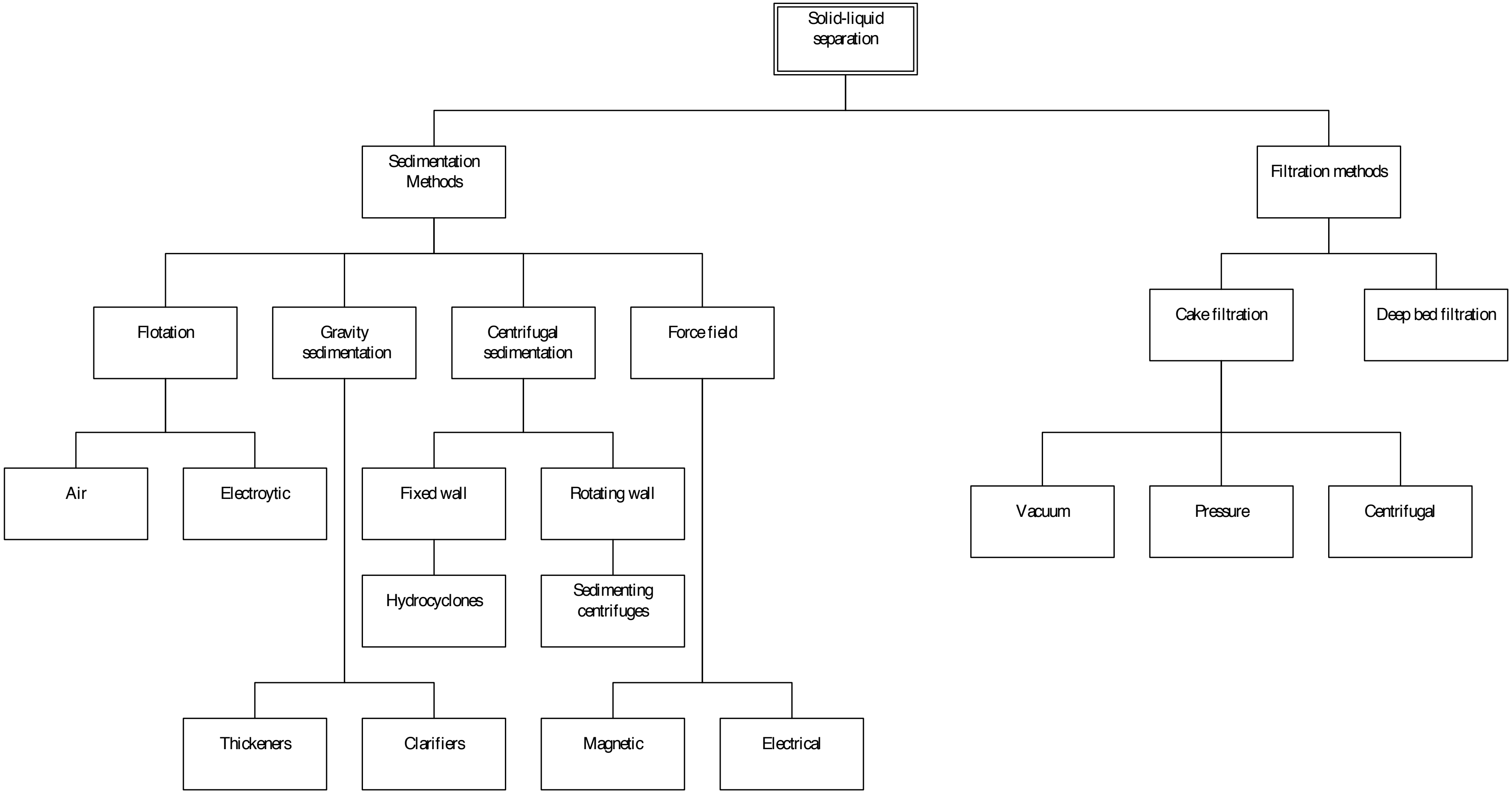


Figure 2- 13 Classification of solid-liquid separation processes

In the filtration group the particles are contained by a medium and the liquid is allowed to flow freely through the medium. Density difference is not important in this group. A continuous operation is not easy to achieve as the medium has to be cleaned by back washing to reduce clogging. Further the costs may be high as the medium has to be replaced.

2.4.2 Flotation

Flotation is a separation process based on the attachment of air or gas bubbles to hydrophobic particles (water-hating, e.g. emulsion paint or mayonnaise), which are then carried to the liquid surface. The process consists of two stages: the production of suitably small bubbles and their attachment to the particles. Depending on the method of bubble production, flotation is classified as dispersed air, dissolved air or electrolytic. Typically bubbles produced are in the range of 30 - 1000 µm diameter and are able to push particle sizes from 300 to 2000 µm upward (Svarovsky, 2000; Tarleton and Wakeman, 2007).

For successful flotation a particle has a net density less than that of water so that the particle can be pushed upward through the slurry by the attached air bubble (Binnie, 2002). Flint and Howarth (1971) indicated that a reduction in bubble size increases the float efficiency for fine particles. Hanumanth and Williams (1988) suggested it is necessary to flocculate the fine or colloidal particles to initiate formation of flocs and enhance its attachment to bubbles during flotation. It implies the size of particle needs to be larger than the rising bubble and the floating force needs to be larger than particle weight. The bubbles produced from electrolysis can be smaller than 50 - 30 µm (Svarovsky, 2000; Tarleton and Wakeman, 2007).

Flotation is generally known to be the most appropriate method for the concentration of fine mineral particles. The method is based on passing bubble streams through a particle suspension where hydrophobic* particles are picked up by the individual bubbles and transferred to the concentrate (Bournival and Ata, 2010). For many years, flotation has been extensively used for separating hydrophobic particles (e.g. coal, bitumen, galena, talc) (Tao et al., 2002; Tu et al., 2005; Bournival and Ata, 2010; Zbik and Smart, 2005). However, clays exhibit properties intermediate between hydrophobic and hydrophilic** behaviour. Therefore, flotation separation may not be suitable in the pipe jacking industry.

*Hydrophobic particles such as quartz suspension which are repelled by water.

**Hydrophilic particles such as soap which are attracted and dissolve well within water.

2.4.3 Gravity sedimentation

Gravity sedimentation is used along with chemicals (coagulants and flocculants) to enhance the efficiency of sedimentation. The theory and principle of coagulation and flocculation are discussed in section 5.1. There are two main kinds of gravity sedimentation – clarification and thickening. If the purpose is to clarify the liquid, the process is called clarification. The main purpose for the thickening process is to produce a highly concentrated slurry.

Common clarification methods use horizontal flow in circular or rectangular vessels and are capable of removing particle sizes ranging between 1 - 50 µm. A typical design is shown in Figure 2- 14. It has a rectangular basin with feed at one end and overflow at the other end. The slurry is mixed with coagulant or flocculant and then passed through to the settling area. Sedimentation occurs as the slurry flows through the settling zone. The solids are discharged from the underflow. The supernatant overflows to the weir. The key principle in the design is that the solids need to settle before they reach the overflow to the weir. In that case supernatant can be obtained free of solid particles (Qasim, 1999; Svarovsky, 2000; Tarleton and Wakeman, 2007). The clarification may be feasible for pipe jacking industry as slurry pre-treatment is able to reduce the amount of slurry sent to centrifuge.

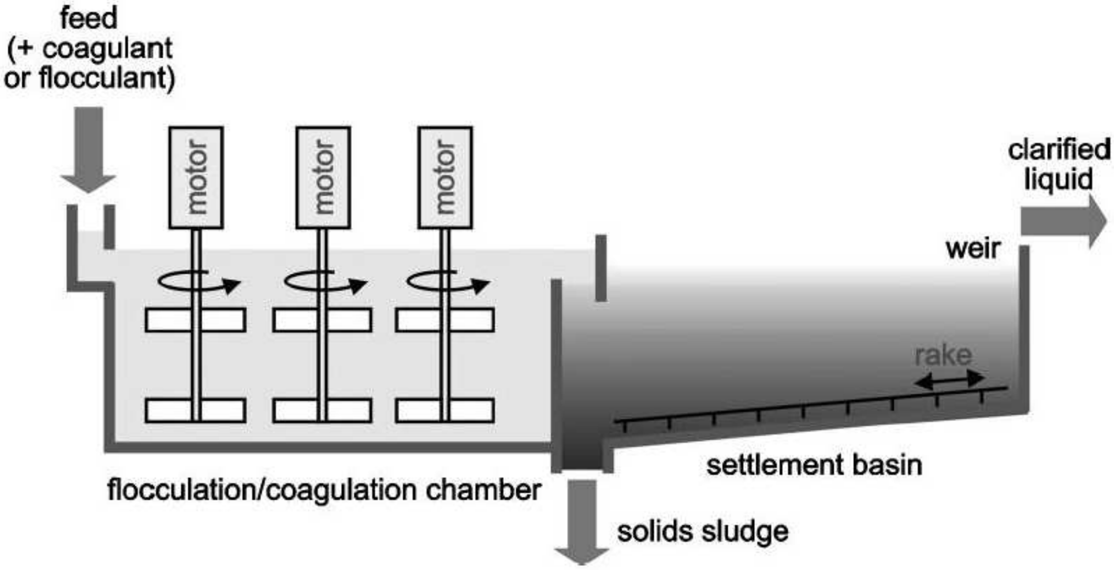


Figure 2- 14 Rectangular basin clarification (Tarleton and Wakeman, 2007)

The most common thickener is the circular basin (Figure 2- 15) which separates particle sizes in the range of 0.1 - 500 µm. The slurry is mixed with coagulant or flocculant before it enters the central feed. The particles in the feed settle until a certain thickness is achieved. Solid concentration increases with depth. The thickening process takes place until it reaches a depth where the density is stable throughout the solid mass. The solid accumulates in the settling zone and discharges from the underflow. The clarified water overflows the weir around the basin. The key principles in the design are the area and depth of the thickener and retention time to concentrate the solids (Svarovsky, 2000; Binnie, 2002; Tarleton and Wakeman, 2007). It may be possible to apply a thickener in the pipe jacking industry as slurry pre-treatment is able to concentrate the solid in the slurry sent to a centrifuge.

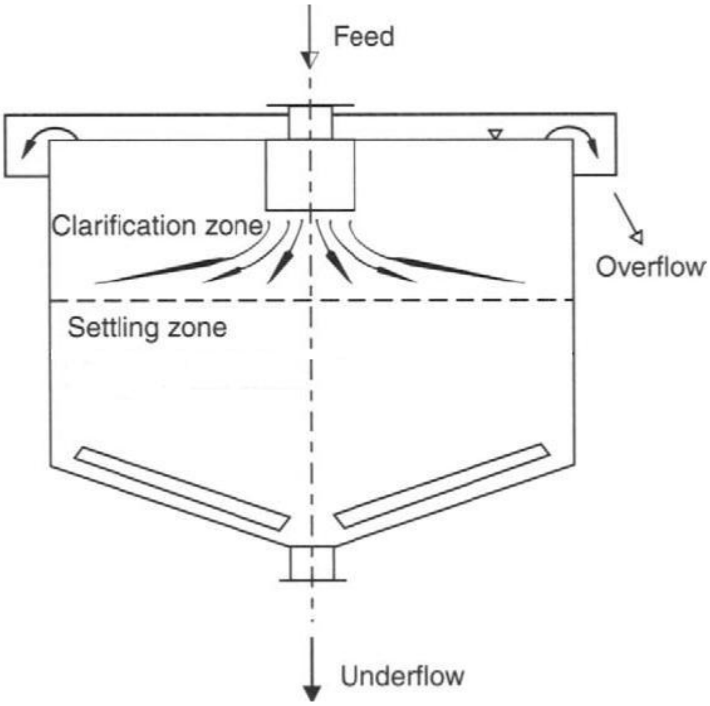


Figure 2- 15 Circular basin thickener (Svarovsky, 2000)

A high rate lamella clarifier was introduced in 1973 (Wenk, 1990). It has a series of inclined parallel plates inside the clarifier. The total settling area (c) is the sum of the vertical projected area (b) of the individual plates (a) (see Figure 2-

16). Therefore a lamella clarifier reduces the land space required for particles settling.

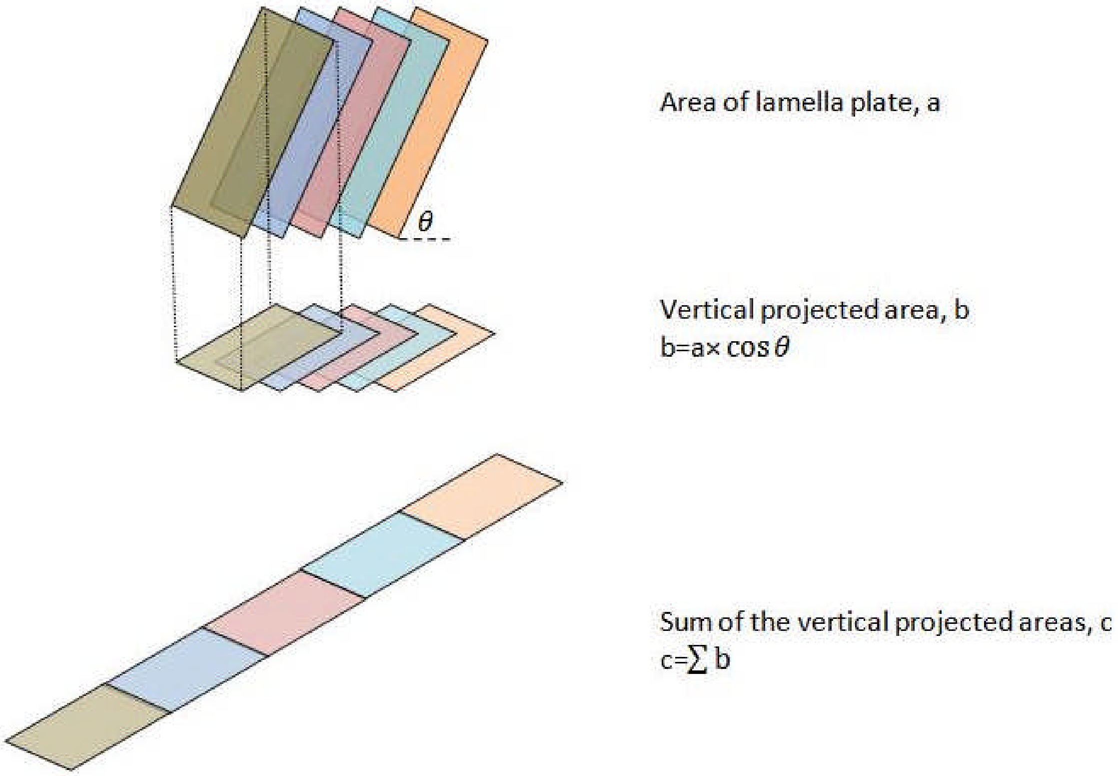


Figure 2- 16 Concept of projected settling area of lamella plates

The plates also help the sedimentation process (Tebbutt, 1998; Letterman, 1999; Svarovsky, 2000; Tarleton and Wakeman, 2007). In a typical counter current lamella clarifier (Figure 2- 17), the flocculated slurry flows upward between the plates while the solids settle out onto the plate surfaces and slide down into the sludge hopper. The supernatant collects at the top (Tebbutt, 1998; Svarovsky, 2000; Tarleton and Wakeman, 2007). The lamella clarifier may be feasible for the pipe jacking industry as slurry pre-treatment can reduce the amount of slurry sent to centrifuge.

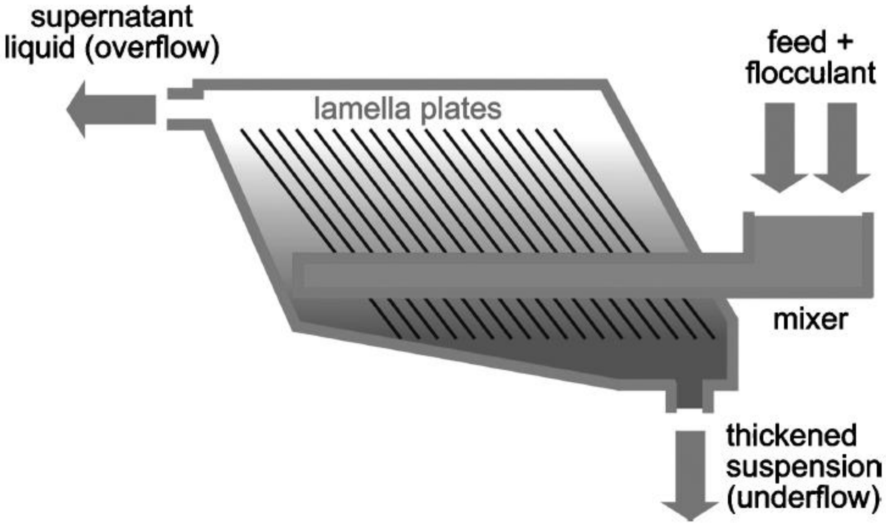


Figure 2- 17 Typical lamella clarifier (Tarleton and Wakeman, 2007)

Some research has been undertaken to reduce the effluent SS (suspended solid) value using a flocculate-clarifier (Anderson and Gould, 1945; Busch and Irvine, 1980; Parker, 1983; Parker and Stenquist, 1986). Parker et al.(1996) reported that low effluent SS levels (average values of 10 mg/l) are realistically achieved by a flocculate-clarifier in activated-sludge plant. Phiri et al.(1996) indicated an optimum inlet nozzle diameter significantly affected the hydraulic detention and solids removal interrelationships in hoppered spiral flow clarifiers. Gasperi et al. (2010) showed that lamella clarifiers were very efficient for Total Suspended Solids (TSS) removal (median rates were evaluated at 86%) in a wastewater treatment plants. Saleh and Hamoda (1999) described how solids removal efficiency increased as the hydraulic residence time was increased or as the surface loading rate was decreased by applying inclined plate settlers.

The effects of flocculant type (anionic, cationic and non-ionic), hydrolysable metal ions addition (e.g. Ca^{+2}, Mn^{+2}, Na^{+1}), pH and mixing conditions on flocculation performance (e.g. zeta potential*) and dewatering behaviour (e.g.

settling rate, final sediment bed height) of clay particle (kaolinite and smectite) have been reported (Levy et al., 1995; Sworska et al., 2000a, Sworska et al., 2000b; Mpofu et al., 2003a; Mpofu et al., 2003b; Dixon et al., 2004; Mpofu et al., 2004; Mpofu et al., 2005; McFarlane et al., 2006; Addai-Mensah, 2007). The findings are that hydrolysable metal ion (coagulant) adsorption onto clay particles is strongly pH-dependent, and significantly influences the dewatering behaviour. There is an optimum concentration for coagulant and flocculant because increasing the metal ion and flocculant concentration above or decreasing below a certain value adversely affected the flocculation performance and causes the settling rate to decrease. The zeta potential* decreases dramatically in the presence of metal ions and is pH dependent but independent of metal ion-type or flocculant concentration on different clays. Flocculant charge density and molecular weight affect the optimal flocculation concentration range (Levy et al., 1995). In more concentrated polymer solutions a higher polymer dosage and a higher stirrer speed is required (Sworska et al., 2000b). Increasing alum dose adversely affects the solids content and centrifugal dewatering behaviour of kaolinite sludges (Tambo and Watanabe, 1979; Dixon et al., 2004). This is due to the yield stress of aggregates reaching high values at relatively low solids content (Dixon et al., 2004).

*Zeta potential is a scientific term for electrokinetic potential in colloidal systems. Colloids with high zeta potential (negative or positive) are electrically stabilized while colloids with low zeta potentials tend to coagulate or flocculate.

2.4.4 Centrifugal sedimentation

There are two separation systems based on the effect of centrifugal forces: hydrocyclones and sedimenting centrifuges (e.g. tabular bowl, basket, disc and decanting centrifuges etc). The main difference between these two is hydrocyclones do not have any rotating parts and sedimenting centrifuges do. More hydrocyclone and decanting centrifuge details are described in section 2.2.2. The main difference between tabular bowl, basket, disc and decanting centrifuges are summarized in Table 2- 3.

Table 2- 3 Basic characteristics of sedimenting centrifuges (Svarovsky, 2000; Tarleton and Wakeman, 2007)

	Tabular bowl centrifuge	Basket centrifuge	Disc centrifuge		Decanting centrifuge
Centrifugal force (g)	14000-65000	Up to 1600	Up to 14000		2000-6000
Throughput (m^3 / h)	4-6	6-10	200		100
Typical particle size (μm)	0.1-100	0.1-100	0.1-100		1-5000
Feed concentration range (% w/w)	<5	<5	Ejecting type	Nozzle type	4-40
			0.05-2	0.5-10	
Operation condition	Batch operation and manual discharge	Semi-continuous operation and intermittent discharge	Manual discharge	Continuous discharge	Continuous operation and discharge

The efficiency of tubular bowl centrifuge separation is significantly influenced by solids accumulating at the wall due to the narrowness of the bowl and its throughput is restricted to less than 4 - 6 m^3/h. In order to avoid the necessity for excessively frequent cleaning, tubular bowl centrifuges are usually used with suspensions which contain less than 1% v/v of solids or dry solid yields of up to 4 kg per batch (Svarovsky, 2000; Tarleton and Wakeman, 2007). Tubular bowl centrifuges are the most efficient of all industrial sedimenting centrifuges because of their high speed and relatively thin settling zone. However, the low throughput, low feed solid concentration, batch operation and manual discharge are not suitable for pipe jacking process. This is because of pipe jacking process is a continuous process with high slurry feed rate.

The basket bowl centrifuge works on similar principles to the tubular bowl centrifuge. The operating centrifugal force is relatively low (around 1600 g) with typical flow rates of between 6 and 10 m^3/h. The feed solid content in basket centrifuges is usually low (3 - 5% w/w), again to prevent frequent cleaning. The supernatant liquid remaining in the bowl is siphoned off using a skimmer pipe and the solids on the wall are removed automatically with a plough, sometimes at a reduced bowl speed (Svarovsky, 2000; Tarleton and Wakeman, 2007). The low g-forces and low feed solid concentration are the main challenge if applied to the pipe jacking process.

Disc centrifuges are operated at speeds up to 14000 g with throughput up to 200 m^3/h. In nozzle-type disc centrifuges (Figure 2- 18) the particles accumulate on the underside of the discs and are automatically discharged through nozzles. In ejecting-type disc centrifuges the thickened solids remain in the bowl until the solids handling capacity of the centrifuge is reached. At this point rotation stops and the trapped solid is manually removal of the bowl (Svarovsky, 2000; Tarleton and Wakeman, 2007). The nozzle-type disc centrifuge may be applied to pipe jacking processes. However, the medium solid concentration feed loading (10 % w/w) might be the challenge, mechanical cleaning can be difficult due to close stacking of conical discs and the cake may break down or de-aggregate under the shear forces of nozzle discharge.

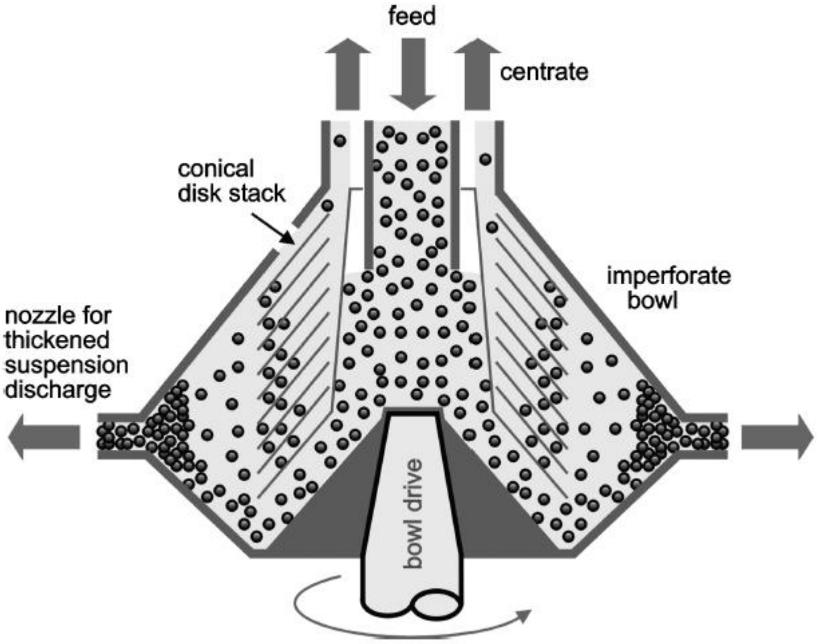


Figure 2- 18 A typical nozzle discharge disc centrifuge (Tarleton and Wakeman, 2007)

Some flocculants are often to be added to the feed upstream of the centrifuge. Svarovsky (2000) summarized a schematic classification of the centrifuge equipment (scroll type including decanting centrifuges), particle size and flow rate shown in Figure 2- 19 and also indicated that sedimenting centrifuges are suitable for slurries that have flocculants added to the feed upstream due to the lack of shear in the flow.

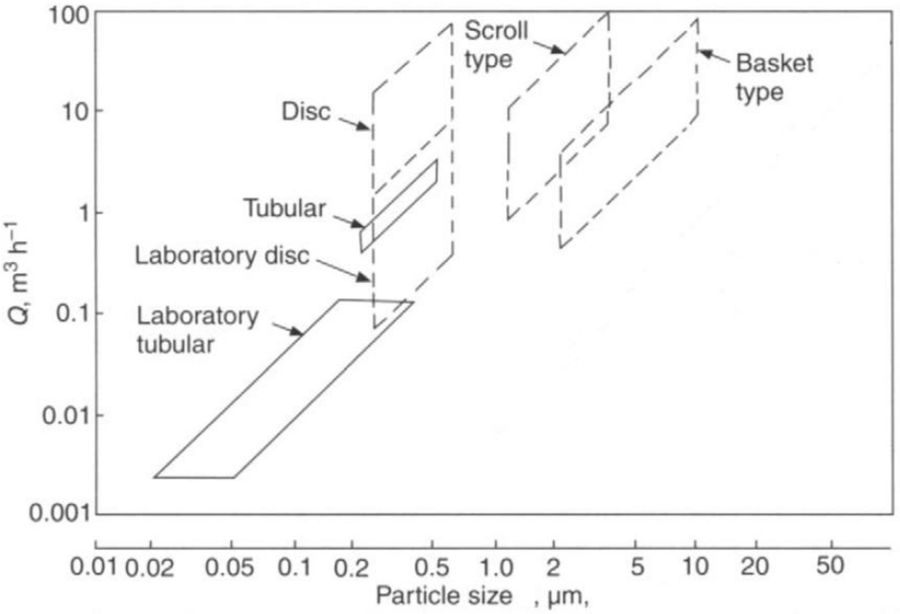


Figure 2- 19 Performance of various centrifugal sedimentation equipment (Svarovsky, 2000)

For many years, centrifugal sedimentation with flocculant aid has been extensively used and focused on the decrease of pollutants (parameter index, e.g. COD, BOD) in the supernatant. However, few studies have been devoted to the application of centrifugal sedimentation on the cake from separation. Until now there has very little research into solids separation in the pipe jacking industry. The relevant research into solid-liquid separation using centrifuges in other industries are described as follows.

Sneath et al. (1988) showed the proportion of solids removed by a decanting centrifuge increased with increasing raw piggery slurry dry matter. Wright (1993) indicated increased feed concentration improves plant throughput by increasing solids concentration of the feed slurry with basket batch filtering centrifuges. Leung and Shapiro (1999) and Peeters and Weis (2004) reported an optimum weir height near the cake discharge can improve the efficiency of a decanting centrifuge. The scrolling torque (a force that causes particles to spin around an axis) required for the conveyor is proportional to the cake dryness produced by a decanting centrifuge (Leung, 1998; Walker, 2000a; Walker, 2000b). Borán et al. (2009) stated It was possible to increase dry solids content in dewatered sludge by 10% at most in mechanical sludge dewatering by using flocculant. Burke et al. (2010) found a higher flocculant dosage resulted in solids re-dispersing into solution in organic slurries tests.

2.4.5 Force field

Magnetic and electric force fields have been used to improve separation processes in recent years. In the magnetic separator, material is passed through the field of an electromagnet to remove ferromagnetic particles from suspension. In the electric field, particles are polarised by redistribution of their surface and/or internal charge and separated by differences in the electrical properties of the materials. Due to the slow electrokinetic reaction, the treatment time can take considerable time, sometimes hours or days depending on the electrode material and configurations. (Grundl and Michalski, 1996; Shang and Lo, 1997). The treatment time can be reduced by increasing the operating voltage with a high energy consumption. Another phenomenon is the pH of the water is in excess of 12 due to the OH^- ions liberated at the cathode along with H_2 gas (Lockhart, 1983; Ju et al., 1991). According to the Freshwater Fish Directive (2006/44/EC), the pH of discharged water needs to be in the range of 6 - 9. To conclude, force fields separation may not be suitable in the pipe jacking industry because it is time consuming and the pH rises in the liquid.

2.4.6 Cake filtration

Cake filtration is based on passing a suspension through a porous medium. The particles are deposited on the surface of a cake on the upstream side of the medium. As soon as the first layer of cake is formed, the subsequent filtration takes place on top of this cake and the medium provides only a supporting function (Svarovsky, 2000). Depending on the required pressure of the filter medium, surface filters are classified into vacuum, pressure and centrifugal filters.

Vacuum filters consist of a section covered by a cloth filter. As this section moves through a slurry tank, a vacuum is applied to the submerged sections. Liquid passes through the cloth filter and the solids are retained forming the cake. The cake discharge is assisted by air blowback which is introduced between the filter and the cake. Some suitable agents may be added to the slurry to cause coagulation or flocculation to enhance the dewatering process (Svarovsky, 2000; Richardson et al., 2002; Tarleton and Wakeman, 2007). Moreover, the cake solids are usually 15 - 25 % and well-digested slurry may result in filter cakes with 40 % solids (Schroeder, 1977; Barnes and Wilson, 1983; Tebbutt, 1998). The drawback of vacuum filters for the pipe jacking process is the higher water content of the output compared to the centrifuge separation output.

Pressure filtration consists of pumping flocculated slurry with increasing pressure into cloth filter chambers which retain the solids but allow liquid to escape. A typical plate-and-frame filter press is shown in Figure 2- 20.

Flocculated slurry is fed to the rectangular chambers which are formed between hollow frames and filter plates. The plates are covered with a filter cloth. The filter cake is formed gradually under high pressure. The filter cakes can be removed when the filter plates are separated and the filters have to be washed (Svarovsky, 2000; Richardson et al., 2002; Tarleton and Wakeman, 2007). Generally pressure filtration is a batch process in which pressing time varies from 2 to 18 hours and results in higher solid content of 25 - 50 % (Barnes and Wilson, 1983; Tebbutt, 1998). The drawbacks of pressure filtration for the pipe jacking process are it requires a large area, fairly heavy on labour to clean and remove cake, long operation time and higher consumption of filter cloths.

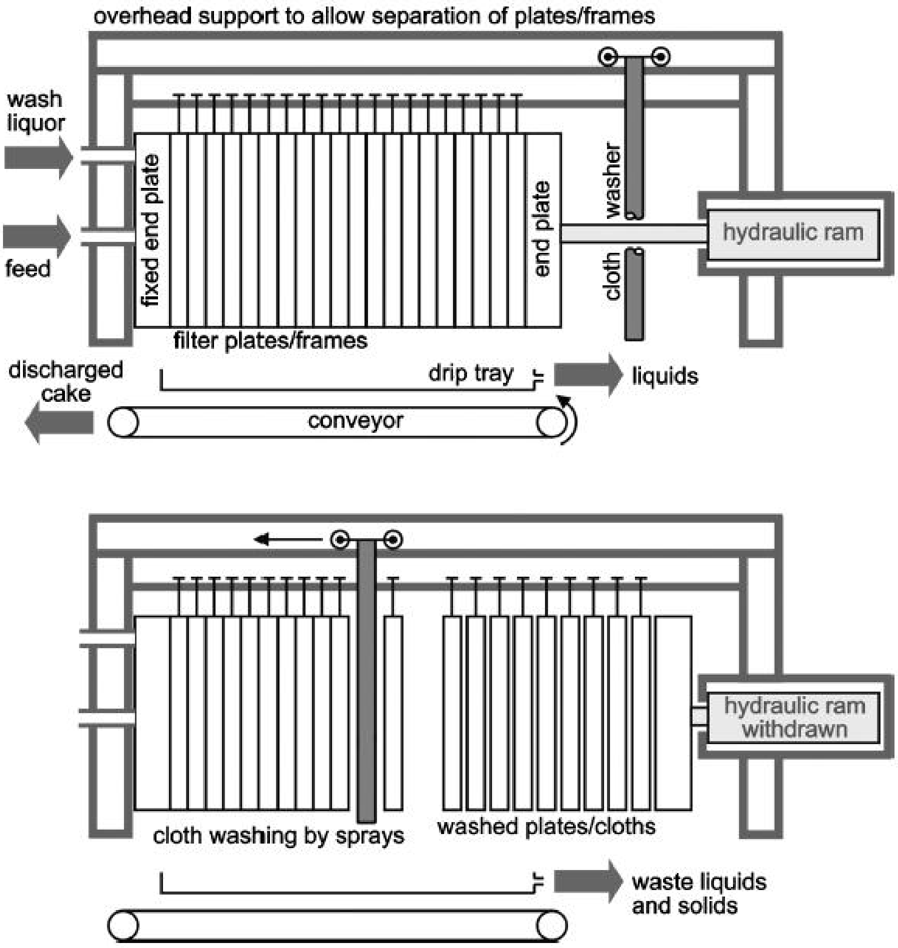


Figure 2- 20 A typical plate-and-frame filter press showing operations (top) and cloth washing (bottom) (Tarleton and Wakeman, 2007)

A centrifugal filter consists of a rotating basket which is fitted with a filter cloth. The difference between centrifugal filtration and a sedimenting centrifuge is a centrifugal filter does not require a density difference between the solids and the suspending liquid. If a density difference exists, sedimentation takes place in the liquid head above the cake, at the start of the filtration cycle. This may lead to particle size stratification in the cake. The difference between centrifugal filtration and sedimenting centrifuge is a function of the particle size range involved. The particle size for the centrifugal filtration range of applications is generally much coarser, from 10 μm to 10 mm, however, micron and sub-micron sizes for the sedimenting centrifuges (Svarovsky, 2000).

There are some researchers who studied filter techniques working on clay mineral dewatering (O'Gorman and Kitchener, 1974; Wright and Kitchener, 1976; Attia, 1983; Agerbæk and Keiding, 1995; Besra et al., 2000; El-Shall and Zhang, 2004). The filtration may produce a dryer cake depending on the filtration time and pressure. The main drawback for application of this technique in the pipe jacking process is in the filtration time which may range from a few hours to a few days. Another constraint is the fact that it is a batch process (discontinuous process) and requires a large facility.

2.4.7 Deep bed filtration

In the second type of filtration, deep-bed filtration, slurry goes through the pores of a filter medium that can keep the suspended solids. This configuration is commonly used for the removal of fine particles from very dilute suspensions, for example, where the quantity of solids to be removed is small where the solid content is about 10 g/m^3 or less in order to keep the frequency of backwash and the wash water demand down. Moreover, the process takes a few days to complete (Richardson et al., 2002; Tarleton and Wakeman, 2007). This is not suitable for pipe jacking use.

2.5 Summary of the literature review and reason for this research

2.5.1 Pipe jacking process

The use of trenchless technique in the tunnelling industry has increased as a result of safety and environmental benefits. Pipe jacking is one of the trenchless techniques used to install pipelines. Slurry tunnelling in the pipe jacking industry is often being used as slurry provides the tunnelling face support, reduces the friction between the pipe and the ground, and transports the excavated materials. Slurry is classified as a “mirror entry” waste in the European Waste Catalogue (EWC). The waste products from the slurry systems are not well-classified because the slurry could either be hazardous or non-hazardous depending on the concentrations of “dangerous substances” in the waste. This depends on the additives used in the slurry system. Slurry is a liquid waste which must be pre-treated before being sent to the landfill as a solid for final disposal.

2.5.2 Legislation

The key effect of the EU/UK directives and regulations on the pipe jacking industry is liquid waste is not acceptable to the landfill. This is a requirement under the landfill directive that aims to minimise the environmental impact of landfill sites by reducing the leachate from landfill sites.

Typically the cake from the centrifuge process is not defined as liquid waste. However, the cake still contains some water. This means the disposal cost, transport and landfill tax are grater because of the water content. Further, if a cake contains biodegradable additives the degradation process will release water into the landfill. These wastes are likely to leach out again once in the landfill. This means that they have been only temporarily immobilised or disguised and therefore have not ceased to be liquid wastes for the purpose of the Landfill Directive. At the moment cake is classified as inactive waste, thus the landfill tax is at a lower rate. However, the landfill tax will increase in the future. If the cake contains water, it means paying more unnecessary landfill tax due to the weight of water. If the water content can be reduced, then there will be a reduction in the environment impact and disposal cost.

Moreover, the cakes need to be classified as hazardous waste or non-hazardous waste. There are many kinds of additives used in the pipe jacking process during the separation process. The compositions of these chemicals varies. After having investigated the component of the separation agent used in the pipe jacking industry, VP1 (anionic polymer), supplied by SNF (UK) limited, is not classified as a dangerous substances. However, TK50 (acrylamide polymer) and T-CAT (aliphatic polyamide polymer), both supplied by Morrison Mud, have a Xi-Irritant hazardous property and are classified as dangerous substances. If the usage is above 20% (threshold limits), the cake will be classified as hazardous waste. The Material Safety Data Sheets (MSDS) state that for use as a geotechnical conditioner for treated slurry it is advised not to exceed 0.05% and 0.1% for TK50 and T-CAT, respectively. This means the cake formed from TK50 or T- CAT is not classified as hazardous waste if the guide is followed.

If additives are used to lubricate the pipe, there may contaminate the groundwater after percolation through soil. It needs to be identified the component of these additives and prohibit or limit it into groundwater if hazardous substances exist. After having investigated the components of the tunnelling slurry additive used in the pipe jacking industry, VL2 (anionic polymer), TK60 (anionic polymer), SLOOP (polyacrylamide lubricant), MX45 (polysaccharide lubricant) and MX (saccharide complex additive) supplied by SNF (UK) limited and Morrison Mud are not classified as dangerous substances.

The main wastes produced from pipe jacking separation plant are cakes during the pipe jacking and wastewater remaining in the slurry tank at the end of the project. The cakes are sent to the landfill after a further dewatering process and wastewater can be disposed of to a sewer. The discharge cost depends on the composition of wastewater (COD and SS) if the wastewater is drained to a sewer. If the water quality is good, it can reduce the discharge cost.

Due to water shortages, the waste water may be not allowed to be disposed of to a sewer unless it satisfies the stricter standards of the future. Therefore, the composition of wastewater (such as the COD and SS) must be low to minimise the waste impact on the environment and human health.

2.5.3 Separation methods

The decanting centrifuge seems to be the best option for fine particle (around 5 μm) treatment from pipe jacking slurry to date. Some other separation methods may produce dryer cake but may take longer (e.g. pressure filtration). The pre-treatment of slurry may improve the decanting centrifuge operation to produce dry cake and clarified water recycled from the slurry system.

The lamella clarifier provides an effective sedimentation process using a small floor space. A lamella clarifier is considered as a primary treatment which sits between a slurry tank and centrifuge to separate solid and liquid immediately thus reducing the amount of slurry to pass through a centrifuge.

2.5.4 Research questions

From the above information, it is evident that a successfully operated slurry system leads to successful pipe jacking. The solid-liquid separation is a critical factor in the slurry system. The key operating parameters in a decanting centrifuge that make separation successful are poorly understood. The main solid waste from the separation plant in the pipe jacking system may not be accepted to landfill because there is a regulatory standard for the waste to be passed as a solid or liquid waste. Only solid waste is accepted in landfill. The characterization of the liquid from separation plant is also not well understood.

Moreover, to assist in checking the efficiency of solid-liquid separation, most researchers have been concerned with the organic parameter index (e.g. COD, BOD) rather than the inorganic index (e.g. suspended solids, total solids, water content). The characterization of slurry and its settling behaviour also need to be investigated.

The research questions are summarised as follow:

- The characterization of waste products from pipe jacking process needs to be investigated to determine their physical and chemical properties. There is a need to assess the possibility of reuse the slurry in other industries and improve the solid-liquid separation in the pipe jacking industry. (Chapter 3)

- Clarity is an indication of potability a measure that can be used to assess whether the supernatant (the liquid separated from separation) can be disposed of safely. Density cannot be used to assess the clarity of the supernatant because of the limited quantity of solid present after separation. Turbidity is a recognised indicator of the clarity of liquid. There is a need to determine the solid concentration of liquid separated from slurry by turbidity. The theory and principle of turbidity is discussed in section 4.1. (Chapter 4)

- Solid separation by sedimentation can be assisted using chemicals. The effects of coagulant and flocculant on slurry settling behaviour needs to be studied. (Chapter 5)

- An improved separation process (clarifier) and a separation method (decanting centrifuge) needs to be studied in a field scale test. This can understand the effect of centrifuge and clarifier on solid-liquid separation of slurry. (Chapter 6)

In summary, the waste produced from the pipe jacking industry needs to be identified as non-hazardous or hazardous waste from the added additive component. Also it needs to be classified as a solid waste so that it can be disposed to landfill. Further the water content has to be reduced to reduce the cost of disposal (transport and landfill tax) due to the weight of the water. A lamella clarifier is considered to improve the separation plan in the pipe jacking process.

Chapter 3 Characterization of products from pipe jacking process

3.1 Introduction

In the pipe jacking process, a slurry system can be used to transport excavated soils from the cutting face to the surface. Slurry from the pipe jacking industry has a low solids content which comprises clay minerals, principally potassium, calcium, and sodium montmorillonites and rock particles, principally sand and gravel (Milligan, 2000). There are a number of components to a slurry separation plant because of the different techniques used to separate out different particle sizes. The solid separating processes are shown in Figure 2- 7 in Chapter 2. The detail for the separation is described in section 2.2.2.

3.2 The sample protocol

It is possible to take soil samples from different places in the soil separation process; from the screens, samples of gravel and lumps of clay (if a clay baller is in use); from the hydrocyclones (sand); from the centrifuge (clay); liquid samples from the slurry tank; the centrate from the centrifuge; and slurry from the pipe. Samples can be taken at different chainages i.e. different times during the pipe jacking cycle. The rate of advance of the pipe varies according to soil type and type of equipment hence sampling at a time interval was not considered appropriate.

For this reason, samples at all sites were taken at three different stages. Stage 1 was at the beginning of pipe jacking process for a single length of pipe (typically 2.5 metre). Stage 2 was in the middle of pipe jacking process. Stage 3 was in the end of pipe jacking process after a pipe had been jacked its full length.

Six sites were investigated. A summary of the site information is shown in Table 3- 1. Carillion Corporation was the contractor at five sites and Delta Corporation at the sixth site.

Table 3- 1 Summary of sites information

Location	Heddon	Newcastle Airport	Murton	Morpeth	London	London
Contractor	Carillion	Carillion	Carillion	Carillion	Delta	Carillion
Soil Type	Gravel & Sand & Clay	Gravel & Sand & Clay	Sand & Clay	Boulder clay	London Clay	Lambeth Group
Sample Location	Tunnel	Tunnel	Tunnel	Tunnel	Shaft	Shaft
Pipe Diameter (meter)	1.2	1.8	1.2	0.6	-	-
Pipe Jacking Machine Type	AVN 1200	AVN 1800	AVN 1200	AVN 600	Decon RVS300	AVN 1200
Additives Type	VP1*	VP1*	VP1*	None	None	None
Quantity of additives VP1	25 kg / 2 weeks	25 kg / 2 weeks	25 kg / 2 weeks	None	None	None

*VP1 is an anionic polymer used as a flocculant in the centrifuge process.

In this study, two laboratory soils: kaolin from Polwhite E (IMERYS Ltd) and bentonite from Calcium Bentonite (RS Minerals Ltd) were used to create slurries since they represented two basic types of clay materials.

3.3 The testing protocol

There were four groups of tests: characterisation test, pilot sedimentation test, sedimentation test on field samples and sedimentation tests on laboratory prepared samples. The purpose of each group of tests is summarized in Table 3- 2.

Table 3- 2 Detail of tests on the pipe jacking product

Group	Test	Illustration
A	Characterisation test	To identify the basic physical and chemical characteristics of product, e.g. density, water content, liquid limit, pH, COD* and settling behaviour.
B	Pilot sedimentation test	To assess solid separation by sedimentation using chemical additives.
C	Sedimentation test on field samples	Sedimentation tests on natural slurry samples from the pipe jacking sites to investigate the sedimentation process in detail. In addition, the CEC** test was used to investigate the possibility of using the cake to extract cation (e.g. Ca^{2+}, Mg^{2+}) from the contaminated water.
D	Sedimentation tests on laboratory prepared samples	Sedimentation tests on laboratory prepared samples to investigate the sedimentation process in detail.

*The Chemical Oxygen Demand (COD) test has been widely adopted as a measure of pollution. It is used to measure the oxygen equivalent of the organic material in wastewater that can be oxidized chemically using dichromate in an acid solution. Most applications of

COD determine the amount of organic pollutants found in surface water (e.g. lakes and rivers), making COD a useful measure of water quality. The EU directive on urban wastewater treatment COD effluent standard is 125 mg/l (91/271/EEC).

**Cation Exchange Capacity (CEC) is the capacity of a soil for ion exchange of cations between the soil and the solution to protect water from cation contamination. It is a measure of the quantity of readily exchangeable cations neutralizing negative charge in the soil. It is usually expressed in milliequivalents per 100 gram of soil. The cations held on the surface of soil minerals and within the crystal framework of some mineral species plus those which are a part of certain organic compounds can be reversibly replaced by those of salt solutions and acid.

When a pipe is installed using a slurry system, the control of the slurry and the separation equipment that removes the excavated soils from the slurry is critical to the success of the pipe jacking operation. The density of slurry can increase as some fine particles can be retained in the slurry. Since the density increases then the pump flow rate will decrease. This leads to slower jacking process, increased energy, increased wear due to more particles suspended in the slurry and lower efficiency of the hydrocyclones. So if the density gets too high, the slurry pumps will stop pumping. There could be a risk of settling and blocking in the slurry pipes during stoppages. In addition, the solids removed are taken to landfill.

In the UK, liquid waste is not accepted for landfill. However, the criterion for acceptable cake is not well defined. There is a suggestion that material with a shear strength in excess of 10 kPa and solid content greater than 35% would be considered (Reeves et al., 2006). A way to identify whether a soil is a liquid or a solid may be the liquid limit. The liquid limit is the water content at which a soil passes from the liquid state to the plastic state. The strength of a soil at its liquid limit is about 10 kPa (Reeves et al., 2006).

Samples were taken to determine the bulk density, dry density, water content, liquid limit, pH, COD and CEC in order to characterise the pipe jacking product in the characterisation test (A). The protocols for each test are shown in Table 3- 3.

Many methods have been and continue to be proposed to determine CEC; the values may vary widely, depending on the particular technique employed. For example, Mehlich (1945) indicated the ammonium acetate method (with NH_4^+) gives lower values for CEC than the barium acetate method (with Ba^{2+}) if soils contain significantly high quantities of organic matter and/or kaolin or other 1:1 type clay minerals. Van Bladel et al. (1975) reported the sodium acetate (with Na^+) and Bascomb's methods (with Ba^{2+}) gave similar values for most natural samples. In the Ca method (with Ca^{2+}), the CEC value is greater than for the sodium acetate (with Na^+) and Bascomb's (with Ba^{2+}) methods if the sample contains a significant quantity of organic matter. The Sodium acetate method can be used on both calcareous and noncalcareous soils (Chapman, 1965). Soils with significant organic matter, and with soils containing kaolin or other 1:1-type clay minerals should be analyzed by the sodium acetate method (EPA, 1986). Slurry from the pipe jacking process contains mostly clay and possibly some organic matter. Therefore, the sodium acetate method was selected as the best method.

Table 3- 3 Protocols for characterisation test

Parameter	Method	Source
Bulk & Dry density	Linear measurement method	(BS1377-2, 1990):7.2 Determination of density
Water content	Oven-drying method	(BS1377-2, 1990):3.2 Determination of water content
Liquid limit	Cone penetrometer method	(BS1377-2, 1990):4.3 Determination of the liquid limit
pH	Electrometric method	American Public Health Association (APHA) Standard method for the examination of water and wastewater, 4500 H+. (APHA, 2005)
COD	Closed reflux method	APHA Standard method for the examination of water and wastewater, 5520 chemical oxygen demand. (APHA, 2005)
CEC	Sodium saturation method	Methods of soil analysis, 57-3 Cation-exchange Capacity by sodium Saturation. (Chapman, 1965)

The sedimentation test focused on testing a range of laboratory prepared slurries (soil with different concentration of additive) and natural samples from different sites (Table 3- 1). The additive, VP1 supplied by SNF (UK) limited, was an anionic acrylamide and acrylate based polymer with a very high molecular weight (greater than 15 millions) and 30% of charge density (the amount of electric charge in the surface) provided by the contractor Carillion. An artificial slurry was prepared by mixing 150 gram of selected soil with 1 litre water to achieve a density of 1.09 Mg/m^3 to simulate a natural slurry from a typical pipe jacking site. The COD value was tested for one sample. The accuracy for pipette was ±1.75%.

The process of the pilot sedimentation test (B) is illustrated below:

1. Collect unflocculated slurries from sites.
2. Mix 1 g portions of the VP1 powder with 500 ml tap water to achieve a concentration of 2000 mg/l polymer and leave to age overnight.
3. Add different amounts, 0-100 mg/l, of additive (polymer: VP1) to the slurries.
4. Manually mix polymer and slurry until they appear to form flocs (flocculated particles).
5. Pour 500 ml of the modified slurry into a beaker to undertake a sedimentation test.
6. Take 10 ml sample to determine the COD at different levels within the beaker (upper and bottom of beaker), at different times (1, 2, 3, 4, 72 hours) as sedimentation take place.

The sedimentation test (C) was carried out on samples from the pipe jacking process in the field. In addition, CEC tests were used to investigate the possibility of using the cake to extract cation (e.g. Ca^{2+}, Mg^{2+}) from the contaminated water. The sedimentation test on natural samples was as follows:

1. 2 litre samples of slurries were collected from the field during different stages of the pipe jacking process.

2. 500 ml samples of slurry were used to undertake a sedimentation test in a constant temperature at 25 °C bath tank.
3. 10 ml samples were taken at different levels within the column (80, 60 and 40% of initial height of initial sample, referring to Figure 3- 1), at different times (0, 1, 2, 4, 8, 24, 32 hours) as sedimentation took place.
4. The COD and dry density of each 5 ml subsample were determined.

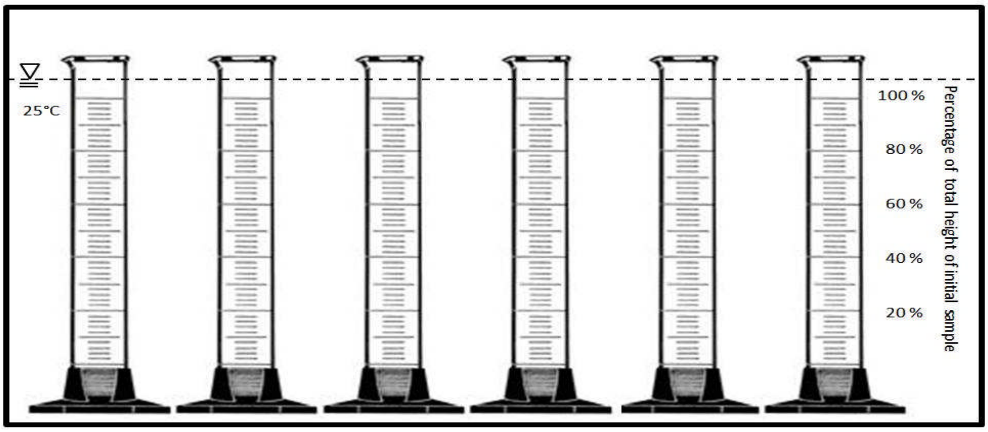


Figure 3- 1 Sedimentation tank and sampling level

The process for sedimentation tests (D) on laboratory prepared samples were:

1. Appropriate quantities of natural soils were taken from pipe jacking sites and dried out at 105ºC over night.
2. 1 g portions of the VP1 powder were mixed with 500 ml tap water to achieve a concentration of 2000 mg/l polymer and left to age overnight.
3. The dry soil was ground and sifted through a 63 μm sieve. (Material passing the 63 μm test sieve is clay particle size.)
4. A slurry formed of 75 gram of sieved soil and tap water filled 500 ml.

5. Different quantities (40-120 mg/l) of additive were investigated.
6. The next steps followed the process described in the sedimentation test (C) on field samples step 3 to 5.

3.4 Test results

3.4.1 Characterisation test

Slurries were taken from Heddon and Newcastle Airport sites. The coarse screens and hydrocyclones had removed most of the rock, gravel and sand. Most clay would have been left in the slurry tank. Table 3- 4 is the basic characterisation of products from the pipe jacking process.

Table 3- 4 Basic characterisation of products from pipe jacking process

Products / Properties	Centrate	Leakage water	Slurry	Cake
Bulk Density (Mg/m³)	-	-	1.02-1.13	1.40-1.65
Dry Density (g/l)	-	-	50-330	770-1030
Water content %	-	-	200-2300	62-81
Liquid limit %	-	-	-	38-44
pH	6.5-8.0	6.5-8.2	6.5-7	6.8-7.2
COD (mg/l)	50-500	50-12000	250-24000	-
CEC (meq/100g)	-	-	-	5-17

The density of slurry varied during the pipe jacking process. All the products had pH near to neutral, which meant that the pH is not an environmental concern in this study. The COD of the slurry varied between 250 and 24000 mg/l. As the EU directive on urban wastewater treatment COD effluent standard is 125 mg/l (91/271/EEC), the COD will be an environmental issue in this study. The COD of the centrate was between 50 - 500 mg/l. This might be because of an overdose of additives or organic particles left in the supernatant after the centrifuge. The COD of the leakage water was between 50 - 12000 mg/l. This could be contaminated by machine oil. Since both the centrate and leakage water flow to the slurry tank, it means that the slurry could be considered an environmental issue.

The water content (62 - 81 %) of the cake was above its liquid limit (38 to 44 %). It implies the cake may be classified as liquid waste and not be accepted for landfill. The CEC of the cake was between 5-17 meq/100g. The CEC of kaolin is variable, but typical values are in the range of 5-15 meq/100g (Gane, 1989) and it is from 16 to 56 meq/100g for neutral soils (Kelley, 1948). The CEC of the cake did not have significantly high value although anionic additive was added.

The characteristics of the slurry and cake varied during the pipe jacking process. The COD of the slurry exceeded the standards of the EU directive. The cake may be classified as liquid waste. Therefore, slurry and cake samples were selected for further research in this project to determine whether it was possible to reduce the environmental impact of the supernatant and solidify the cake.

The settling behaviour test was carried out on unflocculated slurries taken from two sites in London. Slurries were mixed with polymer in the mixing tank (Figure 3- 2). The level of the variation of the mudline was observed with time (Figure 3- 3). The mudline was taken as the line where there was a distinct difference between supernatant and sediment. Settling behaviour varied between: natural samples, laboratory soil samples, flocculated natural samples and flocculated laboratory soil samples. The majority of the sedimentation of the flocculated (30 mg/l polymer) slurries settled within 5 minutes and the rate of settlement reached a plateau within 30 minutes. Unflocculated laboratory soil (kaolin or bentonite) settled slowly over 2 hours; unflocculated natural samples (Lambeth Group and London Clay) settled over 5 hours. The final mudline height of unflocculated soil was in the order: Kaolin < Bentonite < London Clay < Lambeth Group with the mudline for Kaolin being the lowest. However, the order for flocculated soil was Lambeth Group < Kaolin < London Clay < Bentonite. It means flocculation can help both settling time and settling volume for natural samples.

