FUNDAMENTAL STUDY OF THE SEDIMENTATION OF COPPER TAILINGS WITH KYNCH THEORY

by

Yuan Li

B.Sc., University of Science and Technology Beijing, 2011

A THESIS SUBMITTED IN PARTIAL FULFILLMENT OF

THE REQUIREMENTS FOR THE DEGREE OF

MASTER OF APPLIED SCIENCE

in

THE FACULTY OF GRADUATE AND POSTDOCTORAL STUDIES

(Mining Engineering)

THE UNIVERSITY OF BRITISH COLUMBIA

(Vancouver)

May 2015

Abstract

The management of tailings is a significant issue within the mining industry worldwide. An understanding of sedimentation and consolidation of tailings provides a solid foundation for the management of tailings. Kynch theory, the first mathematical formulation of sedimentation theory, is widely used as a tool in the analysis of batch sedimentation. However, due to various idealized assumptions within Kynch theory, the application of this theory to describe and analyze tailings sedimentation in the laboratory setting has not been well developed.

For the purpose of this research, a new apparatus was designed and constructed to carry out column settling tests and to remove and collect samples of water and suspensions in thin layers. Tests conducted with this apparatus aim at investigating the settling behavior and the internal changes in the suspension during the process of sedimentation. Solid content and particle size were selected as the main parameters. Benchmark tests were first conducted to determine the general range of the two parameters. Solid contents of 35% and 40% were selected for the column settling tests. Tests were carried out on total copper tailings as well as fine portions of copper tailings with a particle size smaller than 37 μm. The experimental data collected from these tests was analyzed with Kynch theory.

Total copper tailings, with a large range of particle sizes could not satisfy the assumptions of Kynch theory on particle size, and failed to conform to Kynch theory. In the tests of fines from copper tailings, the influence of segregation decreased as the coarse particles in the copper tailings were removed. Based on Kynch theory and some laboratory data, a prediction curve was

developed and compared with the results of the column settling tests. Changes in the internal attractive force, and the influence of compaction settling were found to be reasons why the prediction curve was unable to completely match the experimental data.

Preface

This dissertation is an original, unpublished, independent work by the author, Yuan Li.

The design of the special made apparatus for the column settling test with sample collection was done primarily by myself. The construction of this apparatus was carried out by Aaron Hope, millwright of CMP laboratory.

Table of Contents

List of Tables

List of Figures

Acknowledgements

I would like to extend my appreciation and thanks to my supervisor, Professor Dirk van Zyl, who took his time to guide, help and support me in completing my research. Your input on my research has been of the greatest value. I also want to express my sincere gratitude to Professor Dobroslav Znidarcic, University of Colorado, Boulder for his suggestions on the design of the experimental apparatus and Dr. Ali Hooshiar for his inspiration regarding the experimental methodology. I would like to thank Mathiew Estepho for his great help with my research.

Financial support from Suncor Energy, the National Science and Engineering Research Council as well as SRK Consulting Inc. has also been very much appreciated. Their support played a significant role in both my research and for my graduate studies.

I would also like to offer my gratitude to Aaron Hope, millwright of CMP laboratory, for his hard work on the construction of the experimental apparatus. I thank Dr. Libin Tong, Dr. Wei He, Pius Lo, for their valuable suggestions on my research.

Last but not least, I would like to thank my dear family and friends. Their love has helped and supported me during my time here at UBC.

Chapter 1: Introduction

1.1 Background

In metal mining, valuable ore materials represent only a small fraction of the whole mined ore mass; the main fraction of the mined ore ends up as tailings. In low-grade metal ore extraction, 99% of the original extracted material may finally end up as tailings (Lottermoser, 2007). Copper ores typically contain 0.5% to 2% copper, and produce a final product with a concentrated Cu from 25% to 45%, signifying that 93% to 99% of these ores are rejected as tailings (Wang, 2012). Over the last century, the production of tailings has rapidly increased as the demands for minerals and metals have grown and low-grade ores are increasingly being extracted. Some mines are currently producing over 200,000 tonnes of tailings per day.

Tailings are generated during mineral processing in mills. Generally, tailings consist of ground rock, residual metal, water and chemical reagents that have been added during processing. After tailings are produced, most of the tailings mass is normally discharged in a storage tailings pond known as a Tailings Management Facility (TMF) in the form of slurry (Lottermoser, 2007). The slurry pumped into the TMF commonly contains a solids content of 20 to 40% (Robertson, 1994). Tailings undergo sedimentation in the storage tailings pond. As shown in Figure 1.1, the larger and heavier particles in the tailings slurry settle near the slurry outlet to form a sand beach, and fine particles, which are usually located further away from the embankment of the tailings pond, remain in the water to form silt or suspension. In addition to the formation of a sand beach and suspension, water is released as particles in the tailings settle, and it forms a layer of supernatant water on top of the tailings. This can be discharged or recycled if the quality of the water meets a certain standard. This liquid-solid separation is known as sedimentation.

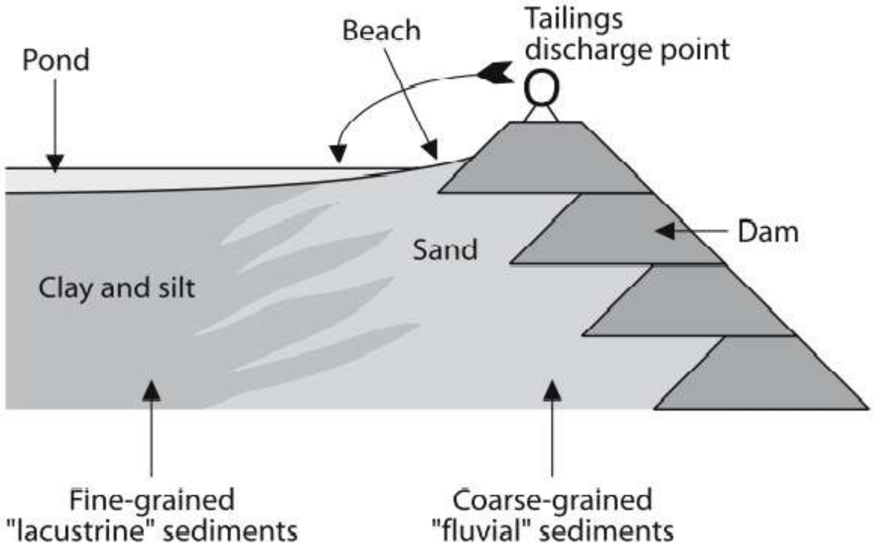

Figure 1.1 Depositional environments of a tailings dam receiving tailings slurries (Robertson, 1994)

The properties of the sediment and the suspension in the tailings pond change as sedimentation continues. These properties include the solids content, void ratio, permeability, compressibility, and effective stress. After the sedimentation ends, the consolidation process begins, leading to a further change of solids content and an enhancement of the strength of the deposit. Thus, a better understanding of the sedimentation of tailings will benefit the management of tailings.

In order to gain further understanding regarding the process of sedimentation, column settling tests are employed in this research to learn about the settling behavior of tailings. This research consists of two components. The first involves an improved methodology through which to collect samples of sediment at different heights in the settling column during the settling test.

This process can provide more details about the internal changes resulting from sedimentation. Kynch theory, the first mathematical formulation of sedimentation in history, is applied to give a theoretical evaluation of the results and analysis, and will serve as the second component of this research.

1.2 Research Question and Objectives of Research

The main objective of this research is to investigate the settling behavior of copper tailings at the laboratory level. A new experiment apparatus was constructed to conduct column settling tests and column settling tests with sample collection. Kynch theory is analyzed and applied to predict various parameters of sedimentation.

The following question was explored in this research:

- How can Kynch theory be applied in studying the sedimentation of copper tailings?

Some specific objectives of this research are:

- Design and construction of an apparatus to collect samples at different heights of the suspension in the column settling test;
- Determine the influence of the solids content and the particle size of copper tailings on the development of the interface between supernatant water and suspension;
- Investigate the change of solids content of the total tails of copper tailings samples and copper tailings fractions with particular particle size ranges in the settling column during the column settling test;
- Use Kynch theory to analyze and predict the settling curve of copper tailings.

1.3 Outline of Thesis

This thesis consists of 5 chapters. A brief summary for each chapter is provided as follows:

In chapter 1, the general background for this research is presented. Several objectives of this study are summarized.

In chapter 2, a literature review of previous researches and studies related to the above topics is presented. Mechanism and types of sedimentation are discussed to provide a general idea of settling behavior, and some developments and applications of column settling tests are presented. Kynch theory is discussed in detail. The continuity equation in Kynch theory and a calculation of the settling curve are all discussed in this chapter.

Chapter 3 presents a description of the test samples of total tails and fines from copper tailings. The design and construction of a new experimental apparatus for column settling test with sample-collection endings is introduced. The new apparatus makes it possible for researchers to collect samples from the settling suspension at different heights. Column settling tests on the total tails of copper tailings with different initial solids contents were conducted to determine the reasonable solids content for the latter test. Column settling tests and the column settling tests with sample-collection on copper tailings with different particle size ranges were conducted to investigate the influence of particle size on general settling behavior.

In chapter 4, results of column settling tests and the column settling tests with sample-collection are presented and analyzed to determine the applicability of Kynch theory for different materials. The results of particle size distribution analysis are discussed in order to investigate the segregation phenomenon in column settling tests and the column settling tests with sample-collection. The calculation of the prediction settling curve was made based on Kynch theory and compared with the experimental data from column settling tests. Tests were also conducted on fines of copper tailings with dispersant, kaolin and a mixture of kaolin and concrete sands.

In chapter 5, the main achievements and important findings of this research are presented. Recommendations on how to improve the experimental apparatus and methodology, as well as recommendations for future studies are suggested.

Chapter 2: Literature Review

2.1 Introduction to Sedimentation

2.1.1 Four Types of Sedimentation

The process of particles settling out of a fluid, usually air or water, is called sedimentation. This phenomenon is widely observed in the formation of sedimentary rocks and associated ore deposits (Chen, 1986). In the mineral processing field, classification, concentration and dewatering all involve the settling of a solid from a liquid phase (Concha and Bürger, 2002). Settling of solids from the liquid phase is influences by various forces including gravity, electromagnetism, and centrifugal force, being applied to the particle (Concha, 2009).

The settling of particles from a suspension depends on both the characteristics and the concentration of the particles. In low concentration suspensions, or dilute suspensions, the concentration of particles is too low to cause significant displacement of water as they settle. Based on these concepts, sedimentation can be classified into four types, which are shown in Table 2.1 (Tchobanoglous et al., 1979).

Type	Description	Application
Discrete Particle Settling/ Unlimited Settling	1. Discrete particles in low concentration suspensions. 2. Particles settle as individuals freely without significant interference from neighboring particles.	Removes grit from wastewater

Type	Description	Application
	3. Acceleration of individual particles in water or other liquid stops when the drag forces on the particle is equal to the submerged weight.	
Flocculent Settling	1. Particles forming flocs in low concentration suspensions. 2. Particles stick together in clumps while settling. 3. Particles settle at a faster rate	Removes a portion of the suspended solids in untreated wastewater in primary settling facilities
Hindered Settling/ Zone Settling	1. Particle concentration is great enough that particles are so close and no longer settle individually 2. Particle concentration is great enough to inhibit the movement of water or other liquid, the whole suspension settles as a 'blanket.' 3. There is an upward flow of water or liquid. 4. Water moves in space between particles.	Occurs in secondary settling facilities
Compression Settling	1. Compression settling occurs when	Occurs in the lower

Type	Description	Application
	the concentration is very high and particles are actually in contact. 2. It results in adjustment within the solid matrix. 3. Water or liquid is squeezed out of the mass.	layers of a deep sludge mass

Table 2.1 Classification of sedimentation (Tchobanoglous et al., 1979)

2.1.2 Hindered Settling

In the operation of many operations in the mining industry, the concentration of suspensions is always high enough to cause hindered settling (Moussavi, 2013). As mentioned above, particles in hindered settling do not settle individually. The settling velocity of a particle in hindered settling may be less than its final velocity in free settling conditions (Richardson et al., 2002). In hindered settling, discrete settling and flocculent settling may also occur in addition to compaction settling (Tchobanoglous et al., 1979).

Coe and Clevenger (1916) identified the settling of an initially homogenous concentrated suspension with four well-distinguished settling zones by studying the sedimentation of metallurgical slimes. The four zones are illustrated in Figure 2.1 and labeled with “A”, “B”, “C” and “D.” In this Figure, Zone “A” represents a clear water zone or supernatant water zone, Zone “B” contains suspensions with the initial concentration, Zone “C” is a transition zone of variable concentration, and Zone “D” is known as a compression or consolidation zone. When the range of the particle size in the suspension is very large, another mode of sedimentation was also observed by Coe and Clevenger in which Zone “C” extends from the top of the interface between the supernatant and suspension to the layer of sediment, and the compaction zone is missing (Richardson et al., 2002, Concha and Bürger, 2003). According to Tan (1995), it can be assumed there is no effective stress in the sedimentation of Zones “B” and “C,” while in Zone “D” it is assumed to be undergoing consolidation.

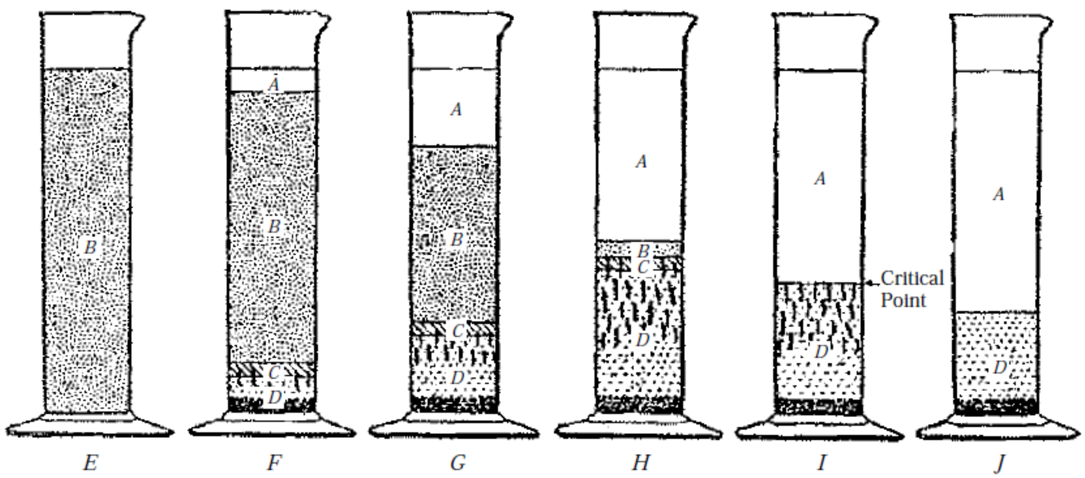

Figure 2.1 Batch settling of a flocculated suspension as illustrated by Coe and Clevenger (1916) (Concha and Bürger, 2002)

2.2 Introduction of Column Settling Test

2.2.1 Application of Column Settling Test

In order to investigate the settling behavior of a suspension, the settling velocity of particles is always required. Settling velocity can be measured directly in the settling column by column settling tests or can be estimated from the measurement of the particle size and density of the settling particles (Wang et al., 1988; Ozturgut and Lavelle, 1986). A conventional column-settling test involves a column or a cylinder (Palermo and Thackston, 1988). Settlement can be measured or observed directly inside the settling column or cylinder based on the time interval or the distance interval that the interface passes. The conventional column-settling test begins with a mixing of the sample with solution to form suspension. After the sample has been fully dispersed, the suspension is decanted into the settling column or cylinder for sedimentation. (Yao, 1979). The detailed procedure is introduced in chapter 3.

2.2.2 Development of Column Settling Test

The conventional settling column has been used widely in the past as a research tool (O'Connor et al., 2002). However, more advanced apparatus were designed and built in order to learn about some of the internal physical characteristics of the behavior of sedimentation.

In 1991, at the University of Alberta (Caughill, 1992), Caughill conducted a series of settling tests on some specially-made standpipes. Most of the standpipe tests were carried out in PVC cylinders of 30 cm height. In addition, two settling tests were performed in two 2-m high standpipes. In the test, tailings mixed with other materials were allowed to settle undisturbed in the standpipes. A tailings-supernatant interface was measured with a tape and recorded over time. Ten manometer ports were positioned on the wall of the two 2-m high standpipes, every 20 cm from the top to the bottom, as shown in Figure 2.2. During the test, manometers were measured and recorded at the same time as the interface between the supernatant and the suspension was measured.

At the end of the test, for the PVC cylinders a water sample was collected and sediment was removed in layers by scooping it out with a ladle. These samples were used to obtain water content and grain size analysis, The first 2 m column was sampled by sucking the sediment through a hose into a vacuum cleaner. This worked well for the layers on the top since the water content was high, but not well for the bottom layers as the water was removed before the sand particles. This phenomenon led to a consequence of higher water content than was the reality in the standpipe. The other 2 m standpipe was not sampled before Caughill's paper was published.

With the standpipe tests, the main experimental data provided by Caughill is a profile of average void ratio profile versus settling time. Moisture content profiles and fines content profiles were also obtained from these experimental data.

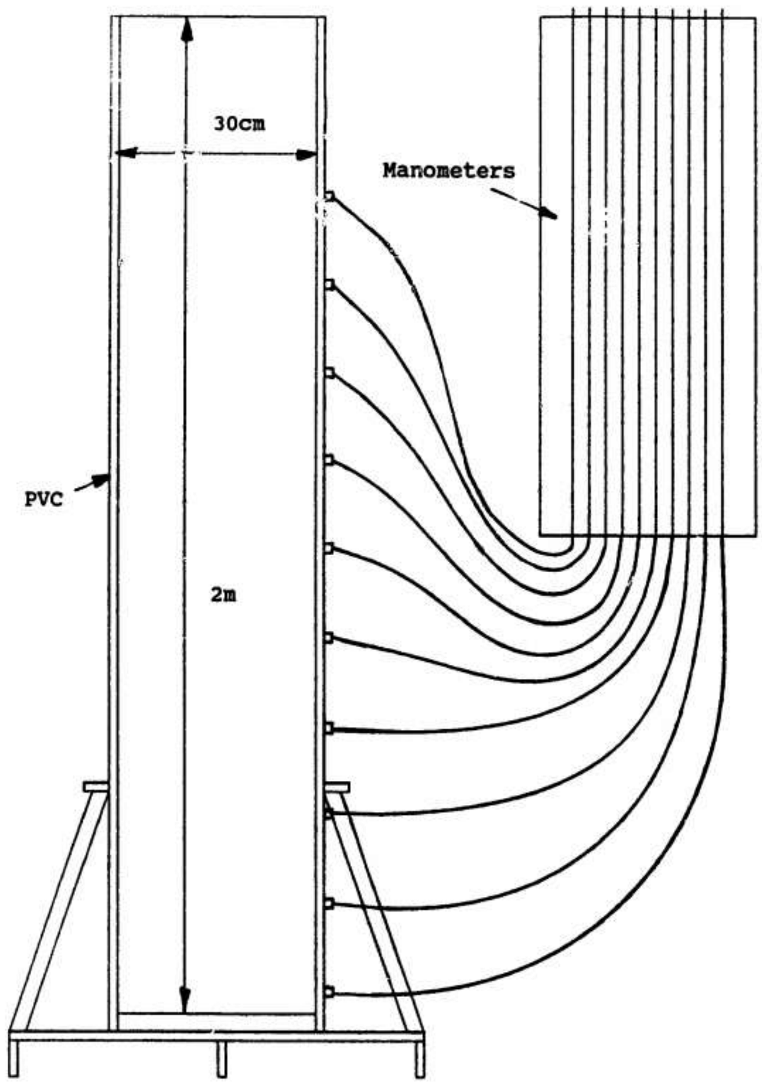

Figure 2.2 Two meter standpipe (Caughill, 1992)

A series of bench scale static column settling tests were designed by Nicholas Partick Arkell (2012) in an oil sand study conducted in Alberta. This research was conducted to examine and monitor the chemical changes occurring in MFT undergoing methanogenic accelerated dewatering. In the first section of this experiment, 2L settling columns were applied to conduct a settling column experiment to monitor the changes in pH and other chemical elements. Different treatments were performed on the MFT samples. Prior to filling the columns, the MFT left were sampled for time zero analysis. After filling, all columns were regularly monitored for water release. At the end of the planned periods, the columns were sacrificed for sampling and analyses. 250 ml samples were withdrawn from the top layer and bottom layer of the columns with a 25 ml syringe.

In the second part of the experiment, a 50L settling column experiment was designed to demonstrate and further validated the biodensification process in oil sands tailings. This experiment consisted of two 50L columns with a height of 195.58 cm. Both the top and bottom of the columns were covered by an acrylic plate. A third bore-through fitting was installed for the vertical sampling of the MFT. The final apparatus is shown in Figure 2.3. Settling and water release were measured regularly after the test was begun, and samples were collected through the pH ports for chemical analysis.

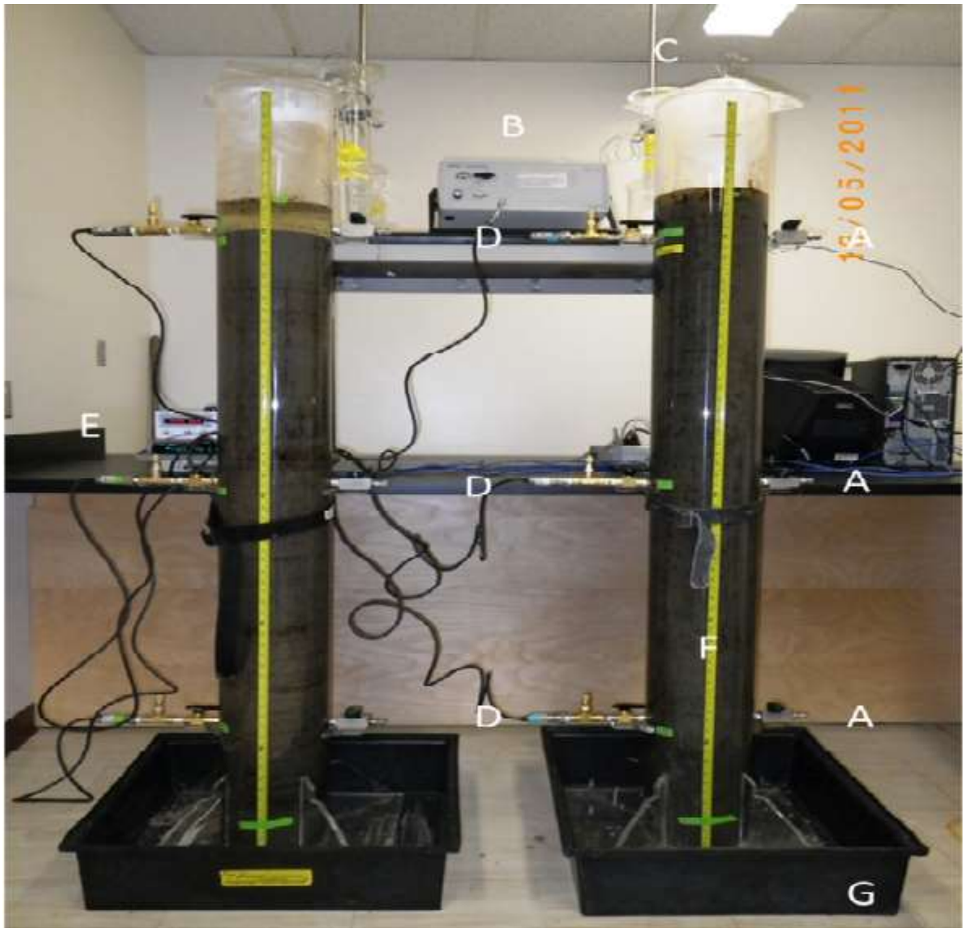

Figure 2.3 Final setup of the columns. Features of apparatus are labeled: (A) pH ports, (B) GC, (C) gas trap, (D) pressure transducers, (E) pressure reading unit, (F) measuring tap, and (G) containment tub (Arkell, 2012)

In the SKN Sinhgad College of Engineering Pandharpur, in India, a column settling methodology was developed to verify a modified method for the efficiency of overall turbidity removal. A settling column of depth 1.2 m and column diameter of 30 cm was constructed. Six sampling ports with a diameter of 12 mm were constructed at 0.1 m, 0.3 m, 0.5 m, 0.7, 0.9 m, 1.1 m from the top of the settling column, as shown in Figure 2.4 (Pise, 2011). Pise filled the specially made settling column with a prepared turbid water sample. At different time intervals (beginning from time zero), samples were drawn from each of the sample ports from top to bottom. The turbidity of each of the samples was measured with the help of a digital turbidity meter. Then, the percentage removal of the turbidities was calculated from their initial turbidity readings at time zero.

Figure 2.4 Settling column of diameter 18.5 cm and 30 cm (Pise, 2011)

2.3 Introduction to Kynch Theory

2.3.1 Introduction

Discrete particle settling refers to the sedimentation of individual particles when the solids content of a suspension is relatively low, and this type of settling is accurately explained by Stokes' Law (1851) and a formulation was presented by Einstein (1911). Other researchers such as Burgers (1942) engaged in research studying the problem in situations where the solids content of particles was relatively low, and in which the size of particles was much smaller than the distance between two particles (Kynch, 1952).

Kynch was the first person to present a formulation of the theory of sedimentation. He published his paper, *A Theory of Sedimentation* in 1952 and suggested a mathematical description of the batch sedimentation of an initially homogeneous suspension based on the movement of the interface between supernatant water and suspension, along with the propagation of the sedimentation wave in the suspension (Kynch, 1952). Since the formulation of the Kynch Sedimentation Theory, researchers have used the theory to develop thickener design methods. However, this theory fails to accurately detail the sedimentation of flocculated suspensions employed in mineral processing or mining field (Concha and Bustos, 1987, 1997).

2.3.2 Assumptions in Kynch Theory

Kynch made the assumption that the falling velocity of particles depends only on the local concentration of particles. This assumption ignores the presence of forces on particles. It has been found that Kynch theory predicts the existence of an upper interface that separates the supernatant water from the suspension (Pane, 1985). The motion of this interface, together with knowledge regarding the initial distribution of particles is sufficient for determining the variation of the velocity of fall with the density for that particular suspension. Besides, the theory also predicts the existence of layers in the suspension where the concentration suddenly changes its value. Experimental observations suggest that discontinuities do occur in certain suspensions with soils (Been, 1980; Imai, 1980). The theory is able to predict various different modes of settling which may occur. However, only one mode is examined in detail in this research.

Main assumptions of the theory are:

- The velocity of downward movement of particles v_p only depends on the local particle concentration ρ, the concentration means the number of particles per unit volume of the suspension;
- The velocity of downward movement of particles v_p tends to 0 as the concentration tends to a maximum value ρ_m;
- In every instance the concentration is the same across any horizontal layer in the suspension;
- The particles are of the same size and shape;
- The wall effects can be ignored.

Since the definition of concentration ρ here refers to the number of particles per unit volume, it is convenient to introduce the particle flux

$$\boldsymbol{S(\rho) = v_p(\rho) * \rho} \quad \textbf{(2.1)}$$

which is the number of particles crossing a horizontal section per unit area per unit time. Based on the first assumption, particle flux S(ρ) is also determined by the particle concentration. As the particle concentration increases from zero to its maximum value ρ_m, the velocity of fall of particles v_p decreases continuously from a maximum value μ to zero. Kynch theory presents various flux modes and claims that the variation of S(ρ) is more complicated. However, for the convenience of exposition, a simplest relationship is assumed in his paper. Since flux S(ρ) is a function of ρ, flux is zero at ρ=0 and $\rho=\rho_m$, a smooth curve with a maximum value can be assumed.

2.3.3 Continuity Equation of Kynch Theory

The main equation of Kynch theory is the continuity equation. The derivation below follows Kynch, 1952. In the process of sedimentation, ρ varies with space and time. Let x be the height of any level measured from the bottom of the column of the suspension and t be the time of settling, the particle concentration can be presented as a function of x and t, so that

$$\boldsymbol{\rho = \rho(x, t)} \quad \textbf{(2.2)}$$

If the particle concentration ρ varies with x, the flux should vary with x as well since flux is also determined by ρ. The relationship between particle concentration and flux is the continuity equation. Consider two layers at x and x+dx, as shown in Figure 2.5. Over a time period of dt, the accumulation of particles between the two layers should equal to the flow in through the upper layer x+dx minus the flow out of the lower layer x. This can be expressed as:

$$\frac{\partial(\rho dx)}{\partial t} dt = S(x + dx)dt - S(x)dt \quad \textbf{(2.3)}$$

This is the original form of the continuity equation. Dividing by dxdt, the continuity equation can be written as:

$$\frac{\partial \rho}{\partial t} = \frac{\partial S}{\partial x} \quad \textbf{(2.4)}$$

Combined with Equation 2.2, this equation can be rewritten as:

$$\frac{\partial \rho}{\partial t} - \frac{\partial S}{\partial \rho}\frac{\partial \rho}{\partial x} = o \quad \textbf{(2.5)}$$

Together with Equation 2.1, S is a function of ρ, and the equation above can be written as

$$\frac{\partial \rho}{\partial t} + V(\rho)\frac{\partial \rho}{\partial x} = 0 \quad \textbf{(2.6)}$$

where

$$V(\rho) = -{}^{dS}/_{d\rho} \quad \textbf{(2.7)}$$

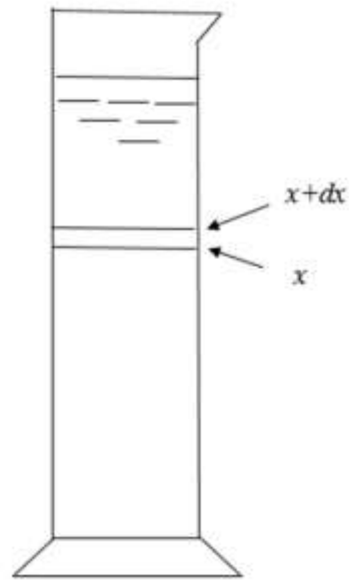

Figure 2.5 Two close layers in the column settling test

In order to visualize a characteristic, refer to the diagram in Figure 2.6. Curves are drawn through all the heights x where the concentration values are the same at different times, meaning that the concentration is constant along those curves. The coordinates (x,t) and (x+dx, t+dt) of two adjacent points on one of the curves are related by the equation

$$\boldsymbol{\rho(x,t) = \rho(x+dx, t+dt)} \qquad \textbf{(2.8)}$$

On account of Equation 2.2, this equation can be written as:

$$\boldsymbol{\frac{\partial\rho}{\partial x}dx + \frac{\partial\rho}{\partial t}dt = 0} \qquad \textbf{(2.9)}$$

Combining Equations 2.6 and 2.9, a new equation can be obtained:

$$\boldsymbol{{dx}/{dt} = V(\rho)} \qquad \textbf{(2.10)}$$

which gives the slope of the curve. Since the concentration on this curve is constant and V(ρ) is a function of ρ, V(ρ) is also constant along the curve. In this case, all the curves should be straight lines as in Figure 2.6. In fact, the variation of V(ρ) with ρ determines the behavior of suspensions during the process of settling. V(ρ) also indicates the velocity of a special value of concentration which propagates upwards with the suspension, which is defined by Equation 2.7.

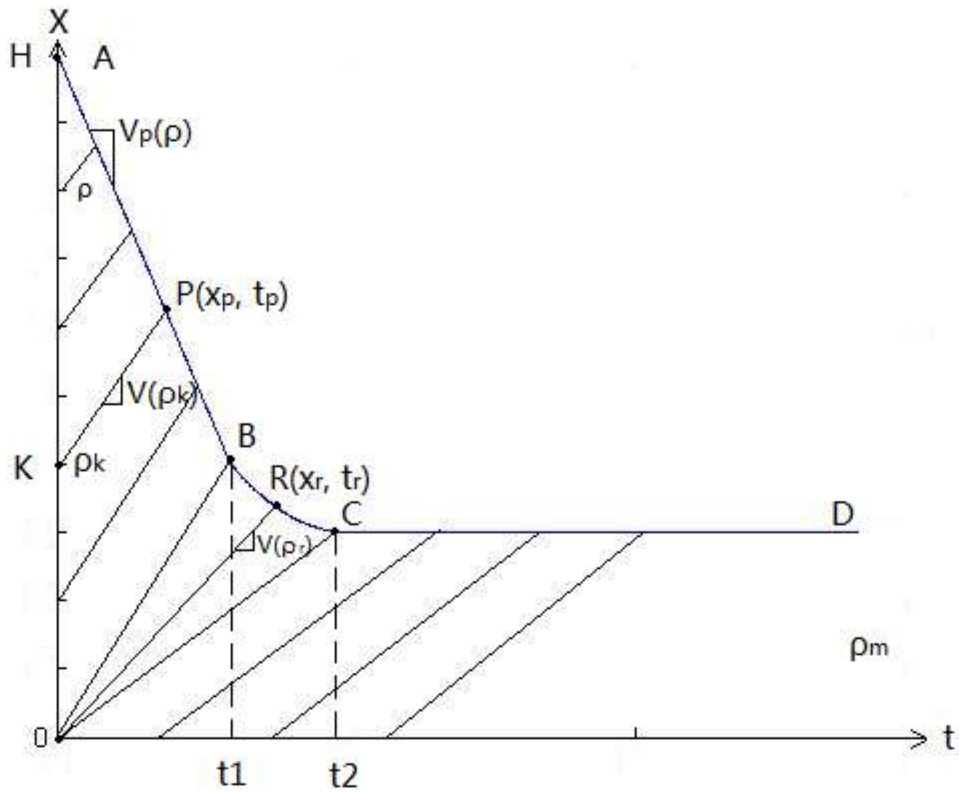

Figure 2.6 Settling curve based on Kynch theory (Pane, 1985)

2.3.4 Calculating Sedimentation of a Suspension

The details regarding the sedimentation of a suspension are discussed in this section. It can be assumed that within a column, a suspension with initial concentration increasing from top to bottom is present. V(ρ) decreases with the change of concentration. Lines of constant concentration are drawn in a coordinate system of x and t, as shown in Figure 2.6. Some sublines have been drawn to help readers understand. A line KP with a constant concentration value ρ_k, which intersects the x axis at K and the line AB at P. Line KP has a slope of $V(\rho_k) = d\rho_k / dt$

since the initial concentration at point K is ρ_k . Let us assume the relationship of x and the initial concentration ρ are known, then all the lines with constant concentrations can be drawn. Since V(ρ) decreases with the increase of the concentration ρ, meaning the slope of all these lines decreases as the value of x decreases from the top value H to 0, all the lines diverge as they depart x axis and no intersection occurs. If any line with a constant concentration crosses the x axis at x_o, the equation of this line can be expressed as:

$$\boldsymbol{x = x_o + V(\rho_o)t} \tag{2.11}$$

where ρ_o is the value of concentration when x is equal to x_o , and V(ρ) is also defined by Equation 2.7:

$$\boldsymbol{V(\rho_o) = -{dS}/{d\rho_0}} \tag{2.12}$$

Since the relationship between x_o and ρ at t=0 is known, this equation provides the concentration of any point x in the suspension at a certain time.

All the lines of constant concentration can be seen as a propagation of a certain level in the suspension. When the propagation reaches the interface of the supernatant water and suspension, the propagation ends. It is easy to identify the termination of all the lines with constant concentration as the line AB represents the fall of the interface between the supernatant water and the suspension. In order to calculate the position of the line AB, the position of any point P and then the co-ordinates of point B (x_1, t_1) need to be determined. At any point P, the velocity of downward movement of the interface is determined by the velocity of the particles on this interface. This can be expressed as:

$$\boldsymbol{v_p(\rho) = {dx}/{dt}} \tag{2.13}$$

where dx and dt are along the curve AB, which is different from Equation 2.11.