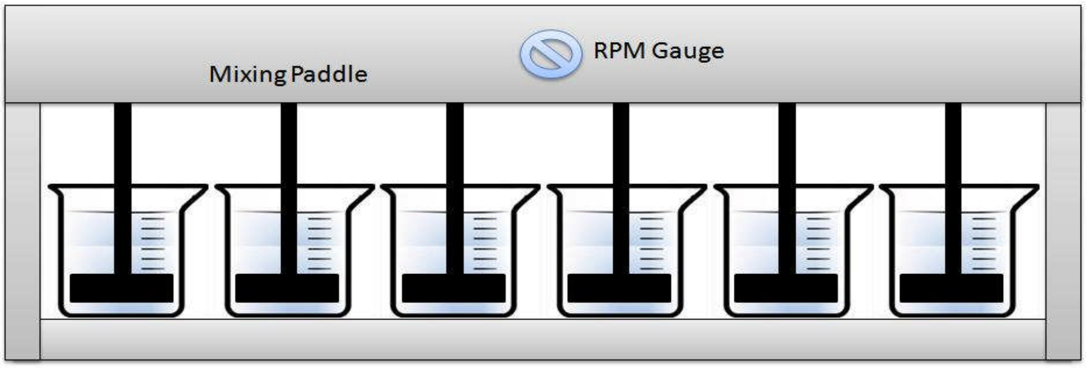


Figure 3- 2 The mixing tank

The COD of the slurry varied between 250 to 24000 mg/l (Table 3- 4). These COD values could be due to the polymer or organic matter in the natural soils. Most soil particles are inorganic therefore this should not create a high COD. The relationship between COD and turbidity of the slurry (Figure 3- 4) was studied to understand why some samples had a high COD. The solid particles can cause turbidity thus high turbidity means higher soil concentration (more details are given in section 4.5). All laboratory soils do not lead to high COD no matter what the soil concentration was. The entire natural sample caused extremely high COD. This might be because the natural sample contained organic matter. This organic matter will lead to a higher COD.

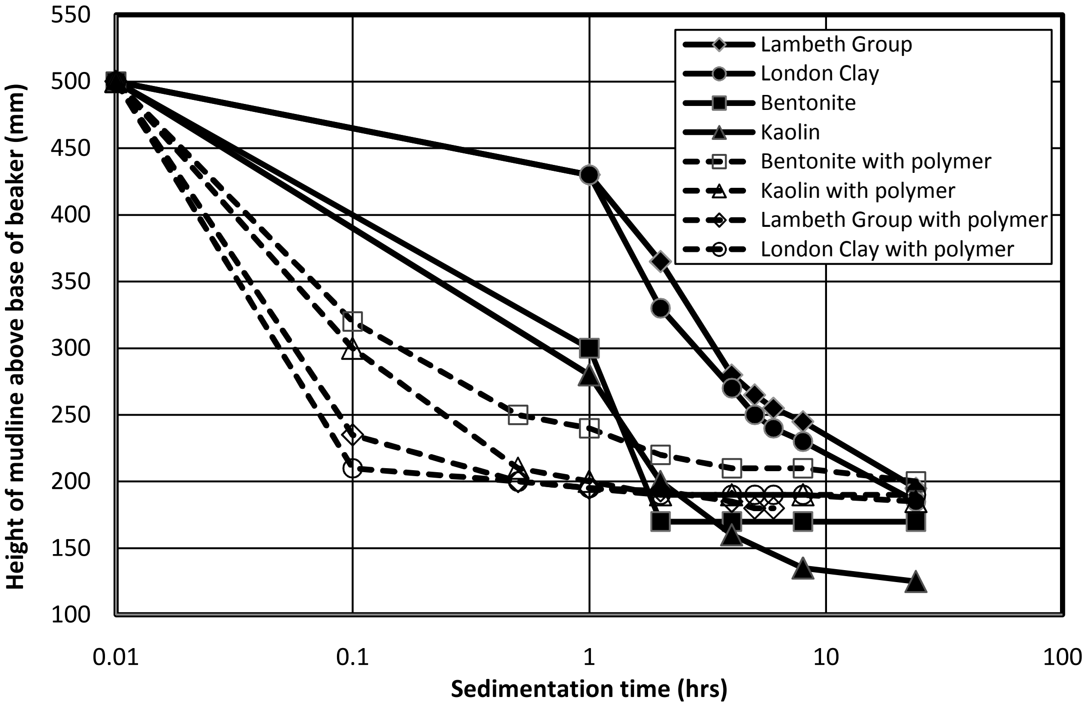


Figure 3- 3 Sedimentation test for settling behaviour of different soils

The relationship between polymer dose and COD was studied to understand if polymer affected COD. Figure 3- 5 shows a linear relationship between COD and amount of polymer (VP1) in tap water. From the trend line equation, 104 mg/l of polymer will reach the EU COD limit of 125 mg/l. Polymer was introduced into the water as a flocculant. Most polymers will be removed with the flocs. However, adding excessive amounts of polymer can result in a non-reactive flocculant. This residual quantity of polymer will raise the COD of the supernatant. The polymer dose used on this project was under 120 mg/l; therefore the maximum would be 142 mg/l COD. The polymer used on site was around 100-200 mg/l, which can cause a maximum COD of 120-230 mg/l. This suggests that the disposal of the centrate containing polymer could be an issue.

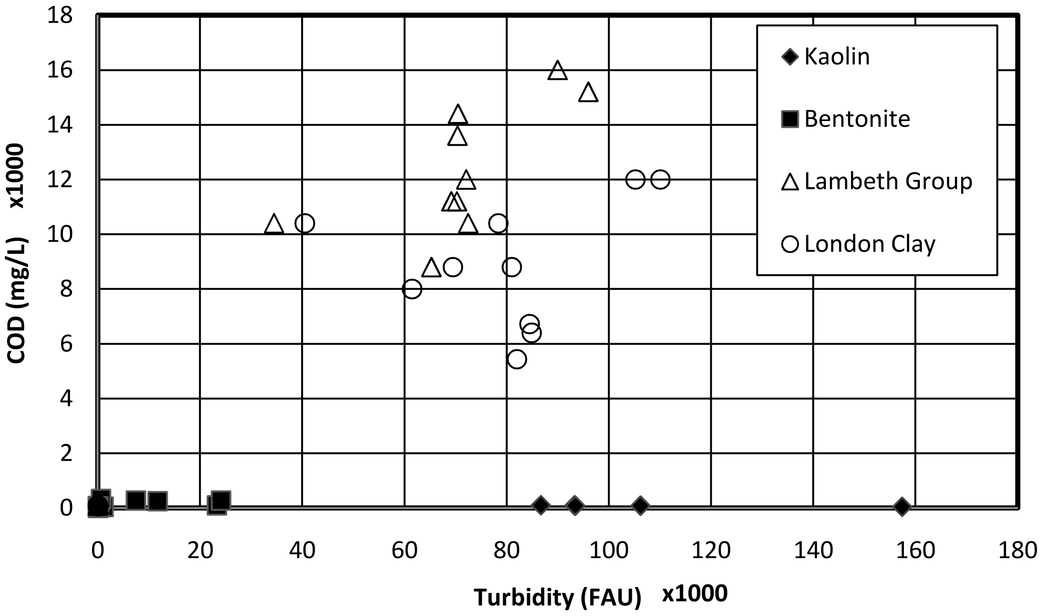


Figure 3- 4 The relationship between COD and turbidity of the supernatant extracted by sedimentation of different soils

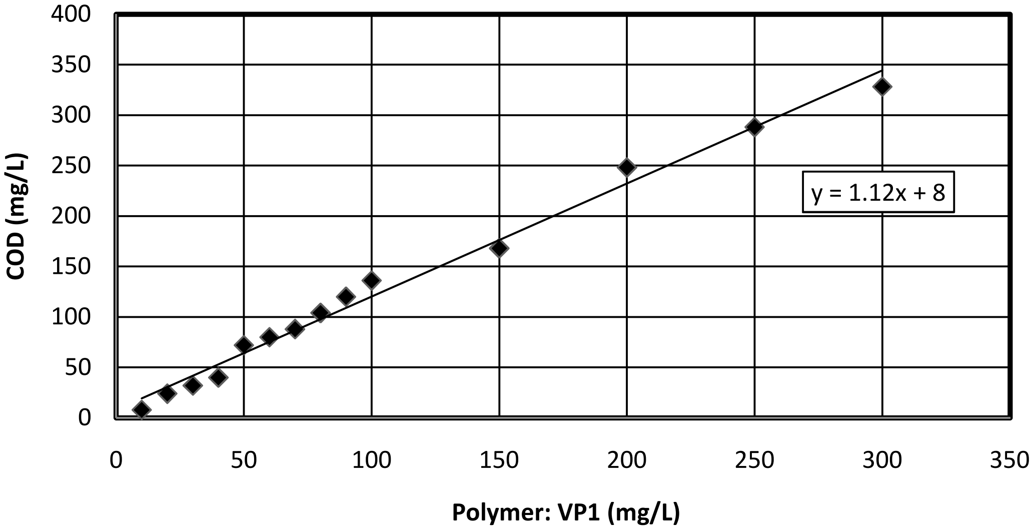


Figure 3- 5 The relationship between COD and polymer (VP1)

3.4.2 Pilot sedimentation test

The pilot sedimentation test focused on testing a number of samples to assess the effect of polymer on the sedimentation process.

Slurries were taken from the Newcastle Airport site. The density was typically 1.06 Mg/m³. The slurry, after mixing with the polymer, separated into two layers creating a mudline between the upper half (supernatant) and the flocs in the lower part. Subsamples were taken from these two parts. Figure 3- 6 shows that the COD of the supernatant increased as the polymer content increased, but they were all under the EU urban wastewater COD effluent standard (125 mg/l). The COD of supernatants with 1 hour sedimentation were higher than those with a longer sedimentation time. There does appear to be a trend of reducing COD with time, which could be due to further flocs forming from the remaining suspended solids.

Figure 3- 7 shows the COD of the solids that will have settled, known as flocs. It can be seen that the COD reduced with polymer content. However, the optimum polymer concentration that produces the lowest value of COD was shown to be 60 mg/l.

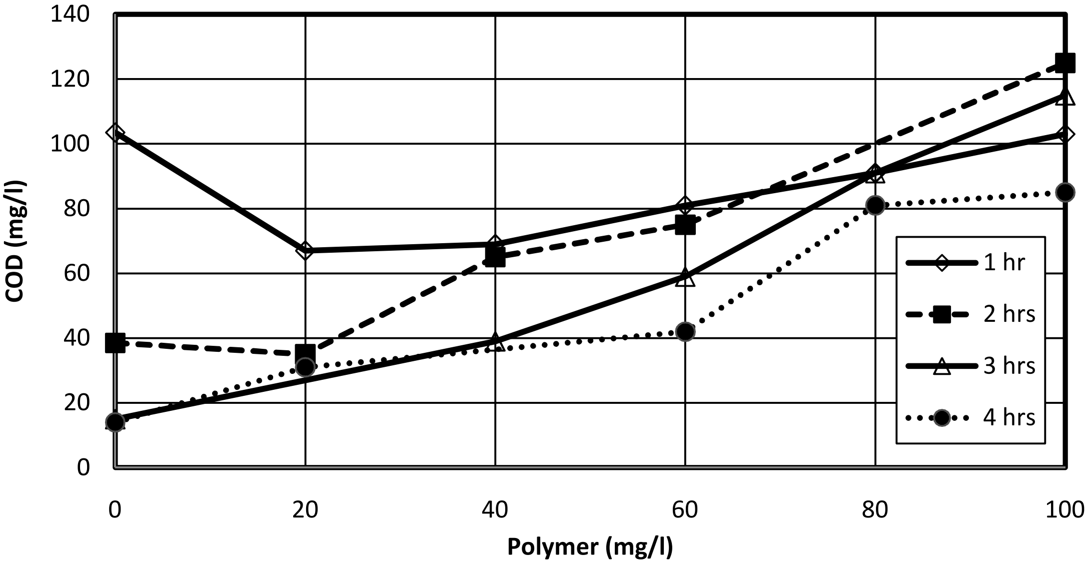


Figure 3- 6 COD of supernatant with different concentrations of polymer

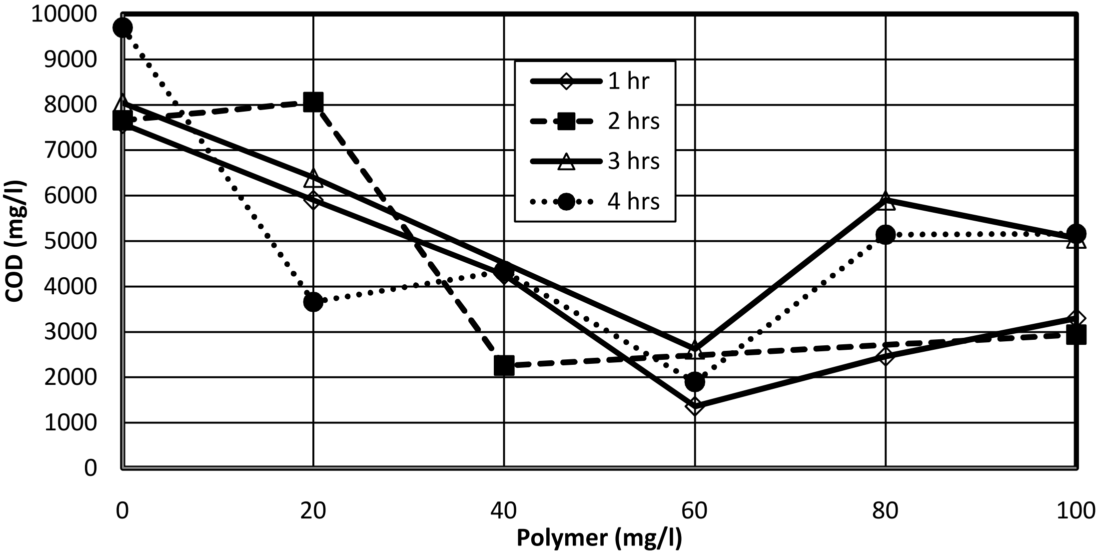


Figure 3- 7 COD of lower part of sample with different concentrations of polymer

3.4.3 Sedimentation test on field slurry samples

Samples were taken from the Morpeth and Murton sites, which comprised glacial till, sands and clays. The bulk density was between 1.02 to 1.13 Mg/m³ and dry density between 50 to 330 g/l. The COD and dry density were investigated to understand the supernatant quality and soil concentration of the slurry at different levels within the column. In addition, the CEC test was used to investigate whether the cake can be reused depending on its CEC value.

The density increased with the stage of the pipe jacking process on the Morpeth site (Table 3- 5). The initial density was 1.03 Mg/m³. More soil was added into the slurry system as the pipe was jacked increasing the density to 1.07 Mg/m³ at halfway and 1.13 Mg/m³ when the pipe of length 2.5 m had been jacked in place. This was most likely due to the increase in clay content as the gravel and sand were removed by the screen and hydrocyclones. Slurry was continually sent to the centrifuge to reduce the soil concentration thus the density reduced to 1.03 Mg/m³ when the next pipe was being put into place ready for jacking. The density increased from 1.03 Mg/m³ to 1.09 Mg/m³ during the second pipe jacking process.

Figures 3- 8, 3- 9 and 3- 10 show the relationship between COD and sedimentation time for different levels of the column of slurry. The polymer and organic matter within the soils caused the COD. The polymer used on site can only achieve a maximum COD of 110 mg/l according to Figure 3- 5.

There may have been organic matter in the soil. The organic matter would have increased as the pipe was jacked because the soil content increased. Therefore, the COD increased as the pipe was jacked. The time required for COD to fall below the EU urban wastewater effluent standard, 125 mg/l, at different levels of the height of column is summarized in Table 3- 6.

Table 3- 5 The density and COD of the slurry at different stages of the pipe jacking process on the Morpeth site

Stage of install 2.5 m long pipe	1^St pipe			2^nd pipe		
	Start	Middle	End	Start	Middle	End
Density (Mg/m³)	1.03	1.07	1.13	1.03	1.08	1.09
COD (mg/l)	6000	10000	14000	6800	10700	13000

Table 3- 6 The time required for COD to fall below 125 mg/l at different levels on the column

Slurry type / Percentage of initial height of initial sample	Glacial till non-flocculated slurries (Morpeth site)	Sand & clay flocculated slurries (Murton site)
80	8 hrs	1 hr
60	24 hrs	1 hr
40	Over 24 hrs	2 hrs

Figure 3- 8 illustrates the relationship between COD and sedimentation time at 80% of the column height during different pipe jacking stages on the

Morpeth (without flocculant) and Murton (with flocculant) sites. The effect of additive and different pipe jacking stages on the COD can be summarised as follows:

1. For non-flocculated slurries (solid lines in Figure 3- 8), the COD decreased from 14000 mg/l to 200 mg/l after 4 hours and down to 100 mg/l after 8 hours. For flocculated slurries (dash lines in Figure 3- 8), the COD decreased from 10000 mg/l to less than 100 mg/l after 1 hour. This implies that the flocculant can decrease the time to produce acceptable levels of COD of the supernatant.
2. The COD increased as the pipe was installed.

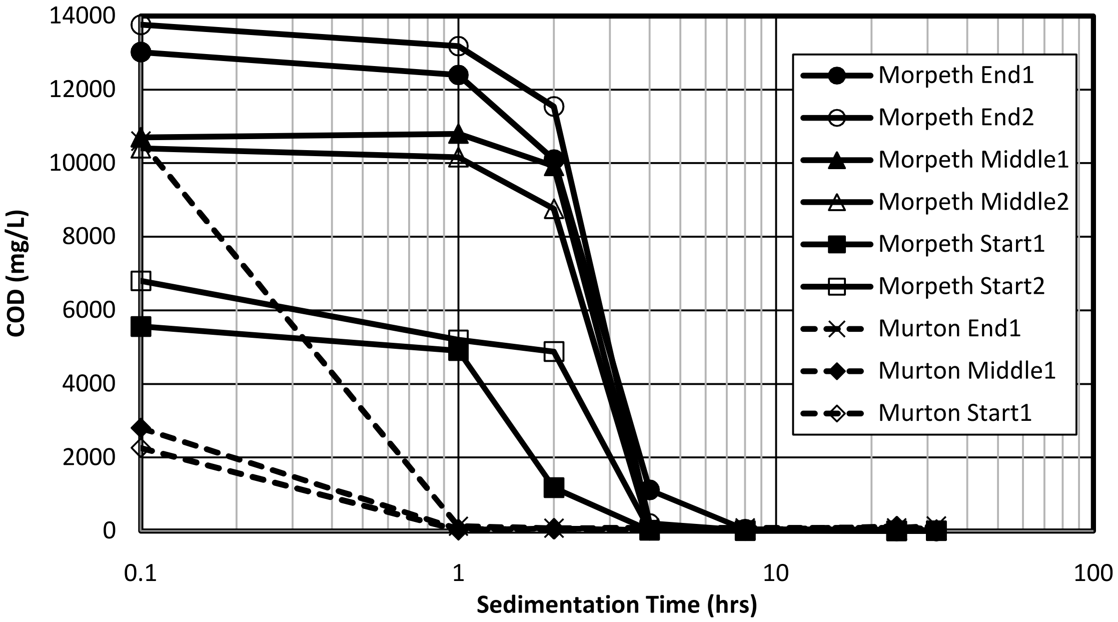


Figure 3- 8 The relationship between COD and sedimentation time at a level 80% of the height of column at different pipe jacking stages

At a level 60% of the height of column (Figure 3- 9), the relationships between COD and sedimentation time for each stage were similar to the times for samples at a level 80% of the height of column. However, it took more settling time to lower the COD for non-flocculated slurries (Morpeth site). The COD of most samples were down to 100 mg/l after 24 hours.

Figure 3- 10 shows the COD change with time at a level 40% of the height of column. For non-flocculated slurries (Morpeth site), the accumulated sediment exceeded the 40% level of the height of column and resulted in a sustained high COD (over 10,000 mg/l) before 24 hours. However, the COD decreased from 12000 mg/l to less than 100 mg/l after 2 hour for flocculated slurries (Murton site). The COD dropped off after 32 hours because the accumulated sediment settled below the 40% level.

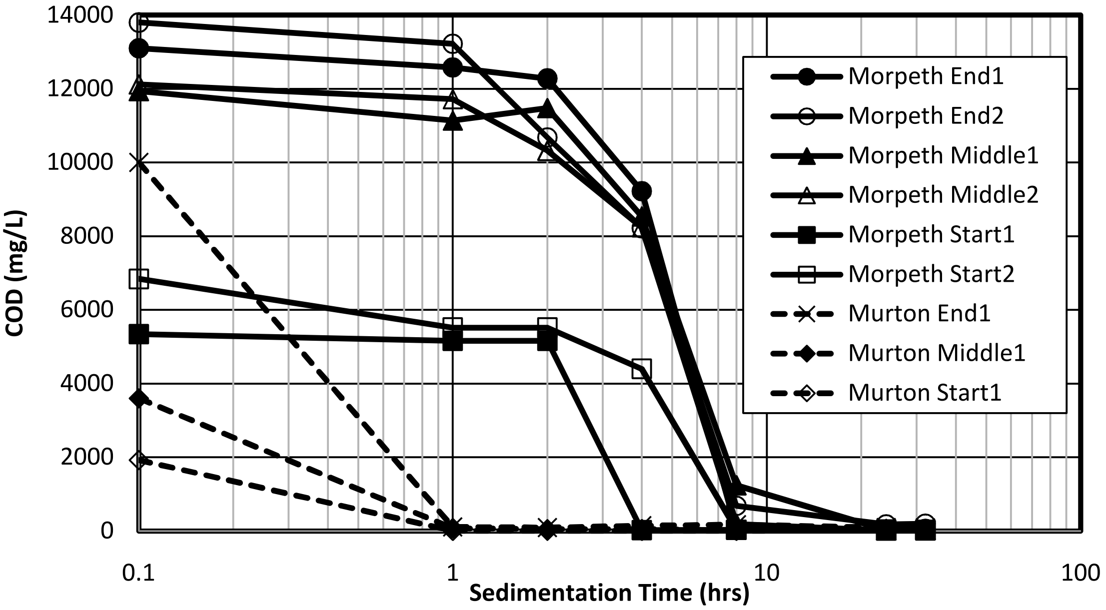


Figure 3- 9 The relationship between COD and sedimentation time at a level 60% of the height of column at different pipe jacking stages

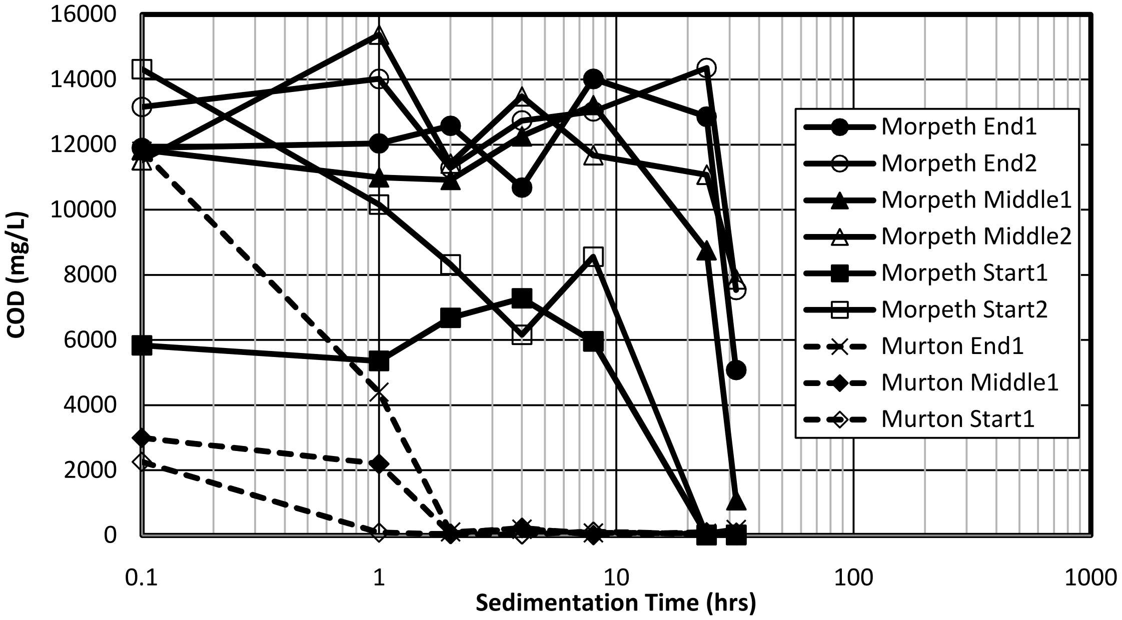


Figure 3- 10 The relationship between COD and sedimentation time at a level 40% of the height of column at different pipe jacking stages

Figures 3- 11, 3- 12 and 3- 13 display the dry density of samples taken from Morpeth and Murton sites at different levels in the column. The dry density of the slurry increased as the pipe was jacked, thus increasing the solid content. Dry densities of samples decreased as the settling time increased. This means the soil concentration in the slurry at levels 80 and 60% of the column height decreased as the settling time increased. Flocculated slurries needed less time to settle.

At level 80% (Figure 3- 11), the dry density decreased from 350 to 2 g/l after 4 hours for non-flocculated slurries (solid lines). However, it just took 1 hour for the dry density to decrease from 100 to 2 g/l for flocculated slurries (dash lines). This shows flocculation can help particle settling. Similar results are shown at a level 60%. From Figure 3- 12, it took 8 hours for the dry density of most non-flocculated slurries to reduce to 2 g/l at level 60%. However, it just took 1 hour for the dry density of flocculated slurries to reduce to 1 g/l.

From Figure 3- 13, the dry density increased at first due to soil accumulated at level 40% before 24 hrs and then decreased due to soil consolidation lower than the level 40% after a long settling time (at 32 hours) for non-flocculated slurries (solid lines in Figure 3- 13). The dry density decreased near to zero for flocculated slurries (dash lines in Figure 3- 13) due to the soil consolidation lower than the level 40% after 1 hour.

Comparing the COD and dry density results (Figure 3- 8 to Figure 3- 13), it can be found there were no relationships between COD and dry density for both samples. The polymer used on site was around 100-200 mg/l, which can cause a maximum value of 230 mg/l COD in the supernatant. However, the COD of the subsample was in the thousands. It can be assumed that organic matter leads to the high COD.

CEC tests were carried out on samples from Morpeth (soil condition: boulder soil) and Murton (soil condition: sand and clay with anionic polymer) sites. From Figure 3- 14, the CEC values were around 5 - 10 meq/100g for glacial till and 9 - 15 meq/100g for sand and clay. The pipe jacking process has little effect on the CEC value. The CEC was slightly higher for soil with anionic polymer.

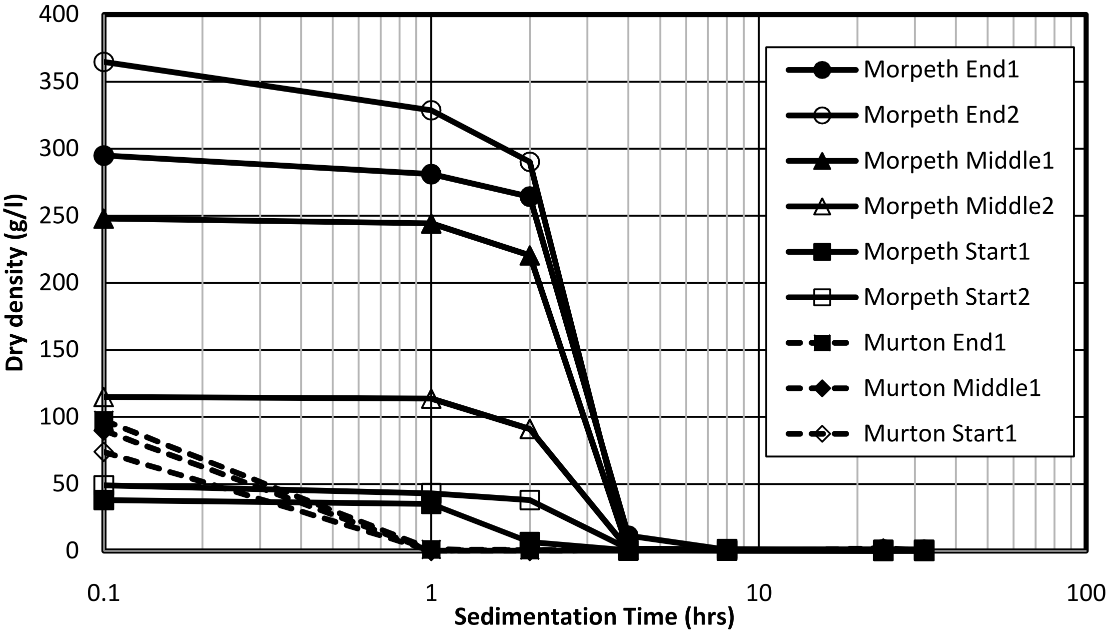


Figure 3- 11 The relationship between dry density and sedimentation time at a level 80% for different pipe jacking process stages

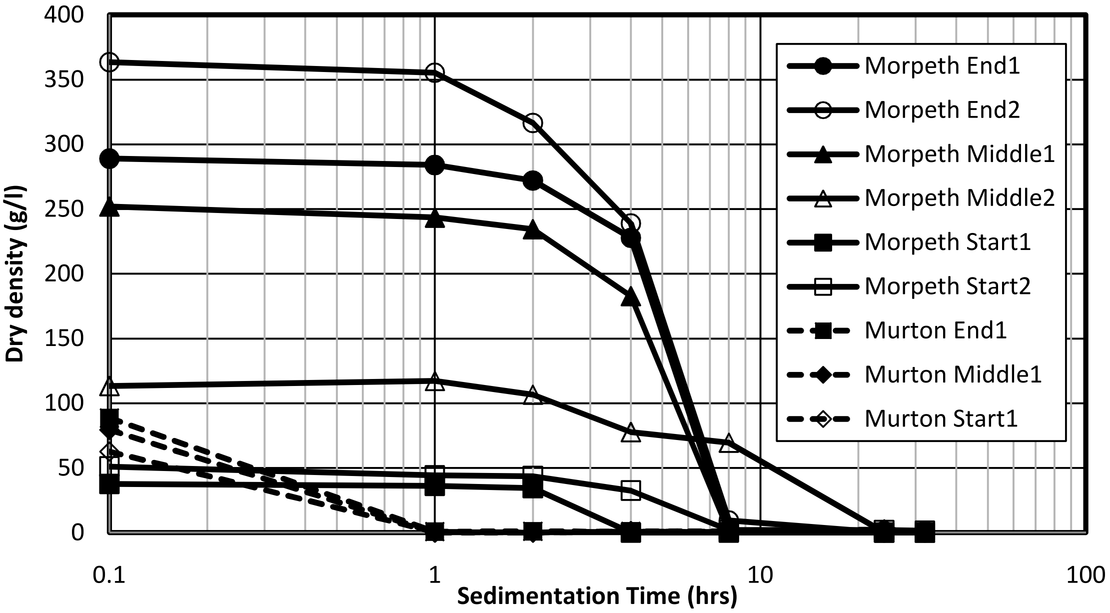


Figure 3- 12 The relationship between dry density and sedimentation time at a level 60% for different pipe jacking process stages

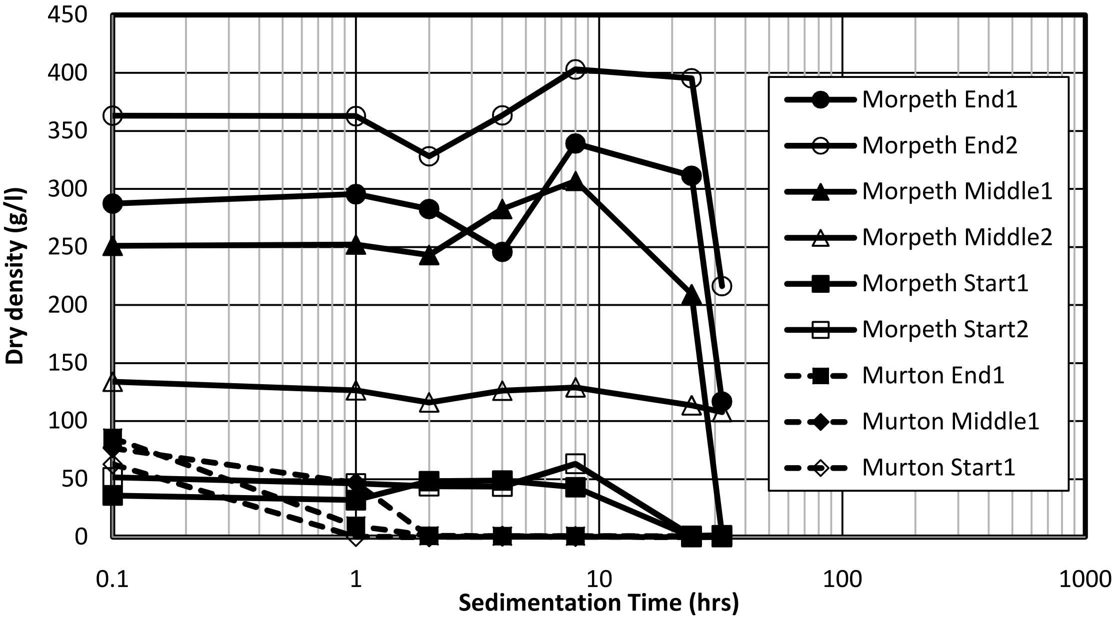


Figure 3- 13 The relationship between dry density and sedimentation time at a level 40% for different pipe jacking process stages

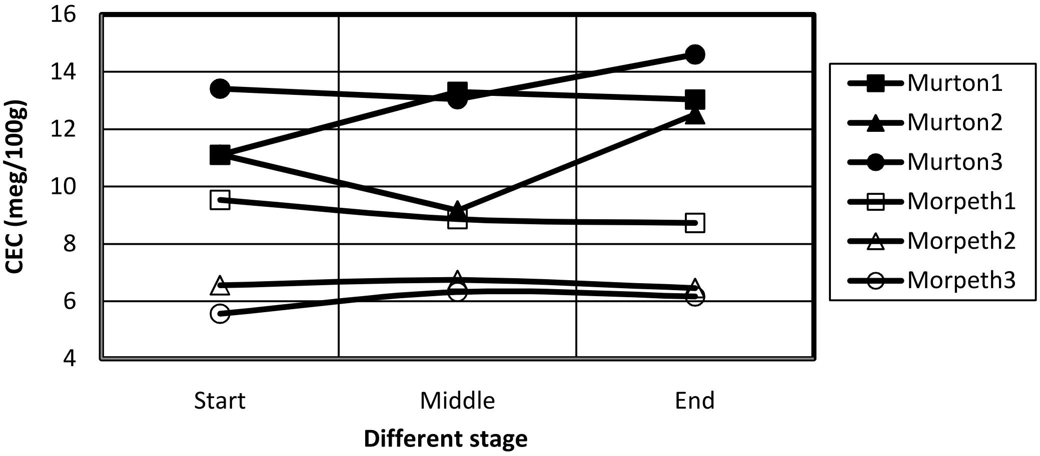


Figure 3- 14 CEC of the cake from the Morpeth and Murton sites

3.4.4 Slurry sedimentation tests on laboratory prepared samples

Sedimentation tests were carried out on a laboratory prepared sample from Morpeth. The soil and polymer were mixed manually to achieve a density of 1.05 Mg/m³. The floc reduction rate was studied to review the settling behaviour. The COD and dry density were investigated to measure the water quality and soil concentration of slurry at different levels in the column of slurry during the sedimentation process. The CEC test was used to analyse the effect on anionic polymer and CEC.

Figure 3- 15 shows the relationship between floc reduction and sedimentation time. The floc reduction is presented as the percentage of the volume of flocs reduced. Increasing the polymer content up to 120 mg/l reduced the time of settlement and reduced the height of the mudline suggesting a denser deposit (see Figure 3- 16). However, increasing the polymer content above 120 mg/l resulted in a reduction in density of the deposit. It could be that excessive polymer creates larger agglomerates of particles with greater void space resulting in increased volume of the sediment volume. In addition, the excessive polymer causes higher viscosity resulting in decreasing settling velocity. This observation was also noted by Rattanakawin and Hogg (2000) in their study on alumina suspension. They noted that floc size increased as the addition of polymer increased in an alumina suspension. Also, Lee and Liu (2001) noticed a similar observation in their study on a sludge system from a synthetic fiber plant. The effect of polymer addition on viscosity is also reported by some researchers. Viscosity slowly increased at first and the increase was accelerated by polymer addition in bentonite slurry (Güngör and Karaoglan, 2001). Abu-Orf et al. (2003) also noticed a similar trend in biosolids dewatering process.

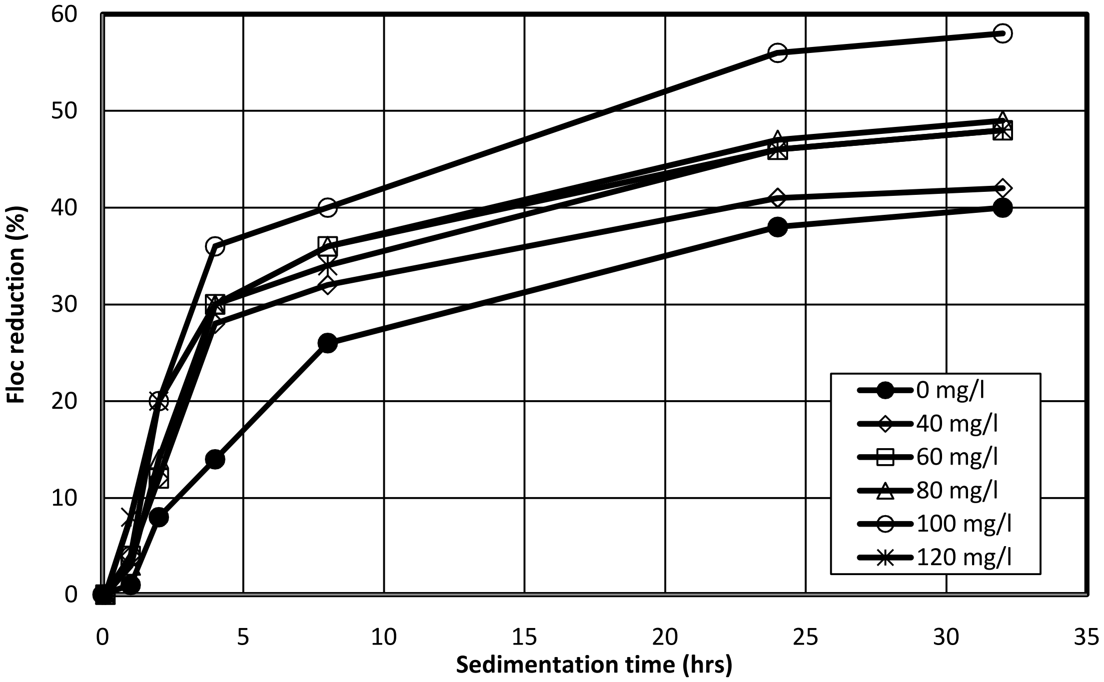


Figure 3- 15 Settling behaviour of floc reduction rate with different polymer content

Figure 3- 15 also shows the settling behaviour of floc reduction rate with different content of polymer. The rate of floc reduction increased rapidly within the first 4 hours for all flocculated samples. After 4 hours the rate decreased slightly and almost flattened after 24 hours for all flocculated samples. From the plot, increasing the polymer content increased the floc reducing percentage. However, polymer doses above 120 mg/l resulted in lower floc reduction percentage. This is probably due to an “overlap concentration” (in this case 120 mg/l). Gennes (1979) reported that after an overdose of polymer, overlap concentration will occur. This means polymer coils start to contact and inter-chain interaction occurs resulting in decreasing efficiency of the polymer. A similar trend was also found in Qian’s (2004)

work. Here, four different optimal doses (before the onset of an overlap concentration) of flocculants were found in kaolin suspensions.

From the result of this study, it can be seen that there is an optimum dose of 100 mg/l and optimum settling time of 4 hours for maximum efficiency of the polymer.

From Figure 3- 16 to Figure 3- 18, subsamples were collected at level 80, 60 and 40% of the height of column. It shows that the dry density varied with time and polymer content. Increasing the polymer content increases the speed of settlement.

The dry density of all the flocculated samples at a level 80% of the height of column (Figure 3- 16) was obviously low after 4 hours. The dry density of flocculated samples at a level 60% of the height of column (Figure 3- 17) reduced after 8 hours. There was no decreasing trend for dry density under a 40 mg/l flocculated sample within 32 hours at a level 40% of the column height (Figure 3- 18). All the data points show a gradual reduction in dry density followed by a dramatic reduction; this was because the mud lines were below the 40% of the column height after long time sediment.

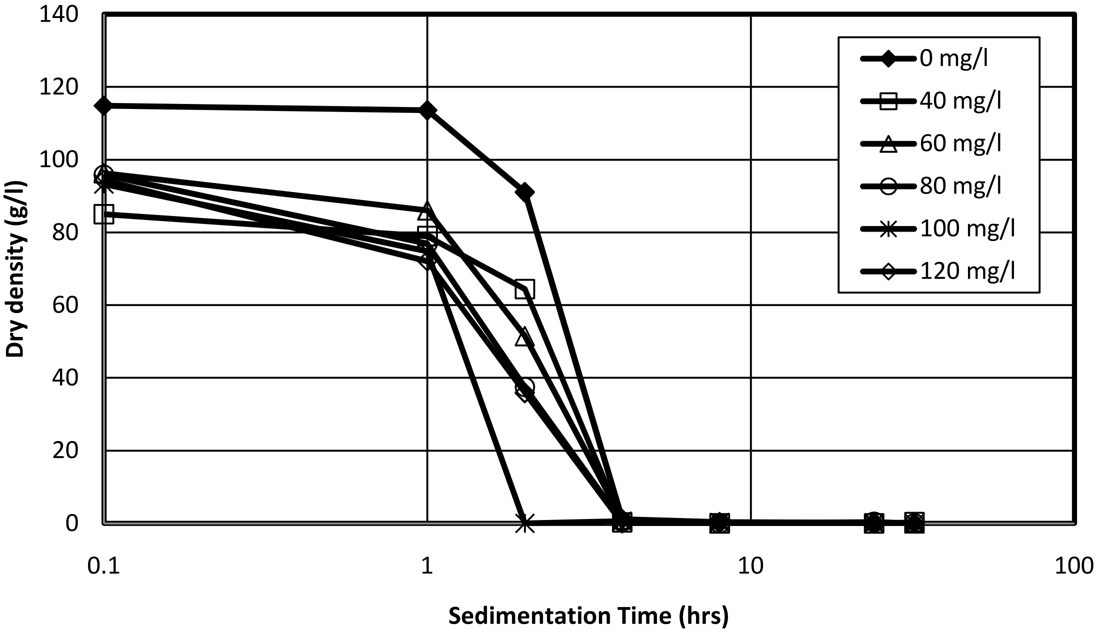


Figure 3- 16 The relationship between dry density and sedimentation time at a level 80% of the column height with different polymer contents

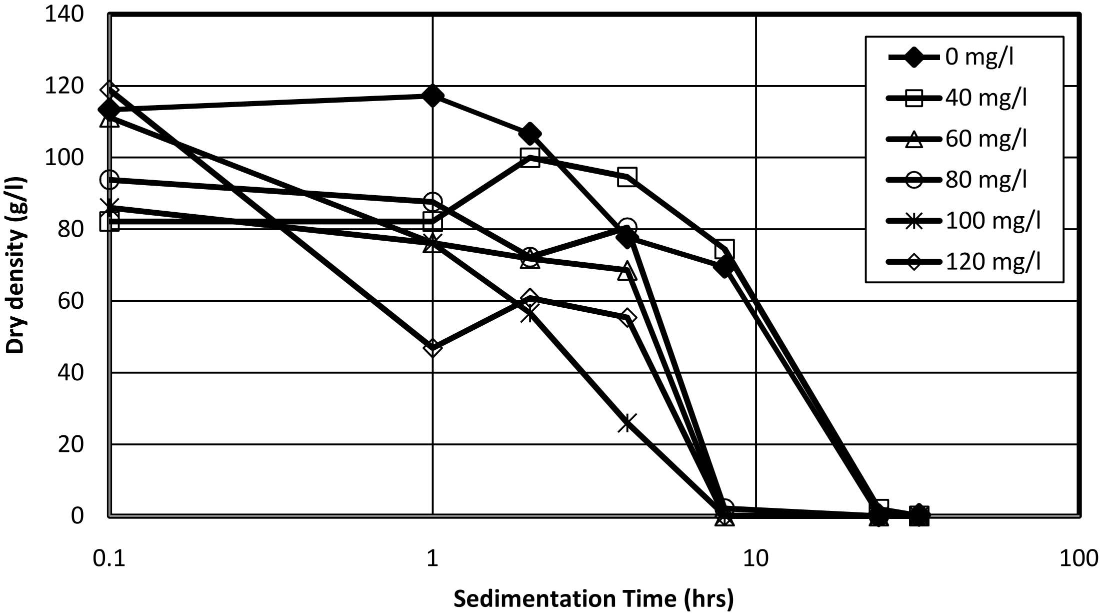


Figure 3- 17 The relationship between dry density and sedimentation time at a level 60% of the column height with different polymer contents

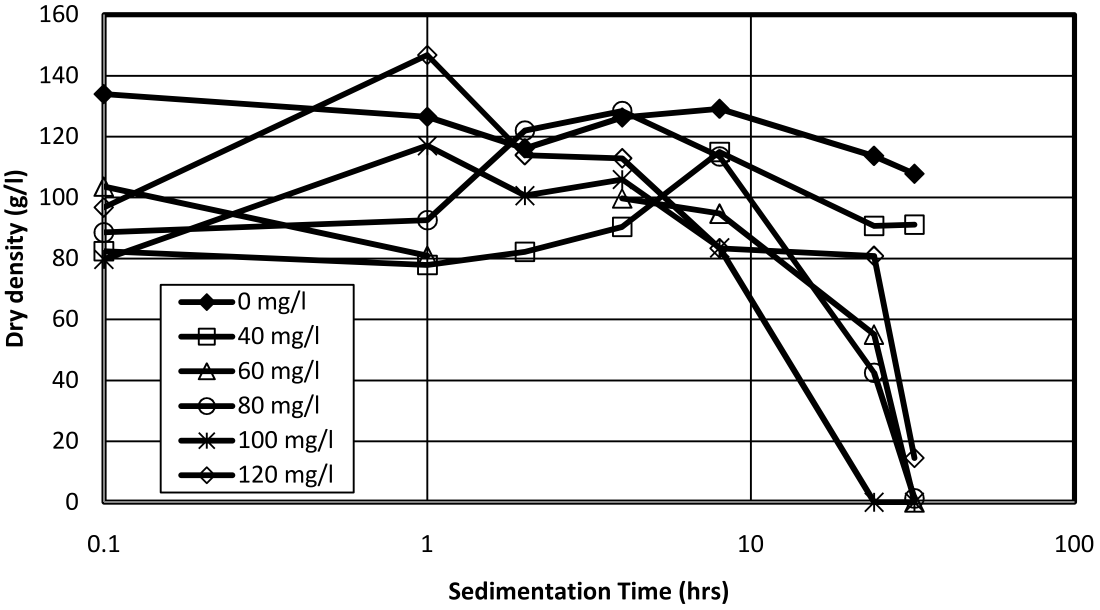


Figure 3- 18 The relationship between dry density and sedimentation time at a level 40% of the column height with different polymer contents

Subsamples were collected from levels 80, 60 and 40% of the height of column (from Figure 3- 19 to Figure 3- 21) for different polymer contents. The COD of most of the flocculated samples at a level 80% of the height of column (Figure 3- 19) were lower than the EU urban wastewater treatment effluent limit (125 mg/l) after 4 hours of sedimentation. However, it only took two hours to reach the effluent limit with a concentration of 100 mg/l polymer. This shows that polymer can reduce the settling time and therefore the time to achieve an acceptable value of COD for the supernatant.

COD of flocculated samples (above 100 mg/l) at a level of 60% of the height of column (Figure 3- 20) were lower than 125 mg/l after 8 hours. Ar 40 mg/l flocculated samples needed 32 hours to reach the effluent limit. Adding polymer can decrease the COD of flocculated samples at a level 60% of the height of column, but the time to achieve an acceptable limit may be unacceptable on site.

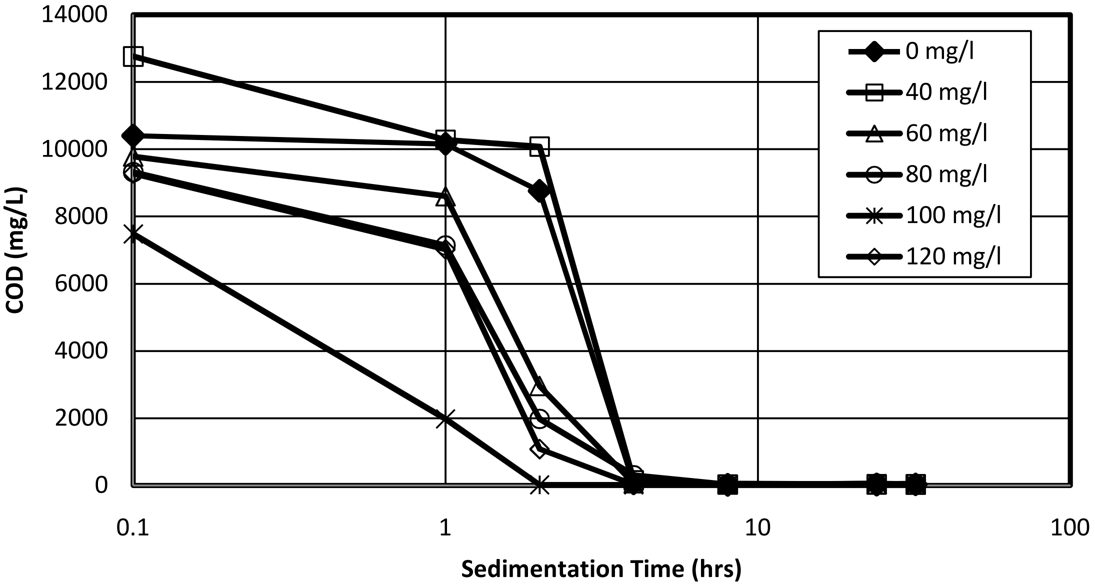


Figure 3- 19 The relationship between COD and sedimentation time at a level 80% of the column height with different polymer contents

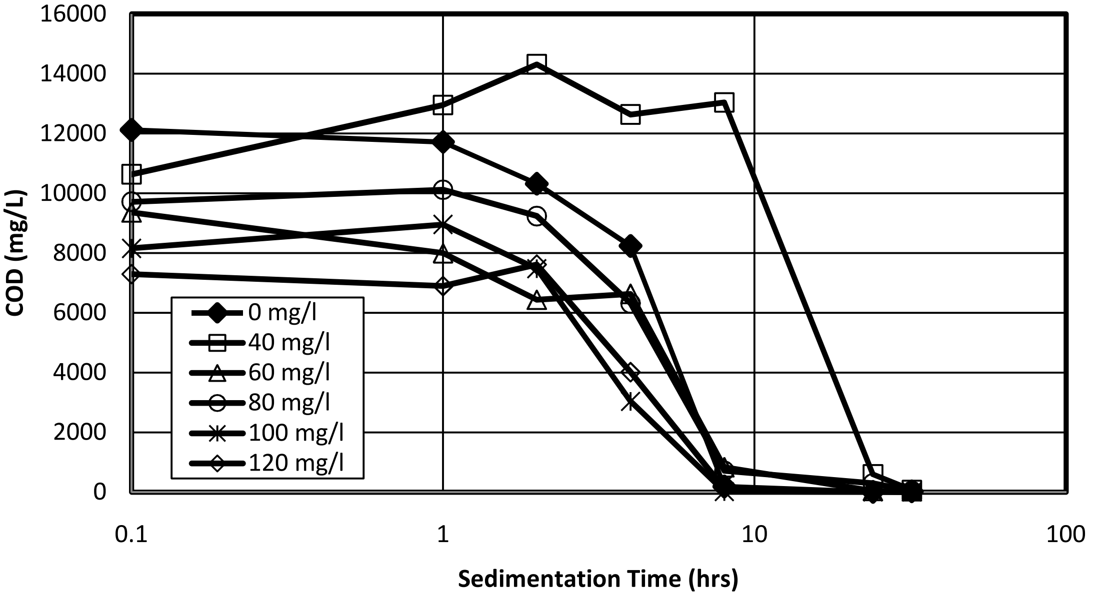


Figure 3- 20 The relationship between COD and sedimentation time at a level 60% of the column height with different polymer contents

Most samples at a level of 40% of the height of column (Figure 3- 21) did not reach the effluent limit within 32 hours. This shows the COD of all samples was sustained above the limit for at least 8 hours. The COD started to decrease after 24 hours for a polymer dose above 60 mg/l. This means that a minimum polymer dose to help sedimentation is necessary if acceptable COD values are to be achieved in the supernatant.

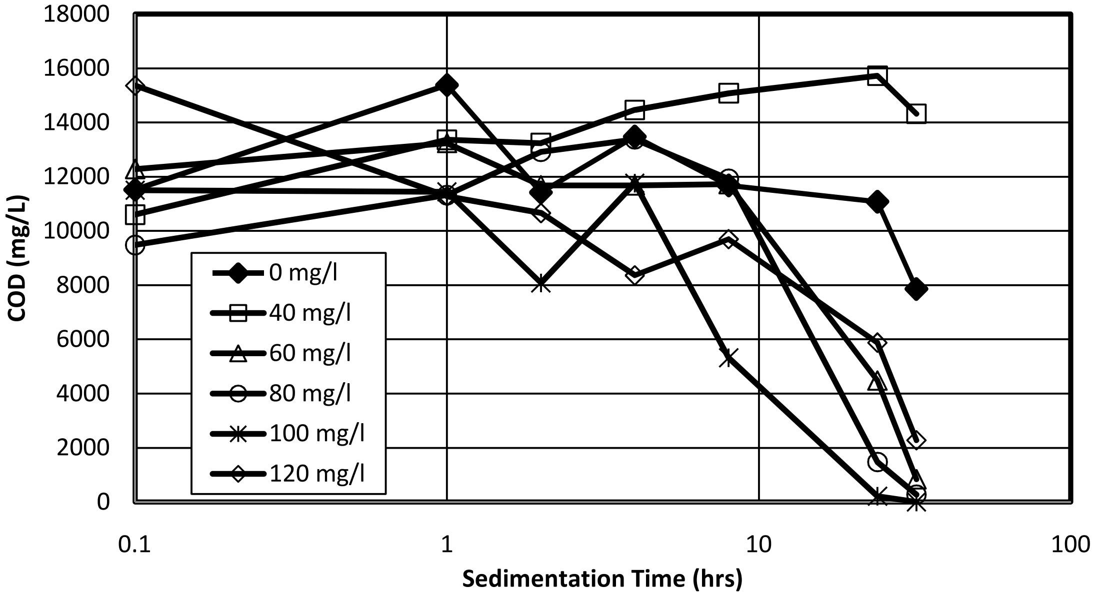


Figure 3- 21 The relationship between COD and sedimentation time at a level 40% of the column height with different polymer contents

The samples for the CEC tests were taken from the Morpeth site. Figure 3-22 shows increasing the polymer content increased the CEC slightly. However, the increase is between 12 to 21 meq/100g, which is not particularly higher than natural soils. Thus, polymer addition in practice has no significant effect on the CEC and might not be exploited for this application (i.e in terms of using slurry for cation extraction from contaminated wastewater).

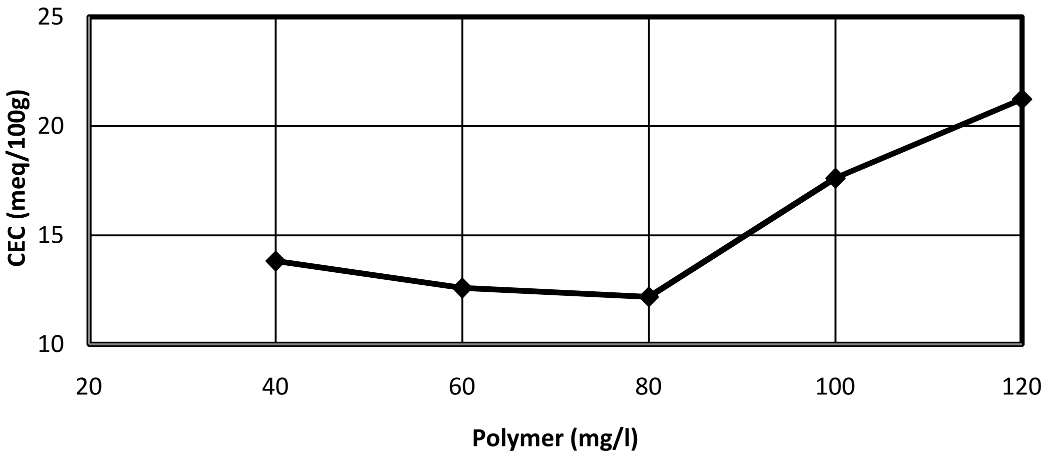


Figure 3- 22 CEC of slurry with different content of polymer

3.5 Conclusion

Separation plants are a feature of cake handling systems in the pipe jacking process. The granular fragments (sand and gravel) from separation plants cause no problems in disposal, but the cake, the solid produced by the centrifuge, may be not be acceptable to landfill as it may be classified as liquid waste.