Line KP represents an upward propagation of a specific level K on which the concentration is constant ρ_o. This also means that the velocity of the propagation is $V(\rho_o)$ and the velocity of the particles falling through this level is v_p (ρ_o). When $t=t_p$, the sum of particles which have crossed this level is

$$\boldsymbol{n(x_o) = \rho\left(V(\rho_o) + v_p(\rho_o)\right) * t_p} \quad \textbf{(2.14)}$$

The number of particles passing this level K is equal to the number of particles that was originally above this level when the propagation reached the interface. Since we know that the concentration varies with the height x, the total particles crossing level K can also be expressed as:

$$\boldsymbol{n(x_k) = \int_{x_k}^{H} \rho d(x)} \quad \textbf{(2.15)}$$

Together with Equations 2.14 and 2.15, time t can be calculated.

Based on the derivation of Kynch theory conducted by Pane (1985) , the original suspension can be considered to be homogeneous at the very beginning, that is to say the original concentration is constant along the x axis when t=0. Based on this assumption, Equation 2.15 can be calculated and expressed as:

$$\boldsymbol{n(x_k) = \rho_o(H - x_k)} \quad \textbf{(2.16)}$$

where x_o is the height of a certain level in the suspension, and ρ_o is the initial concentration of the suspension at t=0. Together with Equation 2.14, t_p can be given by:

$$\boldsymbol{t_p = \frac{H - x_k}{V(\rho_0) + v_p(\rho_0)}} \quad \textbf{(2.17)}$$

The x value of any point P is given by the Equation 2.11. Since t_1 is calculated, x_1 can be written as:

$$x_p = x_k + V(\rho_o)t_p \tag{2.18}$$

or

$$x_p = H - v_p(\rho_o)t_p \tag{2.19}$$

The minimum value of x_k is 0. When x_k=0, the co-ordinates of point B can be calculated from Equation 2.17 and Equation 2.19:

$$t_1 = \frac{H}{V(\rho_o)+v_p(\rho_o)} \tag{2.20}$$

and

$$x_1 = H - v_p(\rho_o)t_1 \tag{2.21}$$

The above equations can only describe the settling process before t_1, which means the settling behavior or the fall of the interface after t_1 is no longer determined by the initial concentration of the suspension. Based on Kynch theory, lines below the line OB which start from the t axis are determined only by the end conditions at x=0 at the bottom of the container in the suspension. In order to find the curve BC, a reasonable assumption is made that there is a continuous but extremely rapid increase of concentration from ρ_b to the maximum concentration ρ_m near point O. Since V(ρ) is determined by concentration, line OB has a slope of $V(\rho_b)$, and line OC has a slope of $V(\rho_m)$. Let us consider a level with concentration ρ_r between ρ_b and ρ_m. As such, the equation of this line OR should be:

$$x = V(\rho_r)t \tag{2.22}$$

To find the position of line BC, the method discussed previously is also used. From Equations 2.8 and 2.15, the total number of particles crossing the level OR can be expressed as:

$$\boldsymbol{N = \rho_r(V(\rho_r) + v_p(\rho_r))t_r} \quad \textbf{(2.23)}$$

and

$$\boldsymbol{N = \int_{x_o}^{H} \rho dx} \quad \textbf{(2.24)}$$

where x_o=0, and N is the total number of particles in the suspension.

Since the original concentration is constant along the x axis, t_r is given by:

$$\boldsymbol{t_r = \frac{H\rho_o}{\rho_r[V(\rho_r)+v_p(\rho_r)]}} \quad \textbf{(2.25)}$$

So, when ρ_r is equal to ρ_m, the co-ordinates of point C can be calculated:

$$\boldsymbol{t_2 = \frac{H\rho_o}{\rho_m[V(\rho_m)+v_p(\rho_m)]}} \quad \textbf{(2.26)}$$

Since the original assumption is that the velocity of downward movement of particles v_p tends to 0 as the concentration tends to a maximum value ρ_m, Equation 2.26 can be written as:

$$\boldsymbol{t_2 = \frac{H\rho_o}{\rho_m V(\rho_m)}} \quad \textbf{(2.27)}$$

The final height h_f can be found easily if we know the maximum concentration ρ_m. Since the total number of particles in the suspension is a constant value,

$$\boldsymbol{N = \rho_o H = \rho_m h_f} \quad \textbf{(2.28)}$$

From Equation 2.28, the final height h_f is given as:

$$\boldsymbol{h_f = \frac{H\rho_o}{\rho_m}} \quad \textbf{(2.29)}$$

2.3.5 Studies and Development of Kynch Theory

McRoberts and Nixon (1976) first expanded on Kynch theory to consider soil sedimentation through the analysis of mathematical formulas and experimental data (Nixon and McRoberts, 1976). They claimed that, for the dispersion of grained particles prepared in a low concentration, there is a time period in which the movement of the interface between the dispersion and water settles in a linear fashion. This phenomenon functions according to the theory of hindered settling. However, as the settling continues, soil is being formed at the base of the dispersion, and eventually the settlement of the interface is governed by consolidation theory as effective transmission occurs in the soil skeleton. McRoberts and Nixon (1976) suggested modifications to Kynch theory and also combined it with Richardson and Zaki's equation to predict the settlement of thick dispersions of soil grains. McRoberts and Nixon (1976) introduced an experimental method to determine the maximum water content at which hindered settling behavior is no longer possible. Been (1980), Been and Sills (1981) and Imai (1980, 1981) also performed experimental studies with the sedimentation of clay materials and analyzed their experimental results according to Kynch theory.

A modification of Kynch theory was made by Concha and Bustors in 1987. Fernando Concha claimed that Kynch theory is no longer valid when the concentration of the suspension exceeds a certain point. Choncha and Bustors suggested that Kynch theory should only represent the sedimentation of flocculated suspensions with low compressibility. If the compressibility of a suspension is relatively large, the line AB discussed above can be curved (Concha and Bustors, 1987).

Research on non-colloidal sedimentation was conducted by Chang in 1996. In his study, experimental suspensions were prepared by mixing lubricant oil and glass beads. Magnetic resonance imaging (MRI) technology was employed to measure the concentration of the suspension. The results were compared with Kynch theory and showed that the interfaces obtained kept the characteristics of Kynch sedimentation (Chang et al., 1997).

Chapter 3: Experimental Apparatus and Methodology

3.1 Introduction

This research involves the use of various tests in order to investigate the physical properties and sedimentation behaviors of test materials. The tests employed in this thesis are i) particle size distribution test, ii) column settling test, iii) column settling test with a sample-collection, and iv) turbidity measurement test. All the details and procedures of the tests are introduced in this chapter. A new apparatus was designed and constructed to complete the column settling test with a sample-collection ending. The turbidity test was conducted through using a turbidimeter.

3.2 Test Samples

3.2.1 Copper Tailings

All of the tailings samples (copper tailings) were from the Quebrada Blanca mine in Chile, and was provided to UBC by Golder Associates. Particle size distribution is presented in Figure 3.1. The original pH of the tailings was not measured. Since Kynch theory ignores all the chemical and physical forces between particles, no further analysis on the influence of pH values will be discussed. The original solids content of the total tails measured at UBC was found to be 69.7%.

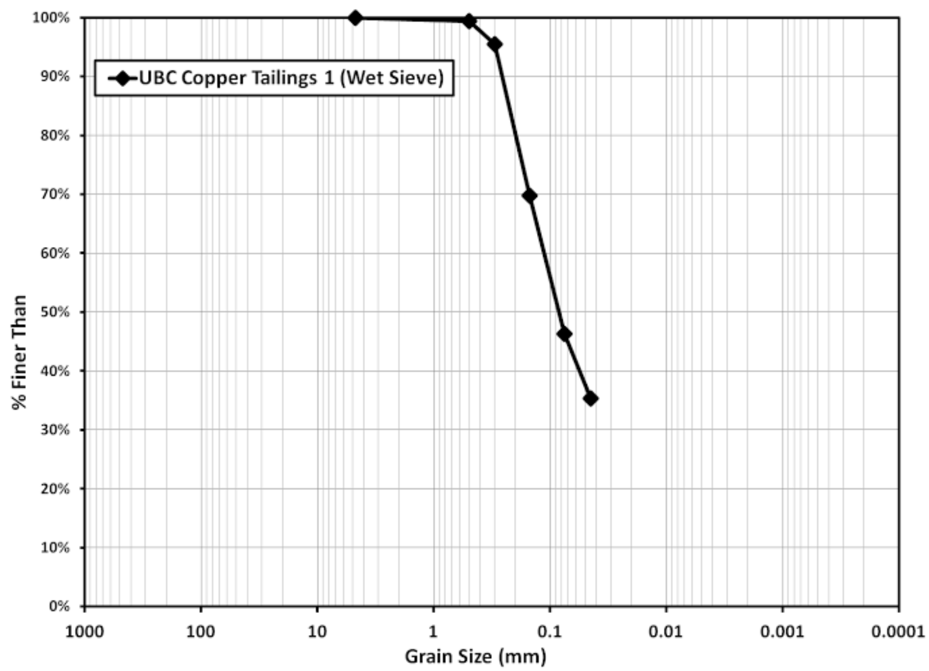

Figure 3.1 Particle size distribution of the copper tailings (Estepho, 2014)

3.2.2 Copper Tailings with Different Particle Sizes

Several assumptions are made in Kynch theory in order to confine the conditions in which the theory can be applied. One of the assumptions which is relevant to the settling of material is that all the particles are of the same size and shape. In practice, tailings materials with particles which are of the same size and shape can never be obtained. In order to decrease the influence of particle size and study Kynch theory, the total tails of the copper tailings sample was divided into different sized fractions. Column settling tests on different fractions of copper tailings were carried out to investigate the settling behavior.

Sieve analysis provides a simple but effective method of separating sand materials into different sized fractions. In most cases, sieve analysis is conducted on dry materials. However, wet sieving is applied when the material is too fine, and dry sieving can't produce an effective degree of separation.

The particle analysis distribution curve from Estepho (2014) illustrates that around 35% of the total tails were finer than 74 μm, so a wet sieving test was selected in order to classify the total tails into different fractions. The total tails of copper tailings were divided into different fractions with different particle sizes. There were eight ranges:

- Particle size < 37 μm
- 37 μm < Particle Size < 53 μm
- 53 μm < Particle Size < 74 μm
- 74 μm < Particle Size < 106 μm
- 106 μm < Particle Size < 150 μm
- 150 μm < Particle Size < 210 μm
- 210 μm < Particle Size <297 μm
- Particle Size > 297 μm

After wet sieving was completed, materials with different particle size ranges were collected in different trays and dried in the oven. Samples with particle sizes larger than 37 μm acted as separate grains of sand after drying, while the samples with a particle size smaller than 37 μm were in the form of clay or clusters. All samples were stored in different containers for further use.

3.3 Experimental Apparatus for Column Settling Test with Sample Collection

3.3.1 Introduction of the Experimental Apparatus

The conventional settling column could not satisfy the requirements for the column settling test with sample-collection. As such, a new apparatus was designed and constructed. The specially-made experimental apparatus consists of four components: settling columns, a pushing device, a stand which is used to fix the settling columns, and a top piece to collect samples from the settling column.

The first part is the settling column that is used for the column settling test. The column is made of PVC pipe with a base that is used to fix the column on a stand. Figure 3.2 shows the settling column and the bottom piece with two O-rings on it. The diameter of the column is 2.5 inches, and the length of it is 16 inches. The column is similar to a hollow pipe. A removable bottom piece is added so that it can form a container. Two O-rings were used on the bottom piece to prevent leakage and to help the bottom piece move smoothly and stably in the column. After putting the bottom piece on, the volume of the column was recorded as 800 ml. The settling column was marked height-wise, recording every 100 ml. Each 100 ml was further divided into eight intervals of 12.5 ml.

Figure 3.2 The settling column and bottom piece

For the conventional column settling test, the movable bottom piece was fixed on the bottom side of the column so that it could function as a normal settling column. A pushing device was designed to perform a sample-collection for the column settling test. This was used to push the bottom piece of the settling column up. As shown in Figure 3.3, with the bottom piece being pushed up, the samples in the column move up and are collected into the specially designed top piece.

Figure 3.3 The top piece which is used to collect samples at the end of column settling tests

A stand was built to hold the five columns down with screws by fixing the bottom part of the settling column to the stand. Below the columns, a track was designed to fix the pushing device. As shown in Figure 3.4, this track also allows the pushing device to move horizontally to different positions.

Figure 3.4 Five settling columns on the stand

3.3.2 Employment of the Experimental Apparatus

In the column settling test with sample-collection, settling columns were filled with tailings samples and fixed on the top of the stand to perform the column settling tests. The pushing device was placed on the track and fixed right below the first column. All the column settling tests were destroyed at the end of the test in a specific order. Once the sedimentation of the first set was completed, the collection device was fixed on the top of the column, and the pushing device was used to push the sample out from the top. The pushing screw was moved up slowly and the sample was pushed into the collection device. Beakers were used to collect samples for other uses. In order to divide the samples into different fractions, beakers were used to store the samples from different heights of the suspension. After the sample collection process of the first set was completed, the pushing device needed to be screwed back and moved to the position below the second column. The collection device also needed to be removed from the first column and placed on the second one. The collection operation was repeated when the interface in the second column reached a certain point. After all the column settling tests with sample-collection were completed, the column was removed from the stand for cleaning. See Figure 3.4 for the schematic.

Step 1: Prepare test samples, fill the settling columns with the prepared samples. Fix all the columns on the stand and place the pushing device below the first column.

⇩

Step 2: When the upper interface in the first set reaches a certain height, use the pushing device to push the suspension out and collect the samples with beakers.

⇩

Step 3: When the samples in the first column are all pushed out, move the pushing device to the position below the next

⇩

Step 4: Repeat the procedure of step 2 and step 3 till the last suspension in the last settling column is sampled.

Figure 3.5 Schematic of the sample collection operation

3.4 Experimental Procedure

3.4.1 Introduction

The column settling test was briefly introduced in Chapter 2. The column settling test with sample collection in this research refers to a column settling test followed by a sample-collection operation when the test ends. The suspension in the column was pushed up and collected in layers with a specially made apparatus. Using this method, high quality data could be gathered regarding what had occurred inside column. The column settling test and the column settling test with a sample-collection provide the main components of this research. These tests were conducted on different samples to get the settling curve and solids content distribution curve along the height of the settling column. With the results obtained from these tests, further analysis was conducted to investigate the applicability of Kynch theory to the tailings.

3.4.2 Procedure of Column Settling Test

The column settling test is a simple test that is always conducted in a column or a cylinder. After the samples are fully mixed, they are ready for the column settling test, and are processed as follows:

- Pour the sample into the 800 ml column (the column that was specially made for this research),
- Seal the top and shake the column up and down 30 times, and then place it on the stand,
- This is when the test starts, the time is recorded, and then recorded again when the interface drops by a 12.5 ml interval.

3.4.3 Procedure of Column Settling Test with Sample Collection

Since the column settling test with sample collection consists of a column settling test and sample collection operation when column settling test ends, the first three steps of this test are exactly the same as with the conventional column settling test. At the beginning, several sets of column settling tests are performed. When one specific column-settling test is finished, the pushing device is used to push the sample out the top of the settling column. For this research, suspensions in the columns were pushed out and collected in beakers every time the interface dropped 50 ml along the settling column from the top. In other words, the first set was sampled when the interface reached 750 ml, and the second set was sampled when the interface reached 700 ml. Once the sample collection process started, the samples were pushed out slowly using the specially made apparatus. Every time the sample was pushed out from the top by a certain amount, a beaker was used to collect and contain the sample for further use. For this study, every 50 ml sample was stored in its own beaker. The first set used 15 beakers to store all the samples. When all the samples had been pushed out, 15 samples from the different layers of the column were collected for further use.

3.5 Column Settling Tests with Different Initial Solids Contents

3.5.1 Introduction

Kynch theory provides a description of hindered settling. According to Kynch theory, the most important observation target is the interface between the supernatant water and the suspension below it. In order guarantee the formation of interfaces in the following column settling tests and column settling tests with sample-collection, two parameters should be determined in advance:

solids contents of the suspension in which clear interfaces can form and particle size ranges in which hindered settling can occur. The issue of solids content is examined in this section and following section will discuss the ranges of particles size.

According to what was noted in the introduction to sedimentation in Chapter 2, the interface between the water and suspension develops in hindered settling, and hindered settling occurs when the concentration of the suspension is relatively high. In this case, a series of column settling tests on samples with different solids contents should be done to obtain the range of the solids contents in which a clear interface can form.

3.5.2 Column Settling Test and Turbidity Measurement

Five sets of column settling tests were performed on the total tails of copper tailings with different initial solids contents. The solids contents were 15%, 20%, 25%, 30%, and 35%. Samples were mixed in a 1L beaker and decanted into the settling columns. After shaking the column up and down 30 times, the columns were placed on the table for observation. For those sets in which the interfaces between the supernatant water and the suspension formed, samples of supernatant water were taken from the 25 ml mark above the interface for turbidity measurement. Turbidity measurement was done with a HACH 2100AN Turbidimeter, as shown in Figure 3.6.

Figure 3.6 HACH 2100AH Turbidimeter

3.5.3 Results and Conclusions

Observations were made during the settling tests. For the first set in which the original solids content was 15%, no interface was observed, which is shown in Figure 3.7. No sample was taken from the first set and one sample was taken from each of the rest. Observations were made on the rest of the four sets and are shown in Figure 3.8. The results of the turbidity measurement are shown in Table 3.1 and Figure 3.9.

Figure 3.7 Settling column test of copper tailings with an initial solids content of 15%

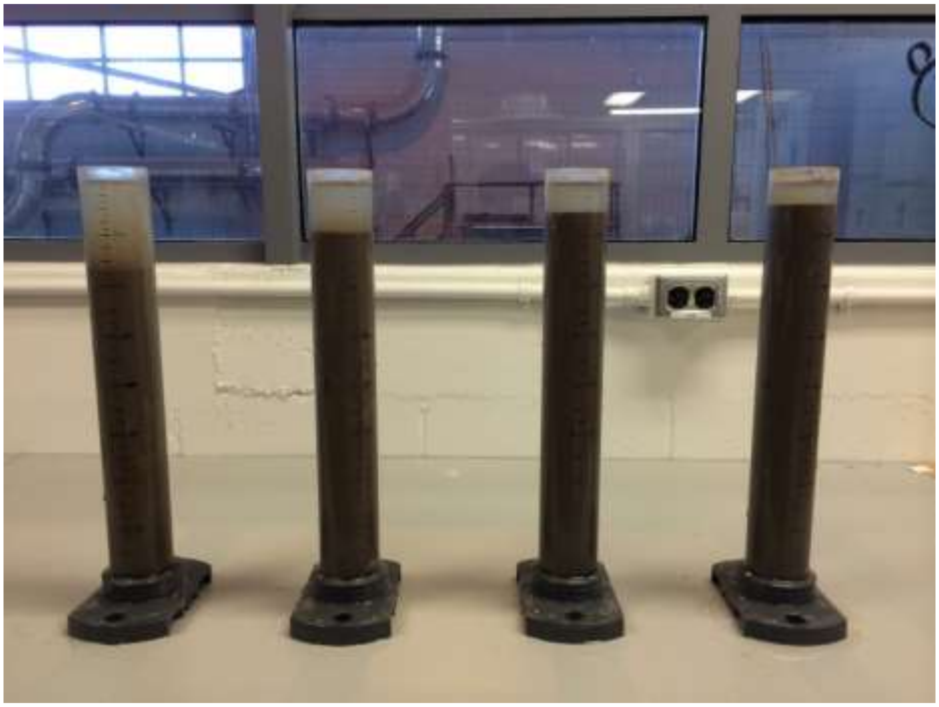

Figure 3.8 Settling column test of copper tailings with an initial solids contents of 20%, 25%, 30% and 35%

No	2	3	4	5
Solids Content	20%	25%	30%	35%
Turbidity	876ntu	365ntu	138ntu	137ntu

Table 3.1 Results of the turbidity measurement with different initial solids contents

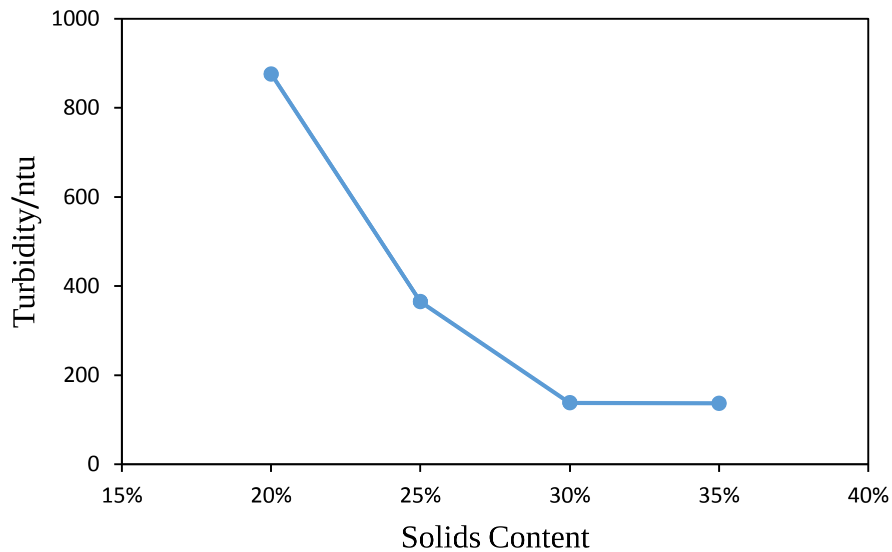

Figure 3.9 Results of turbidity under various conditions with different solids contents

It was noticed that the turbidity of the supernatant water, which was taken from the position that was 25 ml higher than the interface, decreases with an increase of the initial solids content when it's low. The differences between Set 2, Set 3 and Set 4 are obvious. The turbidity of samples with 30% and 35% original solids contents were found to be almost the same, signifying that when the initial solids content is high enough, a stable clear interface develops, and the turbidity of the supernatant water remains the same. In other words, when the value of the solids content exceeds 30%, hindered settling occurs and all particles in the suspension settle as an entire mass.

In order to get clear interfaces and make sure that the sedimentation that occurs in our tests is hindered settling, 35% and 40% were selected as the designed initial solids contents for later column settling tests.

3.6 Column Settling Test on Different Size Fractions of Copper Tailings

3.6.1 Introduction

In order to conduct column settling tests and column settling tests with sample-collection on copper tailings with different particle sizes, the original tailings samples were divided into eight fractions. The details for this have been described in Chapter 3.2.2. A small-scale column settling test should be done to investigate in which fractions hindered settling will occur. Since it is known that materials with particle sizes larger than 74 μm (200 mesh) are defined as sands, and sands will only settle discretely, copper tailings fractions with particle sizes smaller than 74 μm were selected to conduct column settling tests on a small scale.

3.6.2 Procedure of Column Settling Test

Three sets of column settling tests were conducted on a small scale with 250 ml cylinders on samples with different particle size ranges. For each set, 100 g dry samples were mixed with 186 g distilled water to make a mixture with a solids content of 35%. After being shaken up and down for 30 times, the three cylinders were placed on the table for observation.

3.6.3 Results and Conclusions

Observations were made on the three column settling tests to investigate whether hindered settling can occur. The observation target is the development of the interface between the supernatant and the suspension. The results are show in Table 3.2.

No	Particle Size Range	Interface	Description
1	0-37 µm	Yes	Interface was observed in around two minutes, small clusters were also observed on the bottom of the cylinder
2	37 µm – 53 µm	No	No clear interface was observed. Particles settled discretely. Accumulation of coarse particles was observed on the bottom of the cylinder.
3	53 µm – 73 µm	No	No interface was observed. Particles settled discretely. Accumulation of coarse particles was observed on the bottom of the cylinder.

Table 3.2 Results of column settling tests on different sized fractions

The development of an interface only occurred in the first set of the three tests, signifying that hindered settling did not happen during the sedimentation of samples with particle sizes larger than 37 µm. Further tests should be conducted on samples with particle sizes smaller than 37 µm.

Big clusters were observed on the bottom of the column in the first set of tests. This can be viewed as a sign of segregation. The reasons for the formation of clusters are various. One possible reason would be that it was the result of the chemical additives added to the tailings during processing.

Chapter 4: Results and Discussion

4.1 Introduction

In this chapter, the results of column settling tests and column settling tests with sample-collection are presented and discussed in detail. For clarification, a summary of tests are listed in Table 4.1.

Test Name and Figure	Condition	Description
Settling column test 1.1.1, 1.1.2, 1.1.3	Solids content: 35% Samples: total copper tailings	Mixed in a beaker with a stirrer
Settling column test 1.2.1, 1.2.2, 1.2.3	Solids content: 40% Samples: total copper tailings	Mixed in a beaker with a stirrer
Settling column test 1.1.1-2, 1.1.2-2	Solids content: 35% Samples: total copper tailings	Mixed directly in the settling columns
Settling column test 1.2.1-2, 1.2.2-2	Solids content: 40% Samples: total copper tailings	Mixed directly in the settling columns
Settling column test with sample-collection 1.1.4, 1.1.4-2, 1.1.5, 1.1.5-2	Solids content: 35% Samples: fine copper tailings	Sampled when the interface reached 750 ml and 700 ml
Settling column test with sample-collection 1.2.4, 1.2.4-2, 1.2.5, 1.2.5-2	Solids content: 40% Samples: fine copper tailings	Sampled when the interface reached 750 ml and 700 ml
Settling column test with	Solids content: 35%	Sampled when the interface

Test Name and Figure	Condition	Description
sample-collection 1.1.6, 1.1.7	Samples: fine copper tailings	reached 650 ml and 600 ml
Settling column test with sample-collection 1.2.6, 1.2.7	Solids content: 40% Samples: fine copper tailings	Sampled when the interface reached 650 ml and 600 ml
Settling column test 2.1.1, 2.1.2	Solids content: 35% Samples: fine copper tailings	Mixed directly in the settling columns
Settling column test 2.2.1, 2.2.2	Solids content: 40% Samples: fine copper tailings	Mixed directly in the settling columns
Settling column test with sample-collection 2.1.3, 2.1.4, 2.1.5, 2.1.6	Solids content: 35% Samples: fine copper tailings	Sampled when the interface reached 750 ml, 700 ml, 650 ml and 600 ml
Settling column test with sample-collection 2.2.3, 2.2.4, 2.2.5	Solids content: 40% Samples: fine copper tailings	Sampled when the interface reached 750 ml, 700 ml and 650 ml
Settling column test 3.1, 3.2, 3.3, 3.4	Solids content: 30% Samples: concrete sand + kaolin	
Settling column test with sample-collection 4.1	Solids content: 40% Samples: fine copper tailings + dispersant	Sampled when the interface reached 750 ml
Settling column test with	Solids content: 20%	Sampled when the interface

Test Name and Figure	Condition	Description
sample-collection 1,2	Samples: kaolin	reached 750 ml

Table 4.1 Summary of experimental tests

4.2 The Results of Tests on Total Copper Tailings

4.2.1 Sample Preparations

Column settling tests and column settling tests with sample-collection were conducted in order to obtain the settling curve and solids content distribution curve of the total tails of copper tailings with solids contents of 35% and 40%. The test samples were prepared by mixing the original copper tailings with distilled water. The proportion of copper tailings and distilled water was calculated according to Equation 4.1 (the specific gravity of copper tailings are 2.7).

$$Solids\ Content = \frac{W_s}{W_s+W_w} \quad (4.1)$$

Based on calculated results, samples of 529 g original tailings and 494 g distilled water were used for each test with a solids content of 35%, and samples of 630 g original tailings and 437 g distilled water were used for each test with a solids content of 40%.

Two mixing methods were employed for the column-settling test. In the first method, the original total tails and distilled water were mixed in a beaker using a stirrer until the samples were fully mixed. Subsequently, the samples were poured into the settling columns. In order to ensure that the columns would be filled with enough of the sample mixture, extra mixture was intentionally made. In the second method, the original total tails and distilled water were mixed directly in the settling column through the method of shaking up and down.

4.2.2 Results of Column Settling Tests

For the first mixing method, six sets of column settling tests (Test 1.1.1, Test 1.1.2 Test 1.1.3, Test 1.2.1, Test 1.2.2, and Test 1.2.3) were conducted. After the tests were initiated, time was recorded at every instance that the interface dropped 12.5 ml along the settling column. The tests were stopped when the interface took more than four hours to drop 1 interval (12.5 ml). This test is illustrated in Figure 4.1. The results are shown in Figures 4.2 and 4.3. Experimental data is listed in Appendix A.

Figure 4.1 Column settling tests on total copper tailings

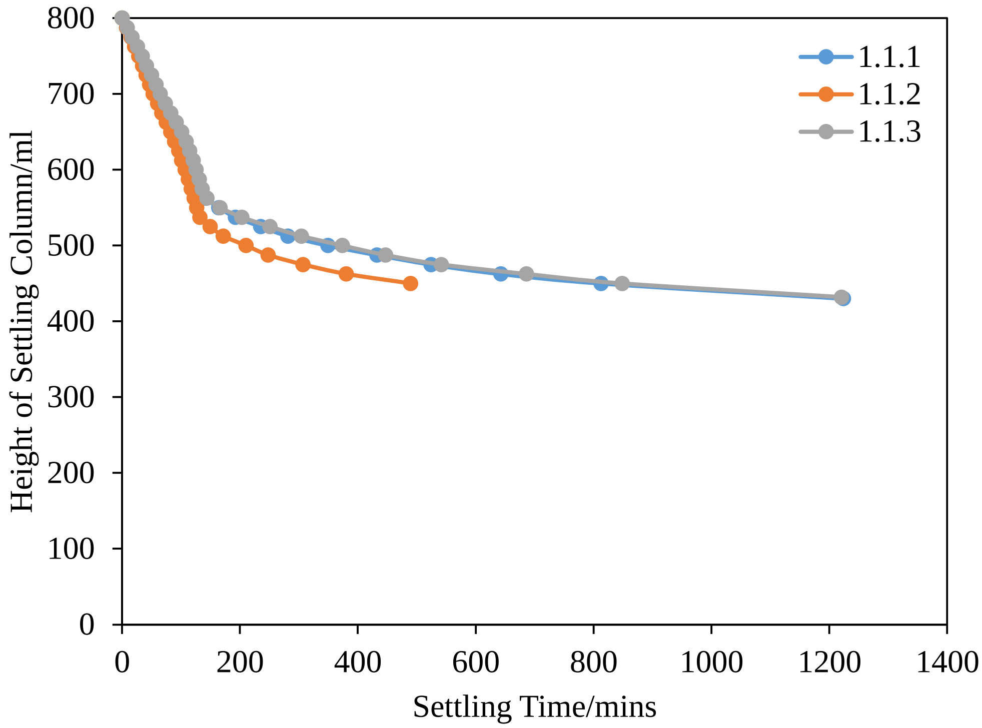

Figure 4.2 Settling curve of total copper tailings with an initial solids content of 35%

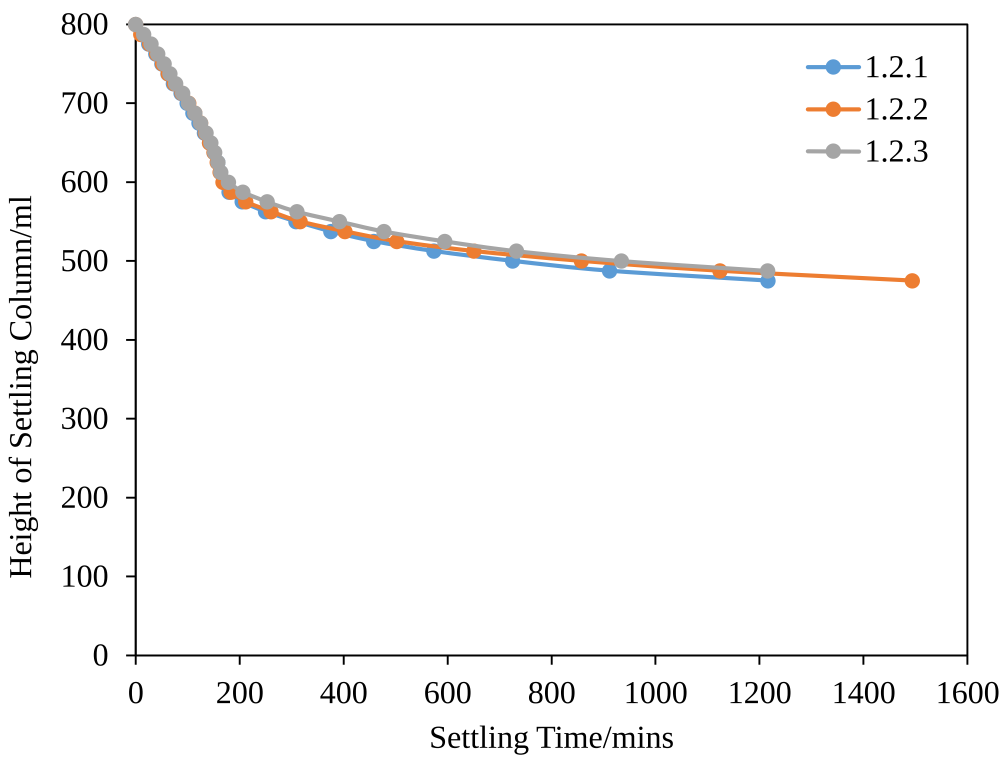

Figure 4.3 Settling curve of total copper tailings with an initial solids content of 40%

For the tests with a solids content of 35%, the results of Tests 1.1.1 and 1.1.3 match, thus guaranteeing the accuracy of those results. The results of Test 1.1.2 have a relatively large deviation from that of Tests 1.1.1 and 1.1.3. A plausible explanation would be the existence of sedimentation in the beaker, and not having stirred enough when the samples were being moved into the settling column, leading to a lower solids content in the settling column. Recording was stopped after noticing the deviation, and the results of Test 1.1.2 are not used with respect to further analysis and discussion.

Since the shapes of the curves in both figures were very similar, the results of tests with solids contents of 35% were chosen for analysis. The curve can be divided into two sections. The first section, from 800 ml to 560 ml is almost a straight line, signifying that the velocity of the downwards movement of the interface was constant. When the interface reached the height of 560 ml, the velocity slowed down dramatically and became increasingly slower. Based on Kynch theory, the only possible reason why the velocity of falling slows down after the interface passes 560 ml is because the interface reaches the propagation wave from the bottom. The final part, which started from a point below 560 ml, can also be viewed as compaction settling. During compaction settling, the structure of the sediment is already formed and future sedimentation only happens through the compression of the whole structure.

On the bottom of the settling columns, large amount of coarse particles were observed, signifying that segregation occurred in those settling column tests. In order to investigate the influence of segregation on sedimentation, a column-settling test with a sample-collection should be done to gain a better understanding on the distribution of the particles in the column.

For the second mixing method, four sets of column settling tests (Test 1.1.2-2, Test 1.1.1-2, Test 1.2.1-2, and Test 1.2.2-2) of the totalcopper tailings with initial solids contents of 35% and 40% were conducted. Recordings were taken for a longer time than had occurred in the first one. The results are shown in Figures 4.4 and 4.5.