The data presented in this study support the following conclusions.

1. Water contents of some cakes after centrifuge are above the liquid limit. It implies some cakes are not acceptable to landfill.

2. Some of the residual water of slurry tank or centrate from centrifuge may not be discharged directly due to exceeding EU urban wastewater COD effluent standards.
3. The CEC value of cake is similar to the typical soil although anionic polymer has been added to the cake. Therefore the CEC will not be applied on de-contamination water in this project.
4. Flocculation can help both settling time and the dry density of the slurry.
5. An optimum flocculant dose can produce an acceptable COD of the supernatant and a denser deposit.

Chapter 4 Determination of solid concentration of slurry by turbidity

4.1 Introduction

Clarity is an indication of potability, a measure that can be used to assess whether the liquid can be disposed of safely. Density cannot be used to assess the clarity of the supernatant, because of the limited quantity of solid present after separation. Turbidity is a recognised indicator of the clarity of liquid and is related to solid concentration. This study examines the relationships between solid concentrations (dry density divided by specific gravity) and turbidity on kaolin, bentonite and natural soils.

The typical density of slurry for tunnelling should be around 1.05 Mg/m^3 but the density will vary depending on the ground conditions, rate of excavation and efficiency of the separation plants during the pipe jacking process. If the density exceeds the critical density of 1.10 Mg/m^3, it can result in the failure of the pipe jacking operation due to a decrease in the flow rate, as the pump will require extra force to pump the denser slurry. In the extreme case, the pump can even stop pumping. Bulk density is used to measure the concentration of slurry on a pipe jacking site. A mud balance is used to determine density to help control the separation process in the pipe jacking process as the slurry density increases. It consists of a graduated arm with a cup and counterweight. Normally the accuracy is ±0.01 Mg/m^3.

4.2 Theory of turbidity

The clarity of water is affected by suspended matter, such as clay, silt, finely divided organic and inorganic matter, soluble coloured organic compounds, plankton and other microscopic organisms (APHA, 2005). If the suspended particles do not alter in their physical properties as their concentration varies, a linear relationship between clarity and suspended solids concentration is expected (Gippel, 1989).

The clarity of the water is known as turbidity, which is an optical property that results when light passing through a liquid sample is scattered. The scattering of light results in a change in the direction of the light passing through the liquid. This is most often caused when the light strikes particles in solution and is scattered backward, sideways and forward. Light scattered by the particles allows the particle to be seen or detected in solution (Figure 4- 1). This is a similar effect to sunlight passing through a window which is scattered by dust particles in the air allowing them to be seen (McCluney, 1975).

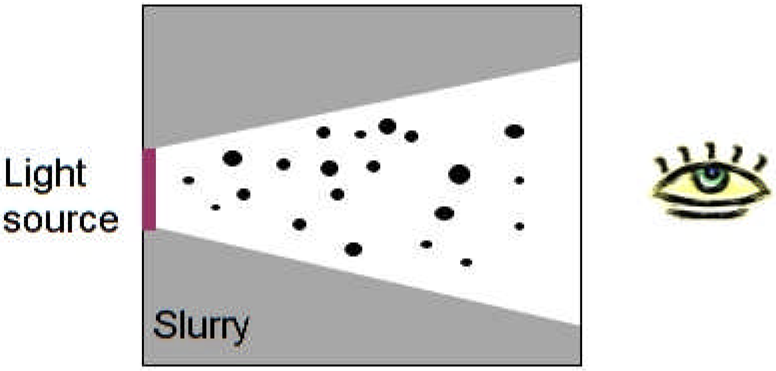


Figure 4- 1 Light passing through solution to show the distribution of particles

Turbidity is measured by detecting and quantifying the scattering of light in the liquid. There are two common methods to measure turbidity: the nephelometric method (measurement of the scattered light at 90°) and the attenuation method (measurement of the weakening of light at 180°).

The most common instrument for measuring scattered light in a liquid sample is a nephelometer. A nephelometer measures scattered light at 90° from a tungsten light source (Figure 4- 2). Light scattered at other angles may also be measured, but the 90° angle and a tungsten lamp with a colour temperature of 2200 – 3000 K was defined as a nephelometric measurement by the U.S. Environmental Protection Agency (US EPA). The units of measurement are nephelometric turbidity units (NTU). The amount of scattered light measured at the detector is directly proportional to the turbidity of the sample. This method is specified as the standard method for measurement of low turbidities (APHA, 2005). However, this means of measuring turbidity is not as effective when turbidity concentrations approach the values of 500 NTU or above. When the turbidity is greater than 500 NTU, it is best to use the attenuation mode (LaMotte, 2005).

Attenuation is a measurement of the weakening of the light beam though the sample, to a single 180° detector. The weakening of the light beam is being caused by the scattering of light due to the particles in the sample. In the attenuation method, the intensity of a light beam passing through a sample is compared with the intensity passing through a turbidity-free sample at 180° from the light source. These turbidity readings are reported as FAU (Formazin Attenuation Unit).

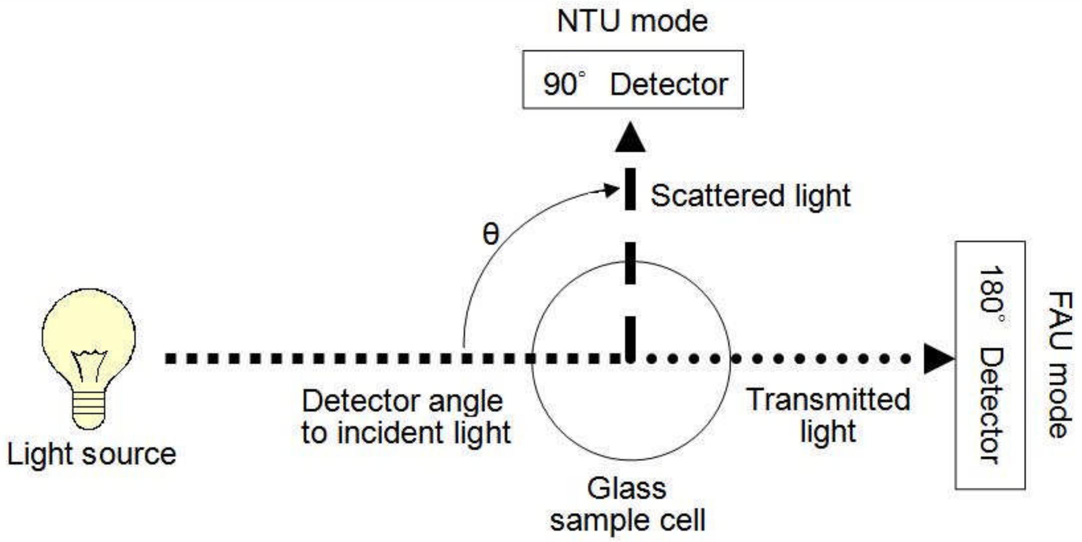


Figure 4- 2 Turbidity is determined by the light scattered at an angle of 90° or transmitted light at an angle of 180° from the incident beam in nephelometric measurement (Modified from Sadar, 1998).

Rayleigh (1899) indicated that the intensity of scattered light M is proportional to the number, N, of particles per unit volume and also to the square of the volume of each particle:

$$M \propto \pi N r_p^2 \qquad (4\text{- }1)$$

where M is the intensity of scattered light, r_p is the radius of a particle, N is the number of particles.

Pozharski et al. (2001) stated if particles can be represented as a solid sphere, the cross-sectional area of the particle is given by the same expression, but the particle concentration is inversely proportional to $r_p{}^3$ (not $r_p{}^2$).

$$M \propto \pi N\, r_p{}^3 \qquad (4\text{- }2)$$

There have been a limited number of studies into the use of turbidity as an index for assessing the number of particles. For example, Petus et al. (2009) reported a robust linear regression was obtained between turbidity and total suspended matter in the Adour river; a linear relationship between turbidity and oil content was observed on emulsion cutting fluid by Chen et al. (2008); a high correlation between turbidity and particle counts of municipal bacteriological measurements was noted by McCoy and Olson (1986); Lammerts van Bueren (1983) reported a linear relationship between turbidity and suspended solids concentration for the Yarra River.

According to these studies, turbidity was believed to be a function of the number of particles and dimensions. It can be expressed as:

$$\text{Turbidity} \propto N\, r_p \text{ per unit volume} \tag{4- 3}$$

Therefore it is possible to establish a relationship between turbidity and concentration of slurry:

$$\text{Dry density} = \frac{\text{Weight of Soil}}{\text{Volume of Slurry}} = \frac{\frac{\pi}{6} N\, r_p^3\, SG}{\text{Volume of slurry}} \tag{4- 4}$$

$$\text{Turbidity} \propto \frac{\frac{\pi}{6} N\, r_p^3}{\text{Volume of slurry}} = \frac{\text{Dry density}}{SG} \tag{4- 5}$$

where SG is the Specific Gravity

Turbidity is an indirect measure of density since it is an indication of the amount of particles in the slurry. It is assumed that the majority of the particles are soil so that the specific gravity can be assumed. It implies that even small differences of the amount of particles can be detected by turbidity which would be difficult to achieve by direct density measures. However, as the number of particles increases it makes turbidity more difficult to measure because light will not pass through the sample; and density easier to measure. It is necessary to dilute the slurry before tests if the limits of the turbidity measuring devices are exceeded (APHA, 2005). In this study, turbidity was measured with the LaMotte 2020e nephelometer, which can determine turbidity up to 4000 FAU. If a sample is encountered that is more than 4000 FAU, dilution with distilled water will bring the sample into an acceptable range. All dilutions are based on a final volume of 10 ml, the amount required for a turbidity test. Guidelines for dilutions of various proportions are given in Table 4- 1.

For example, if there are 5 grams of solids remaining in 1 ml of water, this solution has a solid concentration of 5 g/ml. If adding another 9 ml of water to this solution the solid concentration is reduced to 0.5 g/ml. The diluted solution still contains 5 grams of solid.

This relationship can be shown in the equation:

$$C_1 \times V_1 = C_2 \times V_2 \qquad (4\text{- }6)$$

Where:

C_1=concentration$_1$ (g/ml), V_1=volume$_1$ (ml)

C_2=concentration$_2$ (g/ml), V_2=volume$_2$ (ml)

To present the original concentration, the test result (concentration$_2$) of the diluted sample should be multiplied by a dilution factor (V_2/V_1).

Table 4- 1 The guideline for the dilution factor

Amount of sample (ml)	Distilled water to bring final volume to 10 ml (ml)	Dilution factor
10	0	1
5	5	2
2.5	7.5	4
1	9	10
0.5	9.5	20

Moreover, the dilution procedures may cause an error and there is no guarantee that halving the concentration will produce the same effect on the turbidity value. Particulates often react in an unpredictable manner when diluted (LaMotte, 2005). Suspended particles causing turbidity in the original sample may dissolve when the sample is diluted (Sadar, 1998); though this is unlikely with construction slurries since the solids are soil particles. If the relationship between turbidity and dilution factor is nonlinear, alternative instrument designs that better compensate for interferences should be considered. For example, a tungsten lamp operated at a colour temperature in the range of 2200 to 3000 °K or change the light of ISO 7027 requirement with an incident light output of 860 nm and a spectral bandwidth of less than 60 nm. Tungsten light sources are more sensitive to small particles, but sample colour typically interferes; instruments with an 860 nm output are not as sensitive to small particles but are not likely to have colour interference (Sadar, 1998).

Table 4- 2 shows the dilution effect of turbidity on a kaolin slurry. The turbidities of three different dilutions of the original concentration were linear and correlated positively with the percentage diluted. The accuracy was around ±3% for each reading, which is within the specification of LaMotte 2020e. It can be seen that the dilution did not affect the calculated value of turbidity.

Table 4- 2 Dilution effect of turbidity on kaolin slurry

Percent of the original concentration	Dilution factor	Turbidity reading after dilution* (FAU)	Turbidity = Dilution factor × Turbidity reading (FAU)
100%	1	3906	3906
80%	1.25	3083	3854
50%	2	1954	3908
20%	5	804	4020

*Reading was the average of three samples and six readings

4.3 Clay Types

Slurry is used as a carrying fluid for recycling in the pipe jacking system. It is mostly clay materials that are left in the slurry tank after several solid separation processes including screens and hydrocyclones. Clay materials are composed of solid, liquid and vapour phases (Figure 4- 3). Water is the most important substance of the liquid and vapour phases. It occurs both as adsorbed onto or absorbed into the surfaces of solid particles. The solid phases are mineral and organic phases. The organic matter is present in a variety of forms in clay materials including discrete organic particles, absorbed onto clay and other associated colloidal particles (e.g. iron oxides) and micro-organisms (e.g. bacteria) (Reeves et al., 2006).

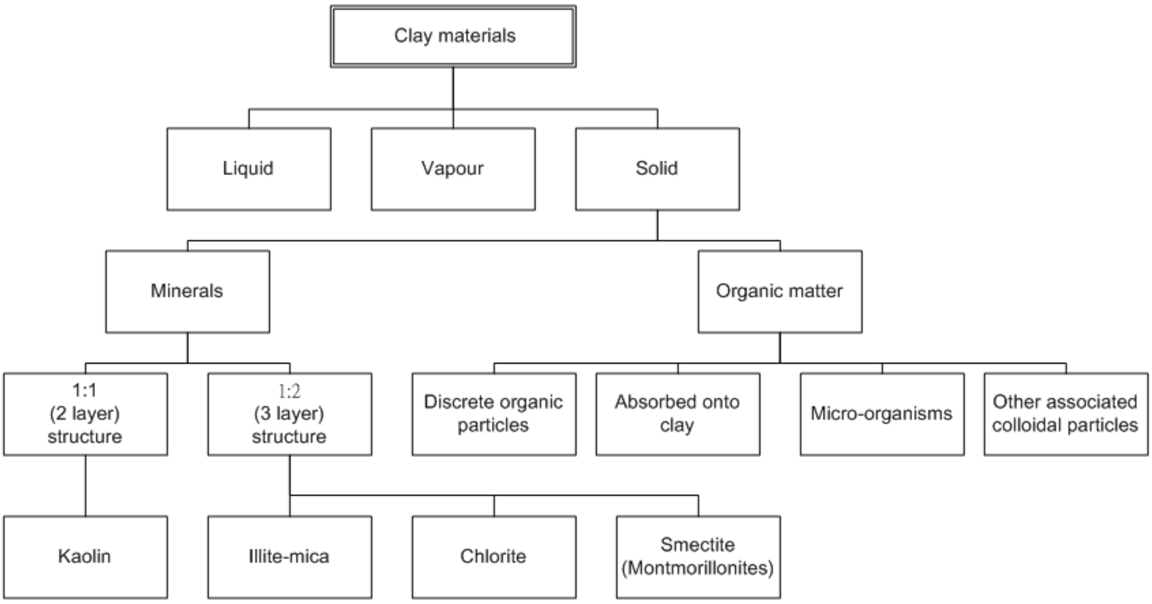


Figure 4- 3 The main composition of clay materials

The clay minerals are a group of hydrous aluminosilicates and the classification of clay minerals is summarized in Table 4- 3 (Olphen and Fripiat, 1979; Reeves et al., 2006). The particle size of the soil depends on the number and combination of clay minerals which comprise of different layers of external surface area and interlayer spacing. The sheet silicates consist of composite layers of tetrahedrally co-ordinated Si and octahedraly co-ordinated cations (principally Fe, Al, Mg). A simple diagram is shown in Figure 4- 4. There are two types of composite layer structures in the clay minerals:

- The two-layer or 1:1 type represented by the kaolin groups (Figure 4- 5);
- The three-layer or 2:1 type represented by the illite-mica, smectite (Montmorillonites) and chlorite groups (Figure 4- 6).

The 2:1 clay minerals (e.g. bentonite) have a net negative charge on their composite layers due to interlayer cations. The 1:1 clay minerals (e.g. kaolin) ideally have neutral composite layer structures (Reeves et al., 2006).

Table 4- 3 Classification of clay minerals

Sheet silicate type	Major groups	Property	Approximately external surface area (m^2/g)	Approximately interlayer spacing (Å) 1 angstrom (Å) = 10^{-10}m
1:1 (2 layer)	Kaolin	Non-swelling	15	7
2:1 (3 layer)	Illite-mica	Non-swelling	25	10
	Chlorite	Non-swelling	15	14
	Smectite (Montmorillonites)	Swelling	50	15

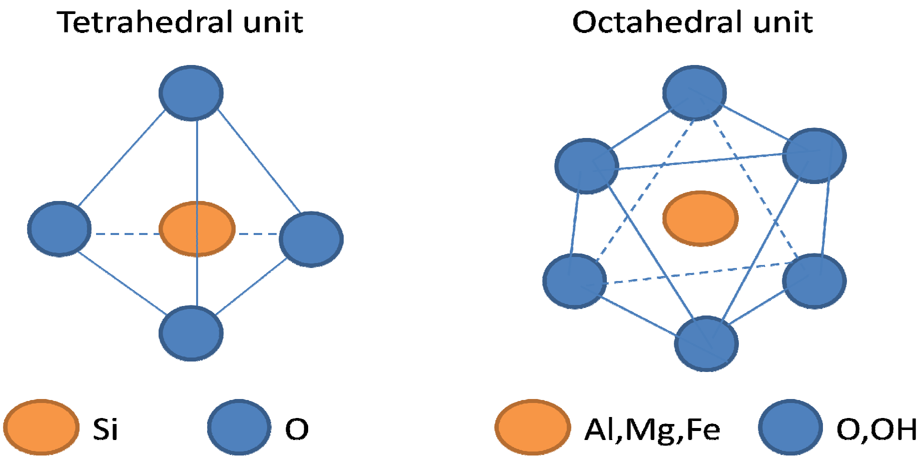


Figure 4- 4 Basic structural units of clay minerals

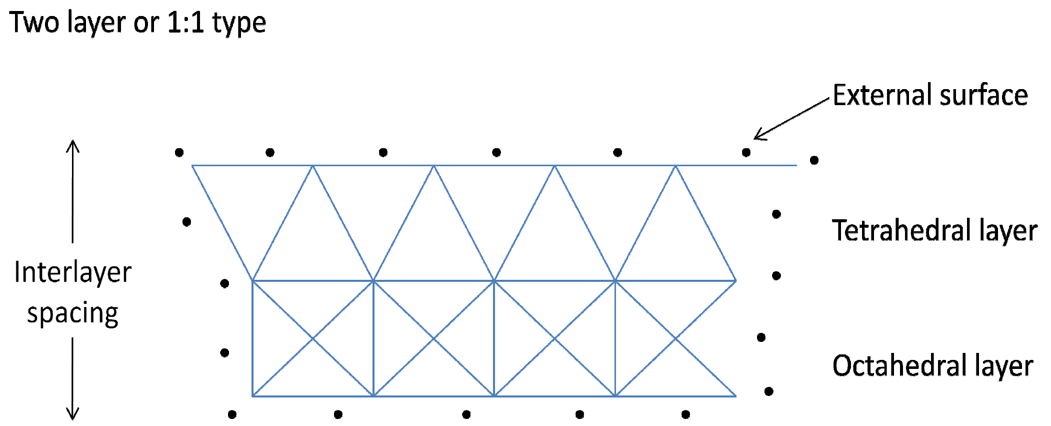


Figure 4- 5 General structures of two layer or 1:1 clay minerals (e.g. kaolin)

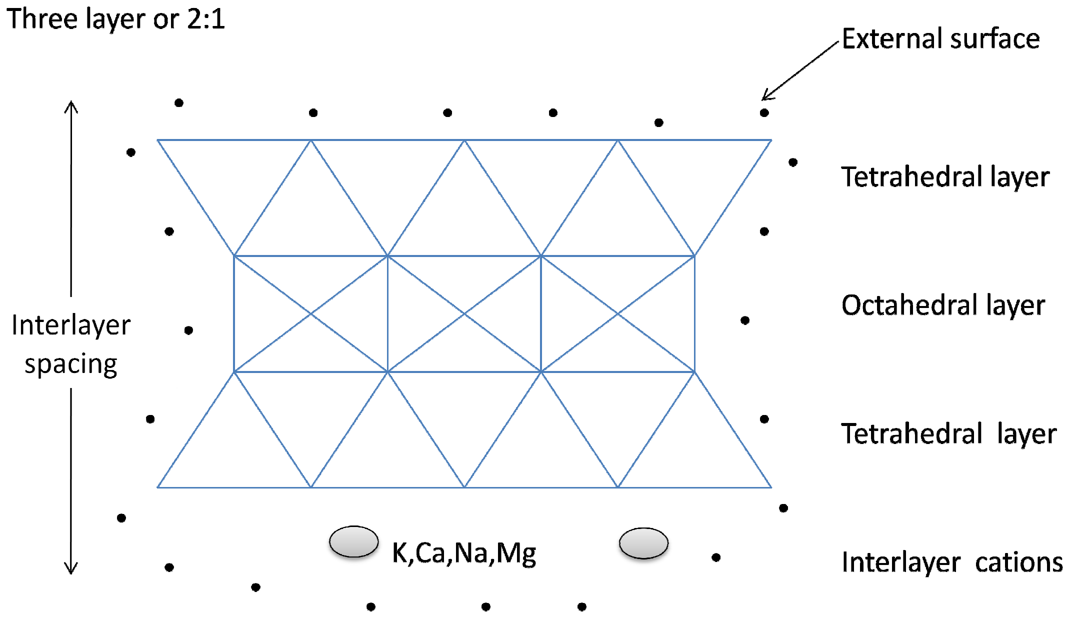


Figure 4- 6 General structures of three layer or 2:1 clay minerals (e.g. bentonite)

In this study, kaolin from Polwhite E (IMERYS Ltd) and bentonite from Calcium Bentonite (RS Minerals Ltd) were used to create slurries, since they represented the two basic types of clay materials. A set of experiments with the following soils were studied to establish the correlation between dry density of the slurry and its turbidity:

1. Laboratory soil. (Kaolin, bentonite)

2. Mixed laboratory soil. (Different proportion of bentonite mixed with kaolin)
3. Slurry from natural soil from pipe jacking sites. (E.g. Lambeth Group, London Clay)

4.4 The testing protocol

Artificial slurry was prepared by mixing 150g of selected soil with 1 litre of water to achieve a density of 1.09 Mg/m³ based on an SG of 2.6 to simulate the real slurry from site. It is not possible to measure the turbidity of these slurries directly because of the degree of opaqueness of the slurry. In this case samples of the slurry had to be diluted before the turbidity was determined to establish a relationship between turbidity and dry density. The turbidity value was an average result from two readings for each sample. The accuracy for turbidity nephelometer was ±3%. The dry density value was tested for one sample. The accuracy for pipette was ±1.75%, and the accuracy for balance was ±0.3mg.

The procedure for these series of experiments was as follows:

1. Slurry was prepared by mixing 150 g of soil particles with 1 litre of water.
2. A 10 ml slurry sample was taken to determine the turbidity and dry density.
3. If the turbidity of the sample was more than the turbidity meter detection limit (4000 FAU), then the sample was diluted with particle

free distilled water to bring the sample into an acceptable range to detect its turbidity. All dilutions are based on a final volume of 10 ml to fill the sample tube.

4. The test was repeated several times using diluted concentrations of slurry. This was achieved by removing half of the slurry and adding distilled water.
5. The steps 2 to 4 were repeated to achieve a decreasing density and turbidity until the turbidity value was below 50 NTU.

The data were presented as dry density divided by SG against turbidity reading to achieve a relationship between particle concentration and turbidity (see equation 4- 5). The SG value was taken from the supplier’s material data sheet.

In the following experiment, turbidity was measured with the LaMotte 2020e nephelometer. The LaMotte 2020e is a nephelometer that is capable of measuring turbidity by both the attenuation method and the nephelometric method. It uses a detector placed at 90° to the light source for the nephelometric method and a detector placed at 180° to the light source for the attenuation method. The LaMotte 2020e also has a third detector that monitors the intensity of the light source. It uses this detector to improve instrumental stability and minimize calibration drift. Results were given in FAU or NTU depending on the sample properties. The detection range for the LaMotte 2020e nephelometer is up to 4000 FAU. Samples have to be diluted until turbidities were within this range.

Due to the limitation of the measurement of turbidity, three ranges were considered: turbidity less than 500 NTU, between 500 to 4000 FAU and greater than 4000 FAU. In addition, Ankcorn (2003) indicated that turbidity is not an absolute value, but a relative value representing a qualitative measurement that can yield different readings based on the method used. Table 4- 4 shows the specifications for different turbidity mode.

Table 4- 4 Comparison of selected turbidity mode

Range of turbidity / Specifications	≤500	500-4000	≥4000
Detection Mode	Nephelometric mode	Attenuation mode	Attenuation mode with dilution
Turbidity unit	NTU	FAU	FAU

4.5 Test results

4.5.1 Laboratory soil tests

The overall relationships between turbidity and solid concentration (dry density divided by SG) up to a density 1.09 Mg/m³ of kaolin and bentonite slurries are shown in Figure 4- 7. This figure shows that there is a linear relationship between turbidity and solid concentration. Moreover, the two different soil types had distinct trend lines. Kaolin showed a higher turbidity than bentonite for the same solid concentration. Thus turbidity is not only a function of the number of particles (expressed in terms of density), but is also a function of the type of particle.

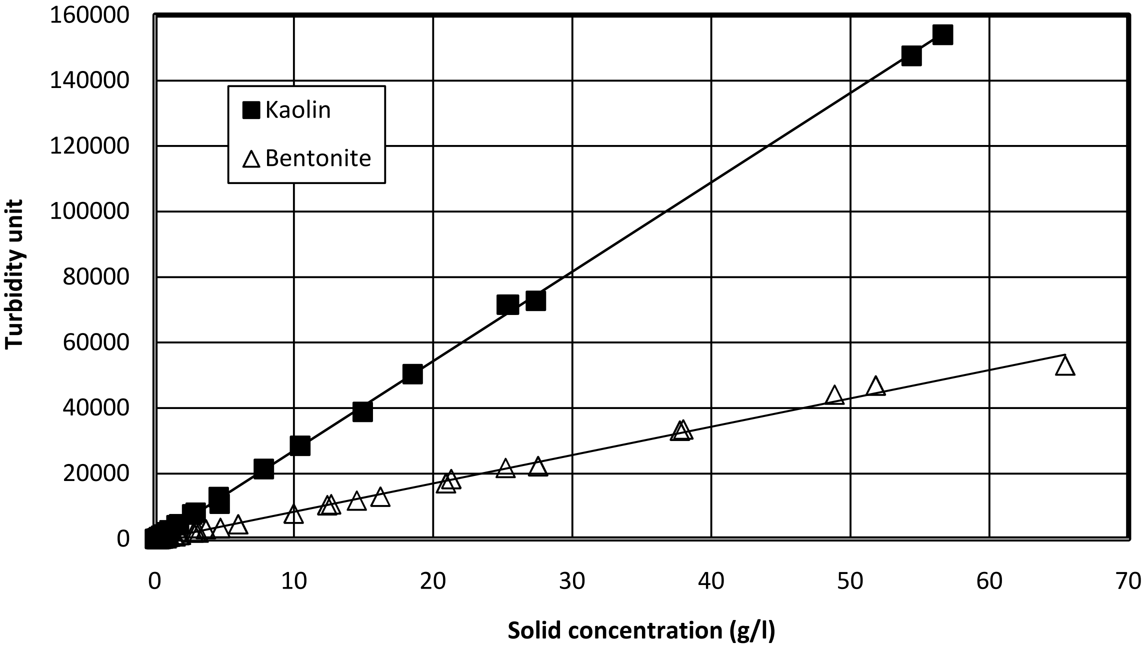


Figure 4- 7 The relationship between turbidity and solid concentration of slurry on kaolin and bentonite

Due to the different ways of measuring turbidity (NTU or FAU) and the need to dilute samples above 4000 FAU, the relationship between turbidity and density was investigated separately using turbidity values less than 500 NTU, 500 - 4000 FAU and above 4000 FAU. The relationships between turbidity and solid concentration of slurry on kaolin and bentonite for these ranges are displayed on Figure 4- 8, Figure 4- 9 and Figure 4- 10, respectively. The slopes (see Table 4- 5) for the turbidity range in 500-4000 FAU and above 4000 FAU of kaolin slurries are similar. It means the diluting process had little effect on the turbidity measurement for kaolin. Kaolin has better correlation than bentonite for low turbidities. The relationship for bentonite is not as good as kaolin for the turbidity range under 500 NTU. There is a high correlation between turbidity and solid concentration for high values of turbidity.

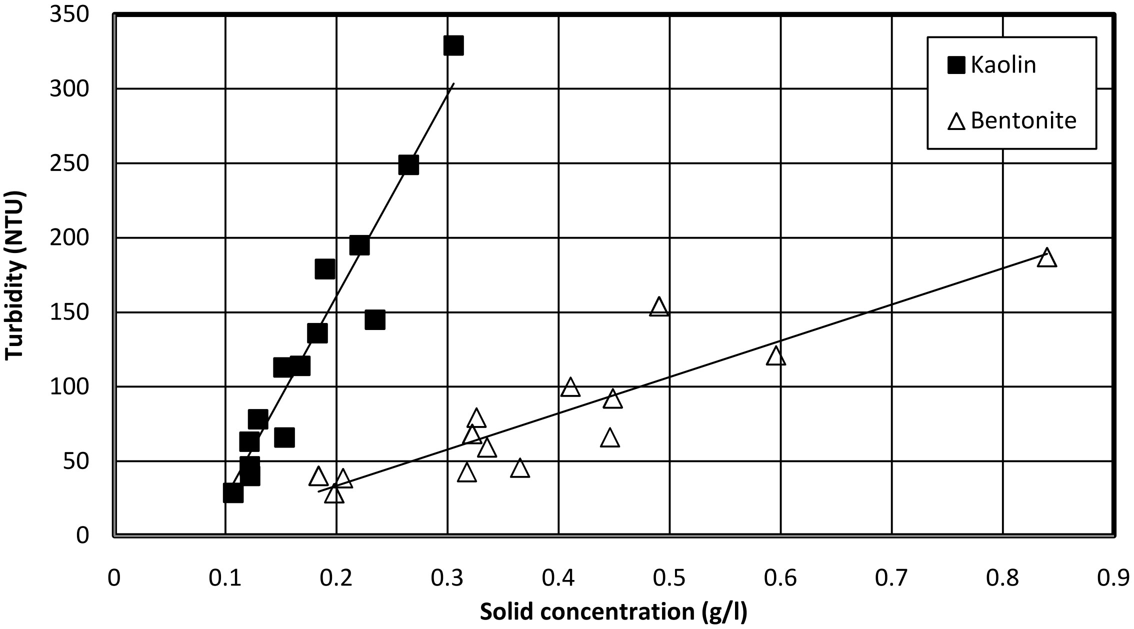


Figure 4- 8 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for turbidity values less than 500

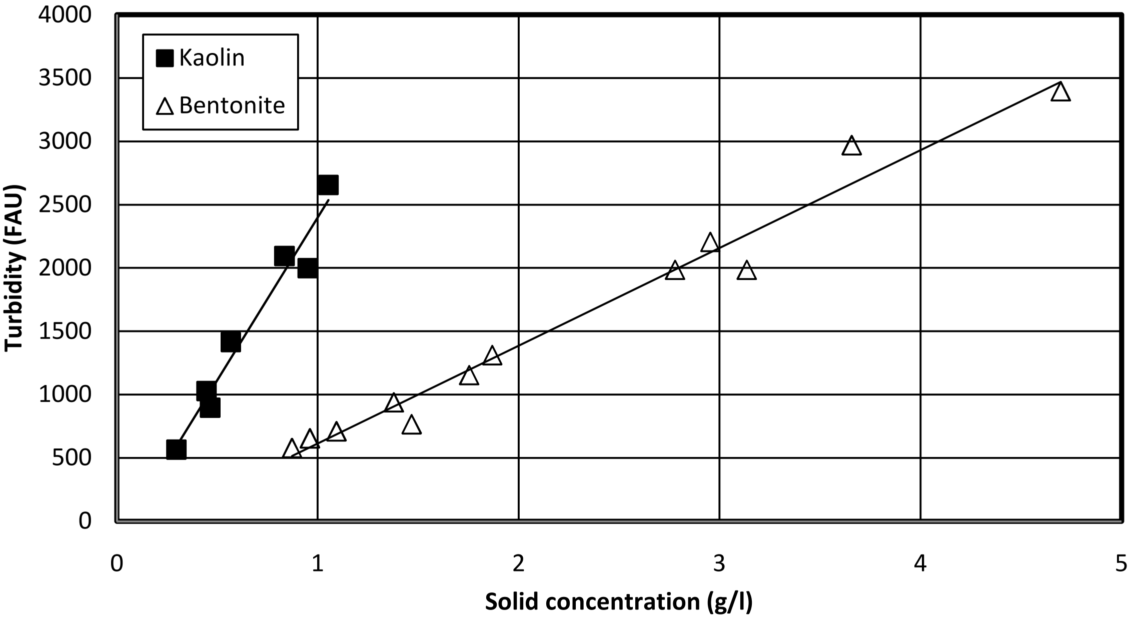


Figure 4- 9 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for FAU values between 500 and 4000

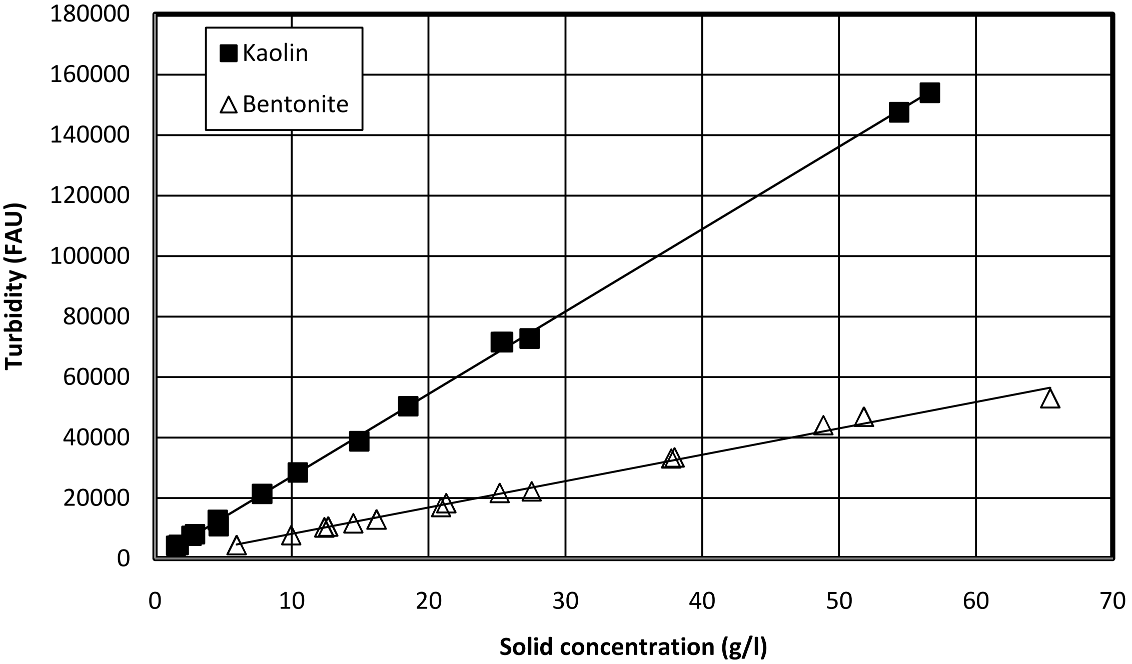


Figure 4- 10 The relationship between turbidity and solid concentration for kaolin and bentonite slurries for FAU values above 4000 based on diluted samples

Table 4- 5 Summary of the regression characteristics of the relationship between turbidity and solid concentration of slurry for kaolin and bentonite slurries for the three ranges of turbidity

Soil type	Turbidity range	Turbidity unit	Calibration regression characteristics (Linear R^2)	Regression equation y = turbidity (NTU or FAU) x = solid concentration (g/l)
Kaolin	≤500 NTU	NTU	0.93	y = 1352x - 110
	500-4000	FAU	0.96	y = 2574x – 175
	≥4000	FAU	0.99	y = 2726x - 111
	Full range	FAU	0.99	y = 2731x – 271
Bentonite	≤500 NTU	NTU	0.82	y = 244x – 15
	500-4000	FAU	0.98	y = 772x – 159
	≥4000	FAU	0.99	y = 873x – 574
	Full range	FAU	0.99	y = 866x – 344

From equation 4- 5, turbidity is directly proportional to dry density divided by SG. This implies the relationship between turbidity and dry density should be linear. This proved to be the case for all three ranges of turbidity. In addition, forcing the trend line through the origin as the turbidity should be zero if there are no particles present results in similar relationships (Table 4- 6). There are not too many differences between Table 4- 5 and Table 4- 6. The main difference is in R^2 which changes from 0.93 change to 0.73, if fitting a linear curve and forcing the trend line through the origin for data less than 500 NTU for kaolin slurry.

Table 4- 6 Regression characteristics of the relationship between turbidity and solid concentration of slurry for kaolin and bentonite slurries with the trend lines being forced to go though the origin

Soil type	Turbidity range	Turbidity unit	Calibration regression characteristics (Linear R^2)	Regression equation y = turbidity (NTU or FAU) x = solid concentration (g/l)
Kaolin	≤500 NTU	NTU	0.73	y = 763x
	500-4000	FAU	0.96	y = 2345x
	≥4000	FAU	0.99	y = 2723x
	Full range	FAU	0.99	y = 2723x
Bentonite	≤500 NTU	NTU	0.80	y = 211x
	500-4000	FAU	0.97	y = 716x
	≥4000	FAU	0.99	y = 857x
	Full range	FAU	0.99	y = 857x

Two different measurement modes (NTU or FAU) of turbidity and two sample dilution conditions (with or without dilution) result in three ranges of turbidity (see Table 4- 4). The trend lines for each of the three ranges (solid lines) are shown in Figure 4- 11 for kaolin and bentonite.

Statistically, a confidence level of 95% is acceptable in practice (Murray R. Spiegel et al., 2009). This means 5% error range is acceptable for turbidity measurement. The data points for the ranges 500-4000 FAU and above 4000 FAU are plotted on Figure 4- 11. The 5% error range of the data used to produce the trend lines covered the two solid trend lines (500-4000 FAU and above 4000 FAU). Moreover, if data from 500-4000 FAU and above 4000 FAU are replaced in each equation, a calibration regression R^2 above 0.90 is obtained (detail see Appendix V). Statistically these trend lines fall within an acceptable limit. This means these two solid trend lines are statistically the same. The implication is that dilution has little impact on the relationship between turbidity and dry density.

This does not apply when the turbidity measurements are below 500 NTU. It means that the detecting mode (NTU or FAU) affects the trend. It could be because of the different way of detecting the light. Nephelometric method (NTU) is using light scattered at an angle of 90° and attenuation method (FAU) is using transmitted light at an angle of 180° (Figure 4- 2).

The correlations between NTU and FAU are displayed on Figure 4- 12 for three different slurries (pure kaolin, pure bentonite and the 50% kaolin with 50%

bentonite slurries). There is a good linear relationship between NTU and FAU but the relationship varies between slurries.

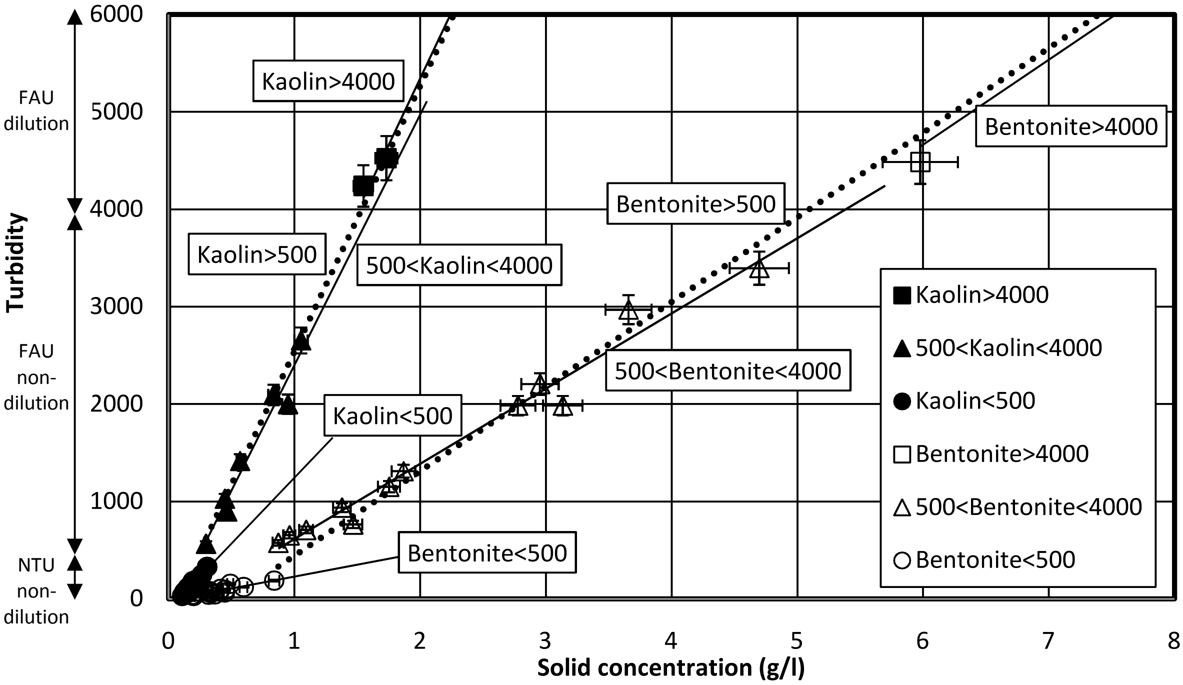


Figure 4- 11 The trend lines of turbidity and solid concentration on kaolin and bentonite slurries

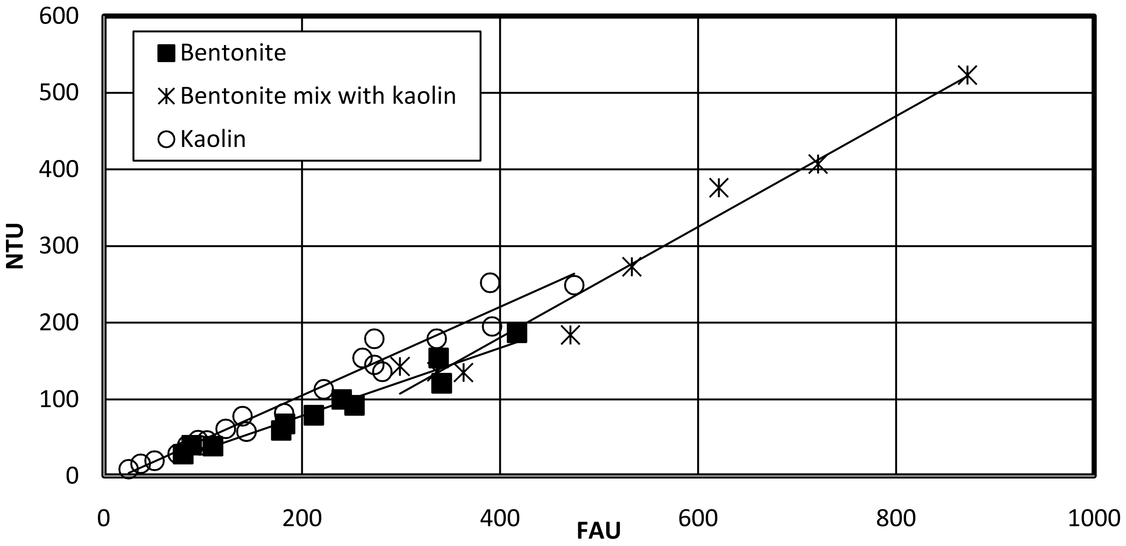


Figure 4- 12 The relationship between NTU and FAU for kaolin and bentonite slurries

4.5.2 Mixture of kaolin and bentonite

The fact that there is an acceptable linear relationship between turbidity and solid concentration for diluted and undiluted slurries means that it is possible to explore the effect of different compositions of clay slurry.

The relationships between turbidity (FAU) and solid concentration for different compositions of kaolin and bentonite are shown in Figure 4- 13. Four samples were tested at each solid concentration of kaolin and bentonite. The results show a linear relationship between turbidity (FAU) and solid concentration expressed as grams per litre of slurry. In addition, when the value of solid concentration has been fixed, the turbidity decreases with bentonite content.

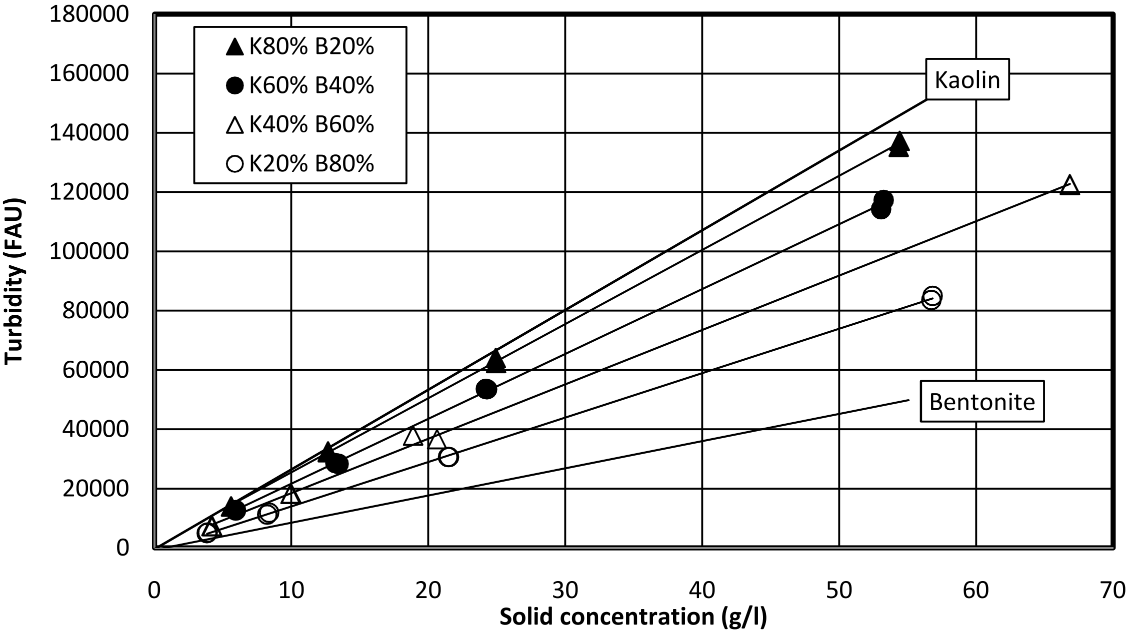


Figure 4- 13 The relationship between turbidity and solid concentration for different mixes of kaolin and bentonite slurries

4.5.3 Natural soil

In the following experiment, slurries were prepared for London Clay, Lambeth Group 1 and Lambeth Group 2 taken from three different pipe jacking sites. Two individual samples were tested for each solid concentration to ensure the repeatability of the result. The overall relationships between FAU and solid concentration of slurry on these natural soils are illustrated in Figure 4- 14. It can be seen that the relationships for London Clay and Lambeth Groups are different (Table 4- 7), which is not surprising as it has already been established that turbidity is affected by mineral type. Furthermore, the trend lines for the London Clay and Lambeth Groups are located between the kaolin and bentonite trend lines. It suggests that kaolin and bentonite may be extreme cases.

Lambeth Group is dominantly composed of smectite and illite with some chlorite and kaolin minerals. London Clay is dominantly composed of smectite and illite clay minerals with some chlorite and kaolin minerals (Reeves et al., 2006; Huggett and Knox, 2006). This suggests the mineral content of both soils is similar. Figure 4- 14 shows that Lambeth Group 2 is similar to London Clay but different from Lambeth Group 1. This means turbidity is not solely affected by mineral type.

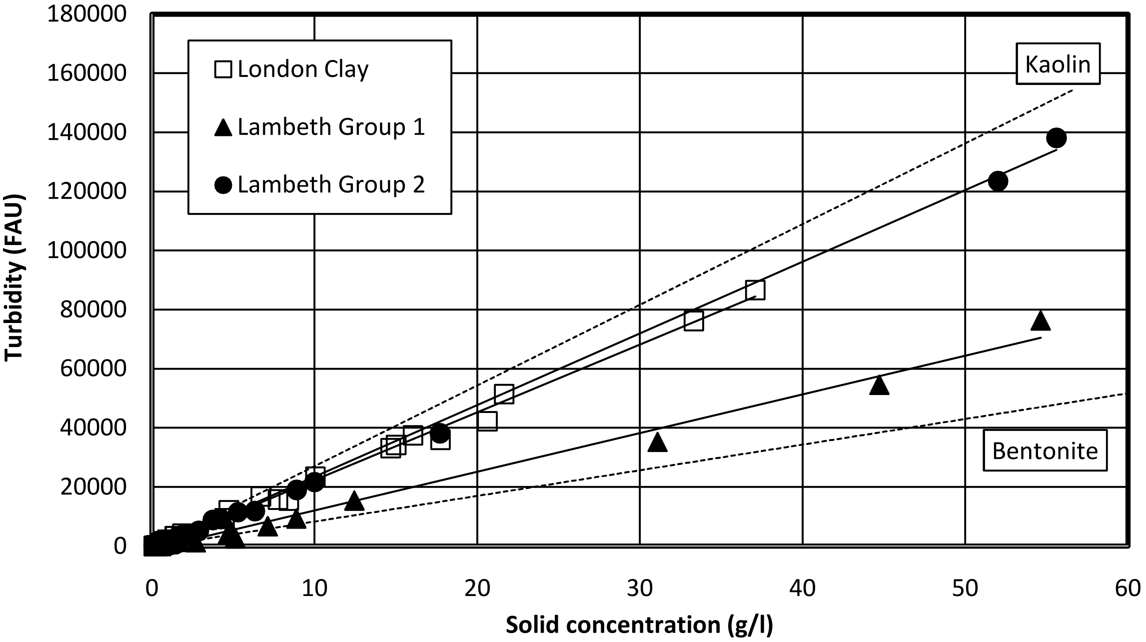


Figure 4- 14 The relationship between turbidity and solid concentration of natural soil sample

Table 4- 7 Summary of the regression equations for turbidity and solid concentration of slurry and calibration regression on natural soil (assuming zero turbidity at zero solids concentration)

Soil type	Regression equation y = turbidity (FAU) x = solid concentration (g/l)	Calibration regression characteristics (Linear R^2)
London Clay	y = 2262x	0.99
Lambeth Group 1	y = 1278x	0.99
Lambeth Group 2	y = 2403x	0.99

4.6 Index testing of turbidity

The turbidity of suspended inorganic matter is affected by particle size, colour of particle, the shape of particle and refractive index* (Gippel, 1989; Kavanaugh and Trussell, 1977). In Ehlerss' (1987) research, if the difference in refractive index between solid and immersion liquid is small, the refraction effects are small. Due to the close range in value between the three soil types there is little disparity in the refraction effect. The refractive index of quartz, illite and kaolin are around 1.54, 1.59 and 1.56 respectively (Weidler and Friedrich, 2007); and water is 1.33. The different of refraction effects between various soils are similar. It means the refractive effect on turbidity is small in this study. The particle size can be identify by the pipette method (BS1377-2, 1990). The colour can be measured with a colorimeter (BSI5339, 1976). The shape of a particle is suggested by measuring from at least two directional projections (Yamamoto et al., 2002; Kempkes et al., 2008). However, it is very difficult and impossible to assess the shape of certain amount of particles in this study. Also, the shape of every individual particle is not homogeneous. Therefore, the following study the effect of particle size and colour of particle on turbidity.

*The refractive index (n) of a substance is a number derived by dividing the velocity of light (V) within the substance into the velocity of light in vacuum: n = $\frac{\mathrm{V\ vacuum}}{\mathrm{V\ substance}}$. For example, air has a refractive index of about 1.0003. However, water is 1.33. This result in a bending of light rays at an angle when light passes from air to water.

4.6.1 Particle size effect

The following results (as shown in Figure 4- 15) were produced from the sedimentation tests in order to find out the effect of particle size on turbidity. Samples of kaolin slurry were taken at various times from individual cylinders in sedimentation tests, as indicated in Table 4- 8. The particle size assessment was based on the pipette method (BS1377-2, 1990).

The equivalent particle diameter, d (in µm), for each sampling operation is calculated from the equation:

$$d=5.531\sqrt{\frac{\eta H}{(\rho 1-\rho 2)T}} \tag{4- 7}$$

where

η is the dynamic viscosity of water (0.891 mPa·s at 25ºC) at the test temperature (in mPa·s);

H is the sampling depth (in mm);

ρ_1 is the density of the liquid containing the soil suspension (in Mg/m³); in this study density of slurry is 1.09 Mg/m³;

ρ_2 is the mean particle density (in Mg/m³); in this study density of kaolin is 2.65 Mg/m³;

T is the pipette sampling time (in min);

5.531 is a constant.

Table 4- 8 The guideline of equivalent particle size, sampling time and sampling depth

The equivalent particle diameter (µm)	Sampling time (mins)	Sampling depth (mm)
4.41	45	50
5.40	30	50
5.91	60	120
6.61	60	150
7.63	30	100

From Figure 4- 15, it can be seen that the turbidity increases with particle size. Peng et al. (2009) also showed a strong linear predictor of turbidity in interconnected reservoir basins of New York City's water supply system.

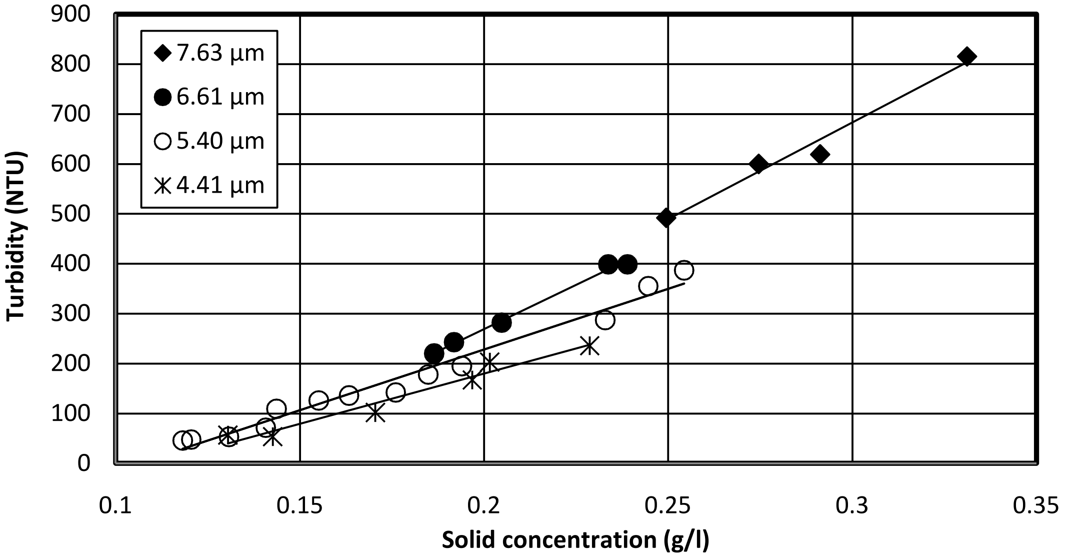


Figure 4- 15 The relationship between turbidity and solid concentration of kaolin slurry for different particle size

4.6.2 Particle colour effect

In the following experiment, the effect of kaolin and bentonite particle colour on turbidity was studied. The unit of colour (1 Pt-Co) is defined in terms of the colour of a solution of 1 mg of platinum, in the form of the hexachloroplatinate ion (K_2PtCl_6), in the presence of 2 mg of cobalt chloride hexahydrate ($CoCl_2 \cdot 6H_2O$) per litre (BSI5339, 1976). In this study, colour was measured with the HACH DR890 colorimeter. The limitation of HACH DR890 with respect to its calibration (≤500 Pt-Co) required further dilution of the sample to lower densities as used for the turbidity measurements. The relationship between turbidity and colour on kaolin and bentonite is shown in Figure 4- 16. The turbidity increased with colour.

However, the colorimeter was highly sensitive and indicated a wide variation in readings for small increments of density at very low density ranges below 10^{-2} g/l. It is difficult to measure solid concentration directly in this condition. Therefore, the relationship between colour and solid concentration shown in Figure 4- 17 was determined by extrapolating results from the colour-turbidity and turbidity-solid concentration trend lines as shown in Figure 4- 16 and Figure 4- 8 respectively. The colour increased with soil concentration.

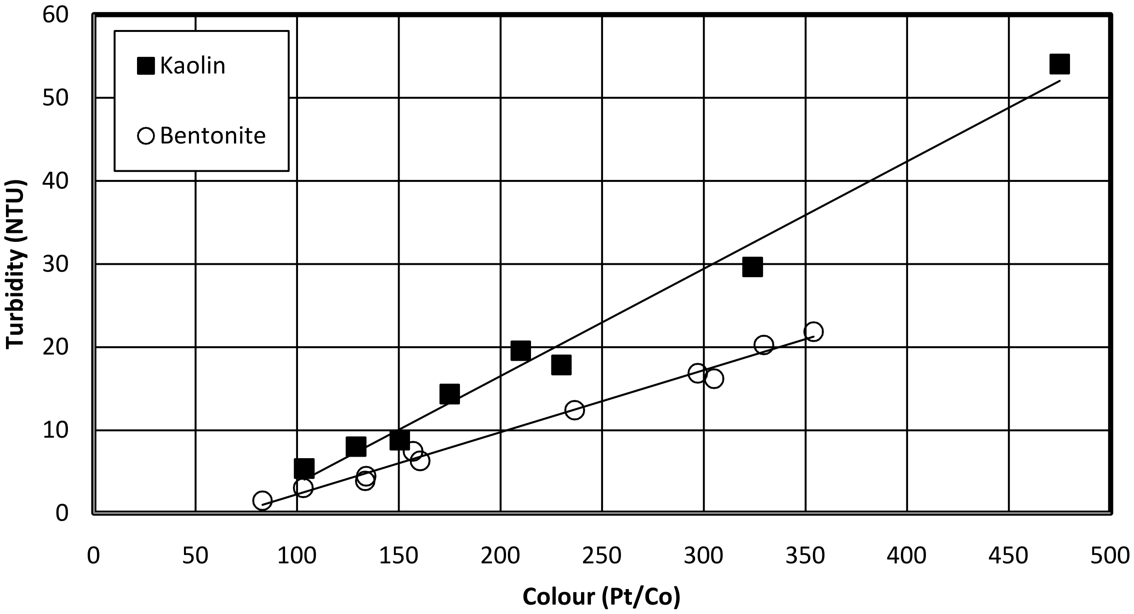


Figure 4- 16 The relationship between turbidity and colour for kaolin and bentonite

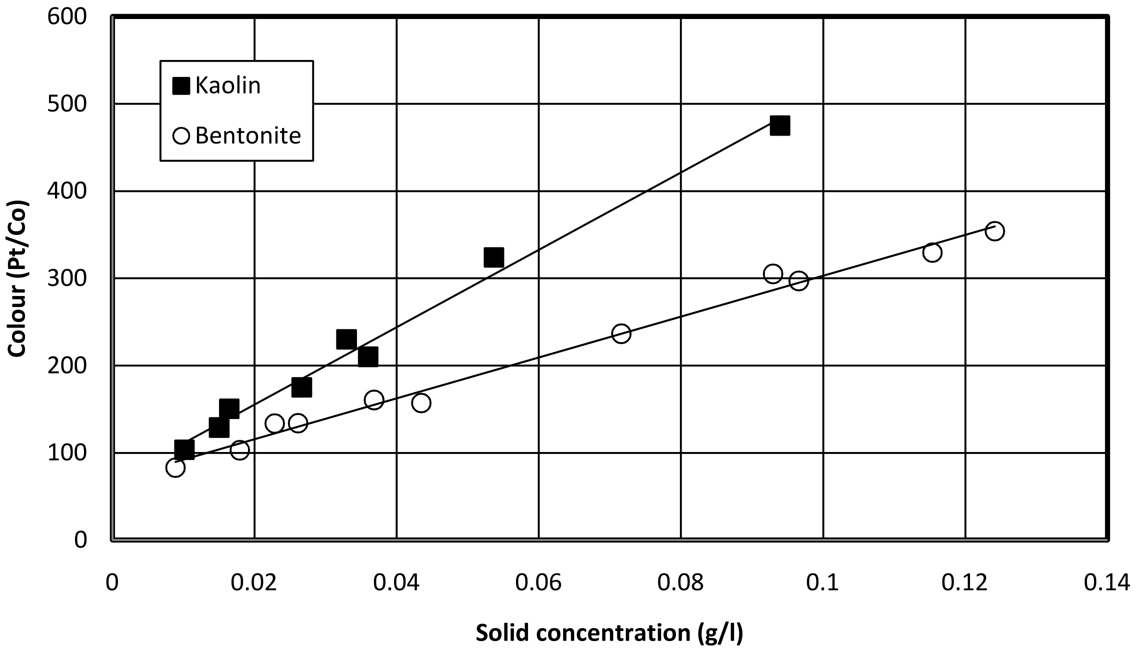


Figure 4- 17 The relationship between colour and solid concentration for kaolin and bentonite

The turbidity increased with particle size or colour. The larger the particle size the greater the turbidity. Bentonite slurry had a higher turbidity than kaolin slurry for the same solid concentration, suggesting that colour did affect the turbidity.

4.7 Conclusion

There is a good relationship between turbidity and solid concentration for every individual sample. The turbidity increased with particle size or particle colour. The turbidity is most effectively used for checking the change in density for a sample in which the composition does not change; in this case the slurries of kaolin and bentonite.

Density of slurry on pipe jacking site varies between 1.03 and 1.09 Mg/m³ which implies 20 - 60 (g/l) solids concentration based on an SG of 2.6. This means the turbidity will exceed 4000 FAU. If the soil type is stable, good practice will be to use the attenuation method (FAU) to detect the turbidity of the slurry which can be related to the solid concentration using the turbidity- solid concentration trend line. The clarity of the supernatant can be measured by the nephelometric method (NTU) to check the amount of solid concentration.

Chapter 5 The effect of coagulant and flocculant on slurry sedimentation

5.1 Introduction

Results from chapter 3 show that solid separation by sedimentation can be improved by adding chemicals. Coagulation and flocculation are both processes that lead to an increase in the effective particle size with the benefit of higher settling rate. However, there are differences between coagulation and flocculation. Coagulation is a process to neutralize the surface charges of particles and allow them to form agglomerates, whereas flocculation connects the colloidal particles into giant flocs. The following experiments were undertaken to understand the effect of coagulation and flocculation on slurry settling behaviour.

5.2 Theory of coagulation and flocculation

Solids can be present in water as: suspended particles, colloids and dissolved solids. Sand and silt particles are considered as suspended solids which can be removed by filtration or sedimentation. Dissolved solids are present as individual molecules or as ions. Most of these can be removed by reverse osmosis. Colloids are very fine particles, typically between 10 nm and 10 μm (Binnie, 2002).

Colloids have a very low settling velocity so that removal by sedimentation is not feasible if time is a restriction. The calculated settling velocity for 2 µm particles with a relative density of 2.6 in water at 20ºC is 0.012 m/hr. Due to time constraint; sedimentation can normally be used to remove suspended particles down to a size of about 50 µm depending on their density. If colloidal particles can be agglomerated, their size may increase to a point that they can be removed by sedimentation. For example, the settling velocity of an agglomeration of particles by adding aluminium sulphate (Alum) is 2.52 m/hr with specific gravity 1.05 at 10ºC (Binnie, 2002).

Colloids themselves are split into two types: hydrophobic (water-hating, e.g. emulsion paint or mayonnaise) and hydrophilic (water-loving, e.g. soap or wallpaper paste) colloids. Clays exhibit properties intermediate between hydrophilic and hydrophobic behaviour (Barnes and Wilson, 1983).

The reason that hydrophobic colloids stay as such small particles is that the particles have similar negative electrical charges, meaning that electrical forces keep the individual particles separate. This results from two effects: an attractive potential due to London - van der Waals forces between the particles and a repulsive potential due to the interaction of the double layers surrounding each particle. The interaction between this force (from the double layers) tends to repel the particles from each in a particle/liquid system (Hamaker, 1936).

Colloidal particles appear to have a surface charge which attracts oppositely charged ions spreading on it, which is the Stern layer. Ions with the same charge as the particle are rare near the particle surface but gradually increase in number with the distance from the particle; this is the diffuse double layer. These two layers are named as the electrical double layer. The strength of these forces is related to the distance between particles. The net force (attractive and repulsive potential) will keep the two negatively charged particles separate (Figure 5- 1).

It is necessary to overcome these forces if sedimentation times are to be reduced. This process is known as particle destabilisation and results in an agglomeration of particles by coagulation. Once this has been done, the particles combine into large particles that do not reform into colloids. In this case, the flocculation is the process of forming flocs from the larger particles previous formed by coagulation.

Hydrophilic colloids cannot be destabilised in the same way as hydrophobic colloids. Hydrophilic colloids would simply revert to colloidal solutions. They normally have to be removed by chemical precipitation, filtration, or adsorption. However, some hydrophilic colloids can be removed from water by flocculation (Binnie, 2002).

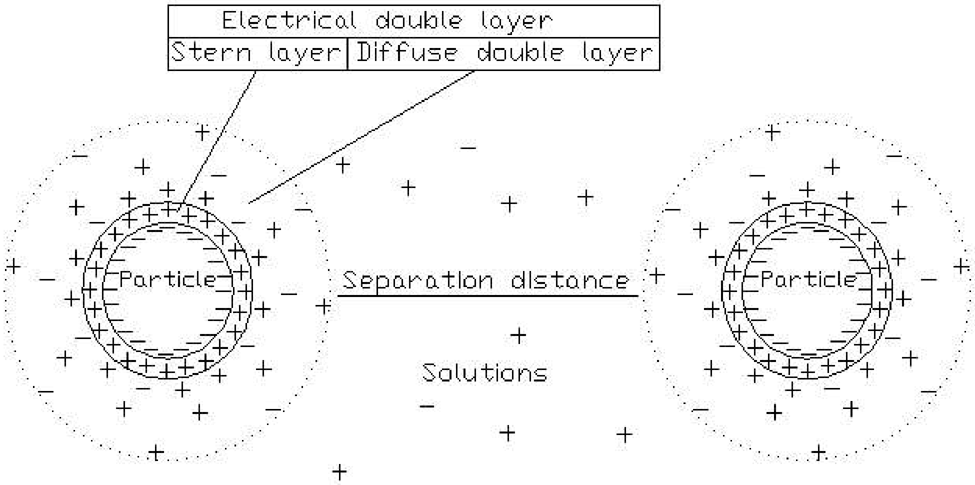


Figure 5- 1 The interaction between two negatively charged colloidal particles with electrical double layers

Coagulation and flocculation theory proposes four methods of destabilization of colloids. The theory suggests that coagulations should have certain properties to enable the following mechanisms of destabilization.

I. Double layer compression

It involves the addition of an electrolyte to water to increase the concentrations of ions. This has the effect of decreasing the thickness of the electrical double layer that surrounds each colloidal particle. The Gouy-Chapman theory shows the double layer thickness decreases as the concentration of electrolyte increases (Verwey et al., 1948). This allows the particles to move closer to each other, meaning attractive forces have more chance of overcoming the electrical forces that keep them apart. Coagulating compounds including trivalent cations (e.g. Al^{3+}, Fe^{3+}) will be very effective.

II. Charge neutralisation

This effect is dependent upon the particular ion and follows the Schulze-Hardy rule, which states that the effectiveness of opposite charged ions increases with charge. The simplified theory leads to the result that for monovalent, divalent, and trivalent ions the coagulant concentrations should be in a ratio $1{:}(\frac{1}{2})^6{:}\ (\frac{1}{3})^6$ = 100: 1.6: 0.14 (Verwey, 1947). However, over dosage of coagulant can result in particle-charge reversal due to adsorption of excess ions and result in a stable colloid again (Schroeder, 1977).

III. Enmeshment in a precipitate

If soluble aluminium or iron salts are added to water at the correct pH value, they will precipitate as hydroxide (e.g. $Al(OH)_3$, $Fe(OH)_3$). If colloids are present then the hydroxide will tend to precipitate using colloid particles as nuclei, forming floc around colloid particles. Once the hydroxide floc has formed it may physically entrap other colloidal particles, particularly during the following flocculation; this effect is known as sweep coagulation (Tebbutt, 1998). The optimum coagulation pH value is dependent on the pH/solubility characteristics of the coagulant used. Coagulants should have the ability to form either a hydroxide (e.g. $Al(OH)_3$, $Fe(OH)_3$) or a carbonate precipitate (e.g. $CaCO_3$).

IV. Particle bridging

Large organic molecules with multiple electrical charges such as polymers are often as effective as inorganic salts (e.g. Alum). In water treatment works such chemicals are normally referred to as anionic or cationic polymers. These are to work by bridging between particles. It is interesting to note that both anionic and cationic polymers are often found to be capable of flocculating negatively charged colloid particles. Negatively charged clay minerals would be expected to repel rather than attract anions polymer. However, in this case an adsorption of anionic polymers on negatively charged soil particles occurs. This is due to the bridging from the exchangeable interlayer cation such as Ca, Na or Mg found on the clay surfaces with the anionic polymer resulting in a "polymer-cation-clay surface" complex (Michaels and Morelos, 1955; Theng, 1979; Laird, 1997; Güngör and Karaoglan, 2001). Polymers are also often used during flocculation to aid particle formation when they are referred to as coagulant aids. Excessive mixing of flocs formed by polymer aggregates can lead to the flocs breaking up (Binnie, 2002).

In practice, alum and ferric sulphates are the most common coagulants used to destabilise colloids and suspended particles. Both anionic and cationic polymers as flocculants can provide a powerful bridging and linking action to promote more rapid settlement. Lime (CaO in solid form, $Ca(OH)_2$ in liquid form) is used for pH adjustment and to supply the demand of alkalinity for precipitation reactions with coagulants. In this study, lime was only supplied to enhance the coagulation reaction. Detailed reactions for chemicals used in the coagulation and flocculation processes are described below.

I. Aluminium sulphate (alum)

A simplified representation of the reaction of alum with alkalinity in water is:

$$Al_2(SO_4)_3 \cdot nH_2O + 3Ca(OH)_2 \rightarrow 2Al(OH)_3 + 3CaSO_4 + nH_2O \qquad (5\text{- }1)$$

From this reaction it can be seen alkalinity will be consumed, if there is insufficient alkalinity in the reaction then lime will need to be added to increase the alkaline content. The solubility of $Al(OH)_3$ is pH dependent and only occurs if the pH is between 5 to 7.5 (Tebbutt, 1998); outside this range coagulation is not successful, in that case the pH has to be adjusted.

II. Ferric sulphate

In the UK the use of ferric sulphate in water treatment increased in the 1990s. The reasons were (Binnie, 2002): the 1989 quality regulations set a limit (200 µg/litre) for aluminium in potable water that could be difficult to attain for some waters if alum was the main coagulant; there was a unjustified public concern relating aluminium in water and Alzheimer’s disease. In fact ferric sulphate can be a superior coagulant to aluminium for some waters and it is now more widely used. It is more pH tolerant (above pH 4.5, Tebbutt (1998)) than alum. The simplified reaction with alkalinity is:

$$Fe_2(SO_4)_3 + 3Ca(OH)_2 \rightarrow 2Fe(OH)_3 + 3CaSO_4 \qquad (5\text{- }2)$$

III. Polymer

Polymers are synthetic chemicals, such as polyacrylamides or polyamides. Polymers can be anionic, cationic or non-ionic, and the strength of the charge and the size of the molecule can be adjusted to suit particular needs. However, there are health concerns over the use of some polymers in water treatment and the EU Drinking Water Directive (98/83/EC, 1998) includes limits for some components in the polymer.

When polymer is adsorbed at a surface, only a fraction of the monomer units need to be involved for strong binding to occur. The adsorbed polymer chain configuration will form as tails, trains and loops of monomer units (Myers, 1999; Bolto and Gregory, 2007) as shown in Figure 5- 2. A polymer may be adsorbed at one end of the chain to produce "tails" (Figure 5- 2a) and produce a thicker adsorbed layer for a given polymer chain length. If two or more points are involved, "loops" and some "trains" (Figure 5- 2b) will usually produce a stronger adsorption.

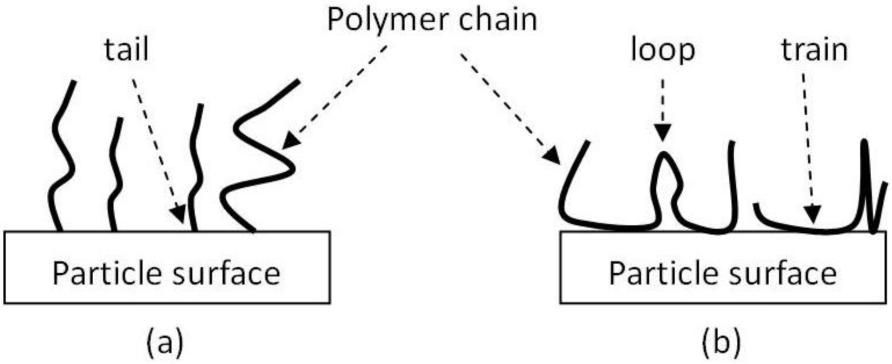


Figure 5- 2 Polymer adsorb at a surface

When polymer is added to colloids, the mechanism shown diagrammatically in Figure 5- 3 occurs and the stages in a bridging flocculation reaction are (Akers, 1975; Gregory, 1988):

a. Mixing polymer among the particles.
b. Adsorption of polymer chains to the particles.

c. Compressing the adsorbed chains to a stable dispersion phase.

d. Agglomerate of particles formed due to bridging of polymer found on the surface of particles (i.e. the particles are attracted to each other by combination of polymer on their surfaces).

e. Breakup of flocs if excessive mixing.

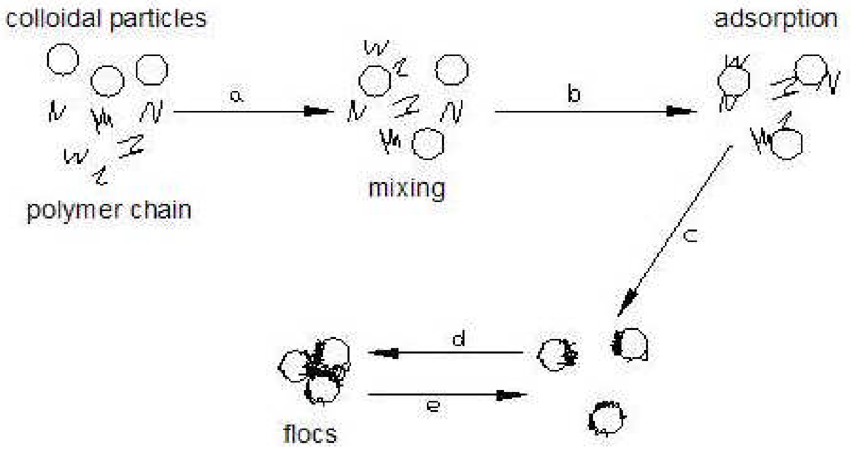


Figure 5- 3 Mechanism of bridging flocculation (Redrawn from Akers, 1975)

5.3 The effect of chemicals on the sedimentation process

As the chemicals used in the coagulation and flocculation process can be expensive, the optimal dosage is critical. Over dosage is not merely uneconomic but may result in particle-charge reversal leading to the restabilization of the suspension. Further, over dosage can contaminate the slurry in the pipe jacking process as the centrate is put back into the slurry tank. Moreover, excessive mixing of flocs can also lead to the breakup of flocs. Some coagulants are more effective than others. Therefore, the optimum dosage, the proper mix time and most efficient coagulant and flocculant need to be found.

The efficiency of the chemicals to create flocs, thereby reducing the time for sedimentation, was assessed using the following parameters namely: dry density of floc, floc production (Floc%) and turbidity of supernatant. This suggests a higher dry density of flocs implying higher solid content. Floc% is the ratio of the volume of settled flocs (after 5 mins) to the total volume of slurry, thus floc% is relative to the spoil volume. The limitation for turbidity of the supernatant is under 1 NTU (England and Wales: The Water Supply Regulations, 2010) or under 5 NTU (WHO, 2008).

5.4 The testing protocol

Alum and ferric sulphate are the most commonly used coagulants in the wastewater industry. Therefore, the following experiments display the effects of the addition of alum, ferric sulphate and polymer and the mixing time on the dry density of the floc, flocs production and turbidity of supernatant. Samples were taken from different levels in the sedimented column (Figure 5- 4). This test was used to imitate the coagulation and flocculation process and to determine optimum chemical dosage. Six samples were prepared at a time. The samples were placed in glass beakers with a powered paddle used to stir the contents of the beaker. The procedure* is described below:

1. Fill the beaker with 500 ml of slurry.
2. Mix slurry and different dosage of alkalinity (lime) for 5 minutes at a speed of 200 rpm.
3. Add coagulant (alum or ferric sulphate) doses into beaker and mix for 2 minutes at a speed of 200 rpm.

4. Continue mixing at a speed of 200 rpm and add flocculant (polymer) dose into beaker until floc size particle develops (larger size particles formed).
5. Wait until the flocs starts to break down.
6. Then stop mixing.
7. Stand for 5 minutes.
8. Measure the height of mudline.
9. Take sample from upper portion (supernatant) and lower portion (floc).
10. Measure turbidity of the supernatant sample and dry density of the floc sample.

*The time and speed defined in the above procedures were results of trial and error.

Slurry after mixing with coagulant and flocculant separates into two layers creating a definite mudline between the supernatant in the upper layer and the flocs in the lower layer (see Figure 5.4).

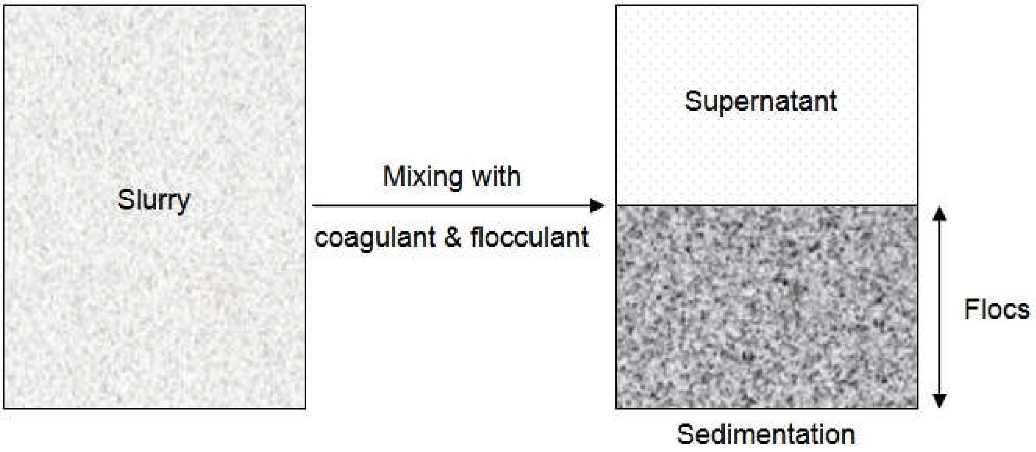


Figure 5- 4 Schematic diagram of sedimentation column

A 10 ml subsample of supernatant liquid was taken to determine the turbidity and therefore identify the water quality. Three 2 ml flocs sample were taken from the same depth to determine the dry density of the floc, taking the average value for the final dry density. The volume of the flocs was estimated from the height of the mudline.

The analysis items can be expressed as the form below.

$$\text{Dry density (g/l)} = \frac{\text{Mass of soil in the flocs}}{\text{Total volume of flocs}} = \frac{\text{Mass of dry soil}}{\text{Total volume of flocs}} \qquad (5\text{- }3)$$

$$\text{Flocs produce (\%)} = \frac{\text{The volume of settled flocs after stand for 5 mins}}{\text{Total volume of slurry}}$$

$$= \frac{\text{The height of the mudline} \times \text{The area of sedimentation column}}{\text{Total volume of slurry}}$$

$$= \frac{\text{Height of the mudline}}{\text{Height of slurry column}} \qquad (5\text{- }4)$$

In general, the suggested dosage of coagulant for waste water treatment is between 0 and 50 mg/l. Therefore, the concentration of coagulant (alum or ferric salts) for these experiments was set between 0 to 50 mg/l. From equation 5-1 and equation 5-2, coagulation will only take place at a certain alkalinity. Lime (CaO) was used to provide an alkalinity on coagulation reaction. An anionic polymer (VP1) supplied by SNF UK Ltd was used as a flocculant which was used on most visited sites (Carillion Corp). Polymer was prepared by mixing 1 g portions of the VP1 powder with 500 ml tap water to achieve a concentration of 2000 mg/l polymer and left to age overnight.

5.5 Test results

The following experiments used kaolin, bentonite and natural soil to investigate the effect of coagulation and flocculant on settling behaviour.

5.5.1 Kaolin with alum and polymer

In these experiments, both coagulant (alum) and flocculant (polymer) were added to determine the effect on dry density of flocs, flocs production and turbidity of the supernatant. The slurry sample was prepared by mixing 150g Polywhite E Kaolin (IMERYS Ltd) with 1 litre of water to produce a density of 1.09 g/ml.

The effects of the addition of alum (from 0 to 50 mg/l) and polymer (from 20 to 60 mg/l) on dry density are shown in Figure 5- 5. Increasing the quantity of polymer reduced the dry density of the floc, but the alum had no obvious influence on dry density.

Figure 5- 6 displays the influence of the addition of alum and polymer on floc%. It can be seen that no matter the dosage of polymer, the average values of floc% remained relatively constant.

The effectiveness of alum and polymer on turbidity is shown in Figure 5- 7. Adding polymer to the slurry increased the potability of the supernatant, since the turbidity values were all under 5 NTU (WHO, 2008) regardless of the dosage of alum and provided the polymer content was less than 50 mg/l. When the concentration of polymer was greater than 40 mg/l, there was a significant increase in turbidity (above 5 NTU). The turbidity reduced when alum was added.

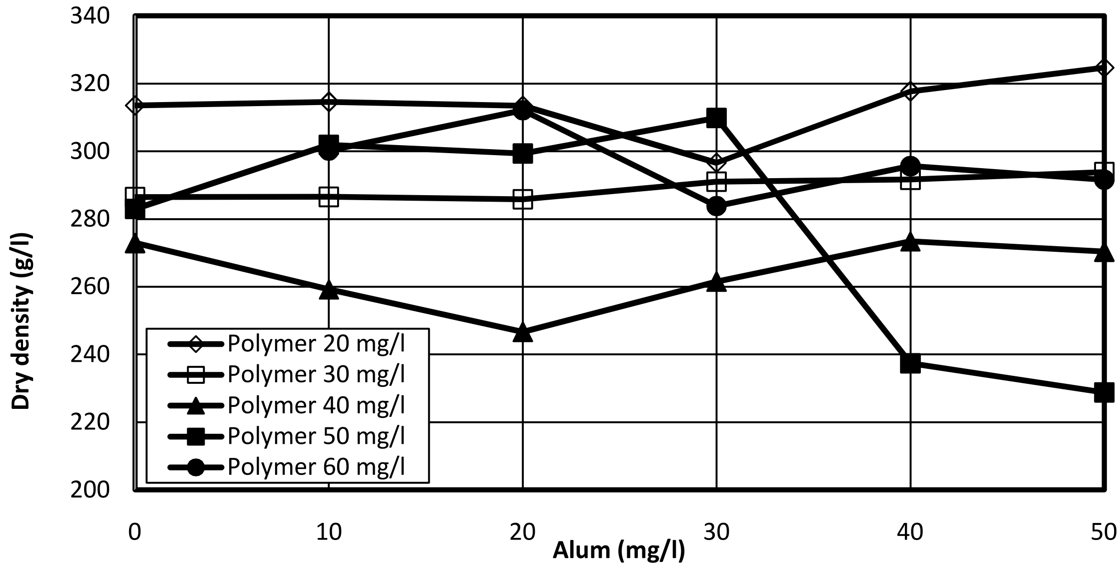


Figure 5- 5 The effects of the addition of alum and polymer on dry density of kaolin slurry

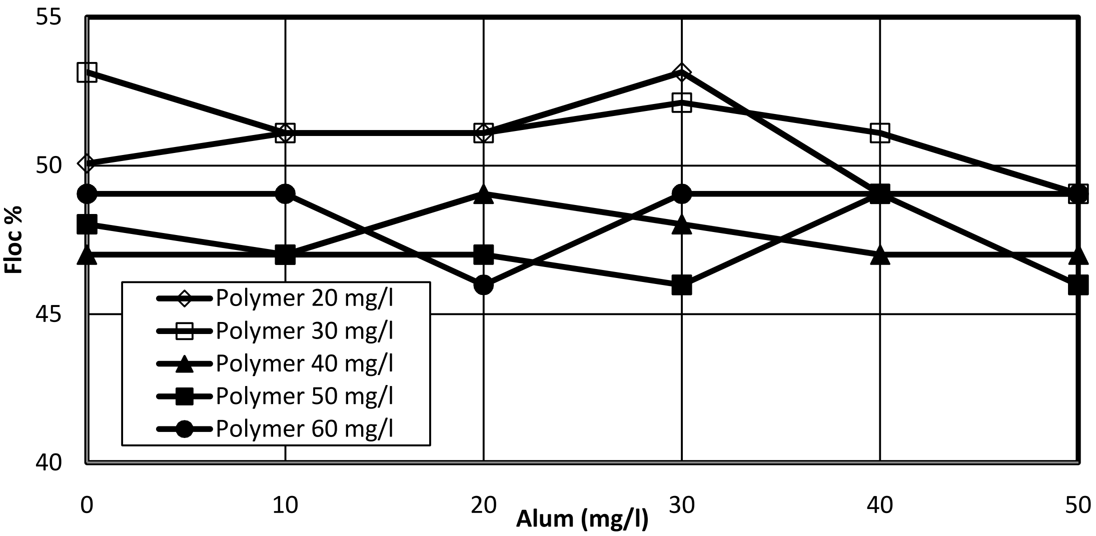


Figure 5- 6 The effects of the addition of alum and polymer on floc% of kaolin slurry

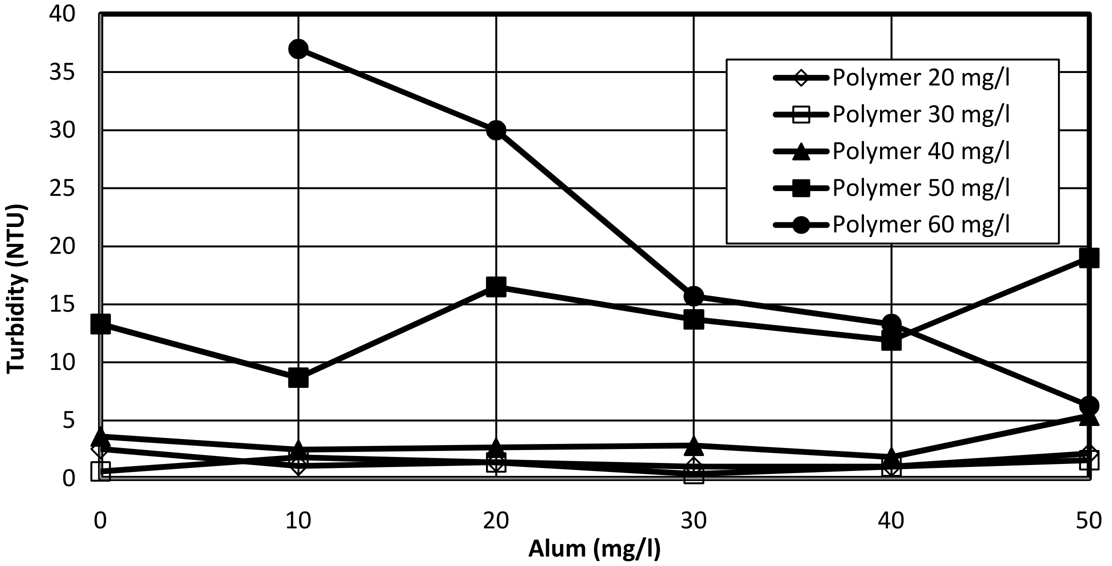


Figure 5- 7 The effects of the addition of alum and polymer on turbidity of kaolin slurry supernatant

Figure 5- 8 shows the effects of a high alum dose (from 100 to 600 mg/l) and polymer (from 20 to 30 mg/l) on dry density. The value of dry density was similar (around 300 g/l) for each dosage of polymer in this diagram. Hence alum has little effect on dry density of the slurry.

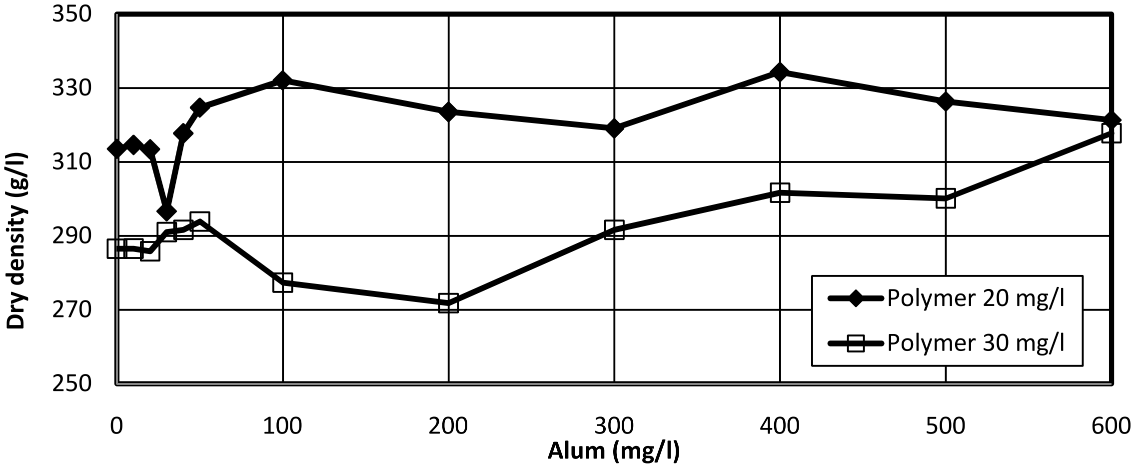


Figure 5- 8 The effects of polymer and high alum dose on the dry density of kaolin slurry

Figure 5- 9 presents the influence of polymer and a high concentration of alum on floc%. Floc% was below 50% when the alum dose was greater than 100 mg/l in this diagram. It can be stated that a high dosage of alum has little effect on floc% when the polymer content is between 20 to 30 mg/l.

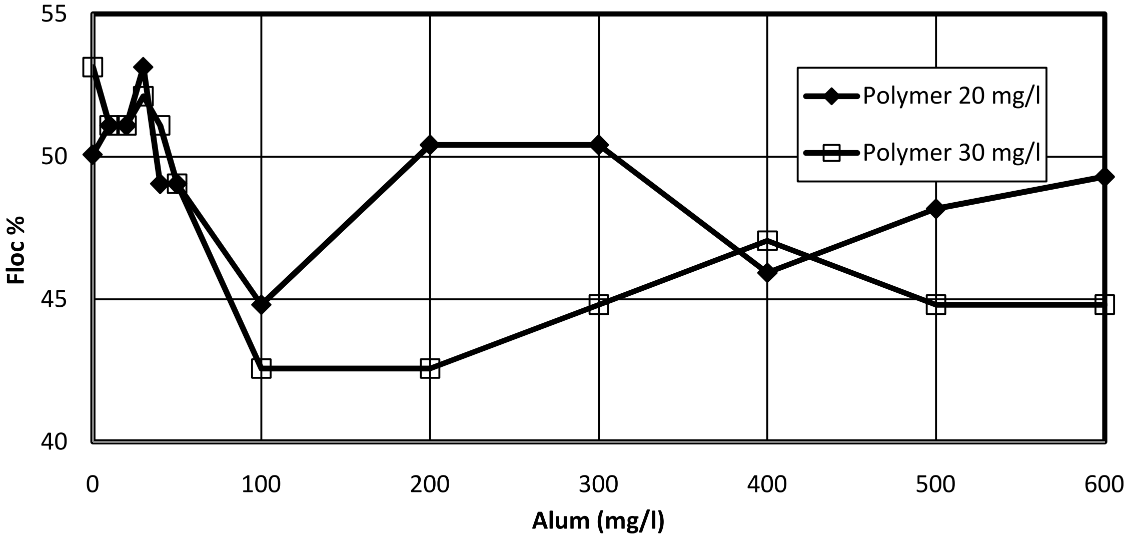


Figure 5- 9 The effects of polymer and high alum dose on floc% of kaolin slurry

The effects of polymer and alum on turbidity are presented in Figure 5- 10. Mostly turbidity was below 5 NTU when 20 or 30 mg/l polymer was added whatever the alum dosage used. Further, the turbidity was under the potable water limit: 1 NTU (England and Wales: The Water Supply Regulations, 2010) when the dosage of alum exceeded 100 mg/l with 20 mg/l polymer.

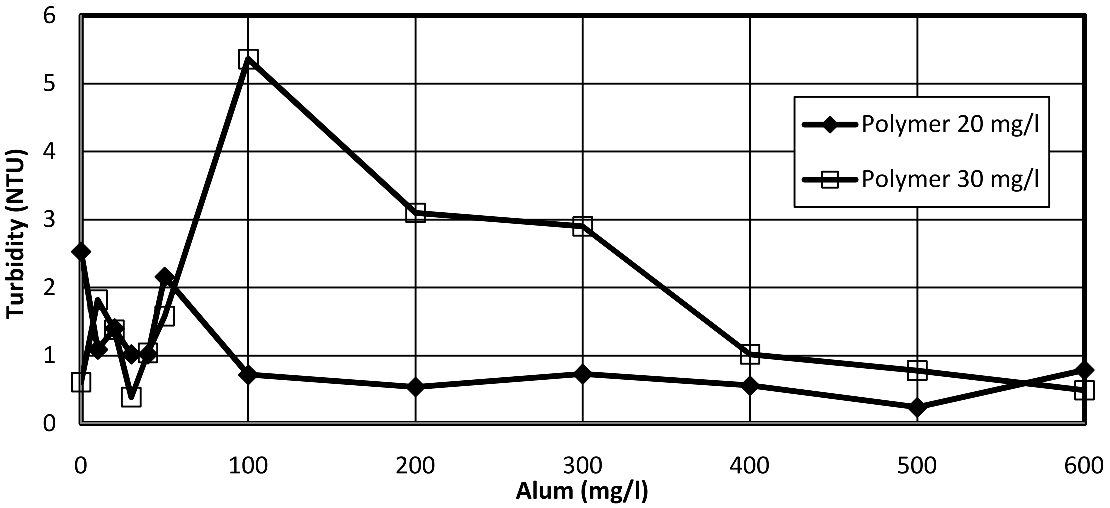


Figure 5- 10 The effects of polymer and high alum dose on turbidity of kaolin slurry supernatant

Table 5- 1 summarises the effects of alum and polymer on dry density, flocs% and turbidity. A minimum polymer dosage is necessary to create agglomerates of sufficient size to achieve sedimentation in the time allowed. The minimum dose was 20 mg/l in this study. Increasing the polymer and alum content did not necessarily reduce the turbidity of the supernatant or reduce the density of flocs.

Table 5- 1 The effects of alum and polymer on dry density, flocs% and turbidity of kaolin slurry

	Dry density of flocs	Floc%	Turbidity of supernatant
Polymer	1. Positive effect and minimum dosage was required to form flocs. 2. There is an optimum quantity for denser flocs.	No obvious effect.	1. Positive effect and minimum dosage was required to produce clarity liquid. 2. Above a certain dosage (50 mg/l) turbidity was increased.
Alum	No obvious effect.	No obvious effect.	No obvious effect.

5.5.2 Kaolin with ferric salt and polymer

From the previous section, it appears that the coagulant (Alum) had little effect on kaolin slurry when polymer was present. In this set of experiments, the effects of another coagulant, ferric salt, was studied in the same manner.

The influences of the addition of ferric salt (from 0 to 50 mg/l) and polymer (from 15 to 120 mg/l) on dry density are shown in Figure 5- 11. When the polymer was greater than 40 mg/l, it resulted in the reduction in dry density of the flocs regardless of the ferric salt dose. The ferric salt had a limited effect on dry density if the polymer dose was above 40 mg/l. The effect of ferric salts and polymer on floc% is shown in Figure 5- 12. Increasing the polymer resulted in decreasing floc%. The addition of ferric salt with polymer had no significant effect on floc% for the range of polymer dose investigated.

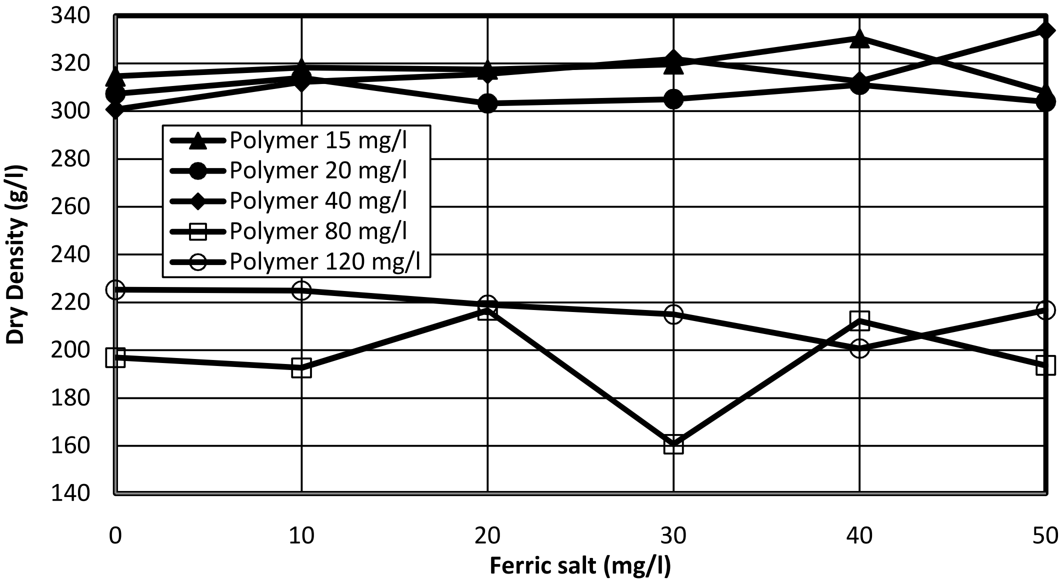


Figure 5- 11 The effects of the addition of ferric salt and polymer on dry density of kaolin slurry

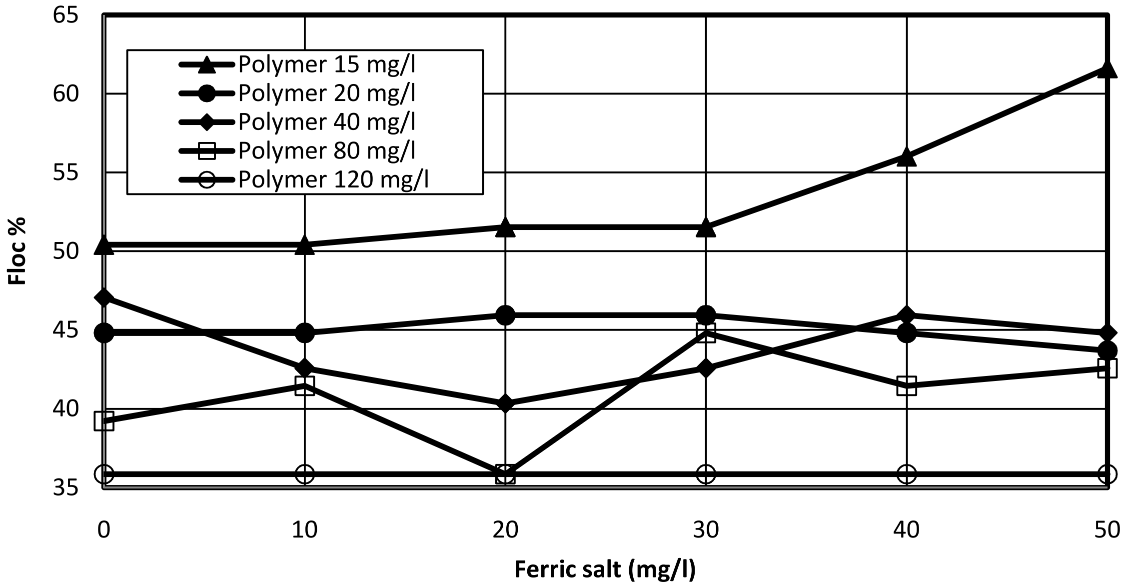


Figure 5- 12 The effects of the addition of ferric salt and polymer on floc% of kaolin slurry

Figure 5- 13 illustrates the effects of ferric salts and polymer addition on turbidity of supernatant. In this figure, it can be seen that a polymer dose between 20 and 40 mg/l lowered the turbidity of the supernatant to the point of acceptability. A polymer dose of less than 20 mg/l or greater than 40 mg/l increased the turbidity. Ferric salts had a small effect on turbidity if polymer dose above 80 mg/l. The turbidity decreased with increasing ferric salts dose.

Excessive mixing of flocs may lead to the flocs breaking up. From Figure 5- 11, Figure 5- 12, Figure 5- 13, it is evident that 20 to 40 mg/l is the optimum dosage of polymer for kaolin slurry, since they produce the denser floc and most potable supernatant. A polymer dose of 30 mg/l was chosen to assess the effect of mixing. The outcome is displayed in Figure 5- 14. In terms of dry density, the trend is an increase in dry density. All the values were between 300 to 350 g/l after 100 seconds of mixing. The floc% was about 50% regardless of mixing time.

The turbidity falls below 5 NTU after 100 seconds of mixing and remains so until 300 seconds, thereafter it increases. The flocculated particles breakup after excessive mixing and result in an increase in turbidity. Moreover, the particles breakup results in mudline drop and hence dry density increases. The floc% was almost constant, fluctuating between 44 and 50% with mixing time. However, the dry density and turbidity increased with the mixing time.

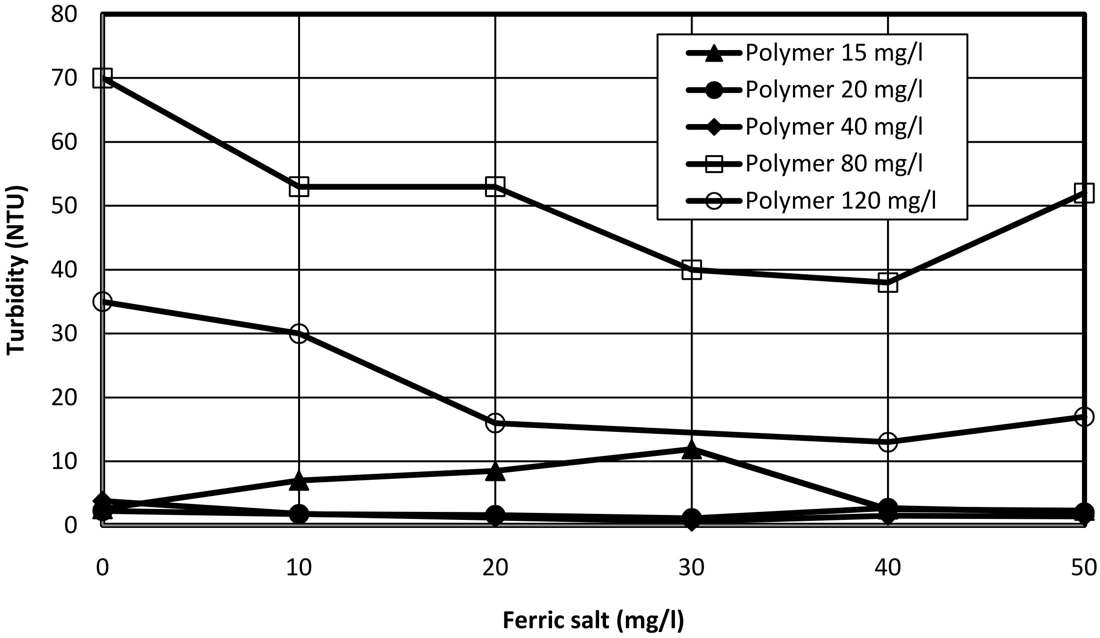


Figure 5- 13 The effects of the addition of ferric salt and polymer on turbidity of kaolin slurry supernatant

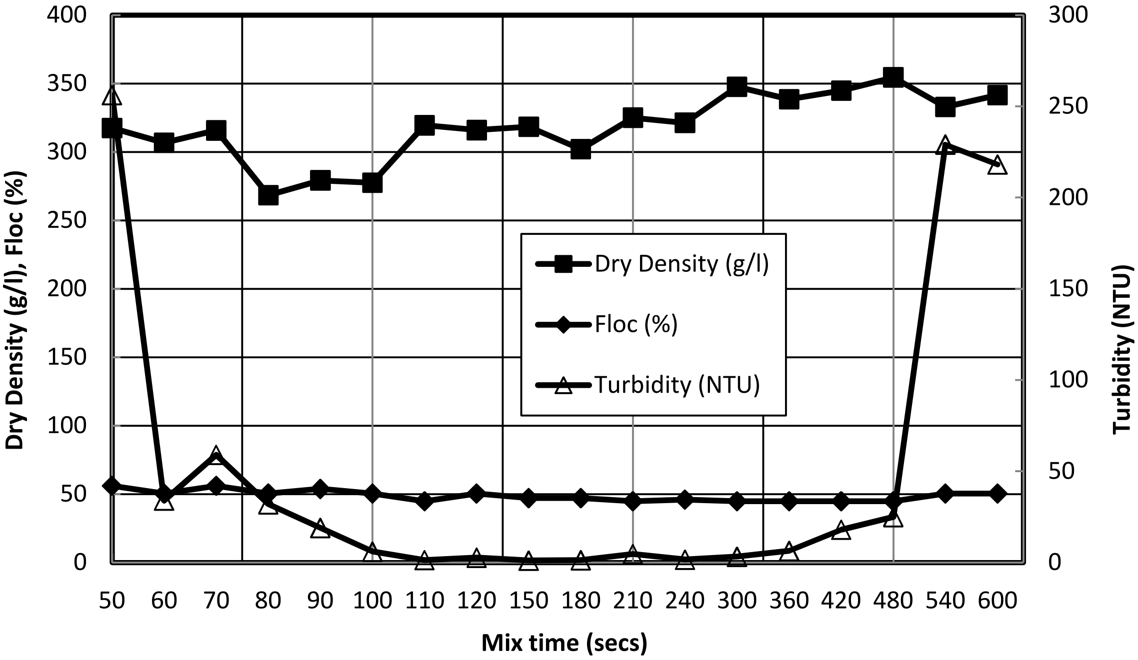


Figure 5- 14 The effects of mixing time on dry density, floc% of kaolin slurry and turbidity of kaolin slurry supernatant

Table 5- 2 summarises the effects of ferric salt, polymer and mixing time on dry density, flocs% and turbidity. Again, in this study ferric salt did not impact significantly on the dry density, flocs% and turbidity. A minimum level of polymer dosage was necessary to achieve the most beneficial effects. Too much polymer reduced the dry density and increased the turbidity. Floc% decreased as the polymer dose increased. Mixing time had a significant effect on turbidity. In practice, the polymer is introduced to the slurry before it is sent to the centrifuge. The retention time for the polymer mix with slurry depends on the position of the point of adding the polymer. The further the injection point to the centrifuge, the longer the retention time. Therefore, it is suggested that the position of the point of adding polymer is a critical factor in the retention time.

Table 5- 2 The effects of ferric salt and polymer on dry density, flocs% and turbidity of kaolin slurry

	Dry density of flocs	Floc%	Turbidity of supernatant
Polymer	1. Positive effect and minimum dosage was required to form flocs. 2. Dry density was decreased if overdose (80 mg/l).	The floc% decreased as increasing polymer.	1. Positive effect and minimum dosage was required to produce clarity liquid. 2. Above a certain dosage (40 mg/l) turbidity was increased.
Ferric salt	No obvious effect.	No obvious effect.	No obvious effect.
Mixing time	Minimum mixing time was required to form denser flocs; in this study at least 110 seconds.	Minimum mixing time was required to form flocs result in particles settling; then no obvious effect.	A certain range mixing time was required to produce clarity liquid; in this study it was between 110 to 300 seconds.

In brief, the results show that the coagulant (alum and ferric salt) has little effect on dry density, floc% and turbidity when used with polymer and kaolin slurry. However, the flocculant (polymer) has significant effects on them.

This observation is, however, not consistent with some past reported findings (Schroeder, 1977; Barnes and Wilson, 1983; Tebbutt, 1998; Qasim, 1999; Binnie, 2002) where coagulant usually has an effect on colloidal solids. The observation in this study could be because the kaolin used here has no net negative charge on the surface, as mentioned earlier by Reeves et al. (2006) (refer to section 4-3).

As reported earlier in section 5.2, there are four methods of destabilization of colloids in the coagulation and flocculation process: (I) double layer compression, (II) charge neutralisation, (III) enmeshment in a precipitate and (IV) particle bridging. In this study the (I) double layer compression and (II) charge neutralisation are likely to have less effect on particles forming agglomeration due to no net particle charge. It is therefore suggested that (III) enmeshment in a precipitate occurs in coagulation based on the possible chemical reaction (refer to equations 5- 1 and 5- 2) that can occur, but the effect is minimal on the dry density, flocs% and turbidity as seen from the results obtained in this study. In contrast, particle bridging mechanisms will very likely play a major role on destabilization of colloids in this study due to bridging of the polymer on the particle surface (see Figure 5- 3). In other words, most particles were trapped by a bridging reaction from the polymer chain. Therefore, the destabilization of colloids from flocculation was more effective than coagulation for kaolin slurry.

5.5.3 Bentonite with alum and polymer

In some unstable ground conditions such as non-cohesive soils, bentonite may be added to the slurry system as a drilling fluid to support the working face to prevent ground loss while excavation proceeds. The slurry sample in the studies was prepared by mixing 150g Calcium Bentonite (RS Minerals Ltd) with 1 litre water to produce a density of 1.09 g/ml. Bentonite has a net negative charge on the composite layer. The effects of alum (from 0 to 50 mg/l) and polymer (from 20 to 70 mg/l) on dry density, floc% and turbidity of the bentonite slurry were studied in the experiments. The outcome is shown in Figure 5- 15. The results showed that there was little effect on dry density, flocs% and turbidity. The dry density remained about 210 g/l, floc% was 52% and turbidity was under 2 NTU. They showed that the potability of the supernatant was acceptable since polymer was added to the bentonite slurry.