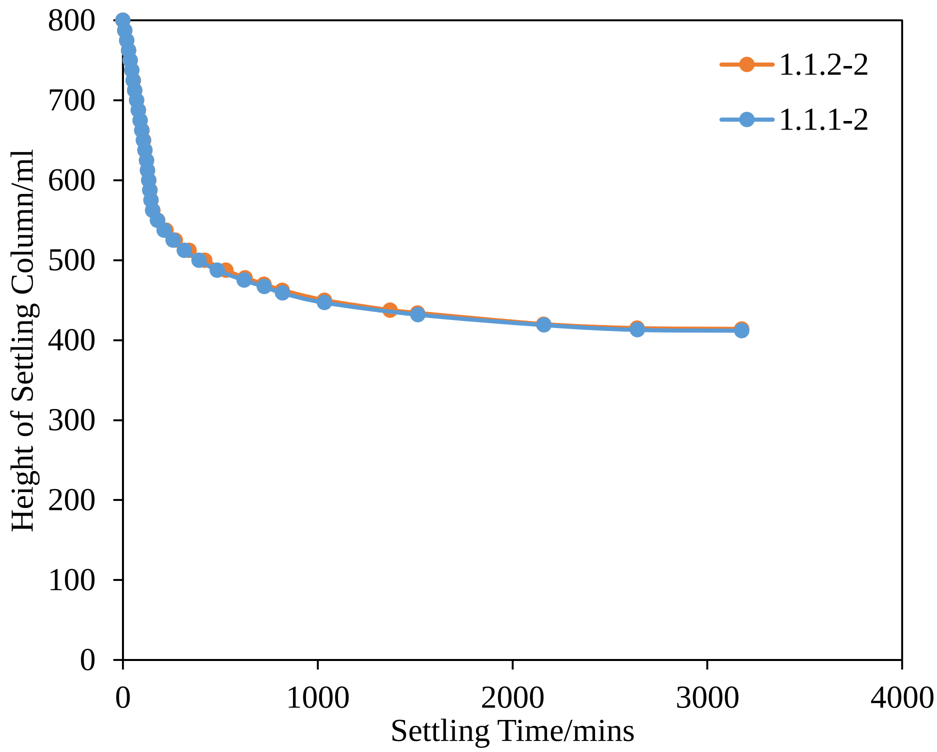

Figure 4.4 Settling curve of total copper tailings with an initial solids content of 35% - 2

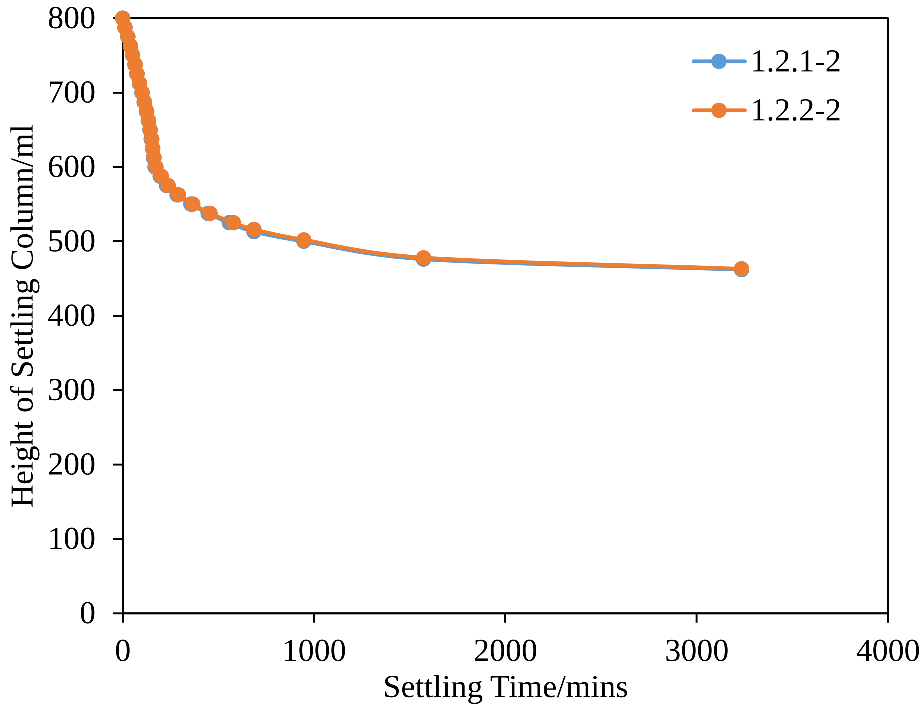

Figure 4.5 Settling curve of total copper tailings with an initial solids content of 40% - 2

4.2.3 Comparison of Two Results

In order to investigate the differences between the first mixing method and the second mixing method, we can examine the differences between the two results, as shown in Figures 4.6 and Figure 4.7.

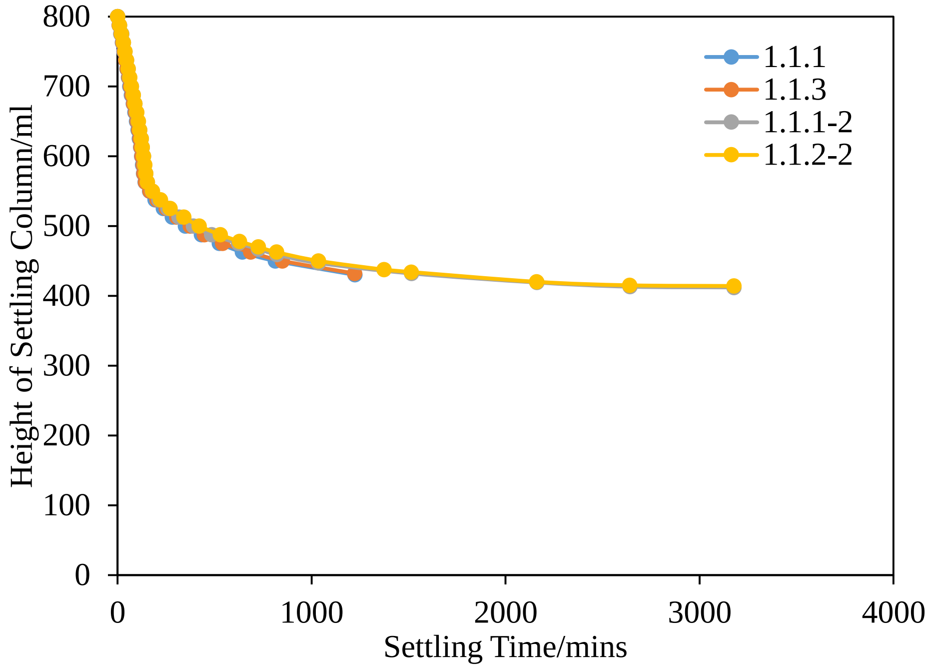

Figure 4.6 Comparison of the two results with solids contents of 35%

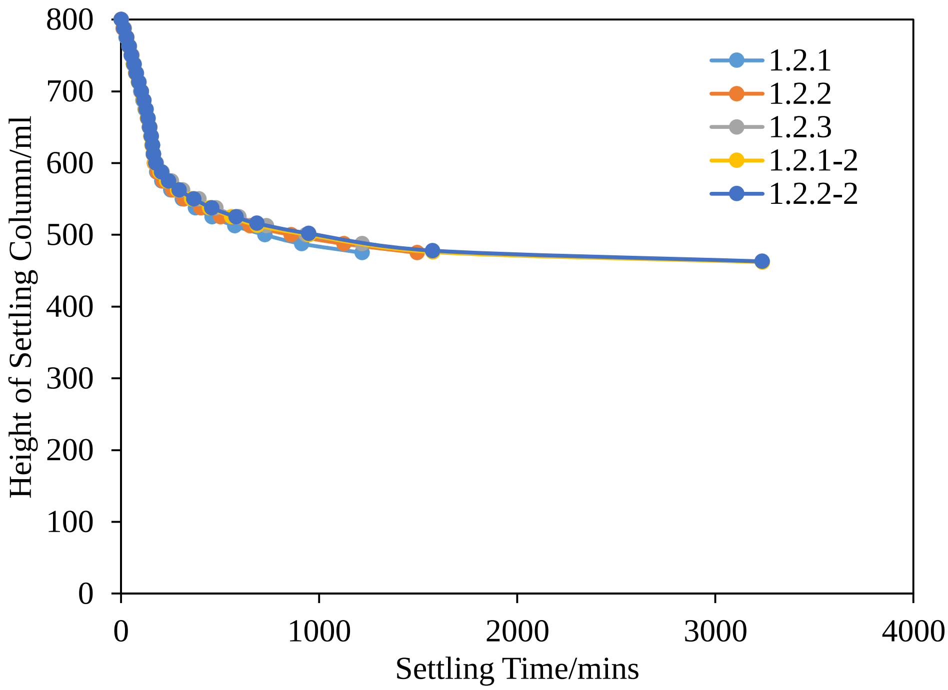

Figure 4.7 Comparison of the two results with solids contents of 40%

Through a comparison of the results of having used the different mixing methods, we can conclude that the mixing method has no influence on the results of sedimentation. Both mixing methods employed in this research can satisfy the mixing requirements and achieve the full mixing of the samples. In the latter tests, the second method of mixing the solution directly in the column and shaking was selected for the rest of the tests since it is more convenient and efficient.

4.2.4 Comparison of the Results between Different Solids Contents

The results of the experiments using solids contents of 35% and 40% are shown in Figure 4.8.

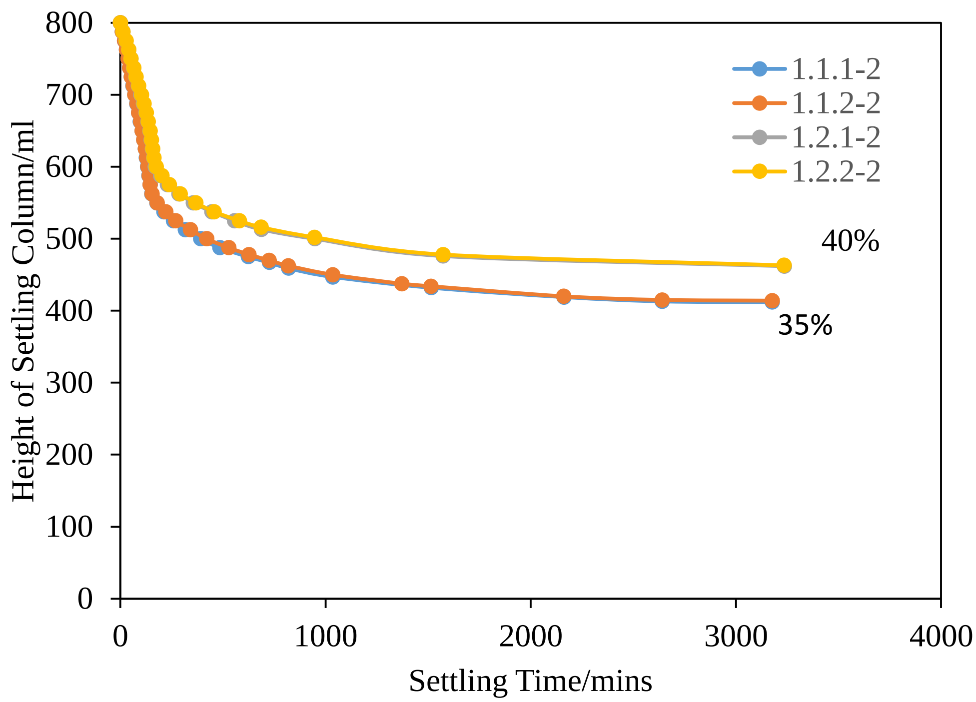

Figure 4.8 Comparison of two results with solids contents of 35% and 40%

Kynch claimed that the velocity of fall of particles is determined only by the local concentration of the suspension. Based on this theory, the comparison of these two results indicates that higher initial solids contents leads to a slower fall of the particles.

4.2.5 Results of Column Settling Tests with Sample Collection

Two sets of column settling tests with sample collection (Test 1.1.4 and Test 1.1.5, Test 1.2.4 and Test 1.2.5) were first conducted on total copper tailings with solids contents of 35% and 40%. The first set was sampled when the interface reached 750 ml, and the second set was sampled when the interface reached 700 ml. Both tests were repeated to examine their accuracy. The samples taken from the column settling tests with sample collection are shown in Figure 4.9. The results are shown in Figure 4.10, Figure 4.11, Figure 4.12 and Figure 4.13. Experimental data is listed in Appendix B.

Figure 4.9 Samples taken from the column settling test with sample collection

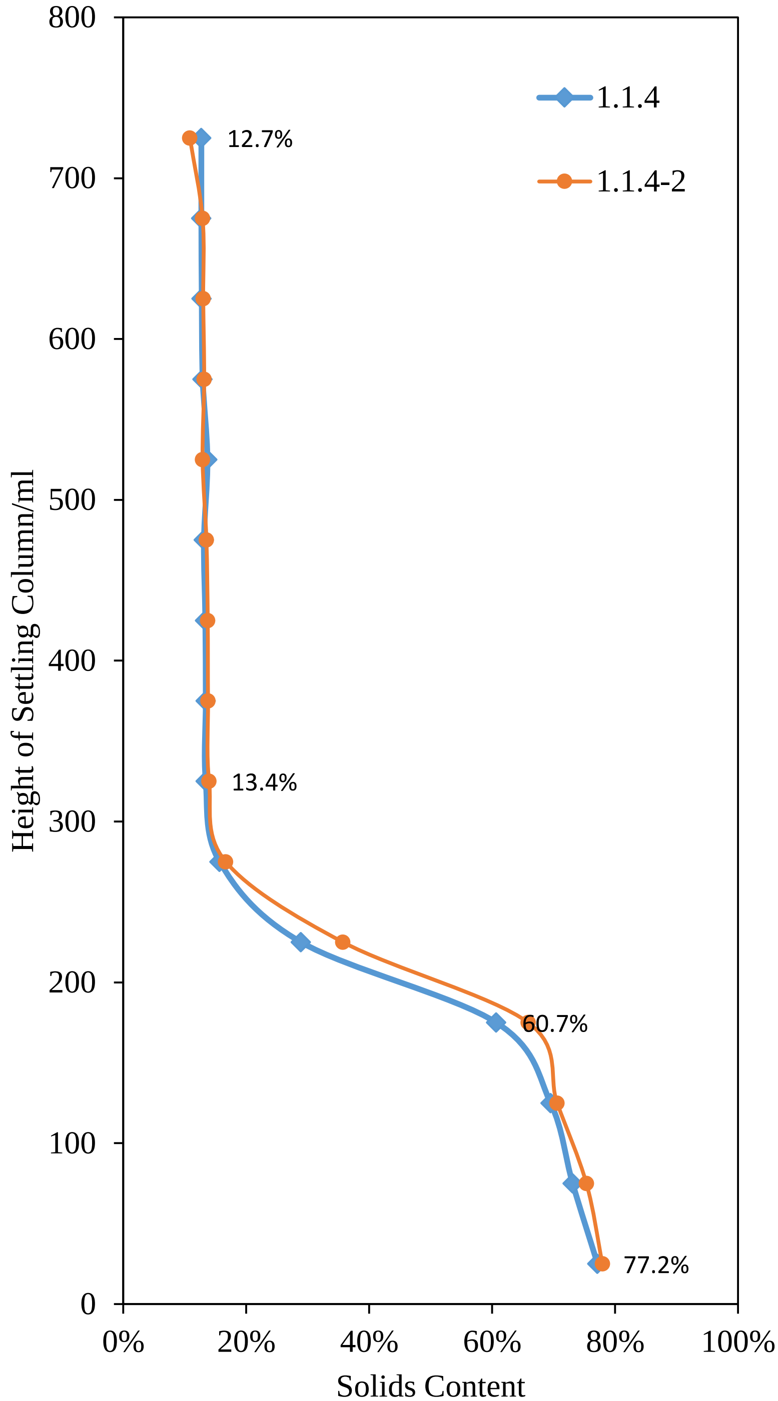

Figure 4.10 Distribution of solids contents (The initial solids content was 35%, sampled when interface reached 750 ml)

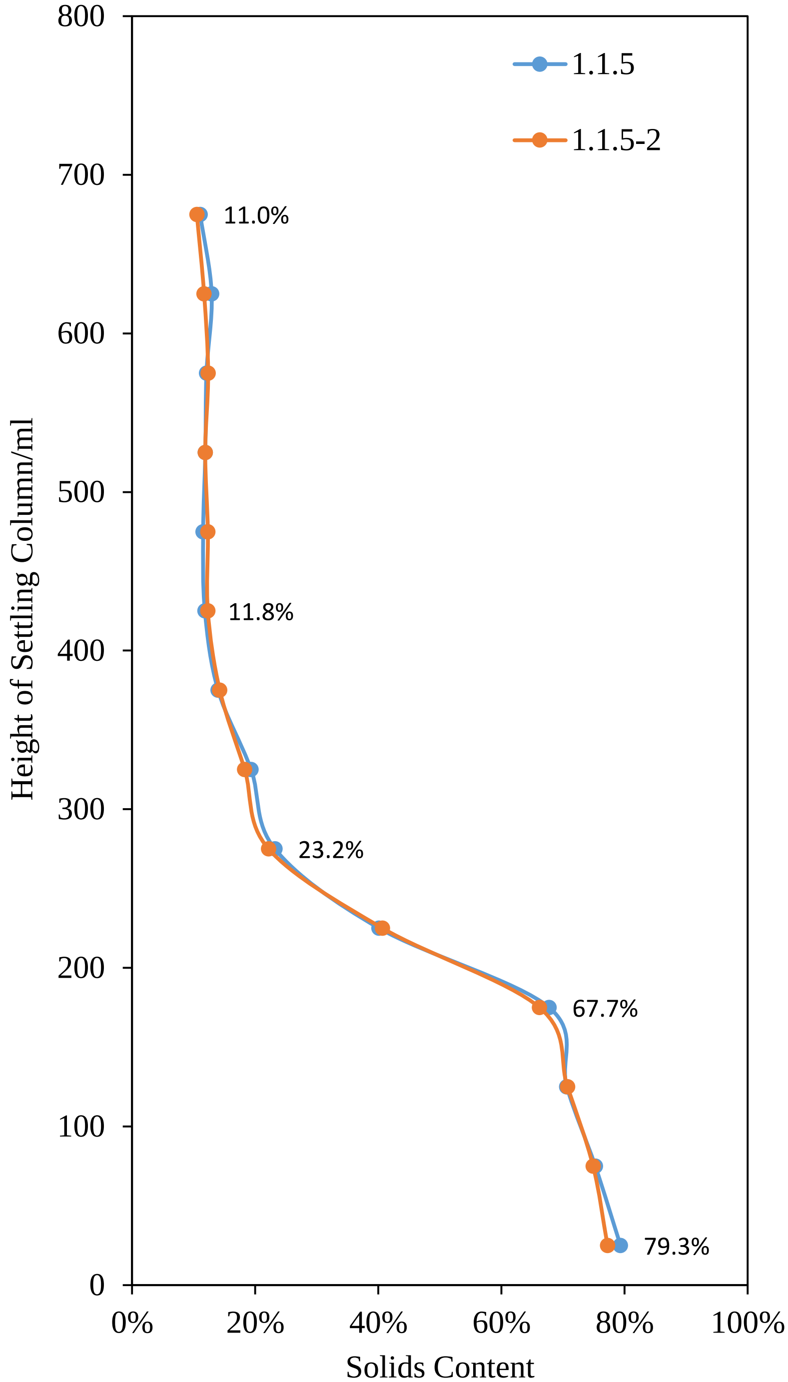

Figure 4.11 Distribution of solids contents (The initial solids content was 35%, sampled when interface reached 700 ml)