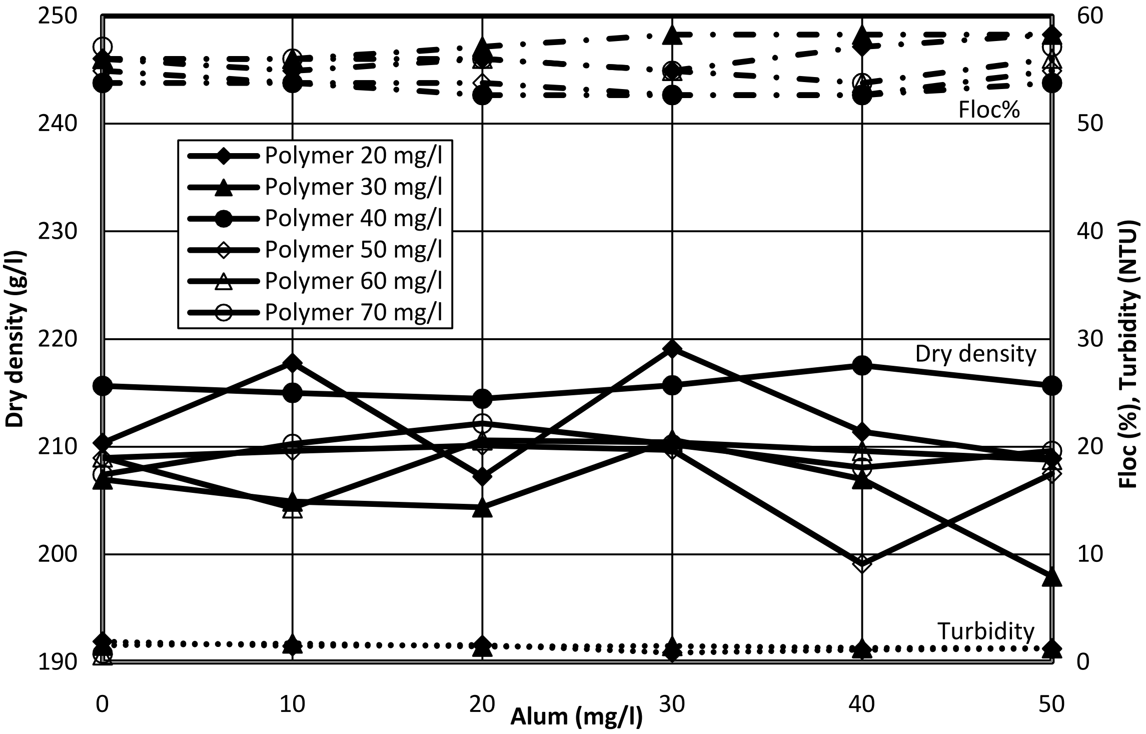


Figure 5- 15 The effects of the addition of alum and polymer on dry density, floc% of bentonite slurry and turbidity of the bentonite slurry supernatant

There was no critical dose of polymer with bentonite to achieve a significant result. The dry density, flocs% and turbidity were not significantly affected by polymer and alum dose. However, there was a minimum dose for kaolin and, given on site, it is likely that different clay types will require a minimum dose of polymer to form denser flocs and produce clarity liquid. Hence, 30 mg/l of polymer was chosen to investigate mixing time.

The influence of mixing time on dry density, floc% and turbidity with 30 mg/l polymer is shown in Figure 5- 16. It does appear that the dry density increases and the floc% decreases with mixing time, though the amount of change is small. However, in order to achieve a potable supernatant, the mixing time had to be at least 90 seconds.

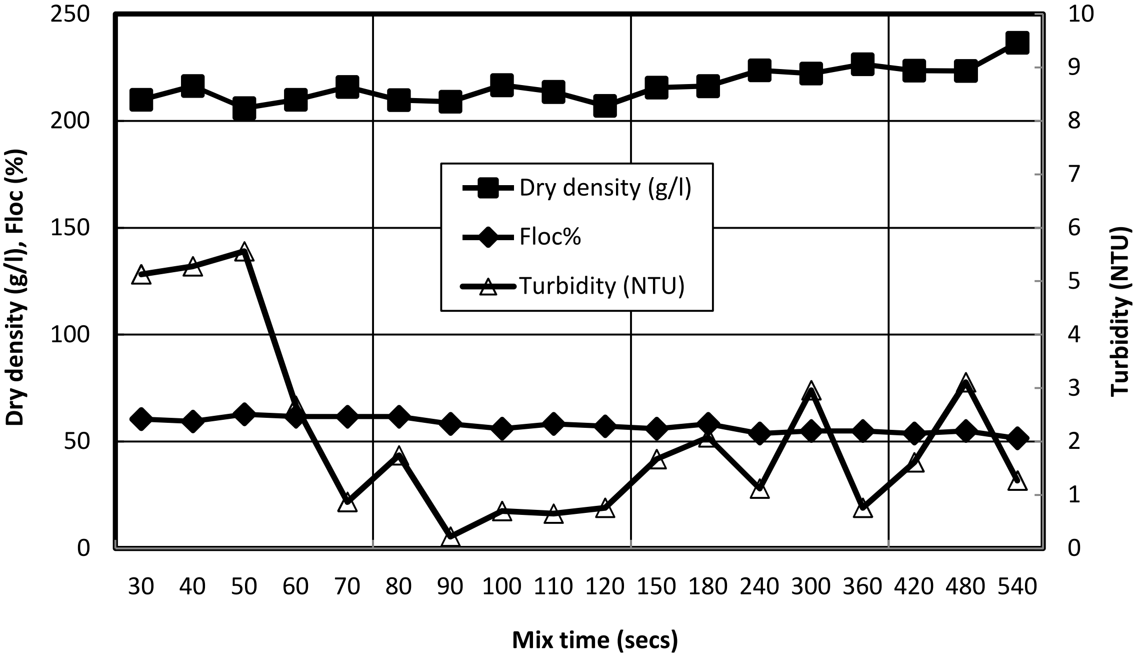


Figure 5- 16 The effects of mixing time on dry density, floc% of bentonite slurry and turbidity of bentonite slurry supernatant

In brief, the results show that the coagulant (alum) has little effect on dry density, floc% and turbidity when used with polymer and bentonite slurry, although bentonite has a net negative charge on the surface (Reeves et al., 2006). From section 5.2, the double layer compression and charge neutralisation destabilizing colloids mechanisms should be affected by the coagulant. However, the results show there is no obvious effect on settling behaviour for bentonite slurry. The results on kaolin and bentonite slurries suggest that destabilization of colloids from flocculation was more effective than coagulation.

5.5.4 Bentonite and kaolin with polymer

The following series of experiments investigated combinations of bentonite and kaolin slurry and the effect of polymer and mixing time on dry density, floc% and turbidity. Bentonite used to be added into non cohesive slurry to provide a lubricating action on the cutter head face (Reeves et al., 2006). Moreover, it can be seen that bentonite reduces the turbidity more than kaolin (compare Figure 5-15 and Figure 5- 16). Table 5- 3 summaries the values of dry density, flocs% and turbidity for the kaolin and bentonite slurry mix with coagulant and polymer.

Table 5- 3 The values of dry density, flocs% and turbidity for kaolin or bentonite slurry mixed with coagulant and polymer

	Dry density of flocs (g/l)	Floc (%)	Turbidity of supernatant (NTU)
Pure kaolin	250-330	45-50	Under 40
Pure bentonite	200-220	55-60	Under 2

The slurry samples for these experiments were composed by weight of pure kaolin, 95% kaolin with 5% bentonite, 90% kaolin with 10% bentonite, 50% kaolin with 50% bentonite and pure bentonite. The initial density of sample was about 1.09 g/ml and the concentration of the polymer varied between 10 and 60 mg/l.

The influence of different combinations of soil (pure kaolin, 5%, 10%, 50% bentonite and pure bentonite) and the addition of polymer on dry density is presented in Figure 5- 17. The dry density decreased with increasing polymer content for pure kaolin slurry. Polymer had little effect on the bentonite slurry. Adding bentonite to kaolin slurries reduced the dry density as the polymer content increased.

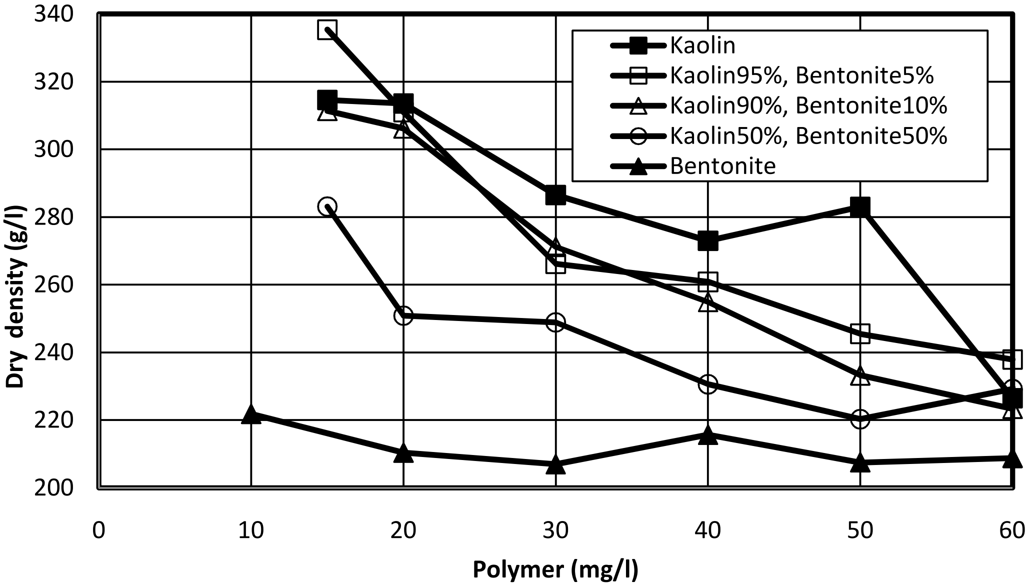


Figure 5- 17 The effects of different combinations of soil and polymer on dry density

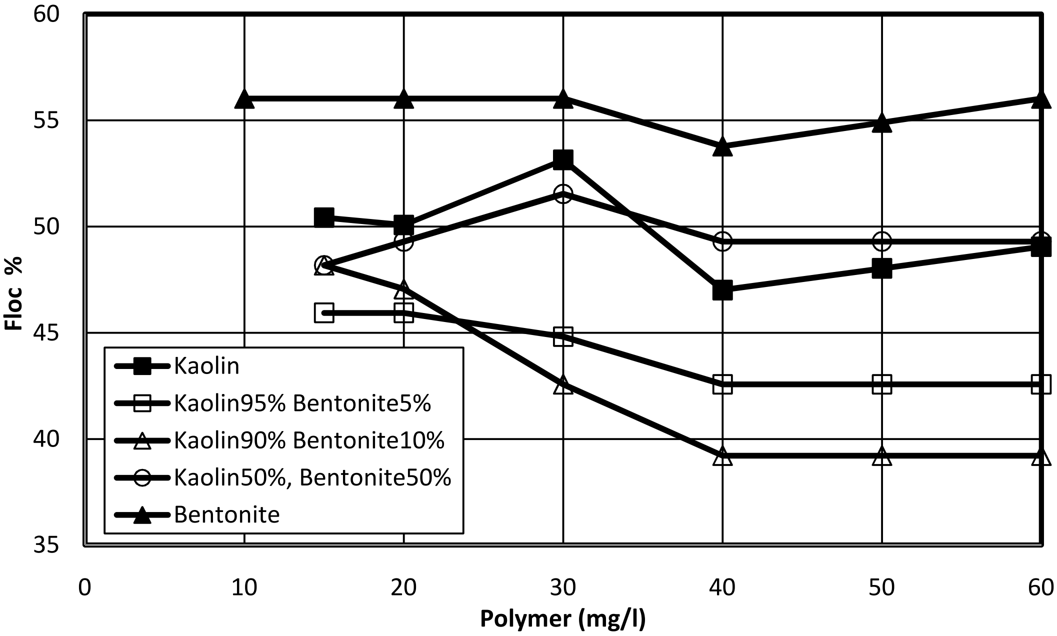


Figure 5- 18 The effects of different combinations of soil and polymer on floc%

The effect of different combinations of kaolin and bentonite slurry and polymer on floc% is displayed in Figure 5- 18. There is little effect of polymer on pure kaolin, pure bentonite or the 50% kaolin with 50% bentonite slurries. A small percentage of bentonite did reduce the floc%. Increasing the bentonite content decreased the floc% as the polymer content increased.

Figure 5- 19 demonstrates the influence of different combinations of kaolin and bentonite slurry and polymer on turbidity. Polymer has no obvious effect on pure bentonite slurry as its turbidity remained low. Turbidity increased as the polymer content was increased when kaolin was present.

In brief, adding bentonite to kaolin slurry did not affect the potability, but decreased the dry density as the polymer content was increased. Moreover, adding a small amount (5-10%) of bentonite into kaolin slurries can decrease the floc%.

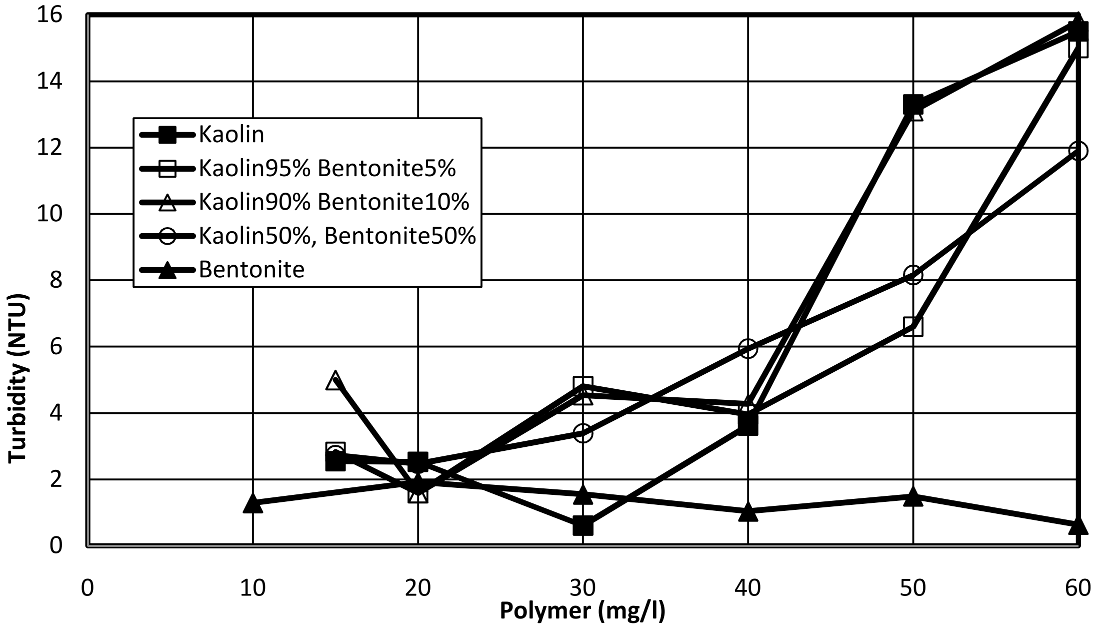


Figure 5- 19 The effects of different combinations of soil and polymer on turbidity of different slurries supernatant

Figure 5- 20, Figure 5- 21, Figure 5- 22 illustrate the effects of mixing time for different combinations of soil on dry density, floc% and turbidity with a polymer dose of 30 mg/l. At a mixing time of less than 120 seconds there appears to be no consistent relationship between mixing time and dry density, floc% or turbidity, suggesting that the mixing process had to exceed 120 seconds.

Figure 5- 20 shows that the dry density increases as the mixing time increases after 120 seconds, but the addition of bentonite reduced the dry density.

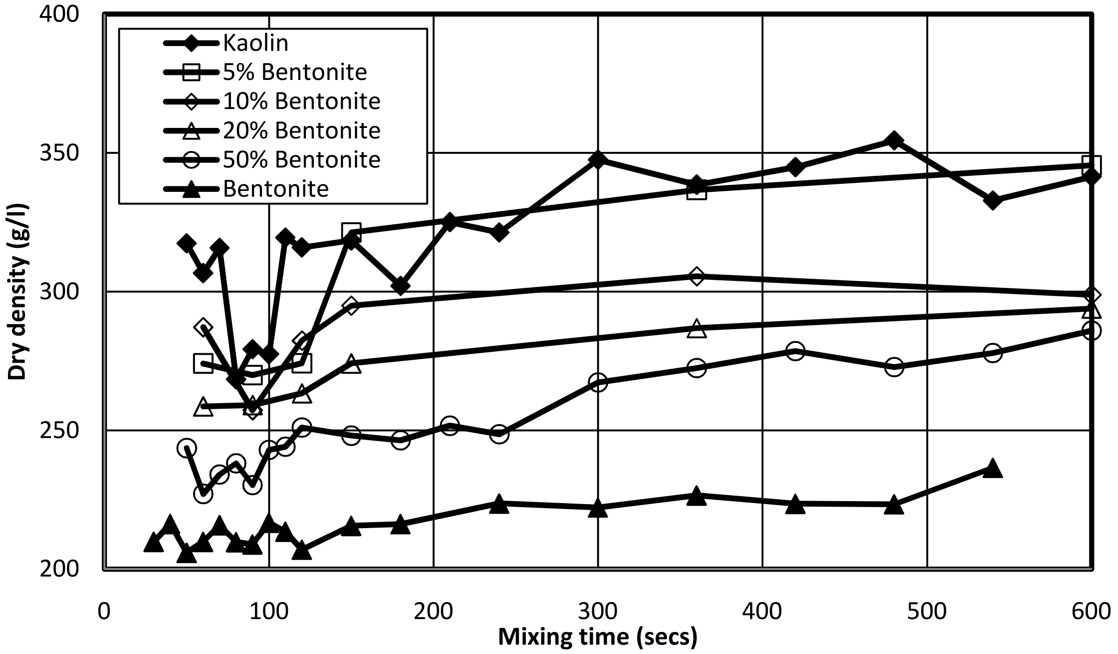


Figure 5- 20 The effects of mixing time for different combinations of soil on dry density

Figure 5- 21 shows the results of floc% were distributed for different combinations of soil after 120 seconds mixing time. Adding a small amount (5-20%) of bentonite into kaolin slurries decreases the floc%.

The effect of mixing time for different combinations of soil on turbidity is shown in Figure 5- 22. After stirring for 120 seconds, it shows that the turbidity is less than 5 NTU. In order to understand the pattern between turbidity less than 5 NTU and mixing time, results exceeding 50 NTU has not been shown in the figure. However, the turbidity displays a dramatic increase on pure kaolin after mixing for 300 seconds. It is noted that a small amount of bentonite will reduce the turbidity below 5 NTU.

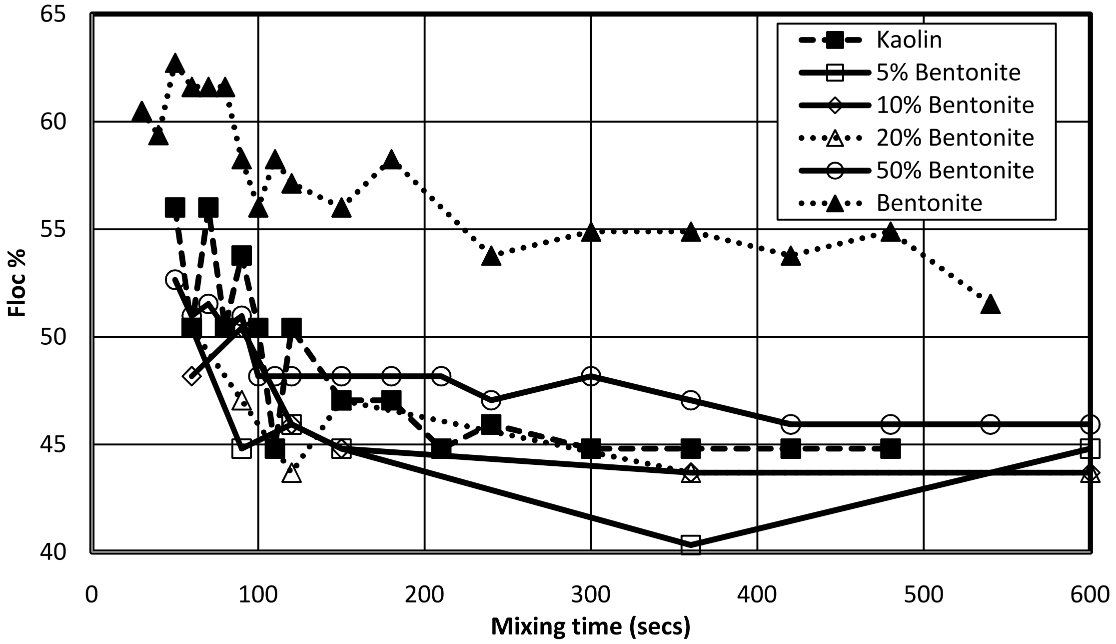


Figure 5- 21 The effects of mixing time for different combinations of soil on floc%

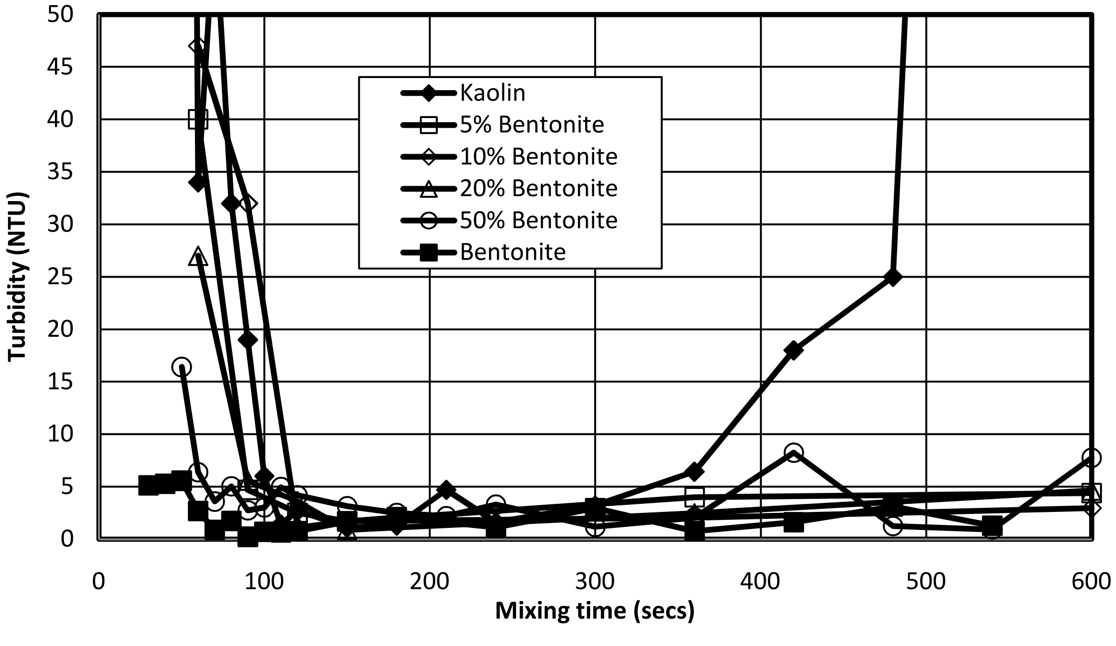


Figure 5- 22 The effects of mixing time for different combinations of soil on turbidity of supernatant

It can be concluded that adding a small amount of bentonite into kaolin slurries and mixing for a minimum time can achieve better results for dry density, floc%

and turbidity (summarize in Table 5- 4). In this study, adding 5% bentonite to kaolin slurry and mixing for at least 120 seconds can reduce the volume of flocs and produce clarity supernatant.

Table 5- 4 The effects of adding bentonite and polymer into kaolin slurry on dry density, flocs% and turbidity

	Dry density of flocs	Floc%	Turbidity of supernatant
Polymer	With increasing polymer dosage, dry density was decreased.	Minimum dosage was required to form flocs result in particles settling then no obvious effect.	With increasing polymer dosage, turbidity was increased.
Bentonite	With increasing bentonite dosage, dry density was decreased.	A small amount addition can help decrease the volume of flocs. In this study it was 5-10%.	1. Adding bentonite to kaolin slurry has slightly positive effect if polymer dosage is high. In this study it was above 40 mg/l. 2. Adding bentonite to kaolin slurry can delay turbidity increase.
Mixing time	With increasing mixing time, dry density was increased.	Minimum mixing time was required to form flocs result in particles settling then no obvious effect.	1. A certain range mixing time was required to produce clarity liquid, in this study it was between 120 to 300 seconds. 2. No obvious effect when bentonite has been added to slurry.

5.5.5 Natural slurry with polymer

The purpose of the following experiments was to determine the effects of polymer and mixing time for natural slurries formed of: Lambeth Group, London Clay, Mercia Mudstone and bentonite with Mercia Mudstone on dry density, floc%, turbidity and COD.

The Lambeth Group, London Clay and Mercia Mudstone slurries were samples collected directly from pipe jacking sites. Figure 5- 23 displays the influence of polymer on the dry density of natural slurries. It can be seen that the dry density is decreasing with an increase of polymer or bentonite content.

Adding polymer to natural slurries has little impact on the floc% (Figure 5- 24). However, increasing the bentonite content increases the floc% of the Mercia Mudstone slurry.

Figure 5- 25 shows the influence of polymer on natural slurries on the turbidity of the supernatant. It is noted that the turbidity increased when the polymer dose exceeded 30 mg/l. Adding bentonite to Mercia Mudstone can decrease the turbidity dramatically, but the final turbidity still exceeded the acceptable limit. There seem to be an optimal polymer dose (20 mg/l) for London Clay and Lambeth Group; the turbidity can be lowered to 10 NTU.

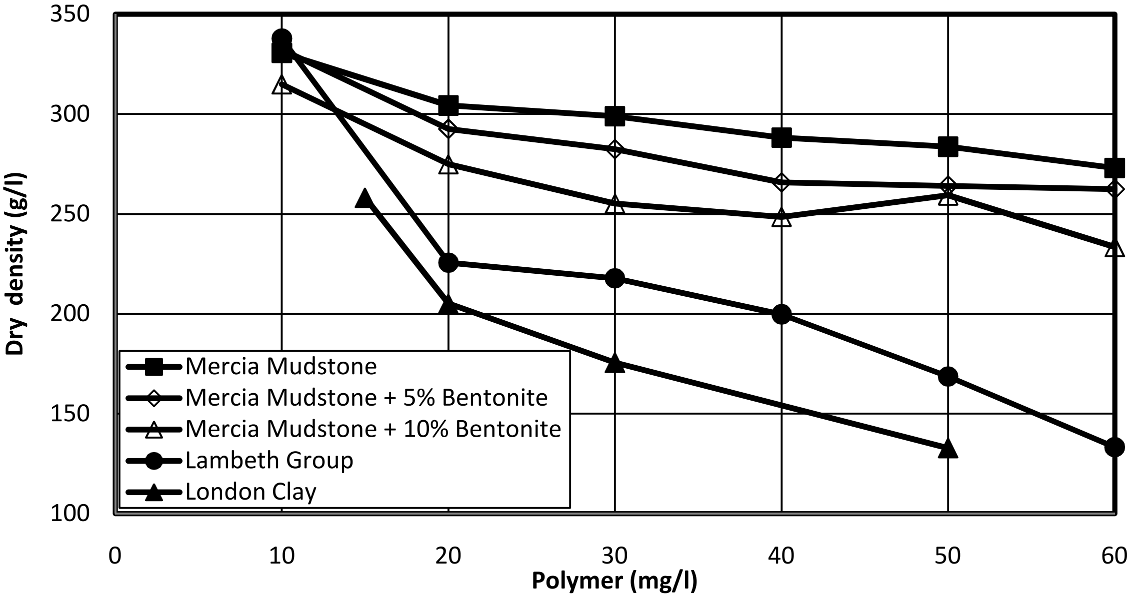


Figure 5- 23 The effects of polymer addition for natural slurries on dry density

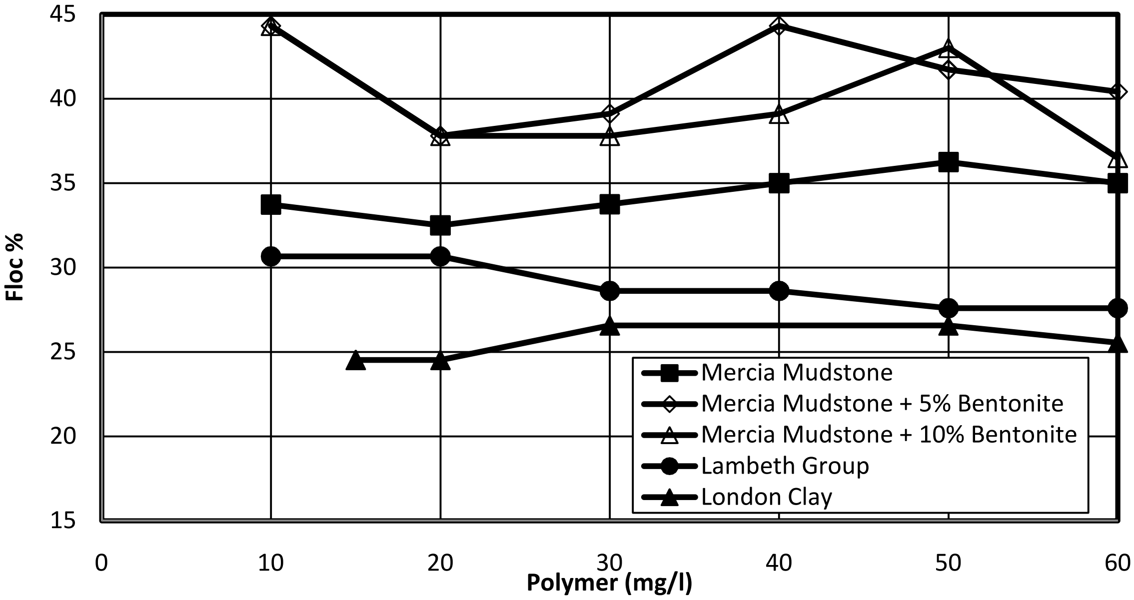


Figure 5- 24 The effects of polymer addition for natural slurries on floc%

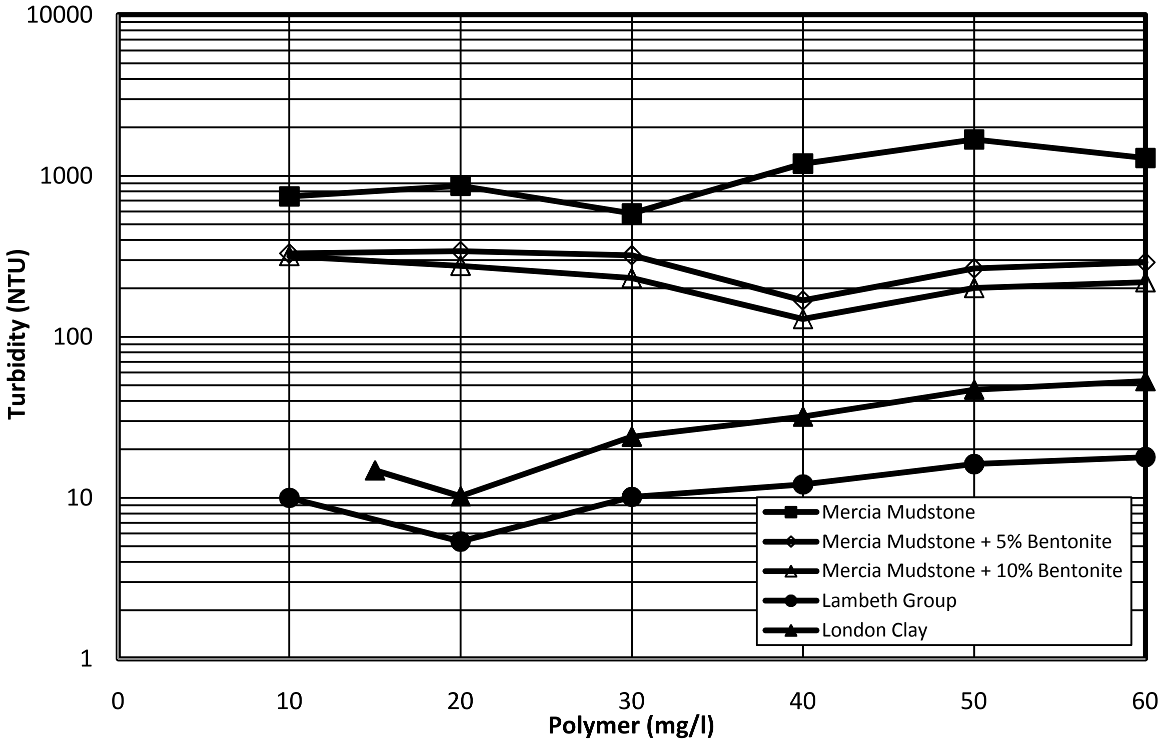


Figure 5- 25 The effects of polymer addition on turbidity of natural slurries supernatant

Figure 5- 26 shows the effects of mixing time on dry density, floc% and NTU of natural slurry with 20 mg/l polymer. All data for dry density, floc% and turbidity show incomplete mixing if the period of mixing is less than 120 seconds. The dry density of Lambeth Group slurry increased with the mixing time but the mix time has no obvious effect on dry density of the London Clay slurry. The mixing time had little impact on floc%. The turbidity of the London Clay supernatant was stable at around 15 NTU with increasing mixing time after 120 seconds. The turbidity of the Lambeth Group supernatant was around 5 NTU between a mixing time 240 to 420 seconds.

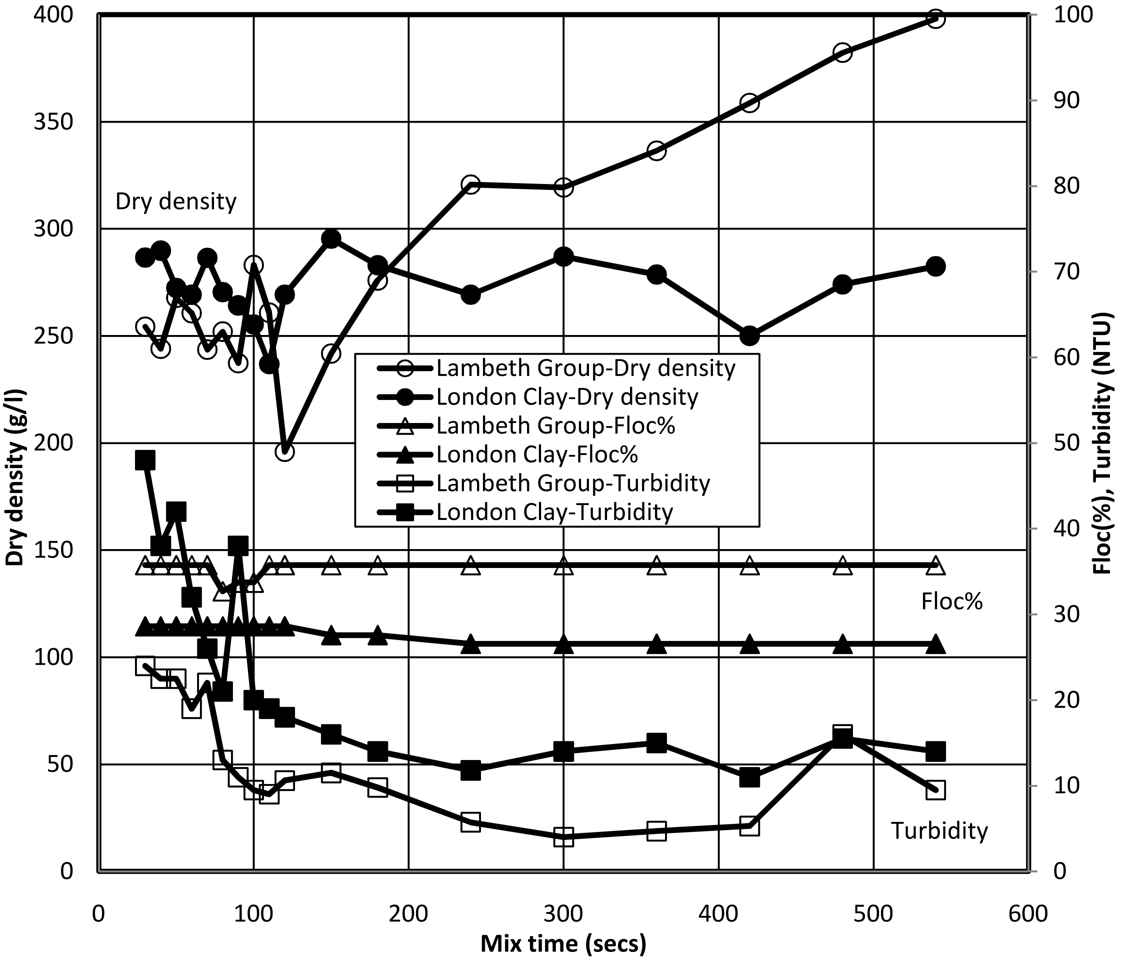


Figure 5- 26 The effects of mixing time on dry density, floc% of natural slurry and turbidity of natural slurry supernatant

Only natural slurry has a higher COD as seen in chapter 4. Therefore, the COD of the natural slurry supernatant was analysed in this study. The COD value of the natural slurry supernatants with 20 mg/l polymer (London Clay and Lambeth Group) were all under 125 mg/l, the EU directive on urban wastewater treatment COD effluent standard (91/271/EEC). The relationship between COD and sedimentation time at different levels within its natural slurry supernatants with 20 mg/l polymer is shown in Figure 5- 27.

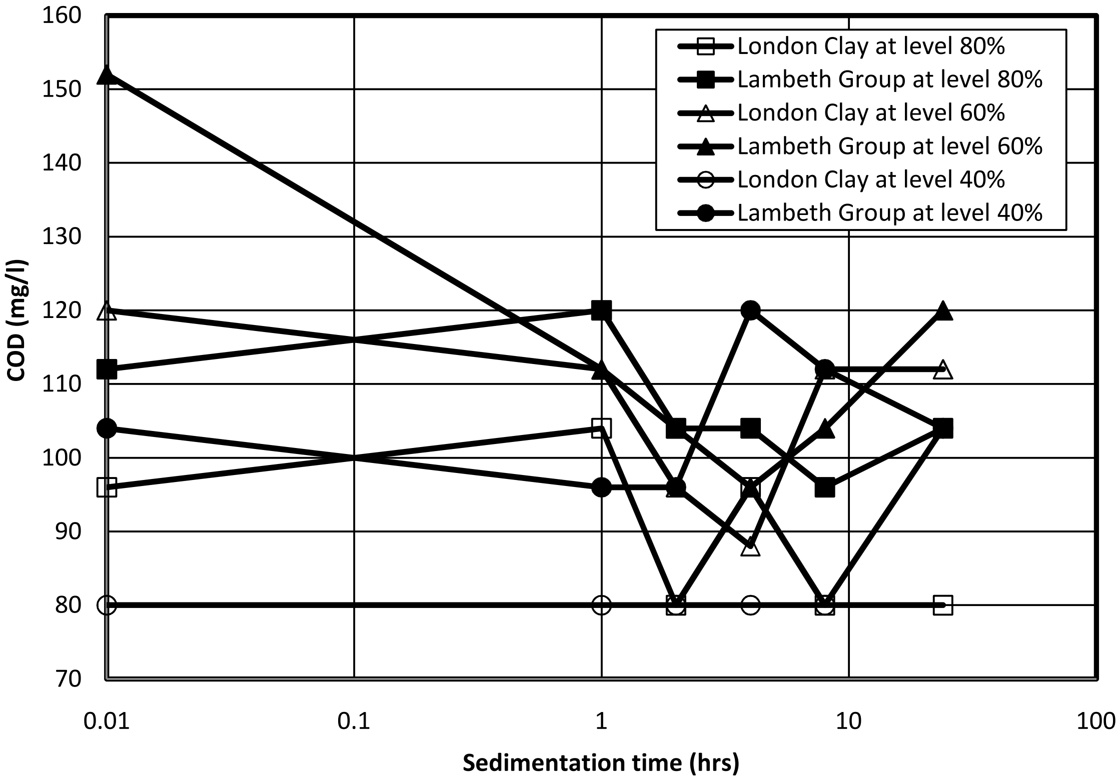


Figure 5- 27 The relationship between the COD of natural slurry supernatants and sedimentation time at different sedimentation levels in the column with 20 mg/l polymer

Table 5- 5 is a summary of the effect of 30 mg/l of polymer on the natural and laboratory slurries. From Table 5- 5, it can be seen that the turbidity of the Mercia Mudstone slurry was extremely high. Therefore, the Mercia Mudstone slurry with alum and polymer was studied in order to overcome the high turbidity problem.

In brief, the effects of polymer, bentonite and mixing time on natural slurry were similar to the observations for the laboratory soil.

Table 5- 5 Typical result of different slurries on dry density, floc% and turbidity.

	Dry density of flocs (g/l)	Floc (%)	Turbidity of supernatant (NTU)
Kaolin	250-350	45-50	2-40
Bentonite	200-220	55-60	2-5
Mercia Mudstone	300	33	600
Lambeth Group	220	30	5
London Clay	180	26	15

5.5.6 Mercia Mudstone with alum and polymer

From Figure 5- 25, the natural slurries showed that most colloid particles were flocculated by polymer. However, there were some residual suspensions in the supernatant of Mercia Mudstone. This residue could have been some organic matter in suspension. The aim of the following experiments was to overcome the high turbidity of suspended particles in the supernatant. The addition of coagulant was investigated to determine the effect for Mercia Mudstone on dry density, floc% and turbidity. Alum was chosen as the coagulant and polymer (VP1) was the flocculant in this study.

The influence of alum and polymer on dry density of Mercia Mudstone slurry is displayed in Figure 5- 28. It can be seen that the dry density was reduced as the alum content increased for various polymer doses.

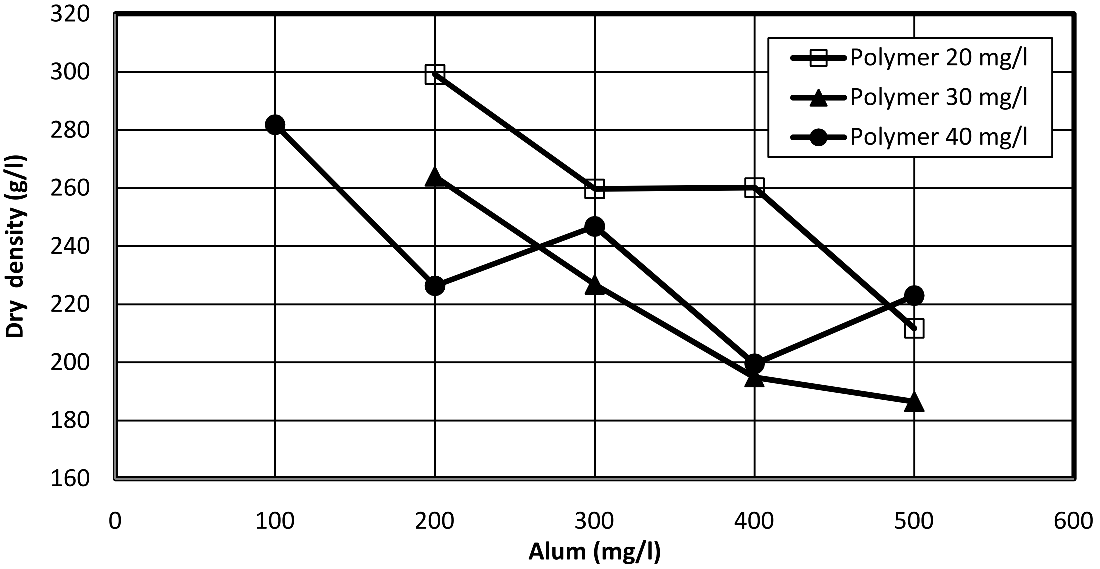


Figure 5- 28 The effects of alum and polymer on dry density of Mercia Mudstone slurry

The effect of alum and polymer on floc% of Mercia Mudstone slurry is shown in Figure 5- 29. From this chart, it can be stated that the floc% increased as the alum content increased for different polymer doses.

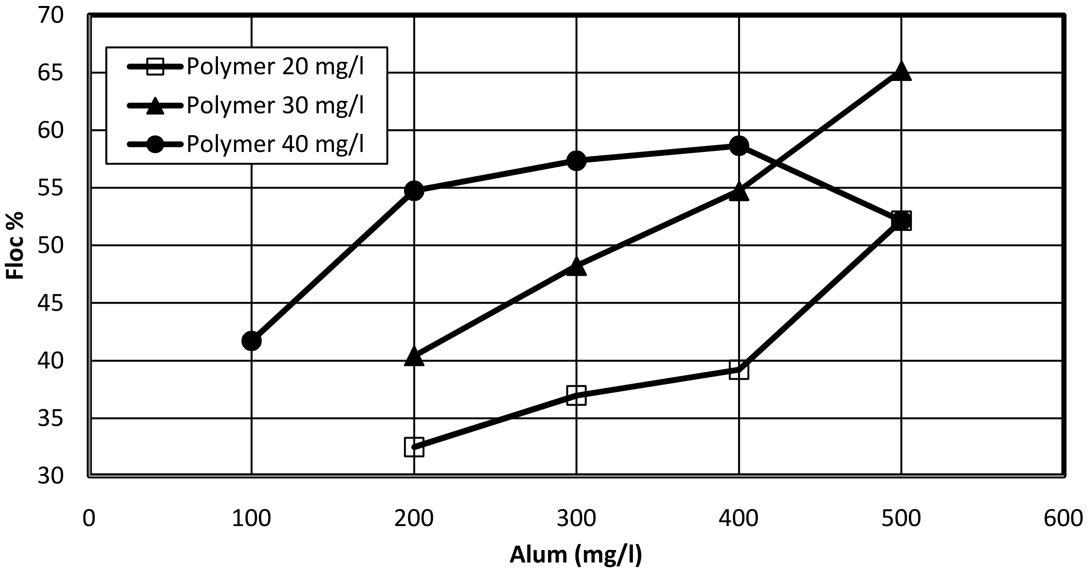


Figure 5- 29 The effects of alum and polymer on floc% of Mercia Mudstone slurry

The effects of alum and polymer on the turbidity of the Mercia Mudstone slurry are shown in Figure 5- 30. Increasing the quantity of alum reduced the turbidity dramatically. In addition, increasing the polymer content reduced the need to increase the alum content. In this study, the turbidity was under 5 NTU when 40 mg/l polymer and 400 mg/l alum were added.

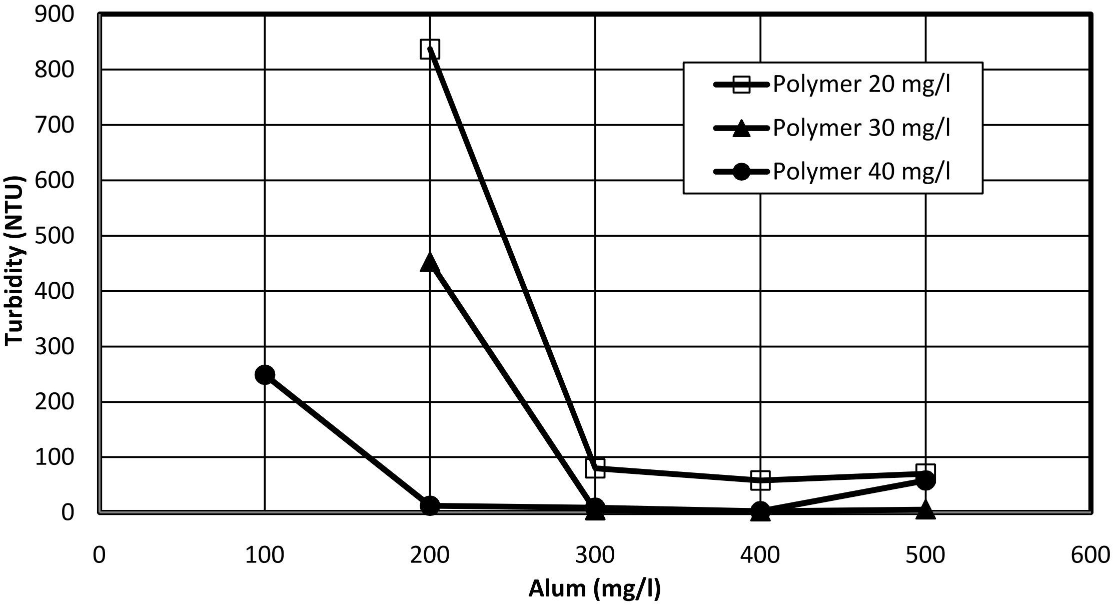


Figure 5- 30 The effects of alum and polymer on turbidity of the Mercia Mudstone slurry supernatant

5.6 Conclusion

From the results, coagulant did not have an obvious effect on the dry density of floc, floc production and turbidity of the supernatant in most soils when polymer is added. However, the turbidity did reduce in some natural soils when the coagulant increased. A minimum dose of polymer and a mixing time of at least 120 seconds were required to achieve the most beneficial effects on settling behaviour. Adding a small amount of bentonite to natural slurry can lead to a reduction in floc% and turbidity. However, there is also a decrease in dry density. The COD values of flocculated slurry supernatants were acceptable. The effect of coagulant and flocculant on slurry settling behaviour is summarized on Table 5- 6.

Table 5- 6 The effect of coagulant and flocculant on slurry settling behaviour

	Dry density of flocs	Floc%	Turbidity of supernatant
Polymer	With increasing polymer dosage, dry density was decreased.	Minimum dosage was required to form flocs result in particles settling then no obvious effect.	With increasing polymer dosage, turbidity was increased.
Bentonite	With increasing bentonite dosage, dry density was decreased.	A small amount can decrease the floc%.	Adding bentonite can delay turbidity increase.
Mixing time	With increasing mixing time, dry density was increased.	Minimum mixing time was required to form flocs result in particles settling then no obvious effect.	A certain range mixing time was required to produce clarity liquid.
Coagulant	1. No obvious effect on most soil. 2. For some natural soil, with increasing coagulant dose, dry density decreased.	1. No obvious effect on most soil. 2. For some natural soil, with increasing coagulant dose, floc% increased.	1. No obvious effect on most soil. 2. For some natural soil, with increasing coagulant dose, turbidity decreased.

Flocculant (polymer) provides a bridging and binding action between particles thus promoting agglomeration. The coagulant (alum or ferric salts) does not appear to neutralize the charges on the particles sufficiently to have a significant effect on the flocs.

Chapter 6 The effect of centrifuge and clarifier separation on slurry

6.1 Introduction

Centrifuges are often used in the pipe jacking industry to remove fine particles from slurry with the aid of flocculants. The aim of the centrifuge process is to achieve a clean centrate and a cake that is not classified as liquid waste. The different types of centrifuge are described in sections 2.2.2.2 and 2.4.4.

Cake from the centrifuge in the pipe jacking process may be not accepted to landfill if it is classified as liquid waste. The following experiments studied the effect of a centrifuge and additives on cake dewatering behaviour in laboratory batch centrifuge tests. A decanting centrifuge and pilot clarifier were used in the field to monitor the dewatering performance.

In order to assess whether a cake is acceptable to landfill it is necessary to have a test to determine whether it is a liquid or not. The liquid limit test is a measure of how much moisture a clay soil can take on before the soil behaves like a liquid. This suggests that the liquid limit is a means of monitoring the difference between a liquid and a solid.

6.2 Laboratory test on centrifuge

6.2.1 The testing protocol

Rickwood (1984) indicated that in a suspension of particles, the rate at which the particles settle depends on the force applied to the particles. A centrifuge increases that force and hence the rate of settlement. In 1856, Sir Gabriel Stokes proposed that the frictional force, F, acting on a spherical particle of radius, r_p, was related to the dynamic viscosity, η, by the equation:

$$F = 6 \pi \eta r_p \frac{dr}{dt} \qquad (6\text{- }1)$$

where $\frac{dr}{dt}$ is the velocity of the particle.

The actual force experienced by particles is determined by the gravitational force and the flotation effects which reflect the differences in the density of the fluid (ρ) and the particle (ρ_s). Therefore Equation (6- 1) becomes:

$$(\rho_s - \rho) V g = 6 \pi \eta r_p \frac{dr}{dt} \qquad (6\text{- }2)$$

Since the particle is assumed to be spherical, then the volume, V, can be expressed in terms of the radius of the particle. Thus:

$$(\rho_s - \rho) \frac{4}{3} \pi r_p^3 g = 6 \pi \eta r_p \frac{dr}{dt} \qquad (6\text{- }3)$$

In practice, the centrifugal force which moves particles away from the axis of rotation is very much greater than the Earth's gravity and therefore the rate of settlement increases. Note that settlement is in the direction of the force so will be radial in a centrifuge. The unit of relative centrifugal force (RCF) is usually given in terms of “g” and can be calculated from the expression:

$$\mathrm{RCF}=\frac{\omega^2 \mathrm{R}}{\mathrm{g}} \tag{6- 4}$$

where $\boldsymbol{\omega}$ is the angular velocity in terms of radians/sec, R is the rotational radius, g is earth's gravitational acceleration.

Substituting Equation (6- 4) into Equation (6- 3) and simplifying the expression in terms of the velocity of particles, namely:

$$\frac{dr}{dt}=\frac{2\, r_p^2\, (\rho_S-\rho)\, \omega^2\, \mathrm{R}}{9\eta} \tag{6- 5}$$

The largest and densest particles will settle first. This means that a centrifuge separates particles according to size and density of particles:

When the rotational speed is given in revolutions per minute (rpm), the RCF can be expressed:

$$\mathrm{RCF}=1.118 \times 10^{-5} \times \mathrm{R} \times \mathrm{N_r}^2 \tag{6- 6}$$

where N_r is revolutions per minute (rpm), R is rotational radius in centimetres.

From Equation (6- 6), it can be seen that the centrifugal force acting on the particle is related to the square of the speed and rotational radius. The centrifuge works using the sedimentation principle, where the centripetal acceleration causes more dense substances to separate out along the radial direction (the bottom of the tube in a batch centrifuge).

The following experiment were carried out to understand the effect of additive dosage, the state of slurry (without or with) settling time, centrifugal time and centrifugal force on slurry dewatering behaviour, water content of the cake, proportion of the cake produced by weight, turbidity of centrate and liquid limit of cake. Two types of samples were collected for the experiment, see Figure 6- 1:

a) Without settling time: slurry mixed with polymer was placed directly in the centrifuge.
b) With settling time: the slurry mixed with polymer was allowed to stand for five minutes and the sediment placed in the centrifuge. This is because the majority of the sedimentation of flocculated slurries takes place within five minutes (see section 3.4.1).

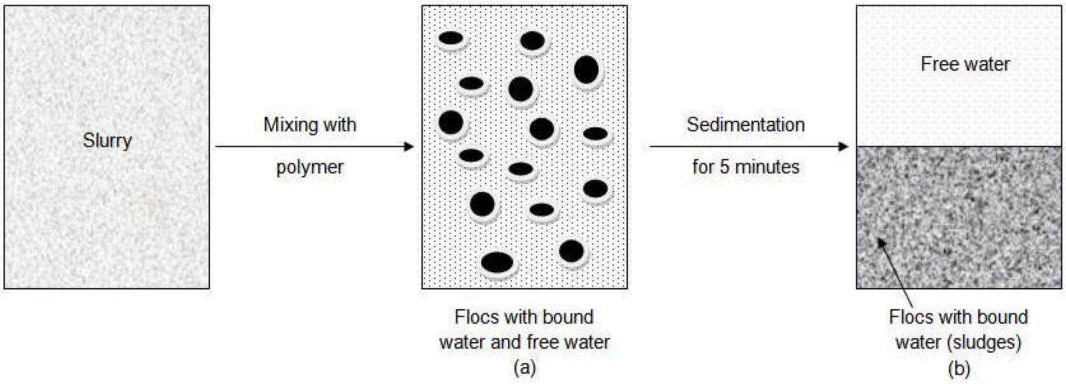


Figure 6- 1 The state of slurry (a) without settling and (b) with 5 minutes settling

Two slurries were used; a laboratory prepared slurry and a slurry from a site operation. A laboratory slurry sample was prepared by mixing 150g Polywhite E Kaolin (IMERYS Ltd) with 1 litre of water to produce a density of 1.09 Mg/m^3; a typical density for slurries in the pipe jacking industry. The Lambeth Group slurries were samples collected from pipe jacking sites. An anionic polymer (VP1) supply by SNF UK Ltd was used as a flocculant which was used on most of the sites visited (Carillion Corp).

Centrifuge tests were carried out in two different centrifuges as the maximum centrifugal force for each laboratory centrifuge is different. Low speed (<2000G) tests were carried out on a MSE Centaur2 batch centrifuge and a Hermle Z400K batch centrifuge was used for tests above 2000G. It was necessary to use the Hermle Z400K batch centrifuge in order to achieve a lower water content in the cake and compare this with results from the other centrifuge.

Two layers were present in the test tube after the centrifuge test; the upper part was the centrate and the lower part the cake. The turbidity of the centrate was measured to consider its clarity. The water content of the cake was measured to assess the dewatering characteristics. The proportion of cake produced was measured to assess the quantity of cake produced by the centrifuge test. The proportion of cake produced is defined as the ratio of the weight of the cake to the total weight of the sample. A liquid limit test conducted on cake was used to define the boundary between a liquid and a solid. This was the limit used to show whether the cake could be considered a solid. The liquid limit is described in section 6.2.2.3. The water content value was tested for one sample. The accuracy for balance was ±0.3mg.

6.2.2 Laboratory test results

6.2.2.1 The effects of polymer on the output from a centrifuge

In these experiments, the effects of polymer on the proportion of cake produced, water content of the cake and turbidity of centrate were studied. In practice, slurry remains in a centrifuge at a centrifugal force of around 2000G for a few minutes. Therefore, samples were placed in the test tubes in the centrifuge and run at a centrifugal force of 2000G for 10 minutes to simulate the operating condition on site.