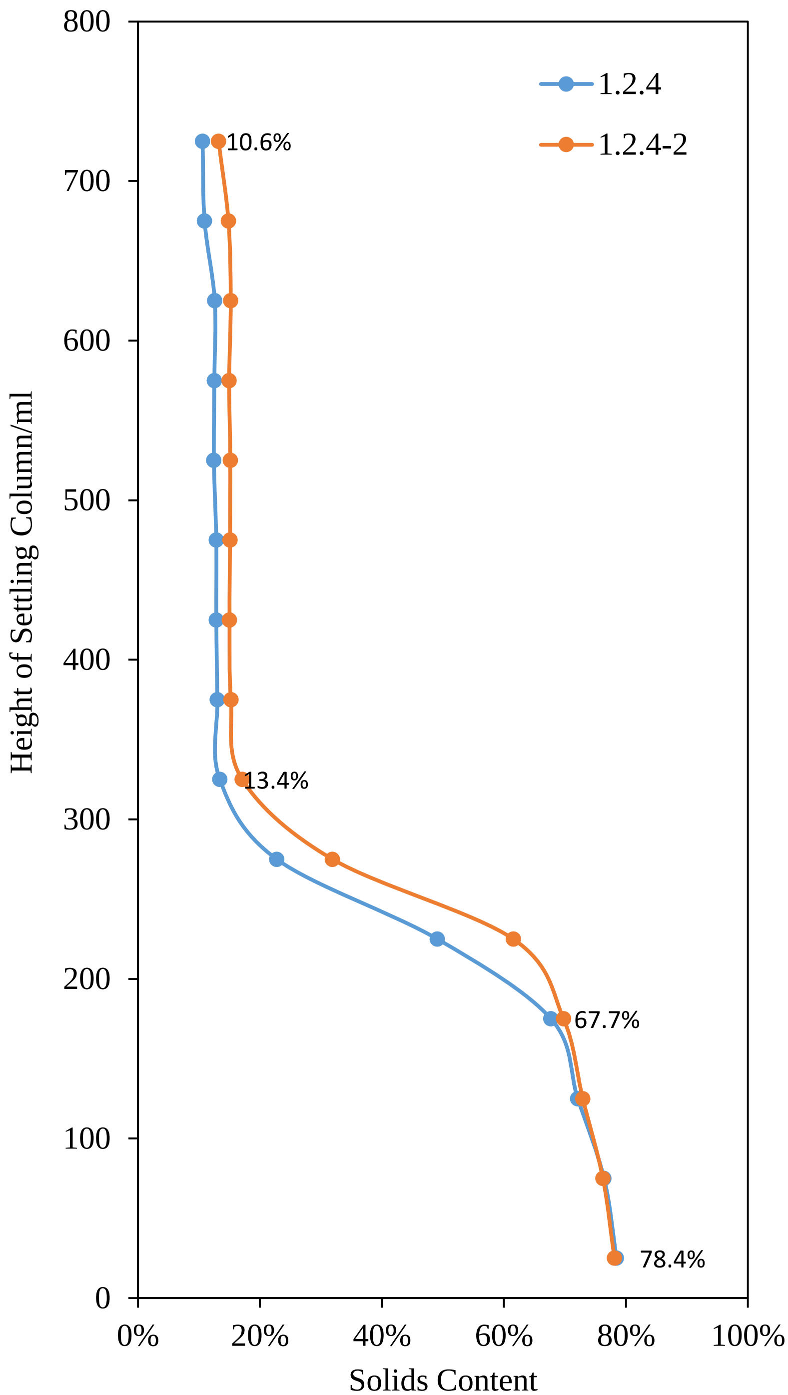

Figure 4.12 Distribution of solids contents (The initial solids content was 40%, sampled when interface reached 750 ml)

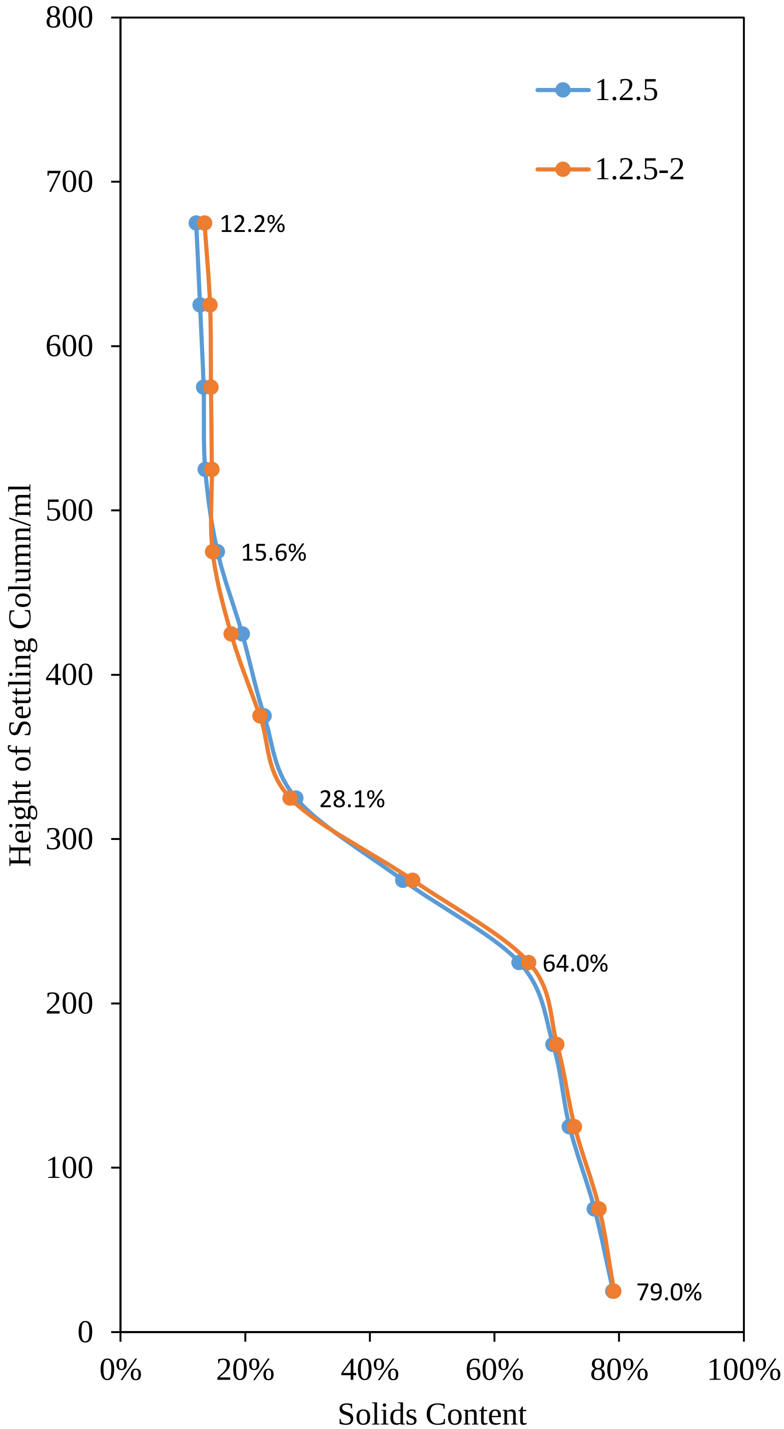

Figure 4.13 Distribution of solids contents (The initial solids content was 40%, sampled when interface reached 700 ml)

The curves represent the distribution of solids contents along the height of the settling column. For the first set, the two results match each other very well, signifying that the test is repeatable. From 750 ml to 300 ml, the solids contents remain constant, as described in the Kynch theory. However, although the Kynch theory claims that the solids content of this part should be equal to the initial solids content, the value here has been found to be just 13%, which is much smaller than the initial solids content of 35%. One possible explanation of this phenomenon is the segregation of the coarse particles. As described before, large particles fall rapidly and individually. A large amount of coarse particles settled at the bottom of the column in the first one or two minutes. The lack of coarse particles leads to a decrease in the solids content in the suspension.

A dramatic increase in the solids content occurs between 275 ml and 175 ml, signifying that the propagation of a specific solids content reaches this height based on Kynch theory. A structure of sediment has developed at the bottom of the column. There is also the other possibility that the dramatic increase of the solids content is simply a result of the accumulation of coarse particles. The end of this curve stops at 77.6% on the axis of the solids content. Based on Kynch theory, a value of 77.6% indicates the maximum solids content that a suspension can achieve at the end of sedimentation.

For the second set, the first section is no longer a vertical straight line. From 300 ml to 400 ml, the small increase in solids content illustrates the occurrence of segregation in this part. The maximum solids content at the bottom of the suspension is still around 77.6%.

Four sets of column settling tests with sample collection were conducted on total copper tailings with solids contents of both 35% and 40%. Tests were sampled when the interface reached 750 ml (Test 1.1.4 and Test 1.2.4), 700 ml (Test 1.1.5 and Test 1.2.5), 650 ml (Test 1.1.6 and Test 1.2.6) and 600 ml (Test 1.1.7 and Test 1.2.7). These results are presented in Figures 4.14 and 4.15.

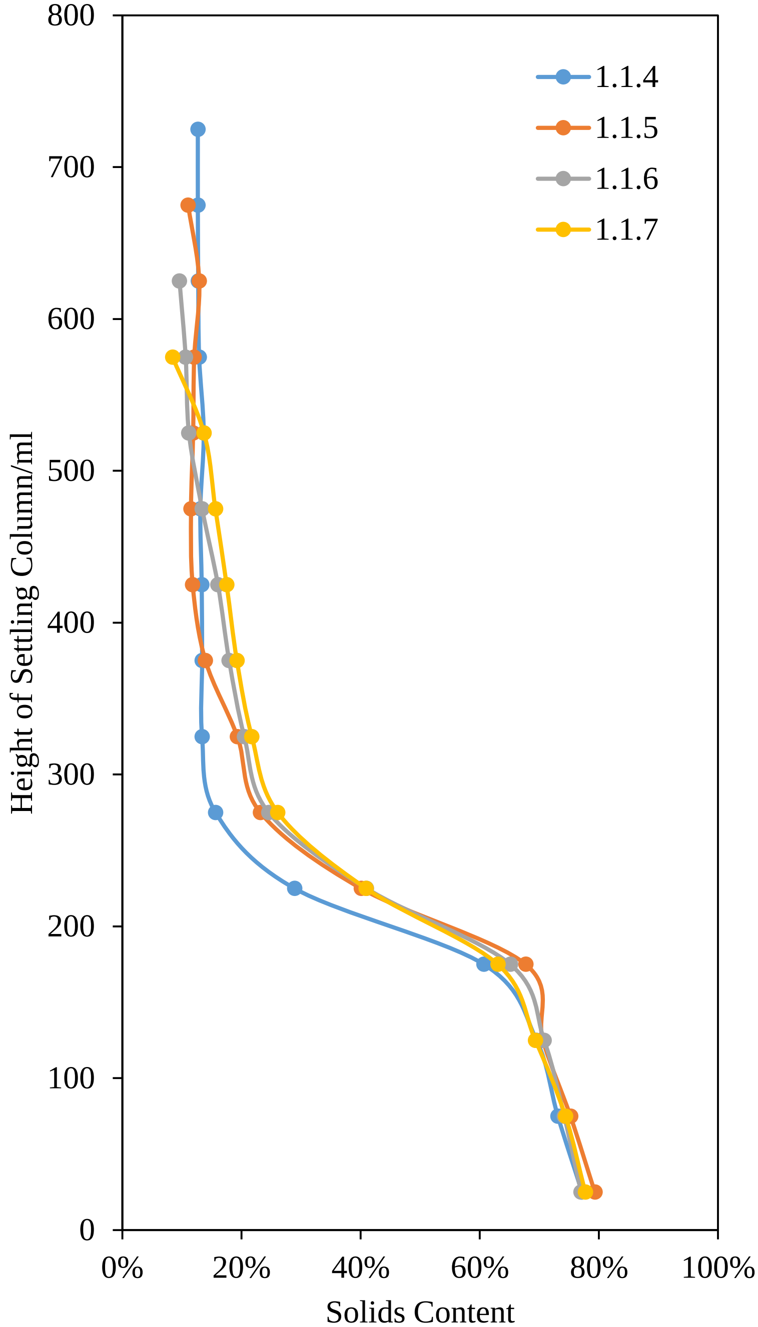

Figure 4.14 Distribution of solids contents of total copper tailings with an initial solids content of 35%

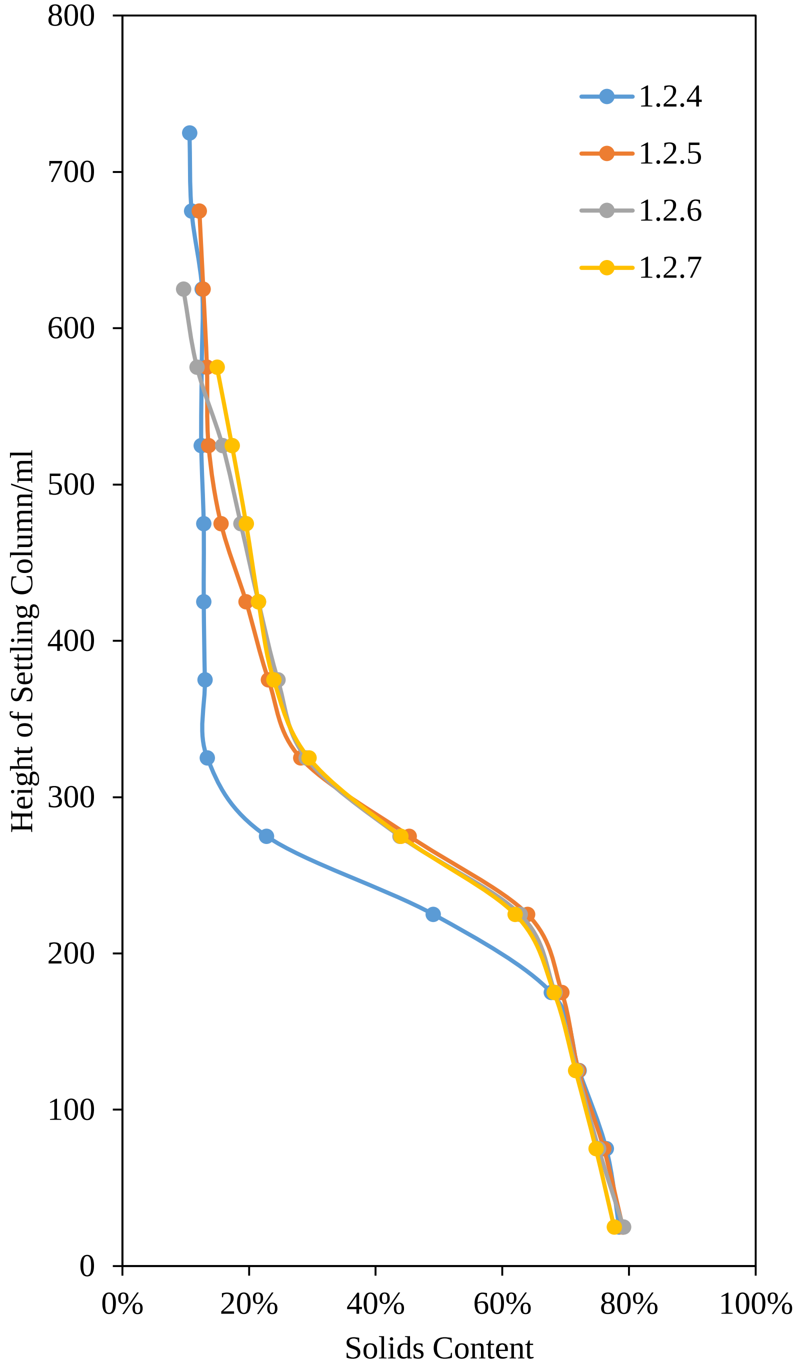

Figure 4.15 Distribution of solids contents of total copper tailings with an initial solids content of 40%

The above results reveal an important fact in that the dramatic increase of the solids content that can be seen in the above figures does not involve the propagation of a specific layer. After the interface reaches 700 ml, the positions of the big changes in solids contents stay the same, indicating that this has been caused by the accumulation of large particles from the bottom of the settling column. After all the large particles settled down at the bottom of the column, the process of segregation stopped.

The structure of the bottom section consists mainly of the coarse particles that have been segregated from the suspension. The drop of the interface or the change of the upper section of the suspension has nothing to do with the structure on the bottom, and for this reason, the last sections of all the curves stay in the same position. Since all large particles have been segregated from the suspension, the fines in the suspension determine the movement of the interface.

Because the influence of the segregation occurs in the process of settling, Kynch theory cannot be unconditionally applied to the analysis of the results.

4.3 The Results of Tests on Copper Tailings Fine Fraction

4.3.1 Samples Preparation

A bench test was described in the previous chapter to investigate the development of the interface in the suspensions of particles with different sizes. The results indicated that only suspensions with particles smaller than 37 μm could form suspensions. Based on this finding, column settling tests and column settling tests with a sample-collection were performed on the fine fraction of the copper tailings. The tests were conducted on suspensions with solids contents of 35% and 40%. The samples were obtained by mixing dry fines and distilled water. Fines were washed several times to get rid of the chemical additives. For the test with a solids content of 35%, 360 g dry sample and 667 g distilled water were used. For the test with a solids content of 40%, 423g dry sample and 635 g distilled water were used. Dry samples and distilled water were mixed directly in the settling column by shaking them up and down 30 times.

4.3.2 Results of Column Settling Tests

Two sets of settling column tests (Test 2.1.1 and Test 2.1.2, Test 2.2.1 and Test 2.2.2) were conducted on the fine fraction of the copper tailings with initial solids contents of 35% and 40%. Time was recorded when the interface dropped 12.5 ml along the settling column. The test ended when the interface took more than five hours to drop 1 interval (12.5 ml). The results are shown in Figure 4.16 and Figure 4.17. Experimental data is listed in Appendix C.

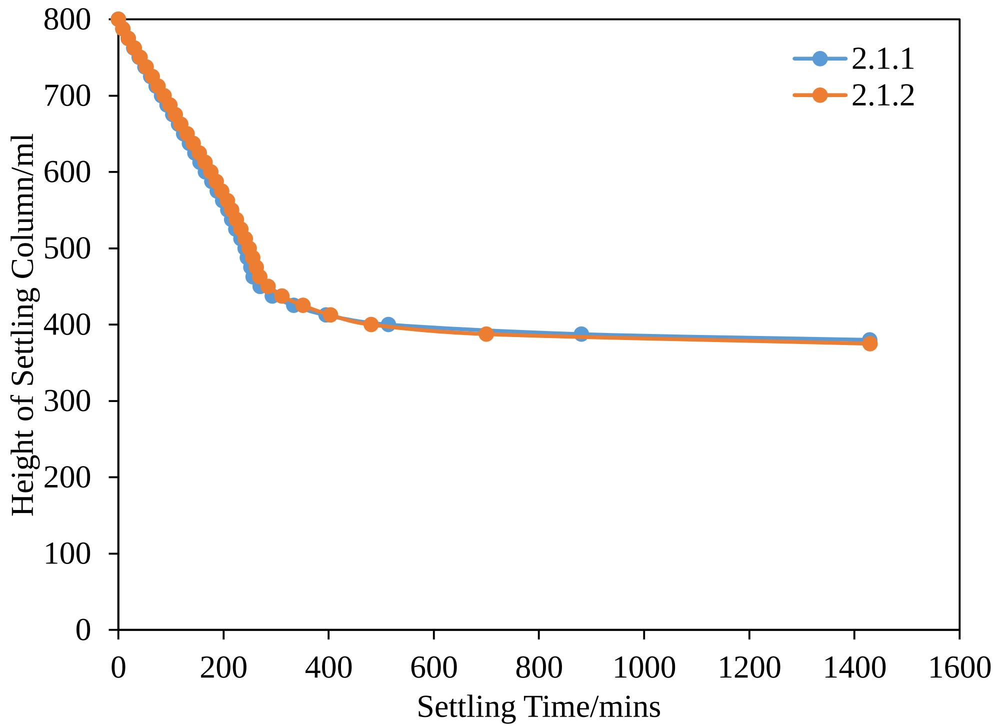

Figure 4.16 **Settling curve of copper tailings fine fraction with an initial solids content of 35%**

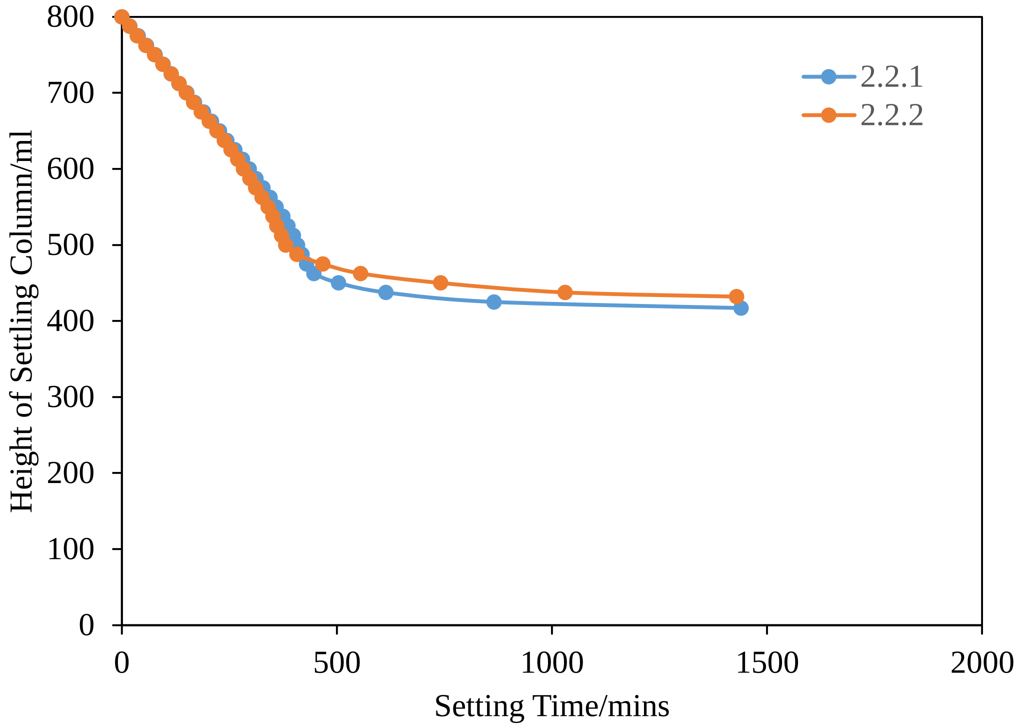

Figure 4.17 Settling curve of copper tailings fine fraction with an initial solids content of 40%

For tests with a solids content of 35%, the settling curve in the figures above can be divided into two sections. The first section is from 800 ml to around 400 ml. This linear portion signifies that the interface drops at a constant velocity. When the interface reaches 400 ml or 450 ml, the velocity suddenly decreases to a relatively low value. After 24 hours, the interface stopped at around 380 ml.

Coarse particles or clusters could barely be observed at the bottom of the column, meaning that the influence of segregation had been weakened. The reason why the interface stopped dropping over such a short time period (in 24 hours) instead of dropping slowly over a long period of time (more than 52 hours as recorded) as had been observed on total copper tailings, might be the result of the accumulation of the fine particles in a well-organized order. The compression of the structure was barely seen to occur.

4.3.3 Results of Column Settling Tests with Sample Collection

Three sets of column settling tests with sample collection (Test 2.1.3, Test 2.1.4, Test 2.1.5, Test 2.2.3, Test 2.2.4, Test 2.2.5) on fines copper tailings with initial solids contents of both 35% and 40% were conducted to investigate of the solids content distribution of the suspension in the settling column test. The tests were sampled when the interface dropped to 750 ml, 700 ml, and 650 ml, respectively. The samples were mixed directly in the settling columns. The results are shown in Figure 4.18 and Figure 4.19. Experimental data is listed in the Appendix D.

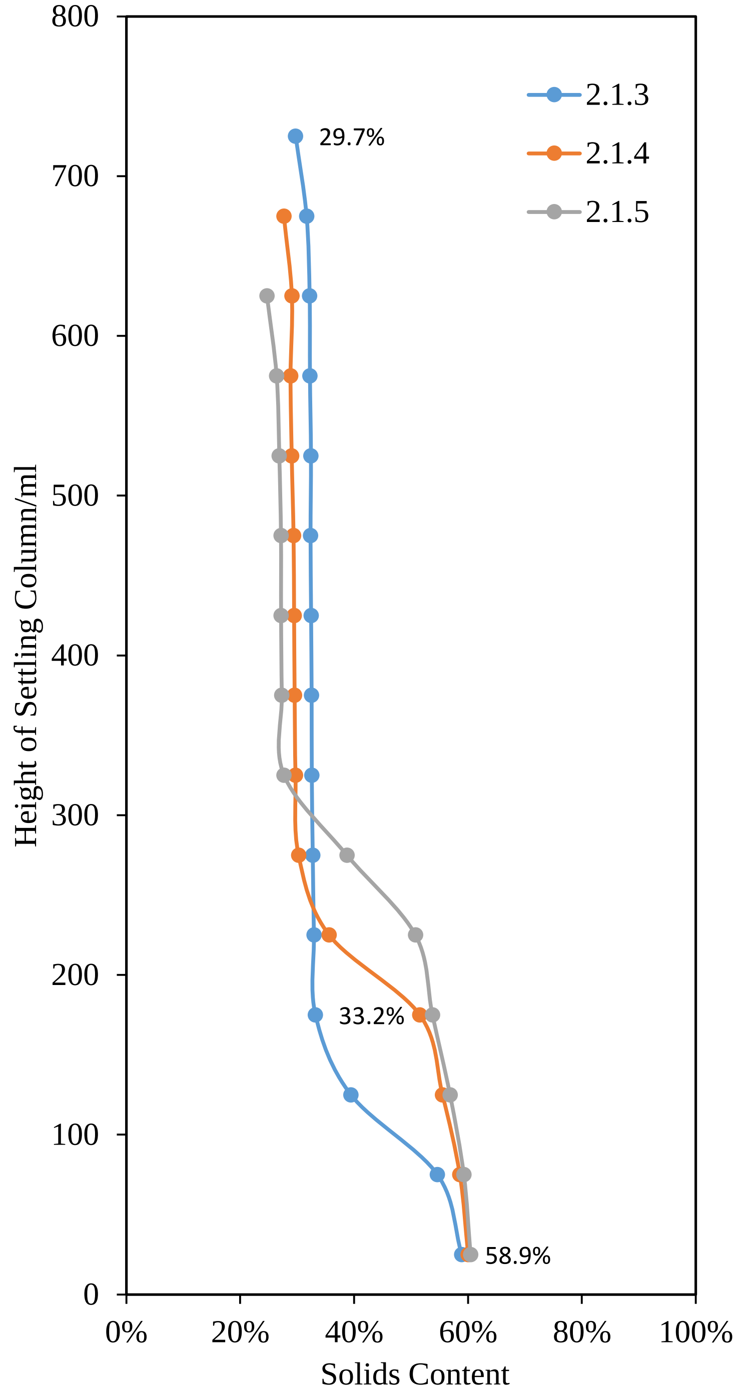

Figure 4.18 Distribution of solids contents of fine copper tailings with an initial solids content of 35%

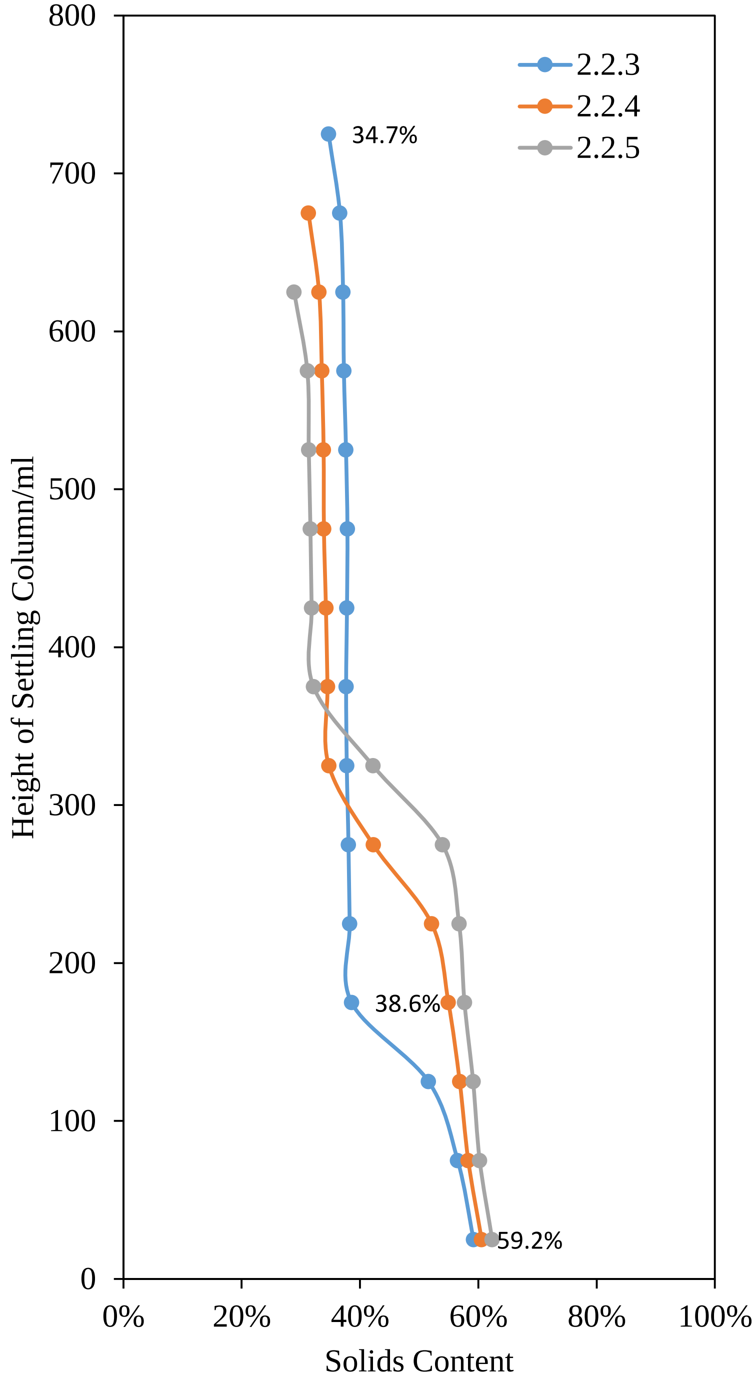

Figure 4.19 Distribution of solids contents of fine copper tailings with an initial solids content of 40%

Each of the curves in the figures above represent the distribution of solids contents along the height of the column at a specific time in the settling column test. The first part of the curve is a vertical straight line, which is considered to be in the hindered settling zone. In this part, the solids content is supposed to be equal to the initial solids content. Based on the data, the solids content of the upper part in the column is slightly smaller than the initial solids content, and as time goes by, it also decreases gradually. One possible explanation for this is the segregation of larger particles in the fines. As such, a decrease in the larger particles in the suspension leads to a decrease in the average solids content in that area when the masses of the other portions don not change.

When the line reaches around 175 ml, a dramatic change is noted in the solids content. Since the material contains only fine particles and no segregation is clearly observed on the bottom of the column, the dramatic change of the solids content is mainly caused by the propagation of a layer with a specific solids content. This phenomenon is well explained by Kynch theory.

4.3.4 Particle Size Distribution Analysis on Copper Tailings Fine Fraction

In order to determine if segregation occurred in the tests on fine copper tailings, particle size distribution analyses were conducted on the samples collected in Test 2.2.5 with a MasterSizer. The results are shown in Figure 4.20.

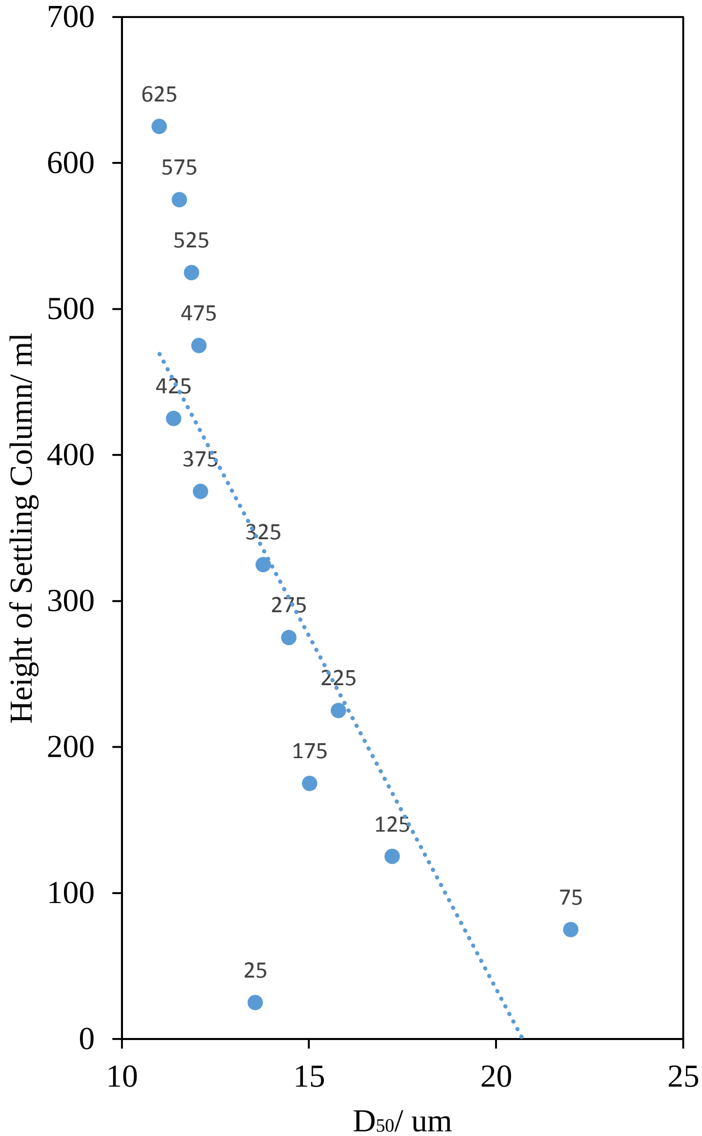

Figure 4.20 D_{50} of samples collected from Test 2.2.5

From the results of particle size distribution, the trend of D_{50} can be obtained. From the top of the suspension to the bottom, the value of D_{50} increases as height decreases, signifying that large particles settle faster than fine particles. The value of D_{50} for the bottom section is much greater than for the upper section, thus proving the existence of segregation.

4.4 Analysis of Sedimentation based on Kynch Theory

As has been noted in Chapter 2, Kynch was the first person to present a kinematic theory of sedimentation based on propagation of waves in the suspension. His theory can be used to analyze experimental results or to predict sedimentation in hindered settling.