The effects of the addition of polymer on the water content of the cake produced from the centrifuge are shown in Figure 6- 2. The water content of the cake was reduced if a small amount of polymer was added. However, if the polymer content was further increased, the water content of the cake would increase. In this study, the state of the slurry (with or without settling) had some effect on water content. The results suggest that for the Lambeth Group without pre settling, the water content of the cake reduced if the polymer dose was below 50 mg/l. It was the reverse for kaolin.

The effects of the addition of polymer on the proportion of cake produced are shown in Figure 6- 3. Increasing the polymer dose increased the cake production. The effects of the addition of polymer on turbidity of centrate are shown in Figure 6- 4. Turbidity reduced up to a dose of polymer of 40 mg/l for the Lambeth Group. Turbidity for kaolin is below the WHO guideline limitation 5 NTU. It seems there is no particular relationship between polymer dose and turbidity, but the turbidity of the natural sample was higher than that of the laboratory soil, kaolin. It could be because there were some organic particles left in the free water causing turbidity. Generally the turbidity decreases when the polymer content increases. But in all cases, the turbidity starts to increase at some polymer content. This may be because neutralized particles at the optimal flocculation concentration become charged particles, which is re-stabilization by over-flocculation (Levy et al., 1995).

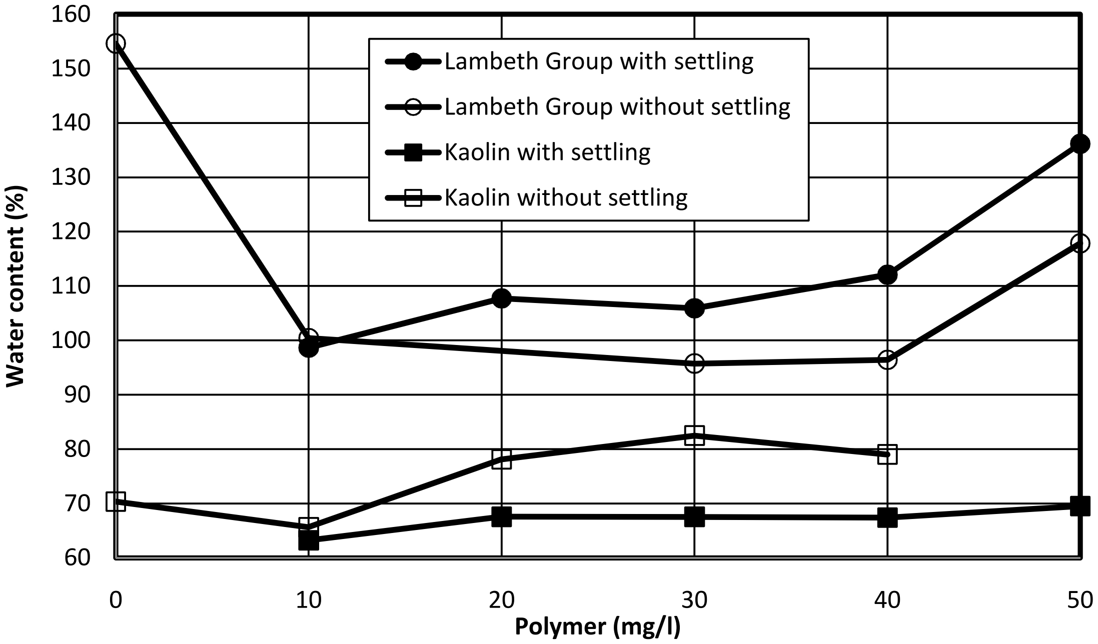


Figure 6- 2 The effects of the addition of polymer on water content of the cakes for kaolin and the Lambeth group

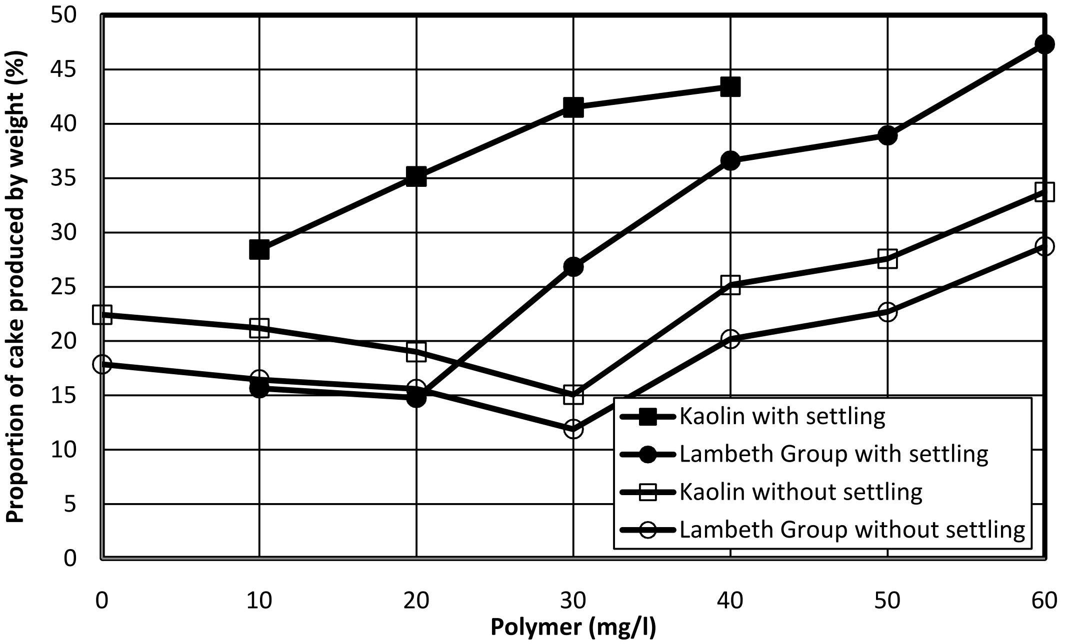


Figure 6- 3 The effects of the addition of polymer on proportion of cakes produced for kaolin and the Lambeth group

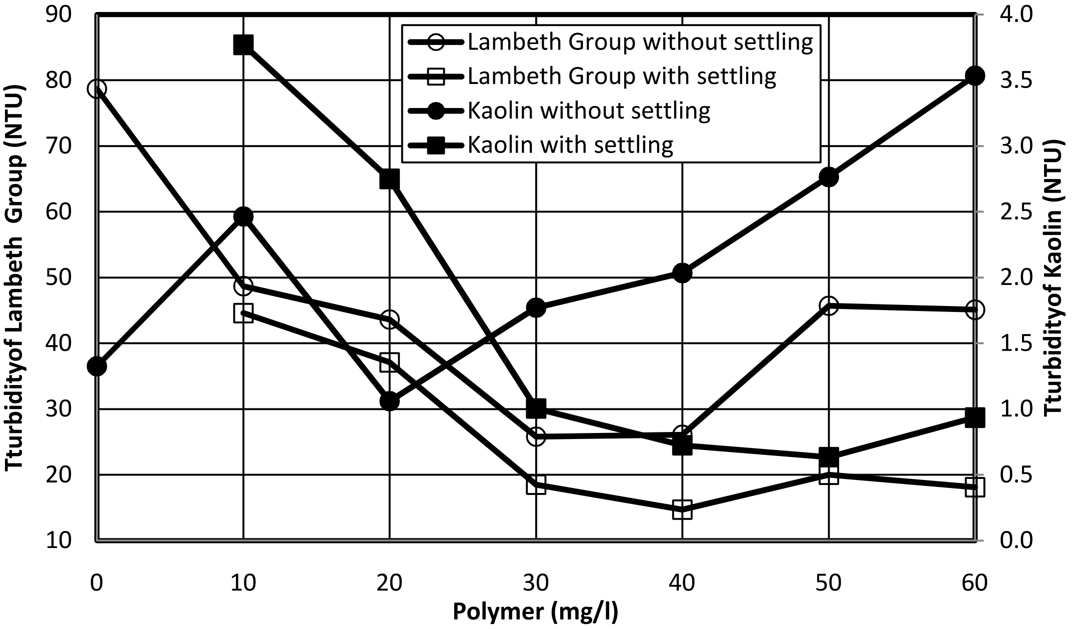


Figure 6- 4 The effects of the addition of polymer on turbidity of the cakes produced for kaolin and the Lambeth group

6.2.2.2 The effect of centrifuge conditions on cake behaviour

In these experiments, the effects of centrifugal time, centrifugal force and polymer dose on water content of cake and proportion of cake produced were studied.

The effects of centrifugal time on the water content of the cake are presented in Figure 6- 5. The sediment from a kaolin slurry mixed with 90 mg/l of polymer and allowed to stand for 5 minutes was used. Samples were subject to different centrifugal forces for different times. The variation in water content with time and centrifugal force are shown in Figure 6- 5. The centrifugal force had to be maintained for at least two minutes to have a significant impact on the water content of the cake.

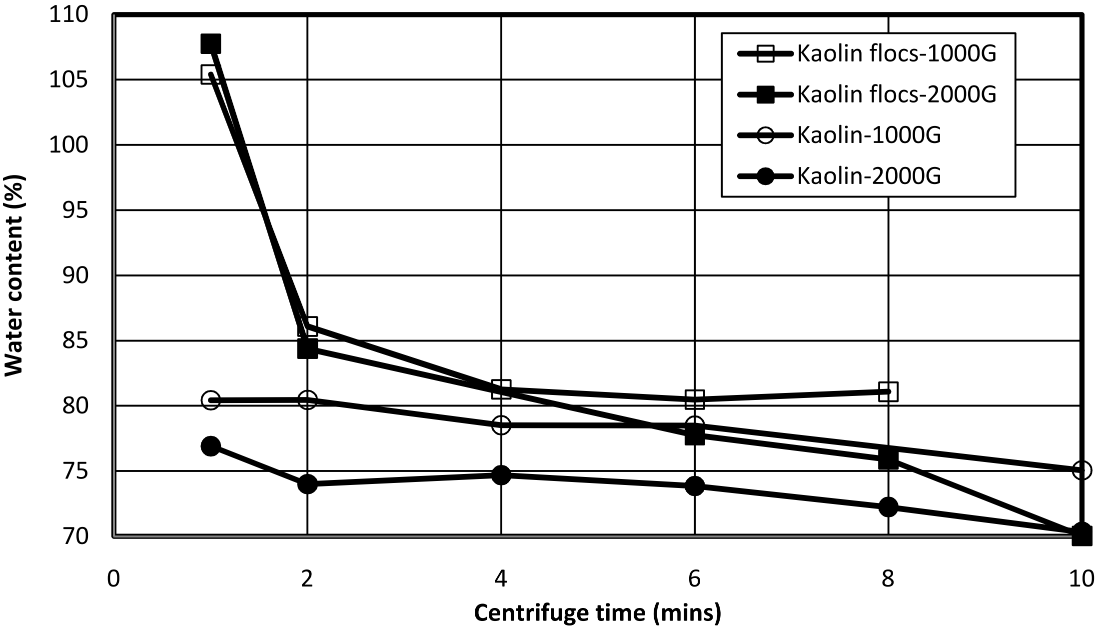


Figure 6- 5 The effects of centrifugal time on water content

The effect of centrifugal time on the proportion of cake produced is shown in Figure 6- 6. It can be seen that the proportion of cake produced was decreasing with an increase of centrifugal time or centrifugal force for the flocculated kaolin cake. However, it was very nearly constant for the kaolin slurry. This could be because water was released from flocs as they broke down under the centrifugal force.

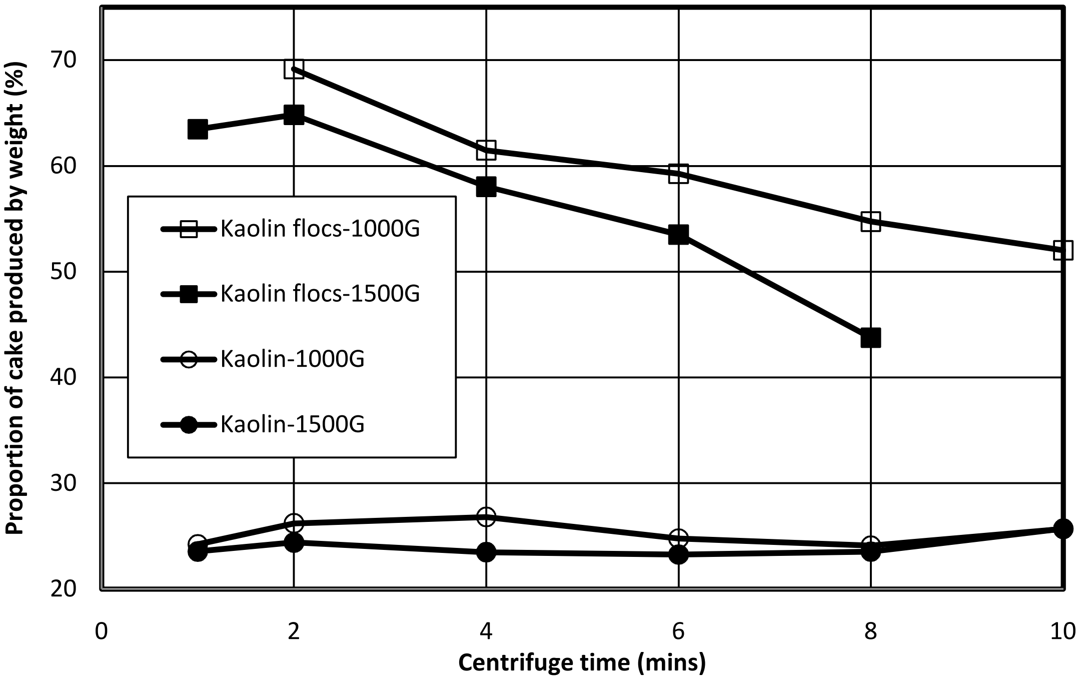


Figure 6- 6 The effects of centrifugal time on the proportion of cake produced

The effects of polymer dose and centrifugal time on water content are shown in Figure 6- 7. Increasing the centrifugal time reduces the water content until it becomes very nearly constant. Increasing the centrifugal force reduces the water content. Above a centrifugal force of 2000G, the water content reduced when polymer was added, but increasing polymer content increased the water content. This is due to trapped water within the floc structure (Mpofu et al., 2003b).

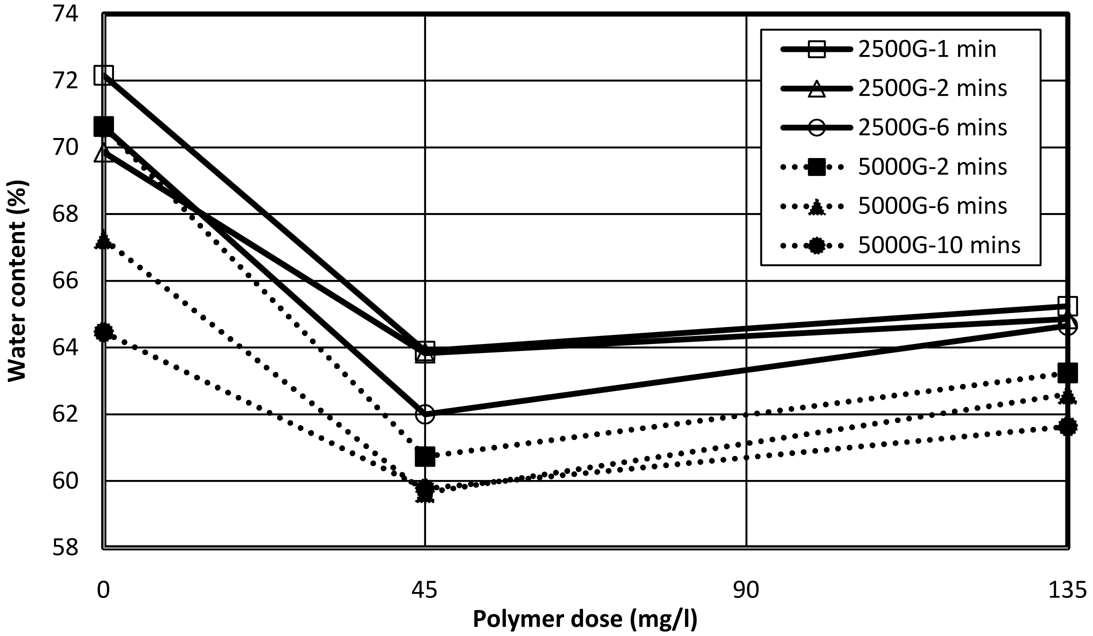


Figure 6- 7 The effects of polymer dose and centrifugal time on water content

The relationship between water content of the cake and centrifugal force is shown in Figure 6- 8. When a small amount of polymer was added, the water content of the cake decreased. However, a further increase in the quantity of polymer increased the water content of the cake. The water content of cake decreased with the increased centrifugal force and time. Wu et al. (2003) also showed that water can still be pressed out of the cake of conditioned sludge when the centrifugal force exceeds 6244 G and a polymer dose has an obvious impact on the cake dewatering behaviour.

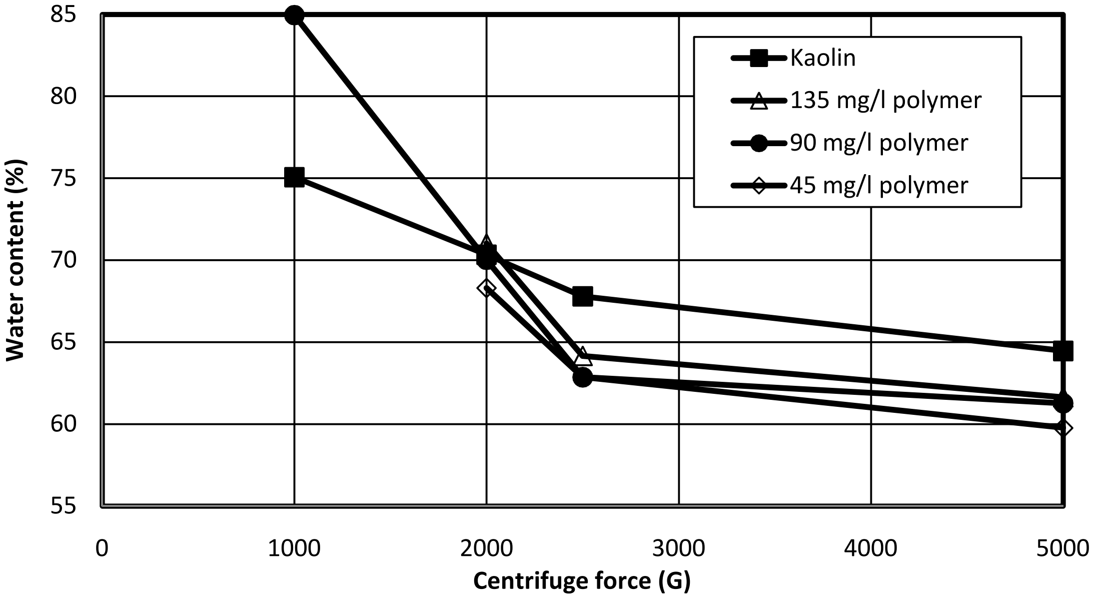


Figure 6- 8 The relationship between water content of the cakes and centrifugal force

6.2.2.3 The effect of polymer on liquid limit

The liquid limit is a way to identify the difference between a liquid and solid. The cake has to be considered a solid if it is to be disposed of to landfill. Liquid limit is determined by a cone penetrometer test (BS1377-2, 1990). The relationship between cone penetration depth and water content of kaolin cake for various dosages of polymer are shown in Figure 6- 9. The liquid limit is defined as the water content of the soil which allows the cone to penetrate exactly 20 mm (BS1377-2, 1990). Figure 6- 9 shows that the liquid limit increases as the polymer concentration increases. This result is similar to the reports by Lambe (1953), Merritt (2004), and Kim and Palomino (2009). It implies the shear strength of the flocculated cake increases with an increase in polymer concentration. This means that adding polymer serves to produce a cake that could be treated as a solid because of the increased in strength even though the water content has increased.

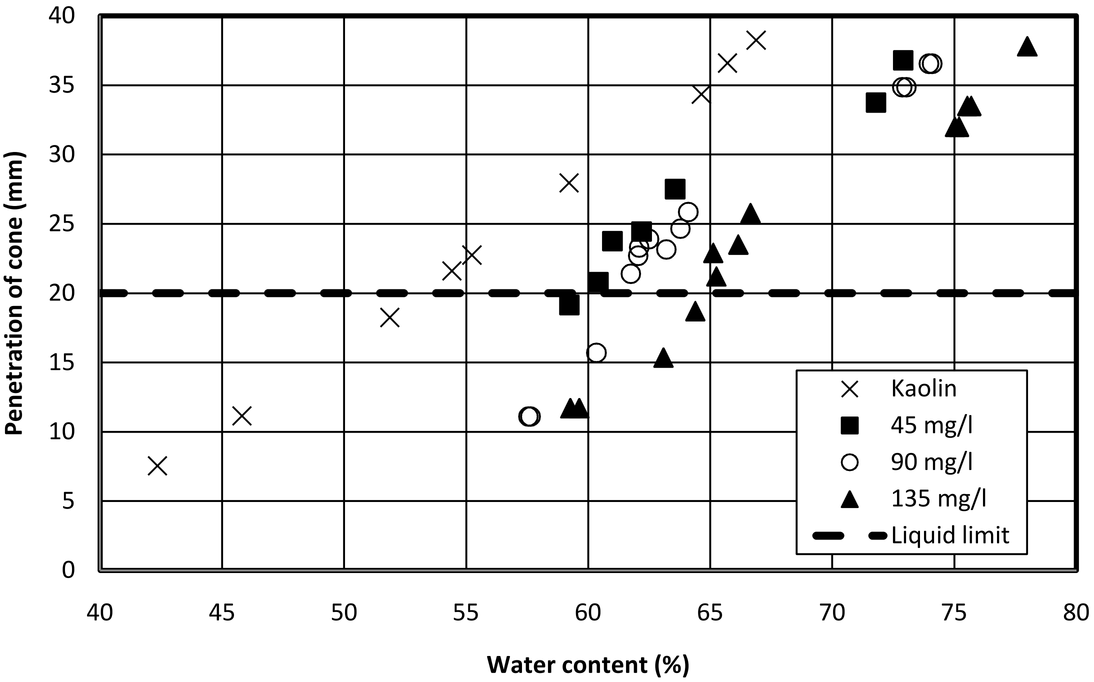


Figure 6- 9 The relationship between cone penetration depth and water content for various doses of polymer with the kaolin slurry

6.2.3 Discussion

A summary of the results of the laboratory tests is shown in Figure 6- 10. It can be seen that adding polymer increased the liquid limit and water content of the cake. Increasing the centrifugal force can decrease the water content of the cake.

In this study, the slurry density was 1.09 Mg/m^3. The water contents of most cakes were above the liquid limit of the natural soil. However, the water contents of the cakes were below the liquid limit when polymer was added. This was because the liquid limit increased with the addition of polymer.

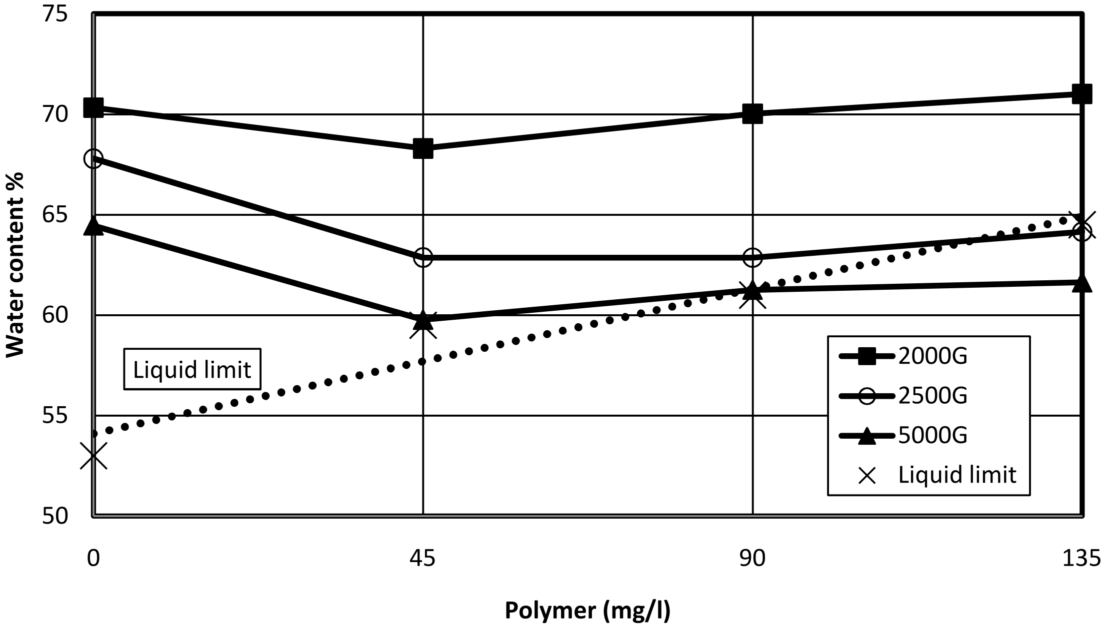


Figure 6- 10 The effects of polymer and centrifugal force on water content in laboratory tests

6.3 Field scale test on centrifuge and clarifier

6.3.1 The centrifuge and clarifier separation plant

The decanting centrifuge is the most commonly used centrifuge in the UK pipe jacking industry. However, these centrifuges are often compared with the Rolls-Royces in the car industry: they perform well but the capital and running costs are high (Svarovsky, 2000). From section 2.4.3, a clarifier can be used for rapid solid-liquid separation with the addition of flocculants. The function of a clarifier is to clarify the liquid. The sludge produced in the bottom of the clarifier can be sent to a centrifuge to be further dewatered. Therefore, a pilot clarifier and a decanting centrifuge were studied to determine whether they were a more effective and efficient way to separate the fine particles from the slurry.

6.3.1.1 Centrifuge separation

The centrifuge uses centrifugal force to speed up the sedimentation rate of a slurry. Decanting centrifuges are used offline in the pipe jacking industry so that slurry can be run continuously through a centrifuge. They are used offline for the following reasons. The flow rates in the online slurry separation process are too high to run centrifuges inline unless multiple centrifuges are used in series to reduce the flow rate through one centrifuge. This is too expensive. Running offline has the advantage that the centrifuge can still proceed while a new pipe is being installed even though the slurry system is switched off. In a typical unit, the slurry is pumped into a horizontal rotating cylinder. The solids are spun to the outside of the bowl where they are scraped out by a screw conveyor (see Figure 2- 9 in Chapter 2) to form the cake. The centrate is returned to the slurry tank. The theory and function of a decanting centrifuge is described in section 2.2.2.2.

6.3.1.2 Clarifier separation

Clarifiers are used in the wastewater and water supply industry to separate liquids and solids (Qasim, 1999; Binnie, 2002). As mention in section 2.4.3, a lamella clarifier (see Figure 2- 16 in Chapter 2) is considered between the slurry tank and centrifuge to enhance the separation of solids in the pipe jacking industry. In a clarifier, particles with a density greater than water will settle assuming that no forces other than gravity are involved. Generally, there are three flow directions in clarifiers: counter-current, co-current and cross-flow. In the co-current mode, settled solids move down the surface of the plates in the same direction as the liquid. Settled solids may be mixed in with the supernatant due to disturbance as the liquid is above the settled solid (Gregory et al., 1999). Counter-current settling mode is mostly used in a lamella clarifier (Gregory et al., 1999; Tarleton and Wakeman, 2007). This could be because counter-current flow allows settlement of particles with the smallest settling velocity when a plate is placed with an angle of greater than 60° to the horizontal (Gregory et al., 1999). The counter-current system is more efficient than co-current and cross-flow systems (Binnie, 2002). Therefore, a counter-current clarifier was selected for this study.

A cross section of the lamella clarifier is shown in Figure 6- 11. A flocculated slurry inlet was set below the settling tank in the clarifier. The flocculated slurries form flocs and settle to become sludge. There were two outlets in this clarifier: one was on the top for supernatant, the other was in the bottom settling tank and was connected to the centrifuge. The design of the clarifier was based on the upward flow velocity and retention time. A well designed influent structure also needs to be considered to distribute flow equally and prevent slurry passing directly to the supernatant outlet (Qasim, 1999; Metcalf and Eddy, 2003; Alley, 2007). A round perforated pipe was connected to the inlet as the influent structure to distribute flow uniformly in the clarifier. It dissipated the inlet velocity to prevent disturbance of the accumulated of sludge. In practice, a flow velocity of less than 0.6-0.75 m/sec can allow particles to settle (Metcalf and Eddy, 2003; Alley, 2007).

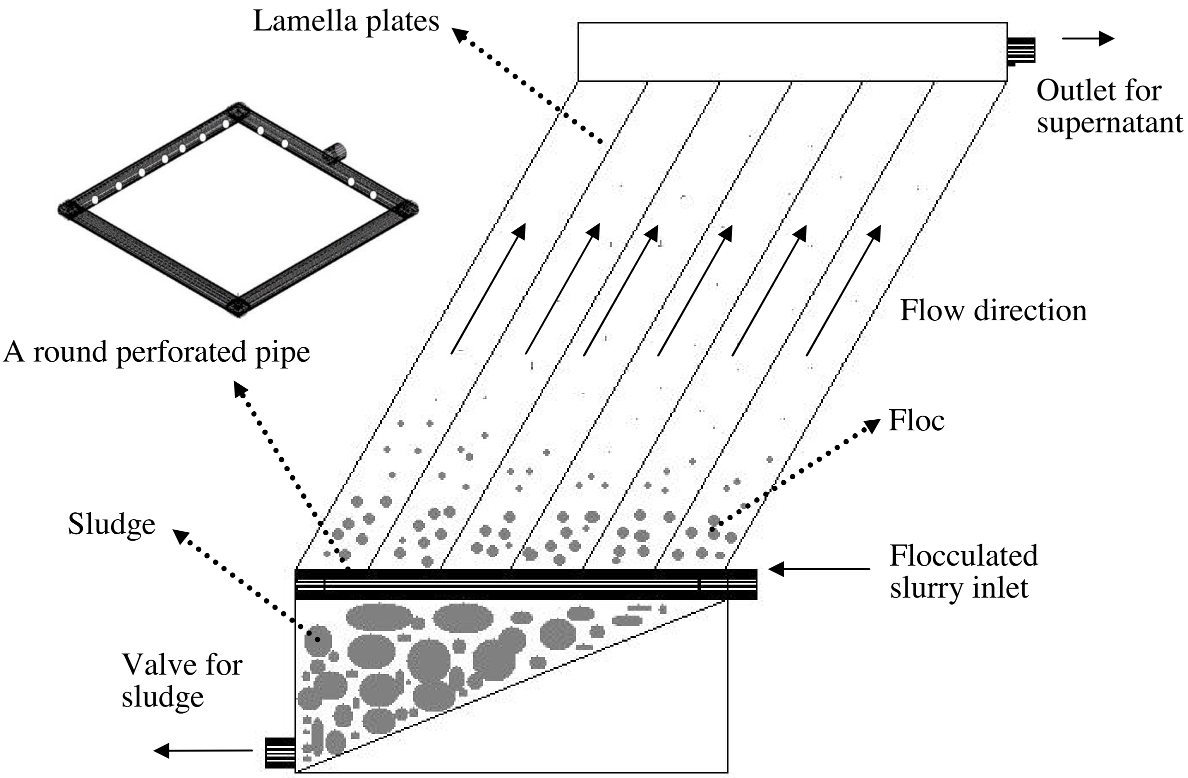


Figure 6- 11 A diagrammatic view of a section of the clarifier

Slurry is a mix of water, soil and, possibly, some additives. The main component of slurry after passing the coarse screens and hydrocyclones is clay mixed with water. As flocculated slurry is injected via the influent structure, a round perforated pipe, the flocs settle and slide down to the bottom settling tank. The small particles will settle onto the plates and will not flow upwards with the liquid if the net settling velocity is controlled correctly (see the following description). This resulting liquid can be collected at the outflow as supernatant.

The following describes the upward flow velocity, settling time and settling areas required for the clay particles to settle in an up-flow lamella clarifier.

The settling velocity (Equation 6- 7) of a particle in laminar flow (Reynolds number (Re) is less than 0.3) can be found from Stokes' law (Qasim, 1999). The diameter of clay is 2 µm (2×10^{-6} m) and the specific gravity is 2.6. The kinematic viscosity of water at 20ºC is 1.01×10^{-6} m^2/s (Tebbutt, 1998).

According to Stokes' law:

$$V_s = \frac{gd^2(S_S-1)}{18\mu} \text{ (Re<0.3, laminar flow)} \qquad (6\text{- }7)$$

where V_s is the particle terminal velocity (m/s), d is the particle diameter (m), S_s is the specific gravity of particle, µ is the kinematic viscosity of the fluid (m^2/s).

Thus, the terminal velocity V_s is 3.45×10^{-6} m/s

It is necessary to check that the resulting Re is less than 0.3, as derived from the calculated settling velocity. This is because Equation (6- 7) can only apply if the Re is within the laminar range (Re<0.3), which is assumed in using Equation (6- 8).

$$\text{Reynolds number (Re)} = \frac{V_S d}{\mu} \qquad (6\text{- }8)$$

Thus, Re is $6.83\times10^{-6} \leq 0.3$ and thus Equation (6- 7) applies.

In an up-flow lamella clarifier (see Figure 6- 12), a particle will settle due to gravity at a velocity (V_s) under the upward velocity (V_f) of the fluid flow. In theory any particles with a settling velocity greater than the upward-flow velocity would settle and be removed from the fluid. During the course of travel settlement of the particle prevents it from flowing out of the clarifier (the maximum travel distance is L_m). This means the net settling velocity of a particle (Us) must be greater than zero. The settling retention time depends on the upward velocity of the fluid and settling length.

The net settling velocity (U_s) of the particle in an up-flow condition is (Yao, 1973):

$$U_s = \frac{V_f \times d_s}{(d_s \times \sin\theta + L_p \times \cos\theta)} = V_s - V_f \times \sin\theta \qquad (6\text{- }9)$$

Thus,

$$V_f = \frac{V_s \times (d_s \times \sin\theta + L_p \times \cos\theta)}{(d_s + d_s \times \sin\theta \times \sin\theta + L_p \times \sin\theta \times \cos\theta)} \qquad (6\text{- }10)$$

From Equation (6- 9) the net settling velocity $U_s = V_s - V_f \times \sin\theta$. Thus increasing the angle will reduce the settling velocity. However, if the angle is too low the sludge will not settle to the base of the plates due to the frictional force between the sludge and plates. Moreover, the settling area is the projected area of the plates which is equal to the plate area $\times \cos\theta$. This means the angle θ needs to be steep enough to overcome the friction between the sludge and plates. In a clarifier, the plates are usually set at an angle between 45 and 60° above the horizontal to be self-cleaning as the friction between the sludge and the plates is overcome by the component of the gravitational force but at the same time there are the benefits of increasing the settling area (Schroeder, 1977; Barnes and Wilson, 1983; Johnson and Chen, 2006). If the plates are inclined at angles less than 45°, solids will tend to accumulate within the plates (Binnie, 2002; Metcalf and Eddy, 2003; Alley, 2007).

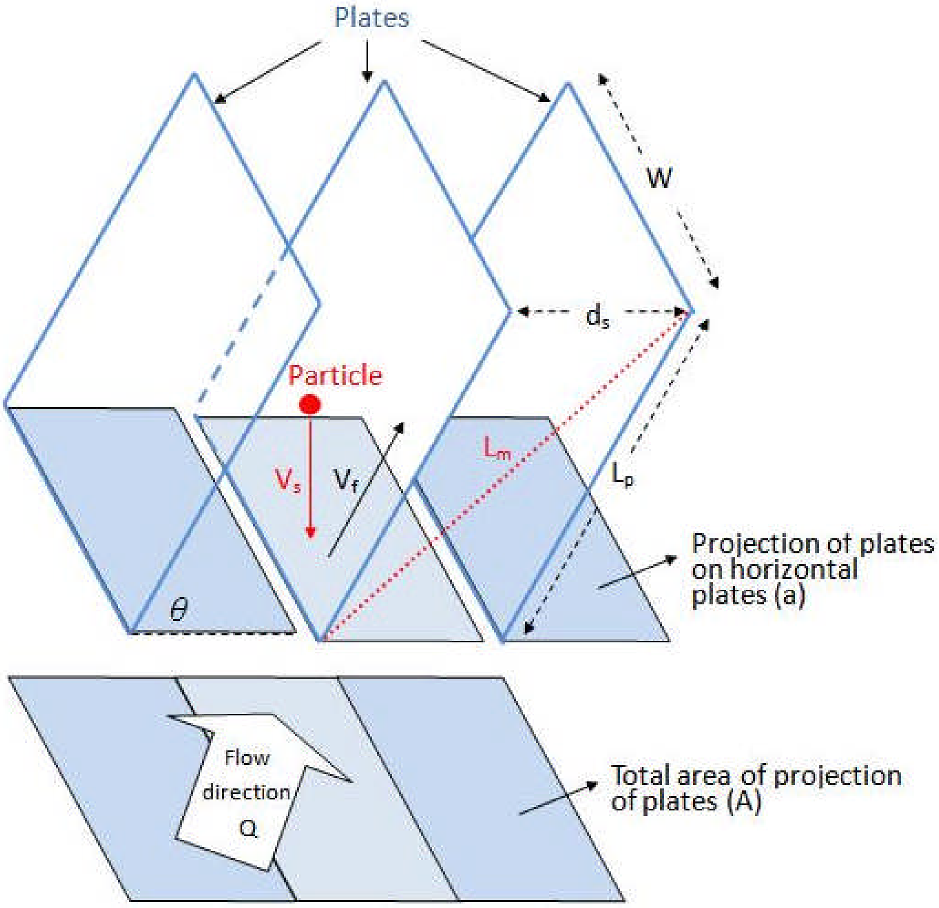


Figure 6- 12 Nomenclature* in an up-flow lamella clarifier

* V_f is upward velocity of the fluid, V_s is particle gravity velocity, d_s is plate spacing, W is plate width, L_p is plate length, L_m is settle particle maximum travel distance, θ is an angle of plate to the horizontal, a is projected area = $W \times L_p \times \cos\theta$, Q is flow rate, A, the settling area, is the sum of the projected areas of the individual plates on a horizontal surface.

The total settling area required, which is a function of the particle size can be chosen arbitrarily. However, this will have an effect on the number, size and inclination of plates. For the pilot clarifier used in this test, the 0.98 m long and 0.75 m wide plates were inclined at 60º. The projected area, "a", of one plate would be: $a=0.75\times0.98\times\cos60°= 0.37\ m^2$. The distance between each plate is typically between 40 and 100 mm but 50 mm is normally used (Binnie, 2002; Metcalf and Eddy, 2003; Tarleton and Wakeman, 2007). In this study it was set at 50 mm between plates. The flow rate Q was 40 litre/min as measured in the decanting centrifuges throughput test (see section 6.3.3.1).

Using the data in Equations (6- 9 and 6- 10), the upward velocity (V_f) of the fluid flow is 3.59×10^{-6} m/s and the net settling velocity (U_s) is 3.4×10^{-7} m/s.

Therefore, the total settling area is:

$$A=\frac{Q}{U_S}=\frac{\frac{40}{60}\times10^{-3}}{3.4\times10^{-7}}=1960\ m^2 \qquad (6\text{- }11)$$

Thus $\frac{A}{a}=\frac{1960}{0.37}$ = 5297 plates would be required.

The retention time is:

$$\text{Retention time } T=\frac{V_c}{Q}=\frac{5297\times0.98\times0.75\times0.05}{\frac{40}{60}\times10^{-3}\times3600}=81 \text{ hours} \qquad (6\text{- }12)$$

Where V_c is the volume of clarifier.

This retention time and number of plates would not be appropriate for a pipe jacking site. It was shown in section 2.4.3, that coagulant and flocculant can reduce the sedimentation time. Using the same conditions, then 12 (0.75 m × 0.98 m) plates and a retention time of 11 minutes would be required for flocculated slurry. The detail is below:

The settling velocity of a flocculated floc varies depending on the polymer characteristics (e.g. molecular weight, charge type and charge density). The settling velocity for flocculated clay was reported by (Owen et al., 2002; Sabah and Cengiz, 2004; Ersoy, 2005; Owen et al., 2007). The settling velocity is in the range 6×10^{-3} to 1×10^{-2} m/s when a high polymer concentration (50-500mg/l) is used. However, the polymer usage in a clarifier is less than 15 mg/l (see section 6.3.1.2). Sabah and Cengiz (2004) measured the settling velocity as below 100 mm/min for an anionic polymer at a concentration of 20 mg/l. The settling velocity is assumed to be 100 mm/min for the low polymer flocculated flocs obtained in these tests. Thus, using Equations (6- 9 to 6- 12) the upward velocity of the fluid (V_f) is 1.73×10^{-3} m/s. The net settling velocity (Us) is 1.63×10^{-4} m/s. The total settling area (A) is 4.2 m^2 and 12 plates would be required. The retention time is 11 minutes.

From the above calculation, particles with a settling velocity greater than that assumed (100 mm/min) can be removed via a twelve-plate lamella clarifier with 11 minutes retention time. This may be acceptable on a pipe jacking site. Therefore a pilot lamella clarifier was studied to find out the effects on dewatering behaviour.

6.3.2 The testing protocol

The following experiments were undertaken to understand the effect of slurry flow rate, additive dose, density of slurry and centrifugal force on slurry dewatering behaviour using a clarifier and centrifuge in the field. A clarifier was designed as an inline unit between the mixer (slurry mix with flocculant) and centrifuge. The mixer provides only an initial simple mixture for flocculant and slurry. A diagrammatic layout of the field scale test is shown in Figure 6-13.

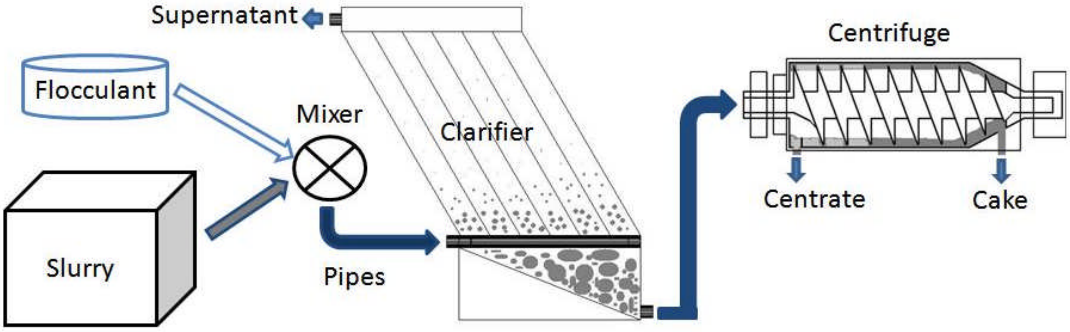


Figure 6- 13 The layout of the field scale test

The slurry sample was prepared by mixing Polywhite E Kaolin (IMERYS Ltd) with water to create various slurries of different density. The slurry was pumped into an agitating tank to maintain the slurry composition. Two popular forms (liquid and powder) of flocculants used in the pipe jacking industry were used in this study. TK50 is a liquid form of anionic polymer supplied by Morrison Mud Corp and VP1 is a powder form of anionic polymer supplied by SNF UK Ltd. When mixing flocculants, it is important for the mixture to age for sufficient time before dosing into the slurry. The time will vary, depending on the form of flocculant. Generally the liquid form is mixed for at least 20 minutes and the powder form for 45-60 minutes. This allows for efficient use of the flocculant and prevents flocculant agglomeration (Phillips, 2010). TK50 (liquid flocculant) was mixed with water for at least 30 minutes to age for sufficient time before dosing the polymer into slurry. The VP1 (powder flocculant) was mixed for 60 minutes. The centrifuge was a Baioni 26L decanting centrifuge, which can provide maximum centrifugal force to 3900G and up to 6000 litre per hour slurry capacity.

6.3.2.1 Clarifier design

In Section 6.3.1.2 it was shown that the particles can be removed after 11 minutes in the clarifier with twelve plastic plates (0.98 m long and 0.75 m wide) with 0.05 m spacing fitted at 60° above the horizontal. The slurry flow rate was set at 36 litre/min (controlled below the allowable flow rate, throughput, 40 litre/min, see section 6.3.3.1) to get a dryer cake. The pilot clarifier is shown in Figure 6- 14.

In the field clarifier test (refer the Figure 6- 13), the sludge (the sediment in the settling tank of the clarifier) was pumped to the centrifuge and the supernatant discharged from the outflow. From the laboratory test results presented in Chapter 5, the proportion of the flocculated slurry was approximately 50% sludge and 50% supernatant. During the continuous clarifier process, there is a tendency for turbulence at the mudline which might result in particles feeding from the sludge into the overlying supernatant. In order to reduce this unwanted mixing at the interface, the flow rate ratio of the sludge and the supernatant were adjusted in the site scale test to 60% and 40%, respectively.

Figure 6- 14 Pilot clarifier in the field.

In the field, before the start of a test, the valve at the bottom of the clarifier was closed, while the flocculated slurry was pumped into the clarifier. This was controlled until clean water came out from the outlet located on the top of the clarifier. The valve was then opened and the flow rate controlled at 60% as explained above. The flocculated slurry within the clarifier was separated into two phases: the liquid phase above and the sludge at the bottom.

Thirty minutes was allowed in between changing the inflow condition and collecting the samples from the top outlet. The 30 minutes was obtained from Equation (6- 13).

Time between samples collection $T= \frac{V_c}{Q_p} = \frac{0.98\times0.75\times0.05\times12}{\frac{36}{1000}\times(100-60)\%}$ =30 mins. (6- 13)

where V_c is volume of clarifier, Q_p is flow rate (i.e flow rate assigned for the supernatant).

6.3.2.2 Scaling up a pipe flow mixer for the field from a laboratory jar test

From Chapter 5, the flocculant can reduce the particle sedimentation time due to the creation of flocs. The mixer prior to the clarifier only provides an initial simple mixing of slurry and flocculant. There has to be sufficient time for mixing to ensure flocculation occurs. The effect of mixing time on dewatering behaviour was studied in Chapter 5. It is necessary to scale up from the laboratory tests to the field scale tests to determine the mixing time in the field and hence the injection point.

To scale up a pipe flow mixer from laboratory jar test, it is necessary to determine the flow regime for the laboratory jar test and the field pipe flow mixer (Jefferis, 2010). For the laboratory stirrer configuration, the Reynolds number is given by:

$$Re_j = \frac{\rho\, N_f\, {d_f}^2}{\eta}\times1000 \qquad (6\text{- }14)$$

where ρ is density of slurry to be flocculated (Mg/m³), N_f is rotational speed of the mixer paddle (rps), d_f is diameter of jar test mixer paddle (m), η is viscosity of slurry after flocculation (Pa . s).

The density of the laboratory slurry was 1.90 Mg/m³. Clay suspensions with flocculants are non Newtonian fluids in which the viscosity is not a constant value. The viscosity of kaolin which was used on site at a density of 1.05 and 1.09 Mg/m³ was 2×10^{-3} and 6×10^{-3} Pa . s, respectively. However, as soon as flocculation has become significant (there are two parts present), the viscosity of the top part (supernatant) of slurry is likely to drop to close to that of water and 2×10^{-3} Pa . s has been assumed for the fluid viscosity at this stage. Re_j is 6540 by using the dimensions and other data for the jar test, in which N_f, the rotational speed of mixer paddle, is 200 rpm, d_f, the diameter of jar test mixer test paddle, is 60 mm.

Laminar flow occurs when a liquid is stirred when Re < 10 and turbulent flow occurs when Re > 10000. The laminar - turbulent transition in a simple paddle mixer is likely to occur at a Reynolds number between 10 and 10000 (Qasim, 1999). Thus the flow regime in the jar test will be a laminar - turbulent transition.

For a pipe flow mixer, the Reynolds number is given by:

$$\mathrm{Re}_p = \frac{\rho\, v\, D}{\eta} \times 1000 \qquad (6\text{- }15)$$

Where D is the hydraulic diameter of the pipe (m), v is the mean fluid velocity (m/sec).

In this study the slurry flow rates through the Baioni 26L centrifuge was 36 × 60% litres/min. For a 25.4 mm diameter pipe the velocity of the fluid for this flow is:

$$v = \frac{Q_p}{A_p} = 0.7 \text{ m/sec} \qquad (6\text{- }16)$$

where Q_p is flow rate through pipe mixer or centrifuge, A_p is the area of pipe.

Therefore, the Reynolds number is 9335 (assuming density of slurry is 1.05 Mg/m^3, viscosity of slurry is 2x10^{-3} Pa . s).

For flow in a pipe, laminar flow occurs when $\mathrm{Re}_p < 2300$ and turbulent flow occurs when $\mathrm{Re}_p > 4000$ (Douglas et al., 1995). This means the flow regime in this pipe will be turbulent flow.

However, for a soil slurry which is likely to be a Bingham type non Newtonian fluid it is possible that the flow may remain laminar - turbulent transition for the heavier slurries with flocculation, especially when viscosities are greater than 2 x 10^{-3} Pa . s.

The key design parameters for the design of flocculation processes are the intensity of mixing, which the velocity gradient G is used to denote, and the retention time T.

For flocculation it is often assumed that mixing can be scaled on the basis of the dimensionless group G . t (Binnie, 2002).

The degree of agitation in a mixer unit is measured by velocity gradient G_v (S^{-1}):

$$G_v = \surd\,(\frac{P}{V\,\eta}) \qquad (6\text{- }17)$$

where P is power dissipated in the the mixer (W), V is volume of fluid in the mixer (m^3).

The power P for turbulent flow can be expressed as: $P = N_p \times \rho \times N_f^3 \times d_f^5 \times 1000$, and it follows that:

$$G = \surd\,\frac{(N_p \times \rho \times N_f^3 \times d_f^5 \times 1000}{V\,\eta} \qquad (6\text{- }18)$$

where N_p is power number

Therefore, G is 307 $s^{-}1$ by using the jar mixer data in Equation 6- 17: volume of the fluid in mixer is 500 ml and assuming N_p for single flat paddle is 3 (Qasim, 1999).

The retention time in the jar test was about 30 to 300 seconds; then the corresponding range of G . t value is 9.2 x 10^3 to 9.2 x 10^4.

For a pipe flow mixer the power dissipated is a function of the head loss. If the length of pipe prior to the centrifuge is L and the head loss in this length of pipe is H_f the power dissipated is:

$$P = \rho\, Q_p\, g\, H_f \times 1000 \qquad (6\text{- }19)$$

where H_f is friction head loss in pipe mixer (m)

Now the volume of fluid in the mixer pipe will be:

$$V = \frac{\pi\, {d_f}^2}{4} L \qquad (6\text{- }20)$$

where L is length of mixer pipe prior to centrifuge(m)

and hence:

$$G = \sqrt{\frac{P}{V\,\eta}} = \sqrt{\frac{\rho\, Q\, g\, H_f}{V\,\eta}} = \sqrt{\frac{\rho\, \frac{\pi\, {d_f}^2}{4} v\, g\, H_f}{\frac{\pi\, {d_f}^2}{4} L\,\eta}} = \sqrt{\frac{\rho\ \ v\, g\, H_f}{L\,\eta}} \qquad (6\text{- }21)$$

where $H_f = 4\, f\, \frac{L}{d_f}\, \frac{v^2}{2g}$ (6- 22)

For Reynolds numbers in the range 2,500 to 100,000 the friction factor, f can be approximated by the formula:

$$f = 0.0792\ Re^{-0.25} \qquad (6\text{- }23)$$

As the Reynolds number in a pipe flow Re=9335,

$f = 0.008$

Thus,

$$G = \sqrt{\frac{\rho\ \ v\,g\,H_f}{L\,\eta}} = \sqrt{\frac{\rho\ \ v\,g\ \ 4\,f\,\frac{L}{d_f}\frac{v^2}{2g}}{L\,\eta}} = \sqrt{\frac{2\rho\ \ f\,v^3}{d_f\,\eta}} = 737 s^{-1} \qquad (6\text{- }24)$$

To simulate the jar mixer the dimensionless group G t must be in the range:

$G\ t = 9.2 \times 10^3$ to 9.2×10^4

Hence G = 737, the residence time in the pipe mixer must be:

Residence time t = 13 to 125 seconds

L = residence time × flow velocity

and at a flow velocity of 0.7 m/s the length of pipe required will be 9 to 88 m.

In this study, a 30-metre-long with 25.4-mm-diameter pipe was selected to enhance the mixture of slurry and flocculant. The field scale test separation plant is shown in Figure 6- 15. The clarifier was positioned between the point at which the flocculant was introduced and the centrifuge. A 30-metre-long 25.4-mm-diameter pipe was connected between the mixer and the clarifier. The mixer was connected to the inlet of the clarifier.

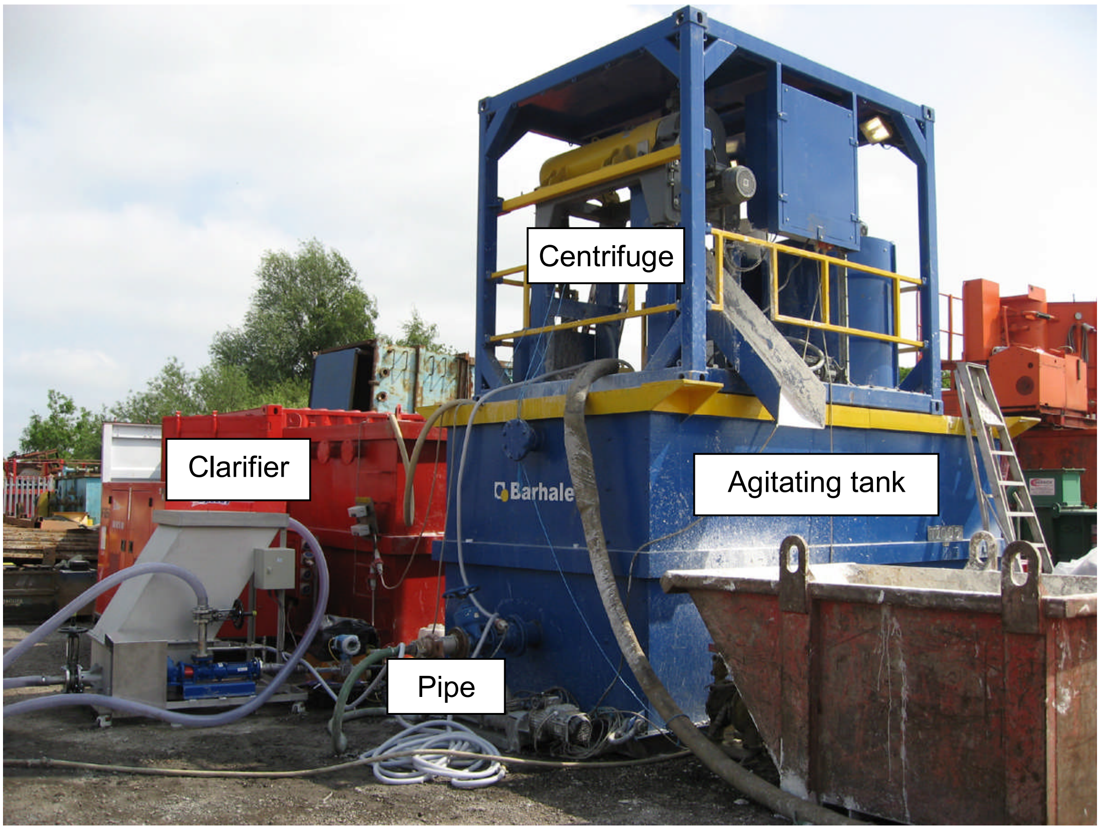


Figure 6- 15 The field scale test separation plant

6.3.3 Field scale test results

6.3.3.1 The effect of slurry flow rate on the behaviour of the cake produced by the centrifuge

The following experiments were undertaken to understand the effect of slurry flow rate, polymer and centrifuge force on slurry dewatering behaviour. The water content of the cake and the turbidity of the centrate were used as indications of that behaviour. Slurries of different densities were mixed with various polymers then pumped into a decanting centrifuge running at 2500G centrifugal force. The conveyor screw continuously conveyed the cake (solid) to the solids discharge port, whilst the centrate (liquid) was continuously discharged in the opposite direction. The aim was to obtain a centrate which did not contain polymer; that is the slurry was not over flocculated. An approximate way to identify over flocculation is by adding centrate into a jar of slurry. If solids settle rapidly then the centrate is over flocculated. The polymer dose was adjusted and the centrate observed to prevent over flocculant under the various slurry flow rates.

The effects of the slurry flow rate and polymer (TK50) dose on the water content of cake are shown in Figure 6- 16. The water content of the cake decreased as the slurry flow rate increased. However, the polymer dose was also reduced at the same time in order to keep the centrate clean. The test was intended to model practice in which the control is the quality of the centrate. It should be noted that the polymer dose exceeded that used in the laboratory. The fact that the water content reduced as the flow rate increased is because the percentage of the flocculant used in slurry is reduced. However, Figure 6- 17 shows that the turbidity of the centrate increased as the slurry flow rate increased, which implies the amount of solids reduced as the flow rate increased.

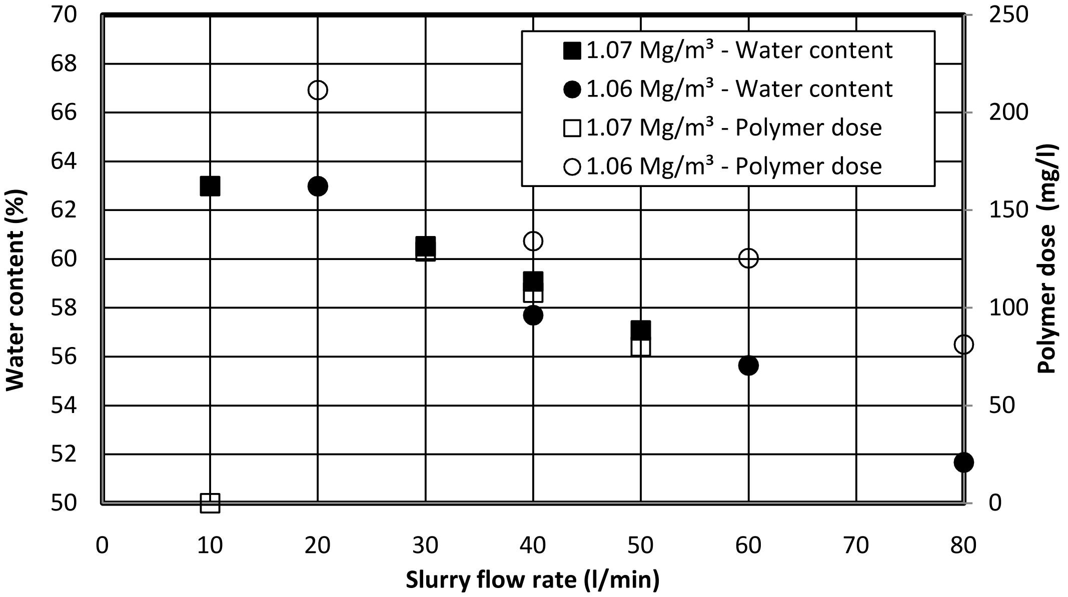


Figure 6- 16 The relationship between slurry flow rate, polymer dose and water content of cakes at 2500G centrifugal force

The effects of the slurry flow rate on turbidity of centrate are shown in Figure 6- 17. The turbidity increased as the slurry flow rate increased. The turbidity also increased as the slurry density increased. For example, the turbidity was up to 1000 NTU if the slurry density was 1.10 Mg/m^3 but the turbidity was around 200 NTU for a slurry density of around 1.06 Mg/m^3 under the same slurry flow rate (40 l/min). In addition, the turbidity was up to 1000 NTU if the slurry flow rate was 60 l/min but the turbidity was around 200 NTU when the slurry flow rate was 40 l/min under the same slurry density (1.06 Mg/m^3). This implies the turbidity is dependent on the quantity of particles passing though the centrifuge. In this study, the turbidity dramatically increased if the flow rate was above 40 litre/min. This could be because the decanting centrifuge is designed with a limited capacity for solid treatment. As mention in section 2.2.2.2, there is a weir inside the decanting centrifuge. When the flow rate or volume of input slurry is above the capacity of the centrifuge, the outflow will contain more solids. Hence, little or no clean water is produced during the centrifuge treatment. Therefore, a throughput (allowable flow rate) of 40 litre/min of slurry flow rate was maintained in this study.

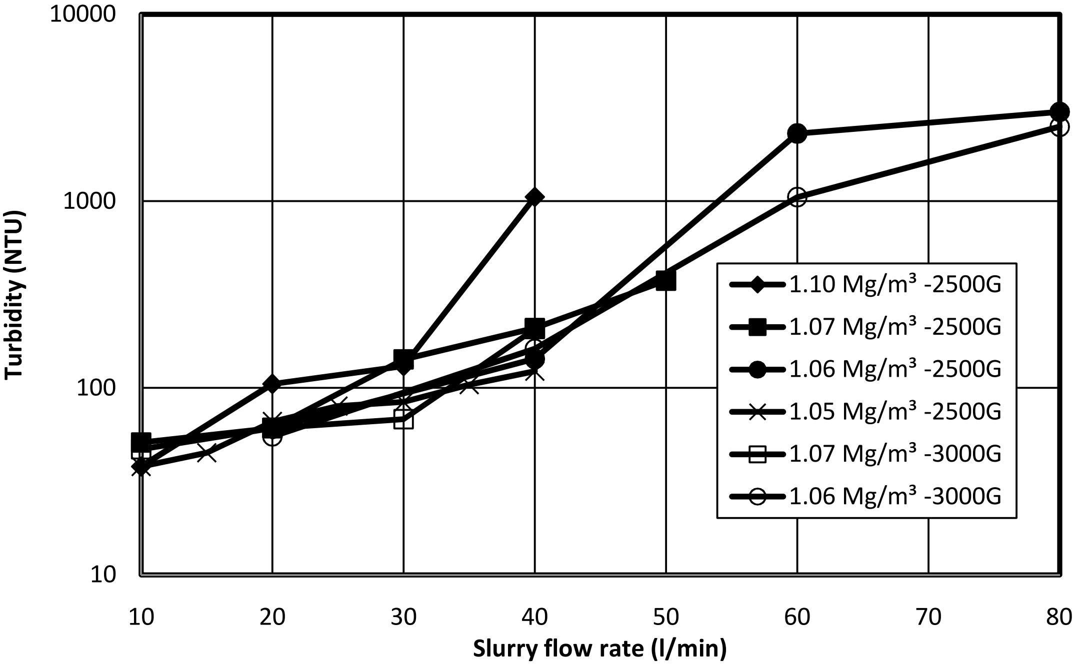


Figure 6- 17 The relationship between slurry flow rate and turbidity of centrate

The time t (mins) required in theory for sedimentation in a centrifuge and the throughput Q (m^3/s) in theory can be found from Equations (2- 3) and (2- 7) in section 2.2.2.2.

$$t = \frac{18\eta}{d^2 w^2(\rho_s - \rho)} \times 1000 \times \ln\frac{R}{r_0} \tag{2- 3}$$

$$Q = \frac{V_L}{t_R} = \frac{d^2 w^2(\rho_s - \rho)R}{18\eta h}\pi(R^2 - r_0^2)\, L_c \times 1000 \tag{2- 10}$$

where d is particle diameter (m), ω is the angular velocity (rad/s), ρ_s is density of solids (Mg/m^3), ρ is density of fluid (Mg/m^3), R is the radius of rotation (m), L_c is length of centrifuge bowl (m), η is dynamic viscosity of the fluid (Pa·s), h is the thickness of the liquid layer at the walls and r_0 (=R-h) is the radius of initial liquid.

The throughput obtained from the field scale test was 40 litre/min. Using data obtained from the field scale tests (Table 6- 1) in Equations (2- 3) and (2-10); the maximum particle size was theoretically 8 μm and the time required 1 minute. However, the size of floc was about 1 mm before passing through the centrifuge. This means the size of floc decreased after passing through the centrifuge. Caron-Charles and Gozlan (1996) showed similar results: particle size of flocs reduce after a 2012G centrifugal force is applied. This is because the flocs break up with the higher speed centrifuges (Records and Sutherland, 2001).

Table 6- 1 The controlled parameters for the field centrifuge tests

angular velocity (ω)	4220 rpm (2500G)
density of solids (ρs)	2.65 Mg/m^3
density of fluid (ρ)	1.07 Mg/m^3
radius of rotation (R)	130 mm
length of centrifuge bowl (L)	1 m
viscosity of the fluid (η)	4×10^{-3} Pa·s
thickness of the liquid layer at the walls (h)	Assuming 65 mm

Figure 6- 18 shows the relationship between theory and field scale test throughput and slurry density. The theory is described in section 2.2.2.2. The throughput decreases with an increasing density. In the field scale test the densities were 1.06 and 1.1 Mg/m^3 and to maintain a clean centrate at a centrifugal force of 2500G the flow rate was 30 and 40 litres/min.

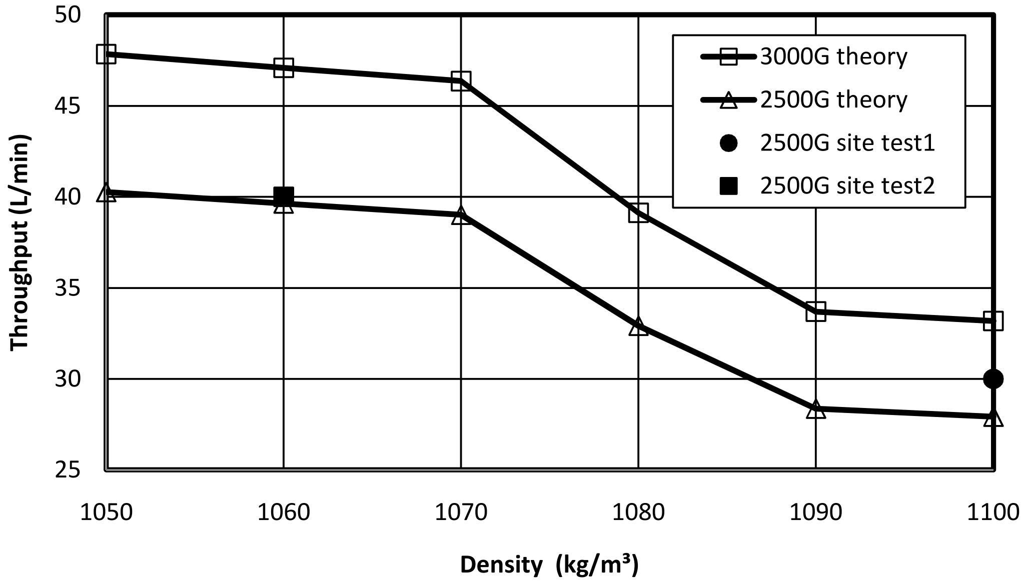


Figure 6- 18 The relationship between theoretical and experimental throughput and slurry density

Table 6- 2 shows the theoretical effect of particle size and density on throughput and sedimentation time. The throughput increases with particle size and increasing centrifugal force. The time required for sedimentation in a centrifuge decreases with particle size and increasing centrifugal force.

The effects of the addition of polymer on water content are shown in Figure 6- 19. The water content of the cake decreased if a small amount of polymer was added. However, further increases in polymer content increased the water content of the cake. Even though the water content increased the cake appeared to be dryer, which is consistent with the findings of the liquid limit test; that is the strength of the cake increased because of the increase in the polymer content not because the cake was dryer. Increasing the centrifuge force from 2500G to 3000G lowered the water content of the cake by 5% on average.

Table 6- 2 The theoretical effect of particle size and density on throughput and sedimentation time

Centrifugal force (g)	Angular velocity (rpm)	Density (Mg/m^3)	particle size (μm)	Throughput (litres/min)	Time required (mins)
2500	4220	1.07	2	2.6	15
2500	4220	1.07	8	40	1
3000	4600	1.07	8	50	0.8

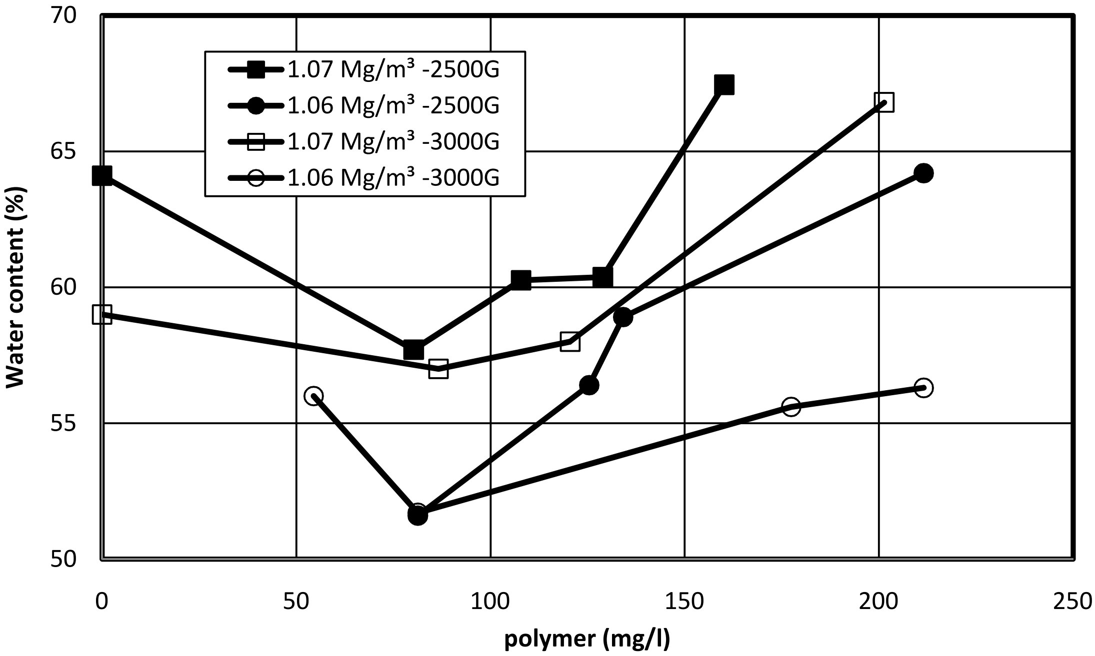


Figure 6- 19 The relationship between polymer dose and water content of cakes

A further test (slurry density was 1.06 Mg/m^3) was undertaken to understand the effects of another polymer (VP1, powder form) on the turbidity of the centrate and water content of cakes (Figure 6- 20). Increasing the polymer dose can decrease the turbidity but lead to high water content. This means there is an optimum polymer dose to balance the water content of the cake and the clarity of the centrate.

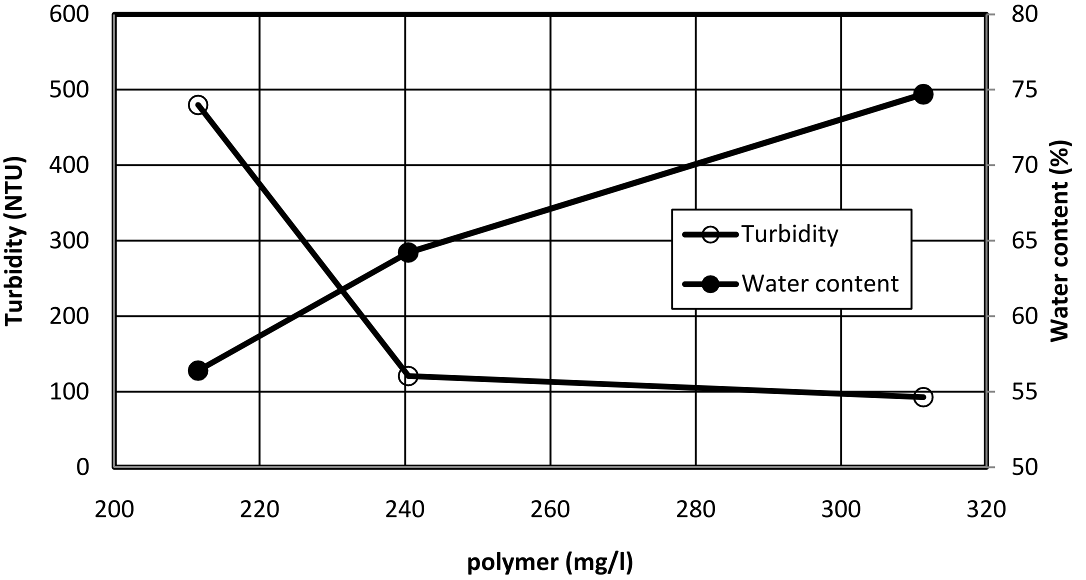


Figure 6- 20 The relationship between polymer dose, turbidity of centrate and water content of cakes

6.3.3.2 The effect of slurry flow rate on cake behaviour after the clarifier and centrifuge

The following experiment was undertaken to understand the effects of the clarifier on slurry dewatering behaviour. The density of the sludge (from the settling tank of the clarifier), the turbidity of supernatant (from outflow of the clarifier), the water content of the cake and the turbidity of centrate were measured. In this study, slurry (density = 1.05 Mg/m^3) was mixed with polymer (VP1) then pumped into the clarifier. The supernatant flowed upward to the top of the clarifier and the flocs accumulated in the bottom of the clarifier to form sludge. The sludge was pumped continuously into a decanting centrifuge to further dewater the sludge. The slurry flow rate was fixed at 36 litre/min, which is lower than the throughput of 40 litre/min which was found from the throughput test in section 6.3.3.1. The sludge production rate was around 50% from the laboratory test results in chapter 5. Therefore, flow rates of the supernatant and centrifuge feed rate were set at 40% and 60% respectively. Thus, the centrifuge feeding rate and supernatant discharge rate were fixed at 21.6 (60% of input) and 14.4 (40% of input) litre/min, respectively.

The effects of polymer on the water content of the cake and density of sludge are shown in Figure 6- 21. The densities of the sludge increased with increasing polymer content. This means the solids content of the sludge was increased when polymer was added. The water content of the cake was affected by the polymer content but it appears that it reached a constant value.

The effects of polymer dose on turbidity of the supernatant and centrate are shown in Figure 6- 22. The turbidity of the supernatant decreased with increase in polymer dose. However, the turbidity of the centrate decreased with the polymer dose at first and then increased when the polymer dose exceeded 12 mg/l. This implies there is an optimum polymer dose that will ensure a clarity supernatant and not result in increasing turbidity of the centrate. Moreover, the supernatant was over flocculated (observed from site test) when the polymer dose was above 13 mg/l. Therefore, in this study the optimum polymer dose was between 10 to 13 mg/l. It is not necessary to remove all the fines completely from the slurry. A certain proportion of suspended matter in the slurry is needed to provide a supporting function in the slurry used to transport the excavated material from the tunnel face (Maidl et al., 1996). Thus, the centrate and supernatant can be returned to the slurry tank although even there are some fines present.

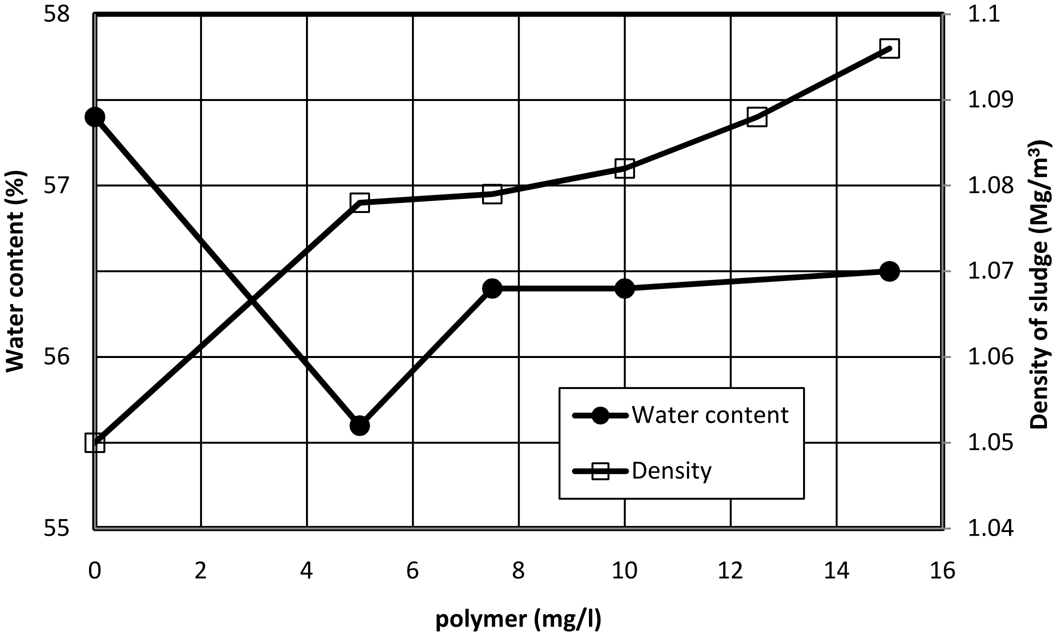


Figure 6- 21 The relationship between polymer dose, the water content of cake and the density of sludge

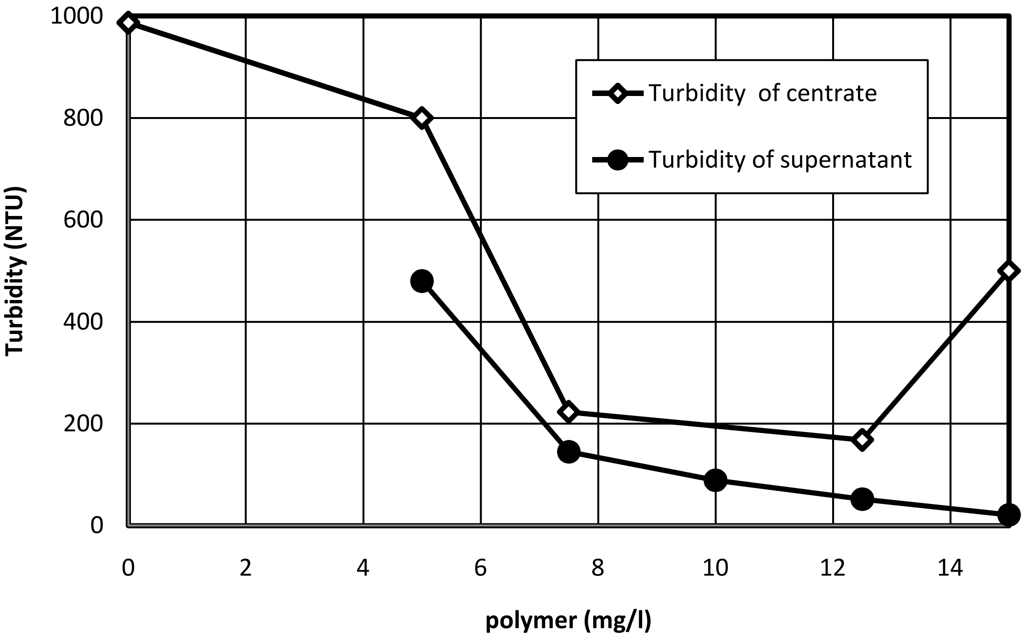


Figure 6- 22 The relationship between polymer dose and the turbidity of supernatant and centrate

6.3.4 Discussion

From the field scale test results, a throughput slurry flow rate of 40 litre/min has been identified (refer to section 6.3.3.1). If the slurry flow rate was above this point, the turbidity of centrate increased significantly.

Results also show that the water content of cake was affected by the addition of polymer. Decreasing the polymer doses resulted in a decrease in the water content but caused an increase in the turbidity of the centrate. Therefore, there is an optimum polymer dose to balance the water content of cake and ensure clarity of centrate.

Introducing a clarifier prior to the centrifuge will require much less polymer for separation than without a clarifier. Solids accumulated in the bottom of the clarifier and a clarified supernatant was drawn from the clarifier. The accumulated solids (sludge) were pumped into the centrifuge. It was observed that the water content of cake was considerably lower when the clarifier was built-in to the treatment process than when it was not. The turbidity of the centrate initially decreased when polymer was added and then increased when the polymer exceeded a certain amount. This could be because increasing the amount of polymer resulted in an increase in density (Figure 6- 21) of the sludge in the clarifier which is subsequently fed into the centrifuge. This means the solid concentration from the feed exceeds the capacity of the centrifuge.

Table 6- 3 shows a comparison between the properties of the cake and centrate from the centrifuge and clarifier. The water contents of cakes through the clarifier were less than those passing directly to the centrifuge. This was because more polymer was required to achieve the same quality of centrifuge centrate. Increasing the polymer content increased the water content. Both the centrate and supernatant did not pass the standard for drinking water but could be discharged to a sewer if they do not contain settling particles. For the process involving the clarifier, only 60% of the total volume of the slurry was sent to the centrifuge where all the slurry was sent to the centrifuge for treatment if there was no clarifier present. This means a clarifier will reduce the energy consumption of a centrifuge, though there may

be some offset because of the additional energy required to pump the sludge from the clarifier to the centrifuge.

The reduction in water content equals about £16 landfill tax per pipe for a pipe diameter of 1.8 metre and 2.5 metre long. However, the cake produced includes polymer, and it is possible that the regulation will include polymer as an active waste in the future, hence the charging rate on the landfill tax. This will increase the cost to £43 per pipe which on a type project of detail as Table 6- 4.

The benefits of using a clarifier in the pipe jacking solid-liquid separation process are:

- Reducing the amount of water left in the cake
- Reducing the cost of transporting to landfill since the volume of water is reduced.
- Reducing the amount of flocculant needed to separate out the solids

Table 6- 3 Comparing the dewatering behaviour of the two different separation processes

	Centrifuge	Clarifier + Centrifuge
Water content of cake (%)	61-67	55-58
Turbidity of centrate (NTU)	100-180	170-220
Turbidity of supernatant (NTU)	-	20-50
Volume of feeding to centrifuge	100%	60%
Polymer dose (mg/l)	90-150	5-15

Table 6- 4 The financial benefits of using a clarifier in the pipe jacking solid-liquid separation process

	Per pipe (2.5 metre)	Typical pipe jacking lengths per project (100 metre)	Maximum pipe jacking lengths between shafts (>500 metre)
(A) Water content reduction	10%	10%	10%
(B) The quantity of cake produced (tonnes)	6	240	1200
(C) Landfill tax at lower rate by 2010 (£/tonne)	2.5	2.5	2.5
(D) Landfill tax at standard rate by 2010 (£/tonne)	48	48	48
(E) Flocculant cost	£80/25kg	£80/25kg	£80/25kg
(F) Flocculant consumption by kg (5kg/per pipe)	5	200	1000
(G) Flocculant consumption reduction	90%	90%	90%
(H1) Cost benefit (pounds) H1=A×B×C + E×F×G by lower rate landfill tax	15.9	636	3180
(H2) Cost benefit (pounds) H2=A×B×D + E×F×G by standard rate landfill tax	43.2	1728	8640

6.4 Modelling of the effect of centrifuge operation on density of slurry

In this section, the effect of the pipe jacking operation (centrifuge feeding rate, slurry flow rate, time for setup a new pipe and time for pushing a pipe) on the change in density of slurry are discussed. However, it is not easy to monitor the effect of the centrifuge on the density of slurry in a pipe jacking field test. This is due to uncertainties surrounding the pipe jacking operation, e.g. varying operating parameters due to variation in the ground conditions. In order to perform the excavation field test, the slurry flow rate and centrifuge rate have to be controlled in order to monitor the effect of centrifuge on the density of slurry during the pipe jacking operation. However, this is extremely difficult on site, as the ground conditions vary and the pipe jacking parameters change depending on these conditions. Carrying out a field test to determine the effect of the control parameters on the performance of the solids separation process is not feasible because it could cause a failure in the pipe jacking process. Therefore, the operation was simulated to understand the effect of centrifuge operation on the change in density of the slurry.

The analysis was based on two conditions: with a centrifuge and without a centrifuge. The simulation starts from the initial slurry condition in the slurry tank before excavation, i.e. the condition of the slurry prepared ready for the start of the pipe jacking process. The pipe jacking excavation removes the gravel, sand and clay from the ground. The gravel and sand are removed from the slurry by the screens and hydrocyclones in the separation plant. The clay accumulates in the slurry tank. An offline centrifuge is used to remove fine particles from the slurry and the centrate is sent back to the slurry tank. Polymer is added in the centrifuge line to facilitate the removal of the fine particles by creating flocs. Cake is produced by the centrifuge. It has been assumed that all the gravel and sand are removed by the screens and hydrocyclones, slurry is pumped at a fixed rate and the quantity of polymer is so small that it can be ignored when considering the weight of the slurry. The detailed calculations are presented in Appendix VI.

The flow rate to the centrifuge is different from the flow rate of the slurry in the pipe jacking system because the centrifuge is operated offline. However, in practice the slurry flow rate varies with the ground conditions, rate of excavation, size of slurry pipes and slurry composition. The centrifuge rate depends on the size of centrifuge, number of centrifuges and weight of slurry because of the efficiency of centrifuge and the condition of the slurry (e.g. density, composition).

The variation of slurry density was simulated using data from a typical pipe jacking site. A Herrenknecht AVN 1800 pipe jacking machine was used in this simulation. The assumed parameters for the AVN 1800 pipe jacking process are listed in Table 6- 5. A standard twenty-foot shipping container is commonly use as slurry tank on a pipe jacking site. The full volume is 39 m³ but it is assumed that the taken operates at 80% capacity, 31 m³. The initial slurry density is 1010 kg/m³. The slurry flow rate is 180 m³/hr for jacking 1.8 metre diameter pipes.

The model simulated the density of slurry based on every slurry cycle. Time of jacking a 2.5 metre long pipe is 2 hours. 70% of the excavated ground, rock and sand, is removed by the screens and hydrocyclones. The density of the centrifuge cake is, on average, 1500 kg/m³ from the results of site investigations. Centrifuge cake production rate was about 2 m³ per hour and the water content of the centrifuge cake is 70% taken from average of the measurements on site. The centrifuge feeding rate was typically between 5-

70 m³/hr. The time for setting up a new pipe is half an hour; the centrifuge continues to work during this time.

Table 6- 5 Assumed parameters for the simulation of pipe jacking process

Volume of slurry tank	31	m^3
Density of initial slurry	1.01	Mg/m^3
Dimension	1.8	m^3
Length of pipe	2.5	m
Volume of excavation soil per pipe	6.36	m^3
Bulk density of soil	2.50	Mg/m^3
Cyclic slurry flow rate	120-180	m^3/hr
Time of finishing one pipe	2	hrs
Screen spoil produce rate	70	%
Density of rock and sand	2.60	Mg/m^3
Density of centrifuged cake	1.50	Mg/m^3
Centrifuge cake produce rate	0.2-2	m^3/hr
Water content of centrifuged cake	70	%
The centrifuge rate	5-70	m^3/hr
Time for setup new pipe	0.5	hr

Using these typical settings, the variation of slurry density is shown in Figure 6- 23. From the simulation (slurry rate fixed at 180 m³/hr), increasing the centrifuge rate reduced the rate of the increase in density. This means increasing the centrifuge rate can control the density. The steps presented in Figure 6- 23 were due to the setting up time for the next pipe, where the centrifuge was still operating. The effect of the slurry flow rate through the pipe jacking system on the density of slurry (centrifuge rate fixed at 40 m³/hr) from the simulation is shown in Figure 6- 24. Increasing the slurry flow rate does not affect the density of the cake. This is because the slurry flow rate does not affect the excavation production rate in this simulation. The effect of time for setting up a new pipe on the density of slurry (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr) is shown in Figure 6- 25. The effect of the time for pushing one pipe on the density of slurry (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr) is shown in Figure 6- 26. Increasing the time for setting up a new pipe and the time for pushing one pipe reduced the rate of the increase in density. This is because there is more time for separating during the process. The effect of these parameters on slurry density is summarized in Table 6- 6.

Table 6- 6 The effect of these parameters on slurry density

Parameters	Density increasing trend
Centrifuge rate	Inverse ratio
Slurry flow rate	No effect
Time for setup new pipe	Inverse ratio
Time of pushing one pipe	Inverse ratio

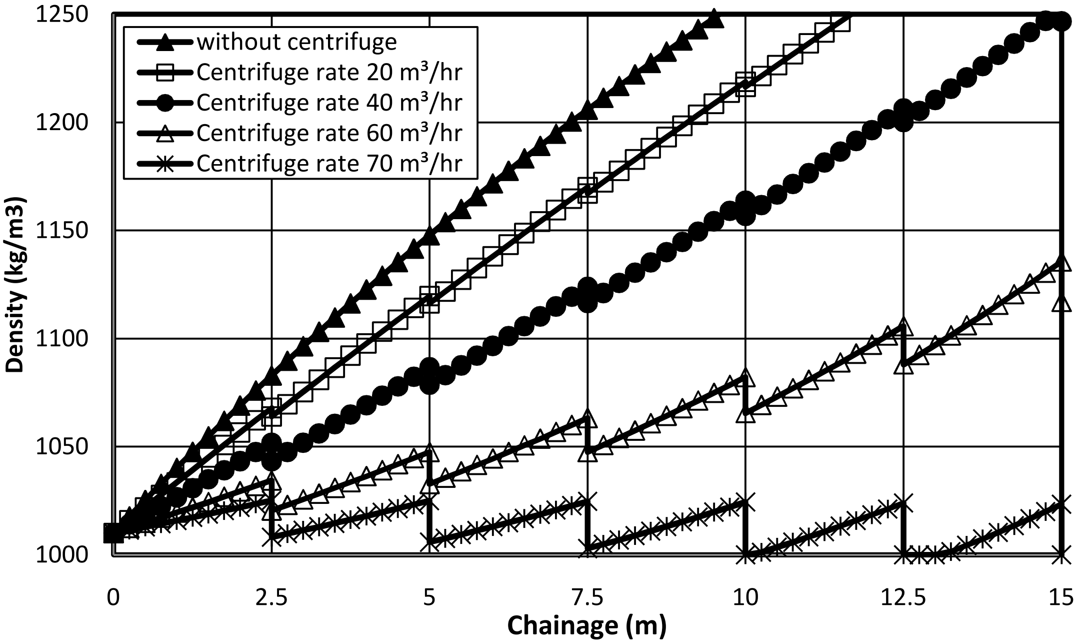


Figure 6- 23 The effect of centrifuge rate on density of slurry from simulation (slurry rate at 180 m³/hr)

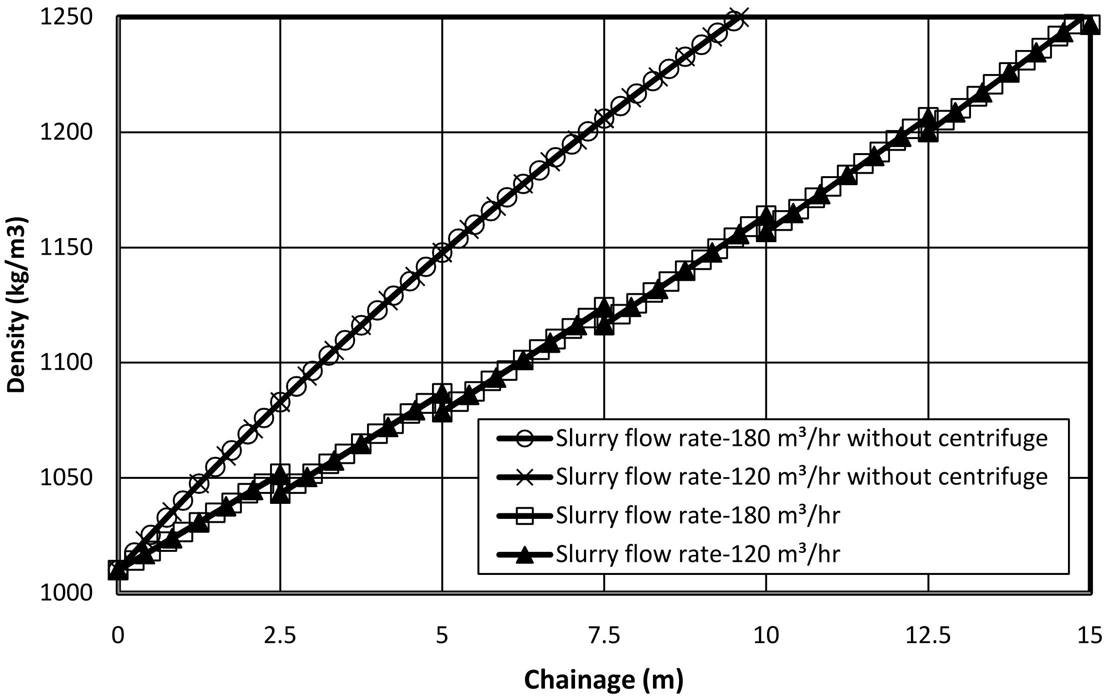


Figure 6- 24 The effect of slurry flow rate on density of slurry from simulation (centrifuge rate at 40 m³/hr)

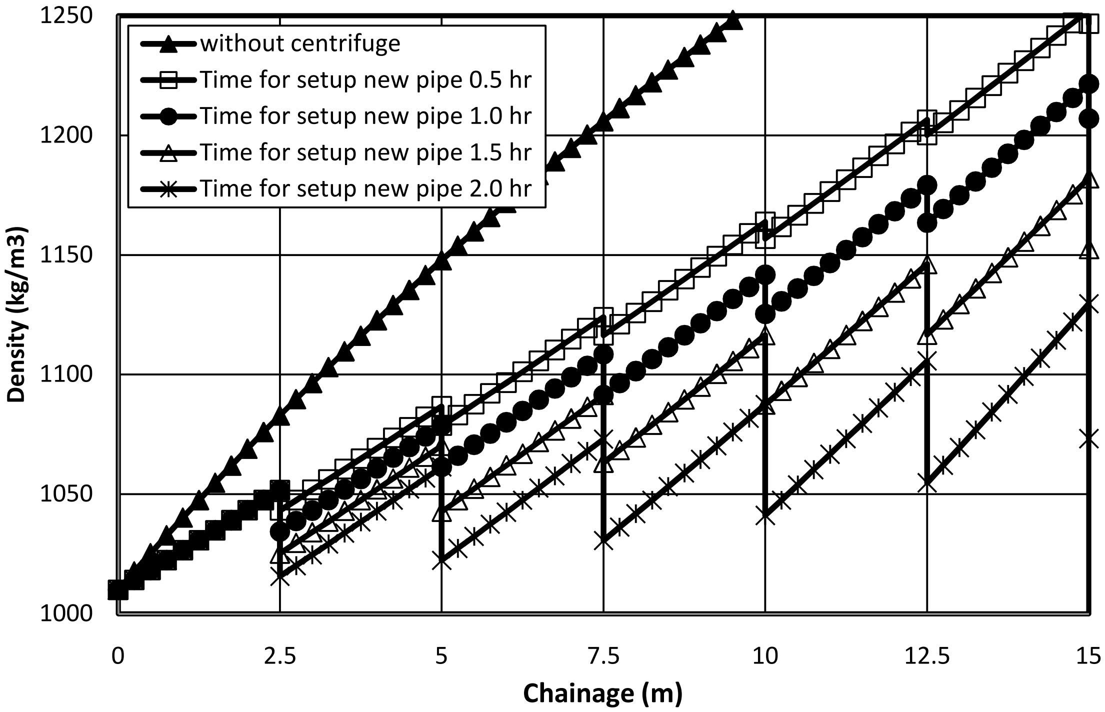


Figure 6- 25 The effect of time for setup new pipe on density of slurry from simulation (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr)

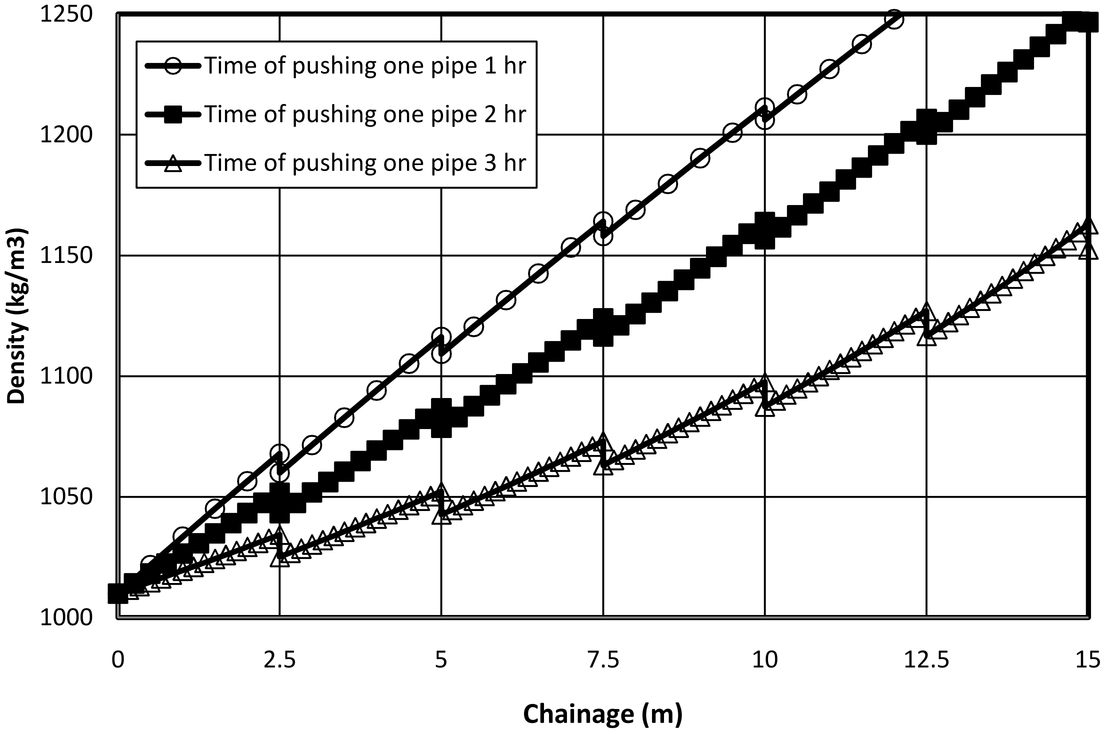


Figure 6- 26 The effect of time of pushing one pipe on density of slurry from simulation (slurry rate at 180 m³/hr and centrifuge rate at 40 m³/hr)

6.5 Discussion

The water contents of the cake produced by the centrifuge with or without a clarifier are shown in Figure 6- 27. The liquid limit is used as the criteria to decide whether the cake is a solid or liquid. The laboratory test shows that the addition of polymer increases the liquid limit. The graph indicates that increasing the density of slurry results in a lower water content of the cake. This is probably due to solid particles with higher density being captured by the polymer, resulting in the lower water content. The laboratory tests show that increasing the centrifuge speed reduces the water content. Introducing a clarifier inline reduces the water content, which is closer to the liquid limit for the laboratory soil.

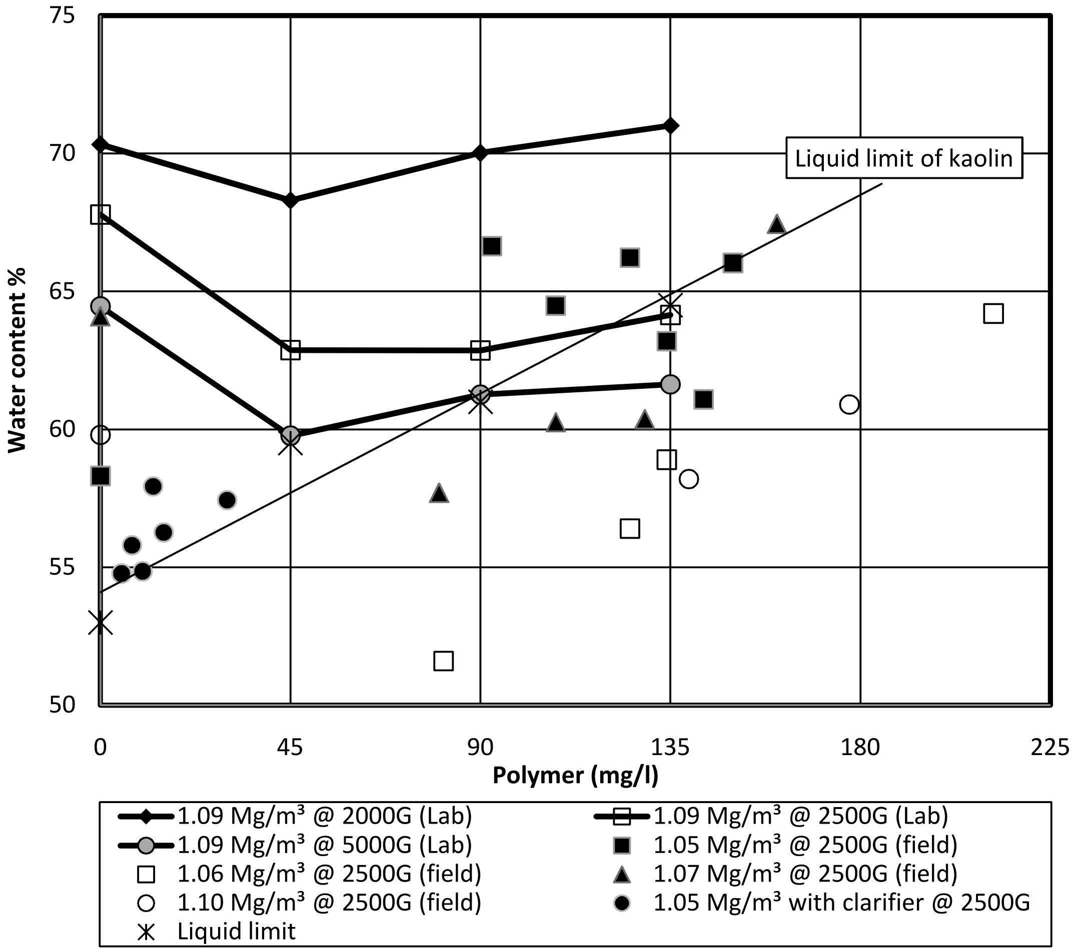


Figure 6- 27 The relationship between polymer dose and water content of cakes from laboratory and field scale tests

6.6 Conclusion

Adding polymer increased the liquid limit and the water content in both laboratory and field scale tests. The water content decreased with increasing centrifugal force in both laboratory and field scale tests. The water content decreased with increasing centrifugal time within the centrifuge in the laboratory tests. When the centrifugal force exceeds 2000G the water content of the cake may be lower than its liquid limit in both laboratory and field scale tests using laboratory soil.

When a clarifier was introduced with a centrifuge, the benefits of the clarifier are:

1. Reduces the amount of polymer needed for flocculation;
2. Reduces the water content of the cake;
3. Reduces the quantity of slurry fed to the centrifuge;
4. Reduces water input into the slurry tank;
5. Reduce the cost of cake disposal to landfill.

When a clarifier was introduced with a centrifuge, the disadvantages of a clarifier are:

1. The water content of the cake may be above the liquid limit;
2. Time consuming for the uncertain result: to deal with the constant change of the ground condition, the operating condition varies. Any change to the condition of the clarifier inlet, waiting time is required for the outcome. However, this waiting time does not guarantee the correct outlet condition (non over-flocculation).

There is an optimum polymer dose for minimising the water content of cakes and ensuring the supernatant and centrate are not over-flocculated. Centrate and supernatant can be returned to the slurry tank to help maintain the water volume.

Chapter 7 Summary and conclusions

7.1 Summary

The major aim of this research was to improve upon the current waste treatment from the pipe jacking industry to comply with the new EU regulations. The research undertaken has covered the following aspects and applications of waste management in the pipe jacking industry.

- A detailed review of the appropriate literature relating to the pipe jacking process, European/UK legislation and solid-liquid separation methods covering:
    - ✓ The role of slurry in the pipe jacking process.
    - ✓ Waste products of the pipe jacking process and their disposal.
    - ✓ EU/UK legislation requirements for the waste produced from pipe jacking.

- Characterization of waste products from the pipe jacking process
    - ✓ Waste products from the pipe jacking process tested to determine whether they are non-hazardous or hazardous waste.
    - ✓ Sedimentation tests on trial and field samples to understand the separation process.

- Determination of solid concentration of slurry by turbidity
    - ✓ The relationship between solids concentration and turbidity.
    - ✓ The effects of solids on the turbidity measurement.

- The effect of coagulant and flocculant on slurry sedimentation
    - ✓ The effects of different additives on slurry sedimentation behaviour.
    - ✓ The effect of additives on different slurry sedimentation behaviour.

- The effect of centrifuge and clarifier on slurry dewatering behaviour
    - ✓ The development of a clarifier that may be used in the pipe jacking industry.
    - ✓ The effect of a centrifuge and clarifier on slurry solid-liquid separation.
    - ✓ The benefit of disposal cost and environmental impact.

7.2 Main conclusions

A number of conclusions with reference to the objectives have been drawn from the research.

- EU/UK legislation requirement on the waste produced from pipe jacking
    - ✓ Slurry is the main waste produced from the pipe jacking industry.
    - ✓ Slurry is a liquid waste. Liquid waste is not acceptable to landfill in the UK. It must be pre-treated to create a solid waste before being sent to landfill for final disposal.

  - ✓ The composition of any lubricating agent between pipes and ground during the tunnelling process need to be checked to prevent the pollution of groundwater caused by hazardous substances (see Appendix IV).

- Classification of slurry: non-hazardous or hazardous waste
  - ✓ Slurry is classified as a “Mirror entry” because it could be either hazardous or non-hazardous depending on the additives used in the slurry system.
  - ✓ The slurry produced from the pipe jacking process may not be classified as hazardous waste if the quantity of the additives introduced during the separation phase is controlled and within the acceptable limits in the relevant guidelines.

- Methods of treating slurry: non-hazardous solid waste or recyclable liquid
  - ✓ The decanting centrifuge seems to be the best option for slurry treatment in pipe jacking industry and is the preferred option.
  - ✓ The cake, the solid produced by the centrifuge, may not be acceptable to landfill as it may be classified as liquid waste.
  - ✓ Water contents of some cakes are greater than their liquid limit. This implies some cakes may be not acceptable to landfill.
  - ✓ Some of the residual water in a slurry tank or centrate may not be discharged directly as it exceeds EU urban wastewater effluent standards using the turbidity index.

  - ✓ The centrate can be returned to a slurry tank even it is unacceptable as liquid waste that could be simply disposed of.

- Improvement of current processes in order to reduce the amount of waste
  - ✓ The pre-treatment of slurry may improve the decanting centrifuge operation to produce dryer cake and clarified water which can be recycled in the slurry system.
  - ✓ Flocculation can reduce the settling time and increase the dry density of slurry by a bridging and binding action between particles thus promoting agglomeration.
  - ✓ Coagulant (alum or ferric salts) did not have an obvious effect on dry density of flocs, flocs production rate and turbidity of supernatant in most soils.
  - ✓ An optimum flocculant dose can produce acceptable levels of COD of the supernatant and a denser deposit.
  - ✓ The turbidity did reduce in some natural soils when the coagulant increased.
  - ✓ A minimum dose of polymer and a minimum mixing time were required to achieve the most beneficial effects on settling behaviour.
  - ✓ Adding a small amount of bentonite to natural slurry can lead to a reduction in dry density of flocs, flocs production rate and turbidity of supernatant.

- Determination of solid concentration of slurry by turbidity
  - ✓ There is a good relationship between turbidity and solid concentration for a given sample.
  - ✓ The turbidity increased with particle size or particle colour.
  - ✓ The turbidity is most effectively used for checking the change in density for a pure sample with known composition such as kaolin or bentonite.
  - ✓ If a slurry contains only one type of soil, good practice will be to use the attenuation method (FAU) to detect the turbidity of the slurry which can be related to the solid concentration using the turbidity- solid concentration trend line.
  - ✓ The clarity of the supernatant can be measured by the nephelometric method (NTU) to check the amount of solid concentration.

- Reduction of the disposal costs and environmental impact
  - ✓ The higher the water content of cake the higher the quantity (by weight) of waste needed to be disposed to a landfill. Since disposal cost and landfill tax depend on weight of waste, this will imply higher cost for waste management and disposal. The high volume of water in a cake disposed to landfill will also have possible negative impact on the environment due to leaching into the groundwater.
  - ✓ Adding polymer into the slurry separation process increased the liquid limit and the water content.

    - ✓ The water content decreased with increasing centrifugal force and centrifugal time.
    - ✓ When a certain centrifugal force was applied (above 2000G) the water content of cake may be lower than its' liquid limit.
    - ✓ The water content of cake is considerably lower when the clarifier is built-in in the treatment process than when it is not.
    - ✓ There is an optimum polymer dose for obtaining lower water content cakes and clarity of the supernatant and centrate.
    - ✓ Supernatant and centrate can be returned to the slurry tank to supply the water needed in the slurry system.

Following the research, new findings are shown as follow:

- Coagulant did not have an obvious effect on settling behaviour in most soils.
- Adding polymer to soils increased the liquid limit and the water content.
- The benefits gained if a clarifier is introduced in slurry separation:
    - ✓ Reduces the amount of polymer needed for flocculation.
    - ✓ Reduces the water content of cake.
    - ✓ Reduces the quantity of slurry fed to the centrifuge.
    - ✓ Reduces water supply in the slurry tank, due to the reduction in water content of the cake where less water has been extracted from the slurry tank.
- The problems encountered with the clarifier:
    - ✓ The water content of a cake may be still above the liquid limit.

- ✓ There is lots of uncertainty involving the retention time duration for flocculation to take place.

7.3 Recommendations and suggestions for further work

Several recommendations and need for further research are summarised:

- Recommendations
    - ✓ Pipe jacking industry
        - ➢ Natural additives have less environmental impact than chemicals used in pipe lubrication and flocculation in a centrifuge. It is suggested that this is employed in the pipe jacking process.
        - ➢ A clarifier may be employed in slurry separation to gain environmental benefit and disposal cost reduction.

    - ✓ Environment agency
        - ➢ There is a need to reassess the classification of solid/liquid waste for environmental impact assessment purposes. For example, using liquid limit as a criterion to identify solid or liquid waste, the cake from the centrifuge may be classified as solid waste even when it contains considerable higher water content. It is therefore suggested that solid/liquid waste are classified based on water content and not liquid limit.

    - ➢ The contents of additives using in pipe lubrication need to be checked to avoid groundwater contamination.

- Further research
    - ✓ There is a need to study the effect of natural additives on pipe lubrication and slurry separation in order to minimise the environmental impact of the chemicals currently used in the pipe jacking process.

    - ✓ The long-term effect of polymer on the water content of the cake needs to be studied. For example, the effect of changes in the water content of the cake during transit to landfill site and landfill processes need to be fully understood in order to quantify the behaviour of the cake in the long term.

Appendix

Appendix I

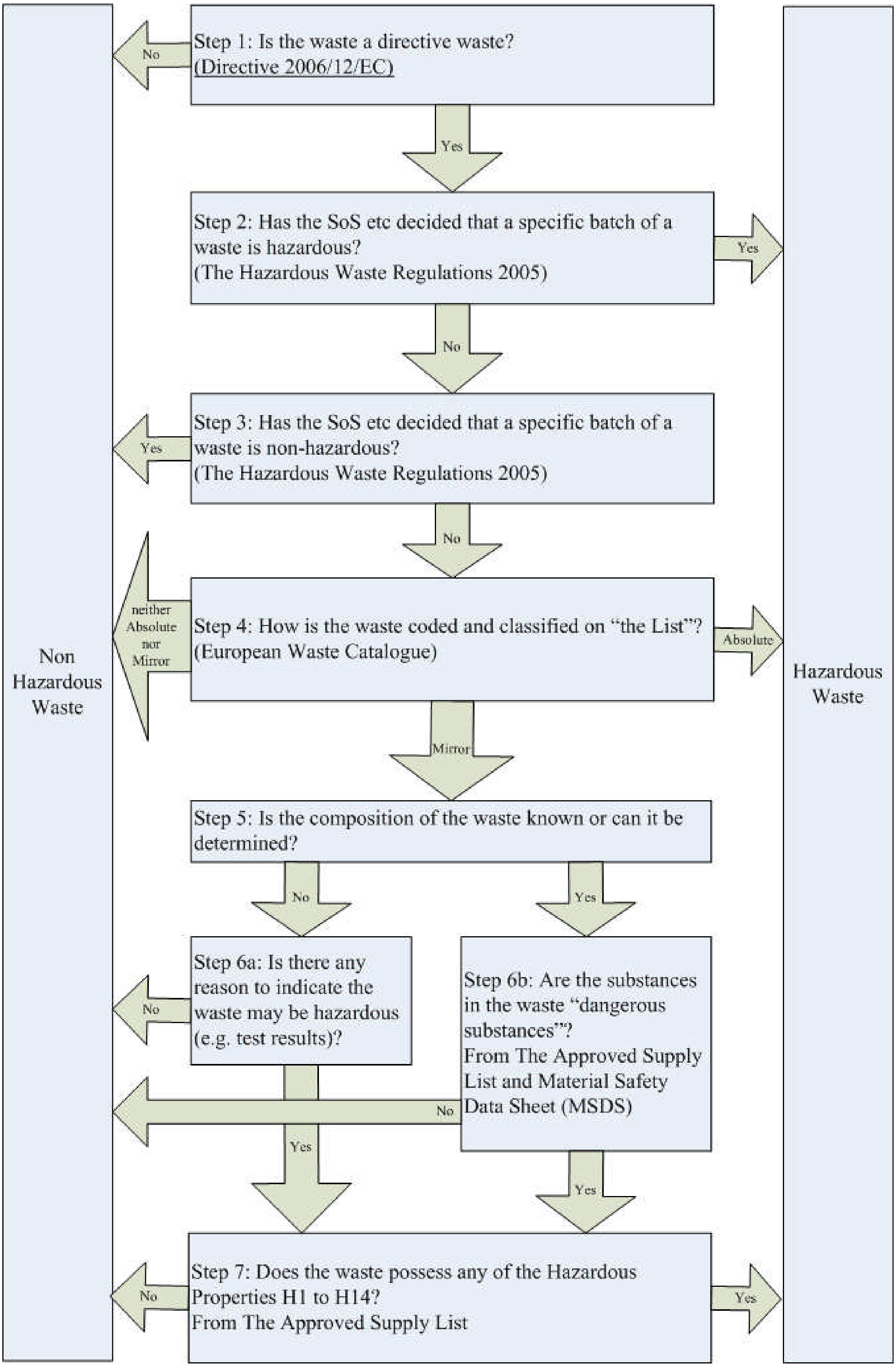


Figure A-1 Hazardous Waste Assessment Methodology (Modified from UK Environment Agency, 2008)

The flowchart in Figure A-1 shows the steps involved in finding out if waste is hazardous or not (EnvironmentAgency, 2008).

Step 1: Is the waste directive waste?

According to the Directive 2006/12/EC on Waste, nearly all household, commercial and industrial waste is directive waste. Some wastes are excluded from the scope of this directive, such as radioactive waste; waste waters, waste resulting from mining process, animal waste and decommissioned explosives etc.

Step 2: Has the SoS etc decided that a specific batch of a waste is hazardous?

The Hazardous Waste Regulations 2005 (HWR) allows the Secretary of State (SoS), the Welsh Assembly, Scottish Executive or Northern Ireland Department of the Environment to determine that a waste identified as non-hazardous on the List of Wastes should be a hazardous waste, because it possesses hazardous properties.

In England, the SoS have regard Annexes I, II and III (see Appendix II in this thesis) in the Hazardous Waste (England and Wales) Regulations 2005 and waste display any of the properties listed in Annex III (this properties listed is same as Annexes III in the Hazardous Waste (England and Wales) Regulations 2005) of Directive 91/689/EEC (Hazardous Waste Directive) as hazardous waste.

Step 3: Has the SoS etc decided that a specific batch of a waste is non-hazardous?

HWR allows the SoS to decide, in exceptional cases, that a specific batch of a waste that a specific batch of waste which does not display any of the properties listed in Annex III to the Hazardous Waste Directive, and is therefore non-hazardous waste.

Step 4: How is the waste coded and classified on “the List”?

The HWR define hazardous waste by referring to the List of Waste Regulations 2005 (LoWR). This list is also known as the European Waste Catalogue (EWC). Waste is listed in the EWC using a six-digit code together with a waste description. In this list, wastes are classified as “Absolute hazardous”, “Mirror entry” or “Non-hazardous” waste. If waste listed as “Mirror entry”, follow the Steps 5 to 7 below to finding out if waste is hazardous or not.

Step 5: Do you know what substances are in the waste?

In the majority of cases the business producing or storing a “mirror” entry waste should have enough information about the chemical substances in this waste to know if it is hazardous or not (e.g. from Material Safety Data Sheets, or knowing how the waste was produced). If lack of the above information the hazardous properties test will need to identify the property (see Step 6a).

Step 6a: Is there any reason to indicate the waste may be hazardous (e.g. test results)?

The hazardous properties test will be needed.

Step 6b: Are the substances in the waste “dangerous substances”?

According to the Approved Supply List (ASL) and Material Safety Data Sheets to identify if the substances in a “mirror” entry waste are dangerous. The risk phrases are used to set the levels that the dangerous substance must be present at in the waste for it to be classified as hazardous or not.

Step 7: Does the waste possess any of the Hazardous Properties H1 to H14?

Waste contains a dangerous substance(s) with a concentration at or above the appropriate threshold (The LoWR gives the thresholds) and/or a test shows a hazardous property will be classified as hazardous waste.

Appendix II

Hazardous waste list from Annexes I, II and III of the Hazardous Waste (England and Wales) Regulations 2005.

ANNEX I

ANNEX I.A. Wastes displaying any of the properties listed in Annex III and which consist of:

1. anatomical substances; hospital and other clinical wastes;
2. pharmaceuticals, medicines and veterinary compounds;
3. wood preservatives;
4. biocides and phyto-pharmaceutical substances;
5. residue from substances employed as solvents;
6. halogenated organic substances not employed as solvents excluding inert polymerized materials;
7. tempering salts containing cyanides;
8. mineral oils and oily substances (e.g. cutting sludges, etc.);
9. oil/water, hydrocarbon/water mixtures, emulsions;
10. substances containing PCBs and/or PCTs (e.g. dielectrics etc.);
11. tarry materials arising from refining, distillation and any pyrolytic treatment (e.g. still bottoms, etc.);
12. inks, dyes, pigments, paints, lacquers, varnishes;
13. resins, latex, plasticizers, glues/adhesives;
14. chemical substances arising from research and development or teaching activities which are not identified and/or are new and whose effects on man and/or the environment are not known (e.g. laboratory residues, etc.);
15. pyrotechnics and other explosive materials;
16. photographic chemicals and processing materials;
17. any material contaminated with any congener of polychlorinated dibenzofuran;
18. any material contaminated with any congener of polychlorinated dibenzo-pdioxin.

ANNEX I.B. Wastes which contain any of the constituents listed in Annex II and having any of the properties listed in Annex III and consisting of:

19. animal or vegetable soaps, fats, waxes;
20. non-halogenated organic substances not employed as solvents;
21. inorganic substances without metals or metal compounds;
22. ashes and/or cinders;
23. soil, sand, clay including dredging spoils;
24. non-cyanidic tempering salts;
25. metallic dust, powder;
26. spent catalyst materials;
27. liquids or sludges containing metals or metal compounds;

28. residue from pollution control operations (e.g. baghouse dusts, etc.) except (29), (30) and (33);
29. scrubber sludges;
30. sludges from water purification plants;
31. decarbonization residue;
32. ion-exchange column residue;
33. sewage sludges, untreated or unsuitable for use in agriculture;
34. residue from cleaning of tanks and/or equipment;
35. contaminated equipment;
36. contaminated containers (e.g. packaging, gas cylinders, etc.) whose contents included one or more of the constituents listed in Annex II;
37. batteries and other electrical cells;
38. vegetable oils;
39. materials resulting from selective waste collections from households and which exhibit any of the characteristics listed in Annex III;
40. any other wastes which contain any of the constituents listed in Annex II and any of the properties listed in Annex III.

ANNEX II. Wastes having as constituents:

C1. beryllium; beryllium compounds;
C2. vanadium compounds;
C3. chromium (VI) compounds;
C4. cobalt compounds;
C5. nickel compounds;
C6. copper compounds;
C7. zinc compounds;
C8. arsenic; arsenic compounds;
C9. selenium; selenium compounds;
C10. silver compounds;
C11. cadmium; cadmium compounds;
C12. tin compounds;
C13. antimony; antimony compounds;
C14. tellurium; tellurium compounds;
C15. barium compounds; excluding barium sulfate;
C16. mercury; mercury compounds;
C17. thallium; thallium compounds;
C18. lead; lead compounds;
C19. inorganic sulphides;
C20. inorganic fluorine compounds, excluding calcium fluoride;
C21. inorganic cyanides;

C22. the following alkaline or alkaline earth metals: lithium, sodium, potassium, calcium, magnesium in uncombined form;
C23. acidic solutions or acids in solid form;
C24. basic solutions or bases in solid form;
C25. asbestos (dust and fibres);
C26. phosphorus: phosphorus compounds, excluding mineral phosphates;
C27. metal carbonyls;
C28. peroxides;
C29. chlorates;
C30. perchlorates;
C31. azides;
C32. PCBs and/or PCTs;
C33. pharmaceutical or veterinary coumpounds;
C34. biocides and phyto-pharmaceutical substances (e.g. pesticides, etc.);
C35. infectious substances;
C36. creosotes;
C37. isocyanates; thiocyanates;
C38. organic cyanides (e.g. nitriles, etc.);
C39. phenols; phenol compounds;
C40. halogenated solvents;
C41. organic solvents, excluding halogenated solvents;
C42. organohalogen compounds, excluding inert polymerized materials and other substances referred to in this Annex;
C43. aromatic compounds; polycyclic and heterocyclic organic compounds;
C44. aliphatic amines;
C45. aromatic amines
C46. ethers;
C47. substances of an explosive character, excluding those listed elsewhere in this Annex;
C48. sulphur organic compounds;
C49. any congener of polychlorinated dibenzo-furan;
C50. any congener of polychlorinated dibenzo-p-dioxin;
C51. hydrocarbons and their oxygen; nitrogen and/or sulphur compounds nototherwise taken into account in this Annex.

ANNEX III: Properties of wastes which render them hazardous:

H1 ‘Explosive’: substances and preparations which may explode under the effect of flame or which are more sensitive to shocks or friction than dinitrobenzene.
H2 ‘Oxidizing’: substances and preparations which exhibit highly exothermic reactions when in contact with other substances, particularly flammable substances.
H3-A ‘Highly flammable’:

— liquid substances and preparations having a flash point below 21 ºC (including extremely flammable liquids), or

— substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy, or

— solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition, or

— gaseous substances and preparations which are flammable in air at normal pressure, or

— substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.

H3-B ‘Flammable’: liquid substances and preparations having a flash point equal to or greater than 21 ºC and less than or equal to 55 ºC.

H4 ‘Irritant’: non-corrosive substances and preparations which, through immediate, prolonged or repeated contact with the skin or mucous membrane, can cause inflammation.

H5 ‘harmful’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may involve limited health risks.

H6 ‘Toxic’: substances and preparations (including very toxic substances and preparations) which, if they are inhaled or ingested or if they penetrate the skin, may involve serious, acute or chronic health risks and even death.

H7 ‘Carcinogenic’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce cancer or increase its incidence.

H8 ‘Corrosive’: substances and preparations which may destroy living tissue on contacts.

H9 ‘Infectious’: substances containing viable micro-organisms or their toxins which are known or reliably believed to cause disease in man or other living organisms.

H10 ‘Teratogenic’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce non-hereditary congenital malformations or increase their incidence.

H11 ‘Mutagenic’: substances and preparations which, if they are inhaled or ingested or if they penetrate the skin, may induce hereditary genetic defects or increase their incidence.

H12 Substances and preparations which release toxic or very toxic gases in contact with water, air or an acid.

H13 Substances and preparations capable by any means, after disposal, of yielding another substance, e.g. a leachate, which possesses any of the characteristics listed above.

H14 ‘Ecotoxic’: substances and preparations which present or may present immediate or delayed risks for one or more sectors of the environment.

Appendix III

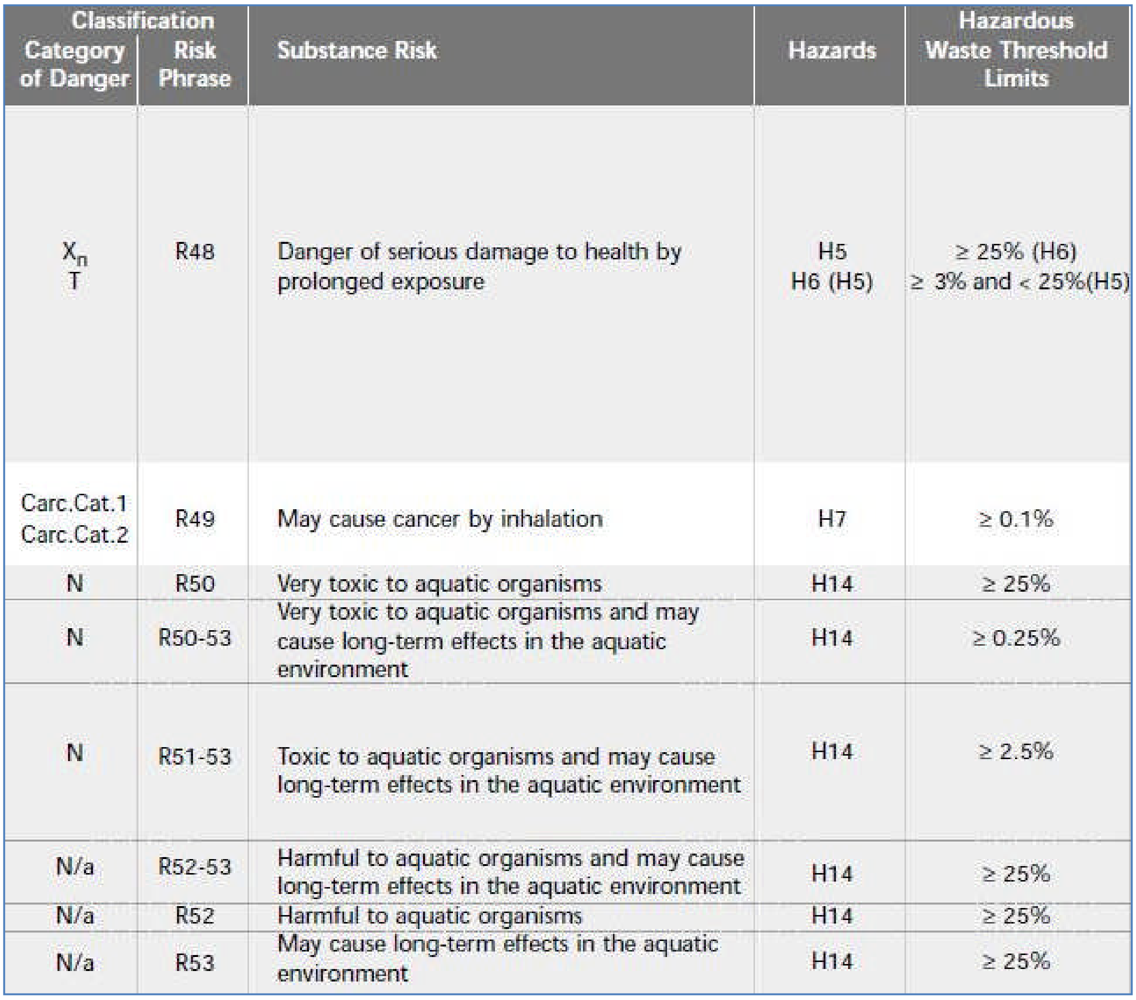
The concentration thresholds for each risk phrase or group of risk phrases are shown in the following table (EnvironmentAgency, 2008).

Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
E	R1	Explosive when dry	H13 by H1	n/a
E	R2	Risk of explosion by shock, friction, fire or other sources of ignition	H1	Test for explosive by ignition or shock
	R3	Extreme risk of explosion by shock, friction, fire or other sources of ignition		
N/a	R4	Forms very sensitive explosive metallic compounds	H13 by H1	n/a
	R5	Heating may cause an explosion		
	R6	Explosive with or without contact with air		
O	R7	May cause fire	H2	Test and/or calculation
	R8	Contact with combustible material may cause fire		
	R9	Explosive when mixed with combustible material		
N/a	R10	Flammable	H3B	Flashpoint: $>21^{\circ}$C to 55°C
F	R11	Highly flammable	H3A(i) (H3B) H3A(iii)	H3A(i) fpt $\leq 21^{\circ}$C H3A(iii) test
F+	R12	Extremely flammable	H3A(i) (H3B)	H3A(i) fpt $\leq 21^{\circ}$C H3A(iv) test

Classification Category of Danger	Risk Phrase	Substance Risk	Hazards	Hazardous Waste Threshold Limits
N/a	R14	Reacts violently with water	n/a	n/a
F	R15	Contact with water liberates extremely flammable gases	H3A(v)	Test and/or calculation
N/a	R16	Explosive when mixed with oxidising substances	H13 by H1	n/a
F	R17	Spontaneously flammable in air	H3A(ii)	Test
N/a	R18	In use may form flammable/explosive vapour–air mixture	H13 by H1 H2 or H3	n/a
	R19	May form explosive peroxides		
X_n	R20	Harmful by inhalation	H5	≥ 25%
	R21	Harmful in contact with skin		
	R22	Harmful if swallowed		
T	R23	Toxic by inhalation	H6 (H5)	≥ 3%
	R24	Toxic in contact with skin		
	R25	Toxic if swallowed		

Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
T+	R26	Very toxic by inhalation	H6 (H5)	≥ 0.1%
	R27	Very toxic in contact with skin		
	R28	Very toxic if swallowed		
N/a	R29	Contact with water liberates toxic gas	H12	Test and/or calculation
N/a	R30	Can become highly flammable in use	n/a	n/a
N/a	R31	Contact with acids liberates toxic gas	H12	Test and/or calculation
	R32	Contact with acids liberates very toxic gas		
N/a	R33	Danger of cumulative effects	n/a	n/a
C	R34	Causes burns	H8 (H4)	≥ 5%
C	R35	Causes severe burns	H8 (H4)	≥ 1%
X_i	R36	Irritating to the eyes	H4	≥ 20%
	R37	Irritating to the respiratory system		
	R38	Irritating to the skin		

Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
T T+	R39	Danger of very serious irreversible effects	H6 (H5)	≥ 3%(T) ≥ 0.1%(T+)
Carc.Cat.3	R40	Limited evidence of a carcinogenic effect	H7	≥ 1%
X_i	R41	Risk of serious damage to the eyes	H4	≥ 10%
X_n	R42	May cause sensitisation by inhalation	n/a	n/a
X_i	R43	May cause sensitisation by skin contact		
N/a	R44	Risk of explosion if heated under confinement	H13 by H1	n/a
Carc.Cat.1 Carc.Cat.2	R45	May cause cancer	H7	≥ 0.1%
Muta.Cat.1 Muta.Cat.2	R46	May cause heritable genetic damage	H11	≥ 0.1%



Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
X_n T	R48	Danger of serious damage to health by prolonged exposure	H5 H6 (H5)	≥ 25% (H6) ≥ 3% and < 25%(H5)
Carc.Cat.1 Carc.Cat.2	R49	May cause cancer by inhalation	H7	≥ 0.1%
N	R50	Very toxic to aquatic organisms	H14	≥ 25%
N	R50-53	Very toxic to aquatic organisms and may cause long-term effects in the aquatic environment	H14	≥ 0.25%
N	R51-53	Toxic to aquatic organisms and may cause long-term effects in the aquatic environment	H14	≥ 2.5%
N/a	R52-53	Harmful to aquatic organisms and may cause long-term effects in the aquatic environment	H14	≥ 25%
N/a	R52	Harmful to aquatic organisms	H14	≥ 25%
N/a	R53	May cause long-term effects in the aquatic environment	H14	≥ 25%

Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
N	R54	Toxic to flora	H14	Not available
	R55	Toxic to fauna		
	R56	Toxic to soil organisms		
	R57	Toxic to bees		
	R58	May cause long-term adverse effects in the environment		
N	R59	Dangerous for the ozone layer	H14	≥ 0.1%
Repr.Cat.1	R60	May impair fertility	H10	≥ 0.5%
Repr.Cat.2	R61	May cause harm to the unborn child		
Repr.Cat.3	R62	Possible risk of impaired fertility	H10	≥ 5%
	R63	Possible risk of harm to the unborn child		
N/a	R64	May cause harm to breast-fed babies	n/a	n/a
X_n	R65	Harmful: may cause lung damage if swallowed	H5	≥ 25%

Classification		Substance Risk	Hazards	Hazardous Waste Threshold Limits
Category of Danger	Risk Phrase			
N/a	R66	Repeated exposure may cause skin dryness or cracking	n/a	n/a
N/a	R67	Vapour may cause drowsiness and dizziness	n/a	n/a
Muta.Cat.3	R68	Possible risk of irreversible effects	H11	≥ 1% (H11)
X_n	R68	Possible risk of irreversible effects	H5	≥ 25% (H5)

Key

N/a	not applicable
H3A (i)	H3A (first indent) “Highly flammable”: - liquid substances and preparations having a flashpoint ≤ 21°C (including extremely flammable liquids).
H3A (ii)	H3A (second indent) “Highly flammable”: - substances and preparations which may become hot and finally catch fire in contact with air at ambient temperature without any application of energy.
H3A (iii)	H3A (third indent)“Highly flammable”: - solid substances and preparations which may readily catch fire after brief contact with a source of ignition and which continue to burn or to be consumed after removal of the source of ignition.
H3A (iv)	H3A (fourth indent) “Highly flammable”: - gaseous substances and preparations which are flammable in air at normal pressure.
H3A (v)	H3A (fifth indent)“Highly flammable”: - substances and preparations which, in contact with water or damp air, evolve highly flammable gases in dangerous quantities.

Appendix IV

The following substances should be prohibited or limited direct/indirect discharge to groundwater (Groundwater (England and Wales) Regulations 2009).

Hazardous substances are prevented into groundwater:

(1) A hazardous substance is any substance or group of substances that are toxic, persistent and liable to bio-accumulate.

(2) This includes in particular the following when they are toxic, persistent and liable to bio-accumulate—

  (a) organohalogen compounds and substances which may form such compounds in the aquatic environment;
  (b) organophosphorous compounds;
  (c) organotin compounds;
  (d) substances and preparations, or the breakdown products of such, which have been proved to possess carcinogenic or mutagenic properties or properties which may affect steroidogenic, thyroid, reproduction or other endocrine-related functions in or via the aquatic environment;
  (e) persistent hydrocarbons and persistent and bioaccumulable organic toxic substances;
  (f) cyanides;
  (g) metals (in particular cadmium and mercury) and their compounds;
  (h) arsenic and its compounds;
  (i) biocides and plant protection products.

(3) The Agency must publish a list of substances that it considers to be hazardous substances.

Any pollutant other than a hazardous substance is limited into groundwater.

Appendix V

Kaolin above 4000 FAU															
Equation from “500 < Kaolin < 4000”	Turbidity = 2519.5 × soil concentration - 161.48														
Data point	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Turbidity (FAU)=	72750	38800	21380	8060	4240	147550	50350	28500	12780	7510	4525	10780	154000	71575	71575
Soil concentration (g/l) =	27.38	14.93	7.83	2.93	1.55	54.39	18.52	10.44	4.59	2.68	1.73	4.65	56.64	25.44	25.29
Turbidity $_{estimate}$=	68830	37463	19570	7218	3742	136882	46505	26137	11400	6578	4203	11563	142548	63936	63556
Soil concentration $_{estimate}$=	28.94	15.46	8.55	3.26	1.75	58.63	20.05	11.38	5.14	3.04	1.86	4.34	61.19	28.47	28.47
Turbidity $_{mean}$ =	46958														
(Turbidity $_{mean}$ – Turbidity)^2	665210069	66558403	654251136	1513080336	1824856003	10118683403	11503403	340710069	1168158469	1556171003	1800587778	1308871803	11457918403	605980278	605980278
(Turbidity $_{estimate}$ – Turbidity)^2	15369047	1786465	3276713	708228	247517	113795878	14780405	5581956	1903371	868113	103605	613777	131146721	58358645	64306134
∑(Turbidity $_{mean}$ – Turbidity)^2	33698520833														
∑(Turbidity $_{estimate}$ – Turbidity)^2	412846574														
$R^2 = 1 - \frac{\sum(\text{Turbidity}_{mean} - \text{Turbidity})^2}{\sum(\text{Turbidity}_{estimate} - \text{Turbidity})^2}$	0.99														

500 < Kaolin < 4000															
Equation from “ Kaolin above 4000 FAU”	Turbidity = 2726 × soil concentration - 111.12														
Data point	1	2	3	4	5	6	7								
Turbidity (FAU)=	2094	1415	565	2655	1028	1999	897								
Soil concentration (g/l) =	0.83	0.57	0.30	1.05	0.45	0.95	0.47								
Turbidity $_{\text{estimate}}$=	2164	1438	700	2761	1108	2478	1157								
Soil concentration $_{\text{estimate}}$=	0.81	0.56	0.25	1.01	0.42	0.77	0.37								
Turbidity $_{\text{mean}}$ =	1522														
(Turbidity $_{\text{mean}}$ – Turbidity)^2	327347	11418	915576	1284013	243895	227665	390446								
(Turbidity $_{\text{estimate}}$ – Turbidity)^2	4952	526	18159	11214	6355	229885	67683								
∑(Turbidity $_{\text{mean}}$ – Turbidity)^2	3400361														
∑(Turbidity $_{\text{estimate}}$ – Turbidity)^2	338775														
$R^2 = 1 - \frac{\sum(\text{Turbidity}_{\text{mean}} - \text{Turbidity})^2}{\sum(\text{Turbidity}_{\text{estimate}} - \text{Turbidity})^2}$	0.90														

Bentonite above 4000 FAU															
Equation from “500 < Bentonite < 4000”	Turbidity = 772.42 × soil concentration - 159.1														
Data point	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Turbidity (FAU)=	44100	21710	10340	53000	18330	12950	10630	4485	46900	33100	33470	22270	17050	11720	7800
Soil concentration (g/l) =	48.86	25.21	12.38	65.44	21.30	16.21	12.67	5.98	51.82	37.74	37.98	27.54	20.92	14.51	10
Turbidity $_{\text{estimate}}$=	37580	19310	9407	50390	16293	12358	9624	4459	39869	28993	29181	21114	15997	11048	7541
Soil concentration $_{\text{estimate}}$=	57.30	28.31	13.59	68.82	23.94	16.97	13.97	6.01	60.92	43.06	43.54	29.04	22.28	15.38	10
Turbidity $_{\text{mean}}$ =	23190														
$(\text{Turbidity}_{\text{mean}} - \text{Turbidity})^2$	437214160	2191387	165131067	888616227	23622840	104864427	157761973	349889495	562148293	98201493	105671547	847013	37703693	131568547	236862360
$(\text{Turbidity}_{\text{estimate}} - \text{Turbidity})^2$	42504341	5760828	870947	6814036	4151349	350049	1011792	684	49441155	16864991	18395295	1335747	1109077	452133	67050
$\sum(\text{Turbidity}_{\text{mean}} - \text{Turbidity})^2$	3302294523														
$\sum(\text{Turbidity}_{\text{estimate}} - \text{Turbidity})^2$	149129475														
$R^2 = 1 - \frac{\sum(\text{Turbidity}_{\text{mean}} - \text{Turbidity})^2}{\sum(\text{Turbidity}_{\text{estimate}} - \text{Turbidity})^2}$	0.95														

500 < Bentonite < 4000															
Equation from “Bentonite above 4000 FAU”	Turbidity = 872.56 × soil concentration - 573.6														
Data point	1	2	3	4	5	6	7	8	9	10	11	12			
Turbidity (FAU)=	1985	1311	938	709	577	2970	2206	1153	654	1985	3396	765			
Soil concentration (g/l) =	2.78	1.87	1.38	1.09	0.87	3.66	2.95	1.75	0.96	3.14	4.70	1.47			
Turbidity $_{estimate}$=	1850	1057	629	380	187	2618	2004	956	265	2162	3526	707			
Soil concentration $_{estimate}$=	2.93	2.16	1.73	1.47	1.32	4.06	3.19	1.98	1.41	2.93	4.55	1.53			
Turbidity $_{mean}$ =	1554														
(Turbidity $_{mean}$ – Turbidity)^2	185689	59090	379559	714166	954692	2004820	424995	160868	810150	185689	3392657	622653			
(Turbidity $_{estimate}$ – Turbidity)^2	18108	64709	95453	108249	152062	124025	40877	38685	151520	31327	16805	3404			
∑(Turbidity $_{mean}$ – Turbidity)^2	9895027														
∑(Turbidity $_{estimate}$ – Turbidity)^2	845224														
$R^2 = 1 - \frac{\sum(\text{Turbidity}_{mean} - \text{Turbidity})^2}{\sum(\text{Turbidity}_{estimate} - \text{Turbidity})^2}$	0.91														

Appendix VI

Modelling of the effect of centrifuge on density of slurry was simulated at two conditions: without centrifuge and with centrifuge. The simulation starts from an initial slurry condition in the slurry tank before excavation. After pipe jacking excavation, the gravel, sand and clay were taken from the ground. The gravel and sand were removed by the separation plant. The clay was accumulated in the slurry tank. A centrifuge with a polymer addition was introduced to remove the fine particle from the slurry and the centrate was sent back to the slurry tank. The cake was produced by the centrifuge. The nomenclature of the simulation is shown in Figure A-2.

The limitations are: assuming all the gravel and sand removed by screen and hydrocyclone; slurry was pumped at a fixed rate and quantity of polymer was ignored. Only clay particles and water left in the slurry tank because of assuming particles great than 20 μm can be removed by the screen and hydrocyclone. The slurry cycle rate was fixed although the density of slurry was changed during the whole process. A very small amount of polymer, around 2.5×10^{-3} % of slurry, was added therefore the quantity of polymer was ignored.

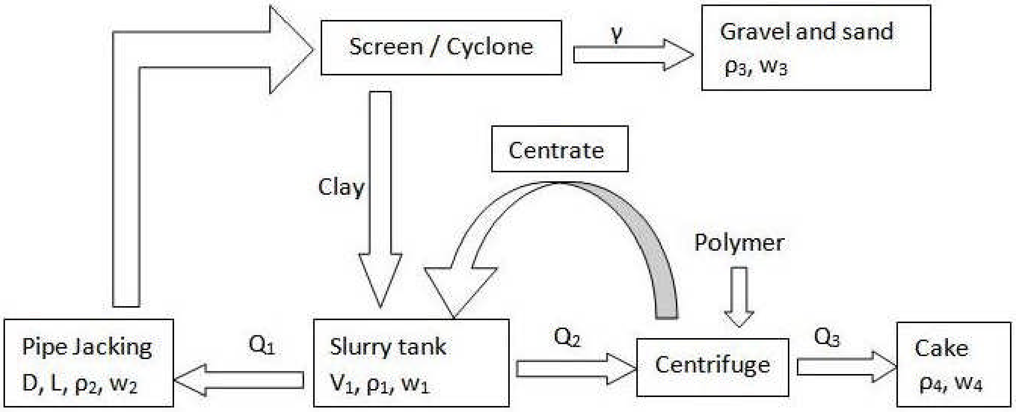


Figure A-2 Nomenclature of the simulation

Nomenclature

V_1: Volume of slurry tank (m^3)

ρ_1: Initial density of slurry tank (kg/ m^3)

w_1: Water content of initial slurry (%)

Q_1: Slurry cycle rate (m^3/hr)

D: Diameter of jacked pipe (m)

L: Length of jacked pipe (m)

ρ_2: Average density of soil (kg/ m^3)

w_2: Average water content of soil (%)

γ: Gravel and sand produce rate (%)

ρ_3: Average density of gravel and sand (kg/ m^3)

w_3: Average water content of gravel and sand (%)

Q_2: Slurry pump to centrifuge rate (m^3/hr)

Q_3: Cake production rate (m^3/hr)

ρ_4: Density of cake (kg/ m^3)

w_4: Water content of cake (%)

T: Time of finishing one pipe

Assuming

1. All the gravel and sand is removed by screen and cyclone.
2. Slurry is pumped at a fixed rate.
3. The excavation produced rate is depending on the waste produced rate.
4. Quantity of polymer is ignored due to small amount was added.

A. Calculation for density of slurry without centrifuge

I. Initial slurry:

The simulation starts from initial slurry condition in the slurry tank before excavation.

Initial total mass of slurry is given by:

$$\text{Mass}_{\text{total}} = \text{Mass}_{\text{solid}} + \text{Mass}_{\text{water}}$$

Since,

$$W_1 = \frac{\text{Mass}_{\text{water}} \times 100}{\text{Mass}_{\text{solid}}}$$

Thus,

$$\text{Mass}_{\text{water}} = \frac{\text{Mass}_{\text{solid}} \times W_1}{100}$$

Thus,

$$\text{Mass}_{\text{total}} = \rho_1 \times V_1 = \text{Mass}_{\text{solid}} + \frac{\text{Mass}_{\text{solid}} \times W_1}{100}$$

Therefore,

$$\text{Mass}_{\text{solid}} = \frac{\rho_1 \times V_1}{1 + \frac{W_1}{100}}$$

Then,

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{total}} - \text{Mass}_{\text{solid}} = \rho_1 \times V_1 - \frac{\rho_1 \times V_1}{1 + \frac{W_1}{100}} = \rho_1 \times V_1 \times \left(1 - \frac{1}{1 + \frac{W_1}{100}}\right)$$

Since,

$$\text{Volume}_{\text{water}} = \frac{\text{Mass of water}}{\text{Density of water}} = \frac{\rho_1 \times V_1 \times (1 - \frac{1}{1 + \frac{W_1}{100}})}{1000}$$

And,

$$\text{Volume}_{\text{solid}} = \text{Volume}_{\text{total}} - \text{Volume}_{\text{water}}$$

Therefore,

$$\text{Volume}_{\text{solid}} = V_1 - \frac{\rho_1 \times V_1 \times (1 - \frac{1}{1 + \frac{W_1}{100}})}{1000} = V_1 \times \left(1 - \frac{\rho_1 \times (1 - \frac{1}{1 + \frac{W_1}{100}})}{1000}\right)$$

II. <u>Additional from pipe after one cycle:</u>

After pipe jacking excavation, the gravel, sand and clay were taken from the ground.

The excavating volume was calculated from the volume of pipe and is given by:

Volume of pipe is $\frac{\pi D^2}{4} \times L$

This section is estimated on every cyclic slurry for pushing one pipe.

Number of slurry cycle for pushing one pipe is $\frac{Q_1}{V_1} T$

Therefore,

Additional volume from pipe after one cycle ($\text{Volume}_{\text{total}}$) is $\frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1} T}$

Since,

Additional total mass from pipe after one cycle (Mass $_{\text{total}}$) = density of soil × additional volume from pipe after one cycle = $\rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}$

And,

Mass $_{\text{water}}$ = $\frac{\text{Mass}_{\text{solid}} \times W_2}{100}$

Thus,

Mass $_{\text{total}}$ = Mass $_{\text{solid}}$ + Mass $_{\text{water}}$ = Mass $_{\text{solid}}$ + $\frac{\text{Mass}_{\text{solid}} \times W_2}{100}$

Thus,

$$\text{Mass}_{\text{solid}} = \frac{\text{Mass}_{\text{total}}}{1+\frac{W_2}{100}} = \frac{\rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}$$

Since,

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{total}} - \text{Mass}_{\text{solid}} = \rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} - \frac{\rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} = \rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} \times \left(1 - \frac{1}{1+\frac{W_2}{100}}\right)$$

And,

$$\text{Volume}_{\text{water}} = \frac{\text{Mass of water}}{\text{Density of water}} = \frac{\rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} \times \left(1 - \frac{1}{1+\frac{W_2}{100}}\right)}{1000}$$

Therefore,

$$\text{Volume}_{\text{solid}} = \text{Volume}_{\text{total}} - \text{Volume}_{\text{water}} = \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} - \frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000} = \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}\right)$$

III. Removal from screen and cyclone:

The gravel and sand were removed by the separation plant.

Since,

$$\text{Volume of gravel and sand spoil} = \frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}$$

Thus,

$$\text{Volume of removal gravel and sand after one cycle } (\text{Volume}_{\text{total}}) = \frac{\text{Volume}}{\text{Cycle times}} = \frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}$$

Therefore,

Total mass of removal gravel and sand after one cycle (Mass $_{\text{total}}$) = density of gravel and sand × removal gravel and sand volume after one cycle $=\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}$

Since,

$$\text{Mass}_{\text{total}} = \text{Mass}_{\text{solid}} + \text{Mass}_{\text{water}}$$

And,

$$\text{Mass}_{\text{water}} = \frac{\text{Mass}_{\text{solid}} \times \text{W}_3}{100}$$

Thus,

$$\text{Mass}_{\text{total}} = \text{Mass}_{\text{solid}} + \frac{\text{Mass}_{\text{solid}} \times \text{W}_3}{100}$$

Thus,

$$\text{Mass}_{\text{solid}} = \frac{\text{Mass total}}{1+\frac{\text{W}_3}{100}} = \frac{\rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}}}{1+\frac{\text{W}_3}{100}}$$

Since,

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{total}} - \text{Mass}_{\text{solid}} = \rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} - \frac{\rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}}}{1+\frac{\text{W}_3}{100}} = \rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} \times \left(1 - \frac{1}{1+\frac{\text{W}_3}{100}}\right)$$

And,

$$\text{Volume}_{\text{water}} = \frac{\text{Mass of water}}{\text{Density of water}} = \frac{\rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} \times \left(1-\frac{1}{1+\frac{\text{W}_3}{100}}\right)}{1000}$$

Therefore,

$$\text{Volume}_{\text{solid}} = \text{Volume}_{\text{total}} - \text{Volume}_{\text{water}} = \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} - \frac{\rho_3 \times \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} \times \left(1-\frac{1}{1+\frac{\text{W}_3}{100}}\right)}{1000} = \frac{\frac{\pi \text{D}^2}{4} \times \text{L} \times \frac{\gamma}{100}}{\frac{Q_1}{\text{V}_1}\text{T}} \times \left(1 - \frac{\rho_3 \times \left(1-\frac{1}{1+\frac{\text{W}_3}{100}}\right)}{1000}\right)$$

IV. Slurry condition after one cycle without centrifuge:

The clay was accumulated in the slurry tank.

The total mass of slurry in the tank after one cycle is given by:

Mass $_{\text{total}}$ = Initial slurry mass + Mass from pipe – Removal mass of gravel and sand

Thus,

$$\text{Mass}_{\text{total}} = \rho_1 \times V_1 + \rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} - \rho_3 \times \frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}$$

Since,

Mass $_{\text{solid}}$ = Initial slurry Mass $_{\text{solid}}$ + Mass $_{\text{solid}}$ from pipe – Removal Mass $_{\text{solid}}$ of gravel and sand

Thus,

$$\text{Mass}_{\text{solid}} = \frac{\rho_1\times V_1}{1+\frac{W_1}{100}} + \frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} - \frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}$$

Therefore,

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{total}} - \text{Mass}_{\text{solid}} = \left(\rho_1 \times V_1 + \rho_2 \times \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T} - \rho_3 \times \frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right) - \left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}} + \frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} - \frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}\right)$$

Since,

$$\text{Volume}_{\text{water}} = \frac{\text{Mass of water}}{\text{Density of water}} = \frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000}$$

And,

Volume of solid = Initial slurry solid volume + Solid volume from pipe – Removal solid volume of gravel and sand

$$= V_1\times\left(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)$$

Thus,

Total volume = Volume of water + Volume of solid

$$= \left(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000}\right)+\left(V_1\times\left(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)$$

The water content is given by:

$$\text{Water content} = \frac{\text{Mass of water}}{\text{Mass of solid}}\times 100$$

Therefore,

$$\text{Water content} = \frac{\left(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right)-\left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}\right)}{\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}}\times 100$$

The density is given by:

$$\text{Density} = \frac{\text{Mass}_{\text{total}}}{\text{Valume}_{\text{total}}}$$

Therefore,

$$\text{Density} = \frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{\left(\frac{\left(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right)-\left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}\right)}{1000}\right)+\left(V1\times\left(1-\frac{\rho_1\times\left(1-\frac{1}{1+\frac{W_1}{100}}\right)}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times\left(1-\frac{1}{1+\frac{W_2}{100}}\right)}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)}$$

B. Calculation for density of slurry with centrifuge

Following the simulation from part A, a centrifuge with a polymer addition was introduced to remove the fine particle from the slurry and the centrate was sent back to the slurry tank. Cake was produced by the centrifuge. The produced cake, centrate and slurry condition were simulated as follow:

V. <u>Produced cake:</u>

Time for one slurry cycle is given by $\frac{V_1}{\mathrm{Q}_1}$

Thus,

Volume of cake produced after one cycle = $Q_3 \times \frac{V_1}{\mathrm{Q}_1}$

Therefore,

Total mass of produced cake after one cycle (Mass $_{\text{total}}$) = density of cake × produced cake volume after one cycle = $\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}$

Since,

Mass $_{\text{solid}}$ + Mass $_{\text{water}}$ = Mass $_{\text{solid}}$ + $\frac{\mathrm{Mass}_{\mathrm{solid}} \times W_4}{100}$

Thus,

Mass $_{\text{solid}}$ is $\frac{\mathrm{Mass}_{\mathrm{total}}}{1+\frac{W_4}{100}} = \frac{\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}}{1+\frac{W_4}{100}}$

Since,

$$\text{Mass}_{\text{water}} = \text{Mass}_{\text{total}} - \text{Mass}_{\text{solid}} = \rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1} - \frac{\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}}{1+\frac{W_4}{100}} = \rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}\left(1 - \frac{1}{1+\frac{W_4}{100}}\right)$$

And,

$$\text{Volume}_{\text{water}} = \frac{\text{Mass water}}{\text{Density of water}} = \frac{\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}$$

Since,

$$\text{Volume}_{\text{total}} = \text{Volume}_{\text{solid}} + \text{Volume}_{\text{water}}$$

Therefore,

$$\text{Volume}_{\text{solid}} = \text{Volume}_{\text{total}} - \text{Volume}_{\text{water}} = Q_3 \times \frac{V_1}{\mathrm{Q}_1} - \frac{\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000} = Q_3 \times \frac{V_1}{\mathrm{Q}_1} \times \left(1 - \frac{\rho_4 \times \left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}\right)$$

VI. Cycle Centrate

Time for one slurry cycle is given by $\frac{V_1}{Q_1}$

Since,

Volume $_{solid}$ of centrate after one cycle = Volume $_{solid}$ of slurry pump to centrifuge after one cycle - Volume $_{solid}$ of cake after one cycle

And,

Volume $_{solid}$ of slurry pump to centrifuge after one cycle

= Slurry centrifuge rate × one cycle time × $\frac{\text{Volume}_{\text{solid}}\ \text{of slurry after one cycle without centrifuge}}{\text{Volume}_{\text{total}}\ \text{of slurry after one cycle without centrifuge}}$

Thus,

Volume $_{solid}$ of centrate after one cycle =

Slurry centrifuge rate × One cycle time × $\frac{\text{Volume}_{\text{solid}}\ \text{of slurry after one cycle without centrifuge}}{\text{Volume}_{\text{total}}\ \text{of slurry after one cycle without centrifuge}}$ - Volume $_{solid}$ of cake after one cycle

$$=Q_2\times\frac{V_1}{Q_1}\times$$

$$\frac{V1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})}{(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000})+(V1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000}))}$$

$$-Q_3\times\frac{V_1}{Q_1}\times(1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000})$$

Since,

Total volume of centrate produced after one cycle = $(Q_2-Q_3)\times\frac{V_1}{Q_1}$

And,

Volume $_{water}$ = Volume $_{total}$ - Volume $_{solid}$

Thus,

Volume of water =

$$=(Q_2 - Q_3) \times \frac{V_1}{\mathrm{Q}_1} - Q_2 \times \frac{V_1}{\mathrm{Q}_1} \times$$

$$\frac{\mathrm{V1}\times (1-\frac{\rho_1\times(1-\frac{1}{1+\frac{\mathrm{W}_1}{100}})}{1000}) + \frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{\mathrm{W}_2}{100}})}{1000}) - \frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{\mathrm{w}_3}{100}}\right)}{1000})}{(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}-\rho_3\times\frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}})-(\frac{\rho_1\times V_1}{1+\frac{\mathrm{W}_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}}{1+\frac{\mathrm{W}_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}}{1+\frac{\mathrm{w}_3}{100}})}{1000}) + (\mathrm{V1}\times (1-\frac{\rho_1\times(1-\frac{1}{1+\frac{\mathrm{W}_1}{100}})}{1000}) + \frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{\mathrm{W}_2}{100}})}{1000}) - \frac{\frac{\pi \mathrm{D}^2}{4}\times \mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{\mathrm{w}_3}{100}}\right)}{1000}))} -$$

$$Q_3 \times \frac{V_1}{\mathrm{Q}_1} \times (1 - \frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000})$$

Since,

Mass $_{\text{water}}$ = Volume $_{\text{water}}$ × Density of water

Thus,

Mass $_{\text{water =}}$

$$\begin{aligned}&((Q_2-Q_3)\times\frac{V_1}{\mathrm{Q}_1}-Q_2\times\frac{V_1}{\mathrm{Q}_1}\times\\&\frac{\mathrm{V1}\times\left(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{\mathrm{W}_1}{100}})}{1000}\right)+\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times\left(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{\mathrm{W}_2}{100}})}{1000}\right)-\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{\mathrm{W}_3}{100}}\right)}{1000}\right)}{\left(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}-\rho_3\times\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}})-(\frac{\rho_1\times V_1}{1+\frac{\mathrm{W}_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}}{1+\frac{\mathrm{W}_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}}{1+\frac{\mathrm{W}_3}{100}})}{1000}\right)+\left(\mathrm{V1}\times\left(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{\mathrm{W}_1}{100}})}{1000}\right)+\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times\left(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{\mathrm{W}_2}{100}})}{1000}\right)-\frac{\frac{\pi\mathrm{D}^2}{4}\times\mathrm{L}\times\frac{\gamma}{100}}{\frac{Q_1}{\mathrm{V}_1}\mathrm{T}}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{\mathrm{W}_3}{100}}\right)}{1000}\right)\right)}\\&-Q_3\times\frac{V_1}{\mathrm{Q}_1}\times\left(1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}\right))\times 1000\end{aligned}$$

Since,

Mass of centrate after one cycle = Mass of slurry pump to centrifuge after one cycle - Mass of cake after one cycle

And,

Mass of slurry pump to centrifuge after one cycle = volume of slurry pump to centrifuge after one cycle × density

$$= Q_2 \times \frac{V_1}{\mathrm{Q}_1} \times$$

$$\left(\frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{\left(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000}\right)+\left(V1\times\left(1-\frac{\rho_1\times\left(1-\frac{1}{1+\frac{W_1}{100}}\right)}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times\left(1-\frac{1}{1+\frac{W_2}{100}}\right)}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)}\right)$$

Thus,

Total mass of centrate after one cycle =

$$Q_2 \times \frac{V_1}{\mathrm{Q}_1} \times$$

$$\left(\frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{\left(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000}\right)+\left(V1\times\left(1-\frac{\rho_1\times\left(1-\frac{1}{1+\frac{W_1}{100}}\right)}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times\left(1-\frac{1}{1+\frac{W_2}{100}}\right)}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)}\right)$$

$$-\rho_4 \times Q_3 \times \frac{V_1}{\mathrm{Q}_1}$$

Since,

Mass $_{solid}$ = Mass $_{total}$ - Mass $_{water}$

Thus,

$$\text{Mass}_{\text{solid}}=\left(Q_2\times\frac{V_1}{\mathrm{Q}_1}\times\right.$$

$$\left(\frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{\left(\frac{\left(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right)-\left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}\right)}{1000}\right)+\left(V1\times\left(1-\frac{\rho_1\times\left(1-\frac{1}{1+\frac{W_1}{100}}\right)}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times\left(1-\frac{1}{1+\frac{W_2}{100}}\right)}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)}\right)$$

$$\left.-\rho_4\times Q_3\times\frac{V_1}{\mathrm{Q}_1}\right)-(((Q_2-Q_3)\times\frac{V_1}{\mathrm{Q}_1}-Q_2\times\frac{V_1}{\mathrm{Q}_1}\times$$

$$\frac{V1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000})}{(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000})+(V1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}))}\ -$$

$$Q_3\times\frac{V_1}{Q_1}\times(1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}))\times 1000)$$

The density of centrate is given by: $\frac{\text{Total mass}}{\text{Total volume}}$

Therefore,

Density of centrate =

$$\frac{Q_2\times\frac{V_1}{Q_1}\times\left(\frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{\left(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000}\right)+\left(V1\times\left(1-\frac{\rho_1\times\left(1-\frac{1}{1+\frac{W_1}{100}}\right)}{1000}\right)+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_2\times\left(1-\frac{1}{1+\frac{W_2}{100}}\right)}{1000}\right)-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times\left(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}\right)\right)}\right)-\rho_4\times Q_3\times\frac{V_1}{Q_1}}{(Q_2-Q_3)\times\frac{V_1}{Q_1}}$$

VII. <u>Slurry condition after one cycle with centrifuge</u>

Since,

Total mass = Mass of slurry after one cycle without centrifuge – Total mass of produced cake

Thus,

Mass $_{\text{total}}$=

$$\left(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right)-\left(\rho_4\times Q_3\times\frac{V_1}{Q_1}\right)$$

Since,

Total volume = Volume of slurry after one cycle without centrifuge – Total volume of produced cake

Thus,

Volume $_{\text{total}}$=

$$((\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000}) + (V_1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000}) + \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}) - \frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times$$

$$(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000}))) - (Q_3\times\frac{V_1}{Q_1})$$

Since density =$\frac{\text{Mass}_{\text{total}}}{\text{Volume}_{\text{total}}}$

Therefore,

Density of slurry after one cycle with centrifuge

=

$$\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\rho_4\times Q_3\times\frac{V_1}{Q_1})}{((\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000})+(V1\times(1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})))-(Q_3\times\frac{V_1}{Q_1})}$$

Since,

Mass of water = Water mass of slurry after one cycle without centrifuge – Water mass of produced cake

Therefore,

Mass $_{water}$ =

$$((\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}))-(\rho_4\times Q_3\times\frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}}))$$

Since,

Volume of water = $\frac{\text{Mass of water}}{\text{Density of water}}$

Therefore,

$$\text{Volume}_{\text{water}} = \frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})) - (\rho_4\times Q_3\times\frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}})}{1000}$$

Since,

Mass of solid = Solid mass of slurry after one cycle without centrifuge – Solid mass of produced cake

Therefore,

$$\text{Mass}_{\text{solid}} = (\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}) - (\frac{\rho_4\times Q_3\times\frac{V_1}{Q_1}}{1+\frac{W_4}{100}})$$

Since,

Volume of solid = Solid volume of slurry after one cycle without centrifuge – Solid volume of produced cake

Therefore,

$$\text{Volume}_{\text{solid}} = (V_1\times (1-\frac{\rho_1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000}) + \frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times (1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}) - \frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times (1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})) - (Q_3\times\frac{V_1}{Q_1}\times (1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}))$$

Since water content is given by $\frac{\mathrm{Mass}_{\mathrm{water}}}{\mathrm{Mass}_{\mathrm{solid}}}\times 100$

Therefore,

$$\text{Water content} = \frac{\left(\left(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\right)-\left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}\right)\right)-\left(\rho_4\times Q_3\times\frac{V_1}{Q_1}\left(1-\frac{1}{1+\frac{W_4}{100}}\right)\right)}{\left(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}}\right)-\left(\frac{\rho_4\times Q_3\times\frac{V_1}{Q_1}}{1+\frac{W_4}{100}}\right)}\times 100$$

Summary the nomenclature in Table A-1 and Table A-2.

Table A-1 Density of slurry without centrifuge

Cycle i	Tank-stage i	Additional from pipe after one cycle	Removal from screen and cyclone	Tank-stage i+1
Water content %	w_1	w_2	w_3	$\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}}\times 100$
Density (kg/m^3)	ρ_1	ρ_2	ρ_3	$\frac{\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{w_3}{100}})}{1000})+(V1\times(1-\frac{\rho 1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{w_3}{100}}\right)}{1000}))}$

Volume (m^3)	V_1	$\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}$	$\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q1}{V1}T}$	$(\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000})+(V_1\times(1-\frac{\rho1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-$
Volume-soild (m^3)	$V1\times(1-\frac{\rho1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})$	$\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})$	$\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})$	$V_1\times(1-\frac{\rho1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})$
Volume-water (m^3)	$\frac{\rho1\times V1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000}$	$\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000}$	$\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{1}{1+\frac{W_3}{100}})}{1000}$	$\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000}$
Mass of solid (kg)	$\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}$	$\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}$	$\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}$	$\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}$
Mass of water (kg)	$\rho_1\times V_1\times(1-\frac{1}{1+\frac{W_1}{100}})$	$\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{1}{1+\frac{W_2}{100}})$	$\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{1}{1+\frac{W_3}{100}})$	$(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})$
Total Mass (kg)	$\rho_1\times V_1$	$\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}$	$\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}$	$\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}$

Table A-2 Density of slurry with centrifuge

Cycle i	Cake produce	Tank-stage i+2
Water content %	w₄	$\frac{((\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}}))-(\rho_4\times Q_3\times\frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}}))}{(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})-(\frac{\rho_4\times Q_3\times\frac{V_1}{Q_1}}{1+\frac{W_4}{100}})}\times 100$
Density (kg/m^3)	ρ₄	$\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\rho_4\times Q_3\times\frac{V_1}{Q_1})}{((\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000})+(V1\times(1-\frac{\rho 1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})))-(Q_3\times\frac{V_1}{Q_1})}$
Volume (m^3)	$Q_3\times\frac{V_1}{Q_1}$	$((\frac{(\rho_1\times V_1+\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}-\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T})-(\frac{\rho_1\times V_1}{1+\frac{W_1}{100}}+\frac{\rho_2\times\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}}-\frac{\rho_3\times\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})}{1000})+(V_1\times(1-\frac{\rho 1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000})))-(Q_3\times\frac{V_1}{Q_1})$
Volume-soild (m^3)	$Q_3\times\frac{V_1}{Q_1}\times(1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000})$	$(V_1\times(1-\frac{\rho 1\times(1-\frac{1}{1+\frac{W_1}{100}})}{1000})+\frac{\frac{\pi D^2}{4}\times L}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_2\times(1-\frac{1}{1+\frac{W_2}{100}})}{1000})-\frac{\frac{\pi D^2}{4}\times L\times\frac{\gamma}{100}}{\frac{Q_1}{V_1}T}\times(1-\frac{\rho_3\times\left(1-\frac{1}{1+\frac{W_3}{100}}\right)}{1000}))-(Q_3\times\frac{V_1}{Q_1}\times(1-\frac{\rho_4\times\left(1-\frac{1}{1+\frac{W_4}{100}}\right)}{1000}))$

Volume-water (m^3)	$\frac{\rho_4 \times Q_3 \times \frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}})}{1000}$	$\frac{(\rho_1 \times V_1 + \rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T} - \rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T}) - (\frac{\rho_1 \times V_1}{1+\frac{W_1}{100}} + \frac{\rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} - \frac{\rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})) - (\rho_4 \times Q_3 \times \frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}})}{1000}$
Mass of solid (kg)	$\frac{\rho_4 \times Q_3 \times \frac{V_1}{Q_1}}{1+\frac{W_4}{100}}$	$(\frac{\rho_1 \times V_1}{1+\frac{W_1}{100}} + \frac{\rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} - \frac{\rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})$ - $(\frac{\rho_4 \times Q_3 \times \frac{V_1}{Q_1}}{1+\frac{W_4}{100}})$
Mass of water (kg)	$\rho_4 \times Q_3 \times \frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}})$	$((\rho_1 \times V_1 + \rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T} - \rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T}) - (\frac{\rho_1 \times V_1}{1+\frac{W_1}{100}} + \frac{\rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T}}{1+\frac{W_2}{100}} - \frac{\rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T}}{1+\frac{W_3}{100}})) - (\rho_4 \times Q_3 \times \frac{V_1}{Q_1}(1-\frac{1}{1+\frac{W_4}{100}}))$
Total Mass (kg)	$\rho_4 \times Q_3 \times \frac{V_1}{Q_1}$	$(\rho_1 \times V_1 + \rho_2 \times \frac{\frac{\pi D^2}{4} \times L}{\frac{Q_1}{V_1}T} - \rho_3 \times \frac{\frac{\pi D^2}{4} \times L \times \frac{\gamma}{100}}{\frac{Q_1}{V_1}T})$ - $(\rho_4 \times Q_3 \times \frac{V_1}{Q_1})$

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