Data recorded in the tests of fine copper tailings were used for the calculations and to predict the sedimentation of this material. Some of the essential parameters needed for this are listed in Table 4.2 below:

Parameters	Description
H	800 ml
ρ_o	35% or 40%
$v_p(\rho_o)$	Can be calculated by equation 2.13
$V(\rho_o)$	Can be calculated by equation 2.10
ρ_m	Can be found in the data
$V(\rho_m)$	Can be calculated by equation 2.10
(x_1, t_1)	Can be calculated by equation 2.20, 2.21
(x_2, t_2)	Can be calculated by equation 2.27, 2.29

Table 4.2 Parameters for the calculation of Kynch theory

For the samples with solids contents of 35%:

The value of parameter H, ρ_o, ρ_m can be directly observed from the test. The calculation of $v_p(\rho_o)$ is based on Equation 2.13.

$$v_p(\rho)_1 = {dx}/{dt} = {(100 - 50)}/{(84.5 - 40.5)} = 1.1.3 ml/min$$

$$v_p(\rho)_2 = {dx}/{dt} = {(150 - 100)}/{(127.4 - 84.5)} = 1.16 ml/min$$

So the average value of $v_p(\rho_o)$ is 1.15 ml/min.

According to Equation 2.10,

$$V(\rho)_1 = {dx}/{dt} = {200 - 110}/{84.5 - 40.5} = 2.04 ml/min$$

$$V(\rho)_2 = {dx}/{dt} = {275 - 200}/{127.4 - 84.5} = 1.75 ml/min$$

The average value of $V(\rho)$ is 1.90 ml/min.

Based on Equations 2.20 and 2.21, the position of point B (x_1, t_1) can be calculated.

$$t_1 = \frac{H}{V(\rho_o) + v_p(\rho_o)} = \frac{800}{1.15 + 1.90} = 262.3\ min$$

$$x_1 = H - v_p(\rho_o)t_1 = 800 - 1.15 * 262.3 = 498.4 ml$$

In order to calculate the coordinate of (x_2, t_2), the value of ρ_m is essential. Since the value of ρ_m cannot be obtained from the results, the calculation of (x_2, t_2) cannot be completed. However, we can still calculate the value of x_2 with the maximum solids content.

For samples with solids contents of 35%, based on Equation 29,

$$x_2 = h_f = \frac{H\rho_o}{\rho_m} = \frac{800 * 35\%}{60.45\%} = 463.0\ ml$$

Since the coordinates of (x_1, t_1) and final height h_f (also known as x_2) are calculated, a prediction curve can be plotted together with the experimental data, which is shown in Figure 4.21.

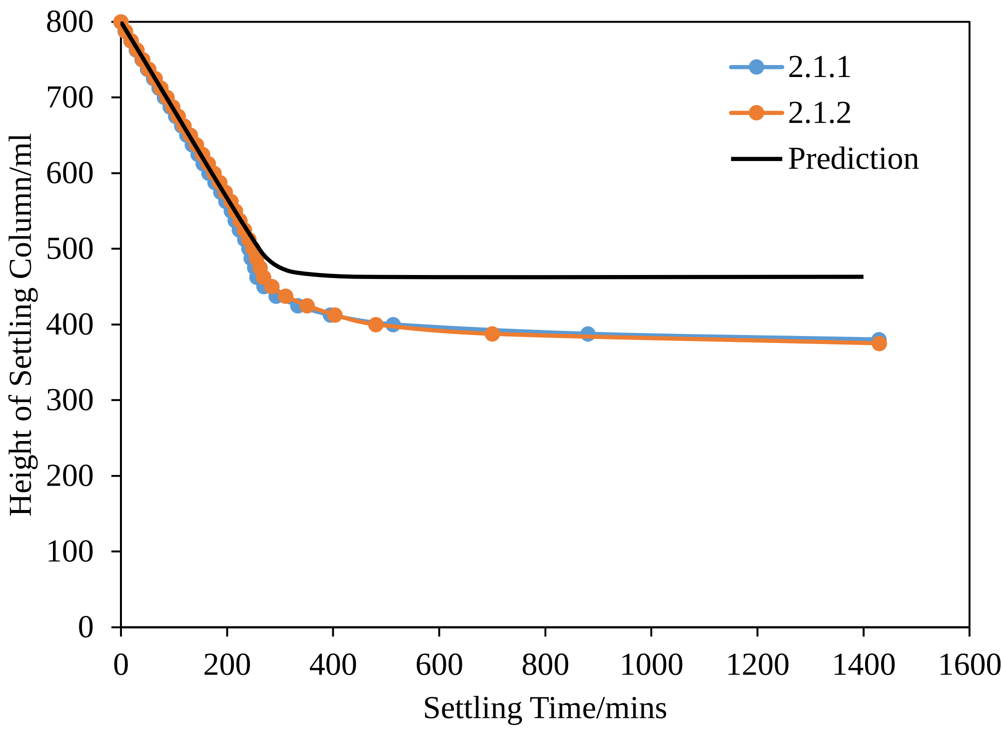

Figure 4.21 The prediction of the settling curve with Kynch theory

The first part of the prediction curve matches the experimental data well. All results are linear, as described in Kynch theory. However, the rest of the prediction curve no longer matches the experimental data, as there is a big difference between the two final heights. When one expands the scale for the figure above, details regarding the trends of those curves can be obtained.

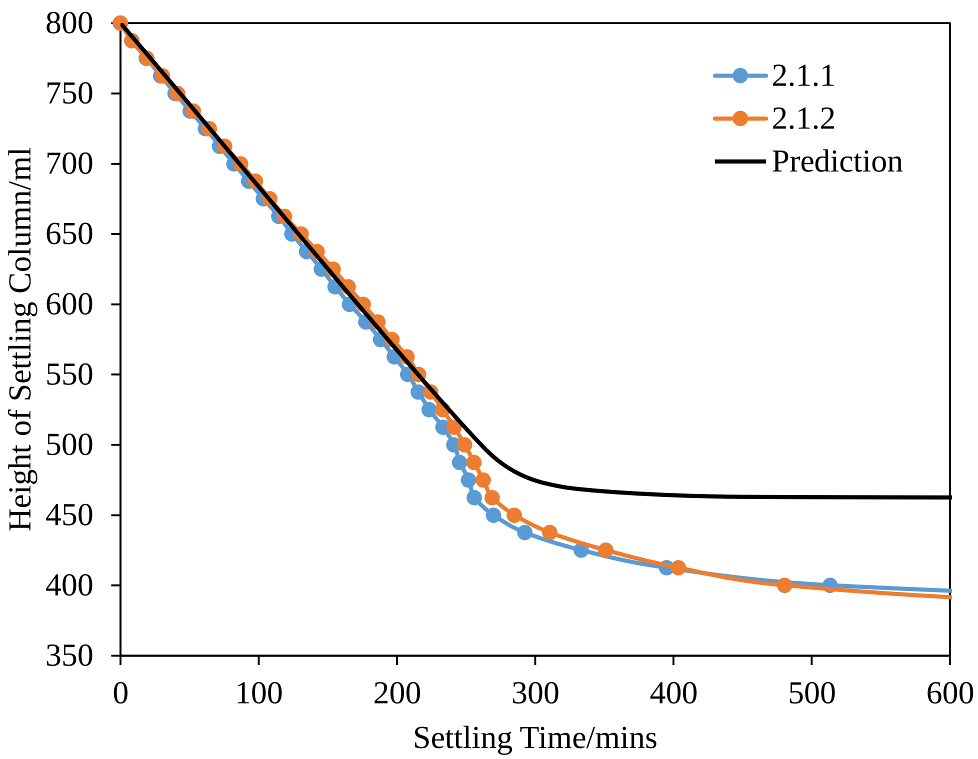

Figure 4.22 Prediction of the settling curve with Kynch theory-2

At about 250 minutes, the prediction curve and curves of experimental data begin to diverge. The prediction curve indicates that the velocity of the reduction of the interface height started slowing down when it reached around 500 ml. However, a period of acceleration process shows up in the experimental data right below 550 ml. Kynch theory does not mention anything about an acceleration process. The fastest velocity of fall of the interface, based on Kynch theory, should take place in the first part of the sedimentation process. This process of acceleration is also observed in the sedimentation of total tail copper tailings and kaolin. The results of the sedimentation of kaolin are shown in Figure 4.23. Experimental data is listed in Appendix F. In the column settling tests on kaolin, the samples were mixed with kaolin and concrete sands in a proportion of 7 to 3. The solids content was 30%. One possible explanation for this process lies in the forces between particles, which is avoided in Kynch theory. When the sedimentation process comes to an end, the distance between particles is much smaller than it had been at the beginning. Some of the attractive forces between the particles have therefore been increased. Since the attractive force tends to pull particles close to each other, the increase of this force enhances this process, and has been expressed through the acceleration of macroscopic sedimentation. Another explanation comes from compression settling. According to this explanation, Concha and Bustors (1987) claimed that Kynch theory is only valid for materials with low compressibility. When systems contain high solid concentrations, the hindrance of both settling and compression settling occur. In other words, in our suspension, it is possible that compression settling occurred in the bottom section. As such, compression settling compressed the structure of the system, and led to an increase in the solids content, and a decrease in the volume.

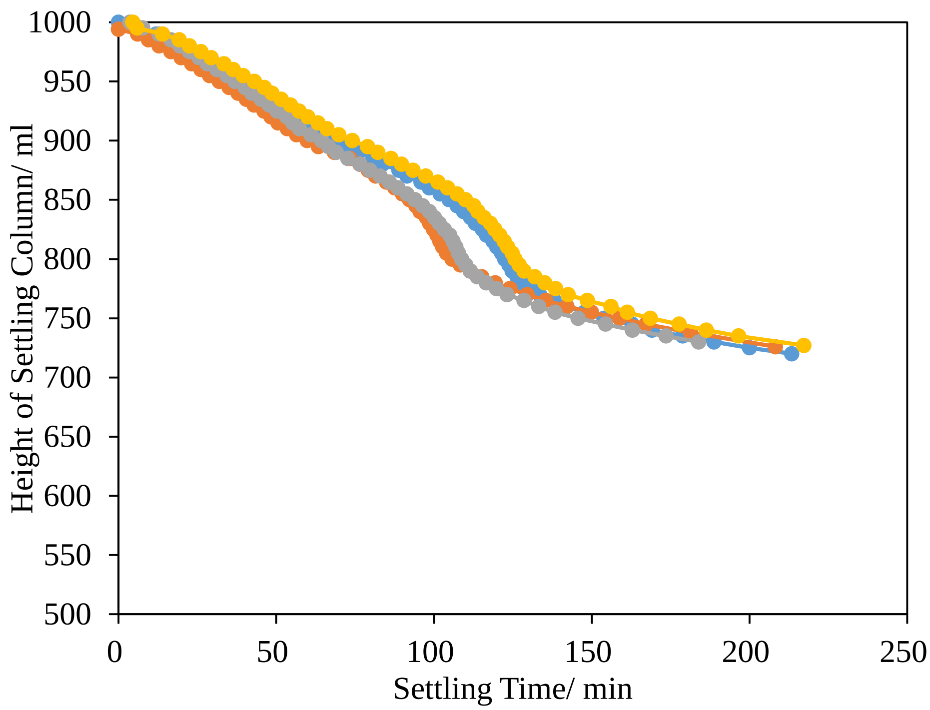

Figure 4.23 Settling curve of mixtures of kaolin and concrete sands

One more column settling test with sample-collection was conducted to check the change in the solids content at the bottom section with a solids content of 35%. Since the acceleration process occurred after the interface passed 550 ml, samples were collected when the interface passed 550 ml. The results are plotted in the Figure 4.24.

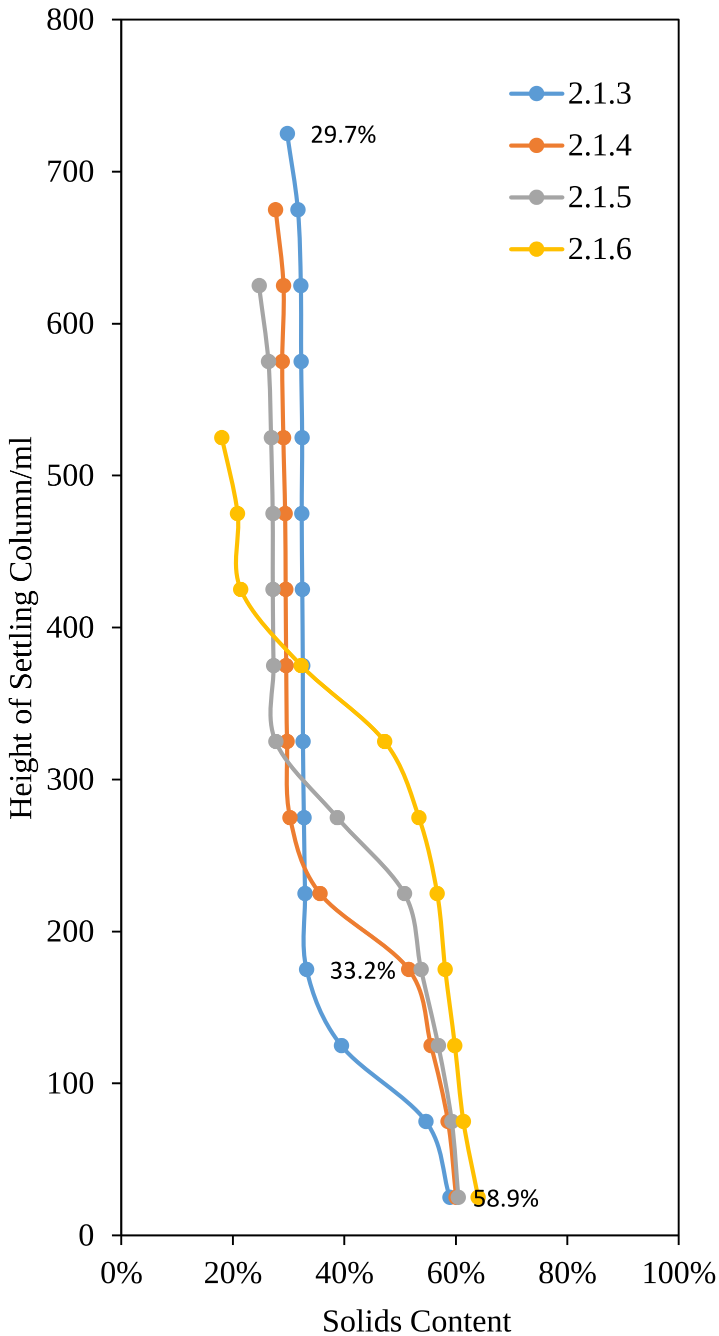

Figure 4.24 Distribution of solids content of fines copper tailings with an initial solids content of 35%-2

The results of Test 2.1.6 indicate that the solids content for the bottom section increased with time. This can be used as support for our explanation of compression settling. The curve of Test 2.1.6 indicates that the "maximum solids content" on the bottom is 64%, which is greater than the "maximum solids content" obtained in Test 2.1.5. If we use this number to recalculate the final height, the new result would be:

$$x_2 = h_f = \frac{H\rho_o}{\rho_m} = \frac{800 * 35\%}{64\%} = 437.5\ ml$$

With this new final height, a new prediction curve is plotted in Figure 4.25.

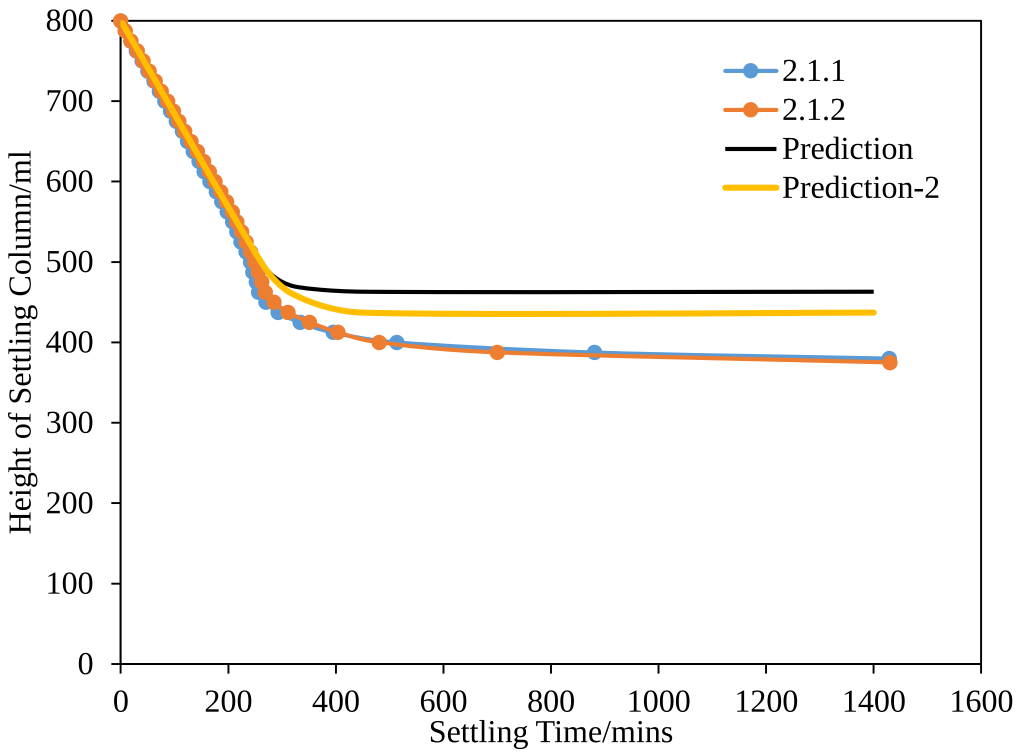

Figure 4.25 Comparison of two prediction curves

With the correction of the "maximum solids content", the second prediction curve is closer to the experimental data. After taking compression settling into consideration, a more accurate prediction curve is obtained. That is to say, in our tests, compression settling can have a significant influence when conducting the analysis with Kynch theory.

4.5 Results of Column Settling Test with Sample Collection on Other Materials

4.5.1 Results of Column Settling Tests with Sample Collection on Kaolin

Kaolin is a clay mineral with an extremely fine particle size. Two sets of column settling tests with sample-collection with a solids content of 20% were conducted to investigate the distribution of the solids content in the settling column since a kaolin suspension with a relatively high concentration can be considered as a non-segregational material. The results are shown in Figure 4.26. Experimental data is listed in Appendix E.

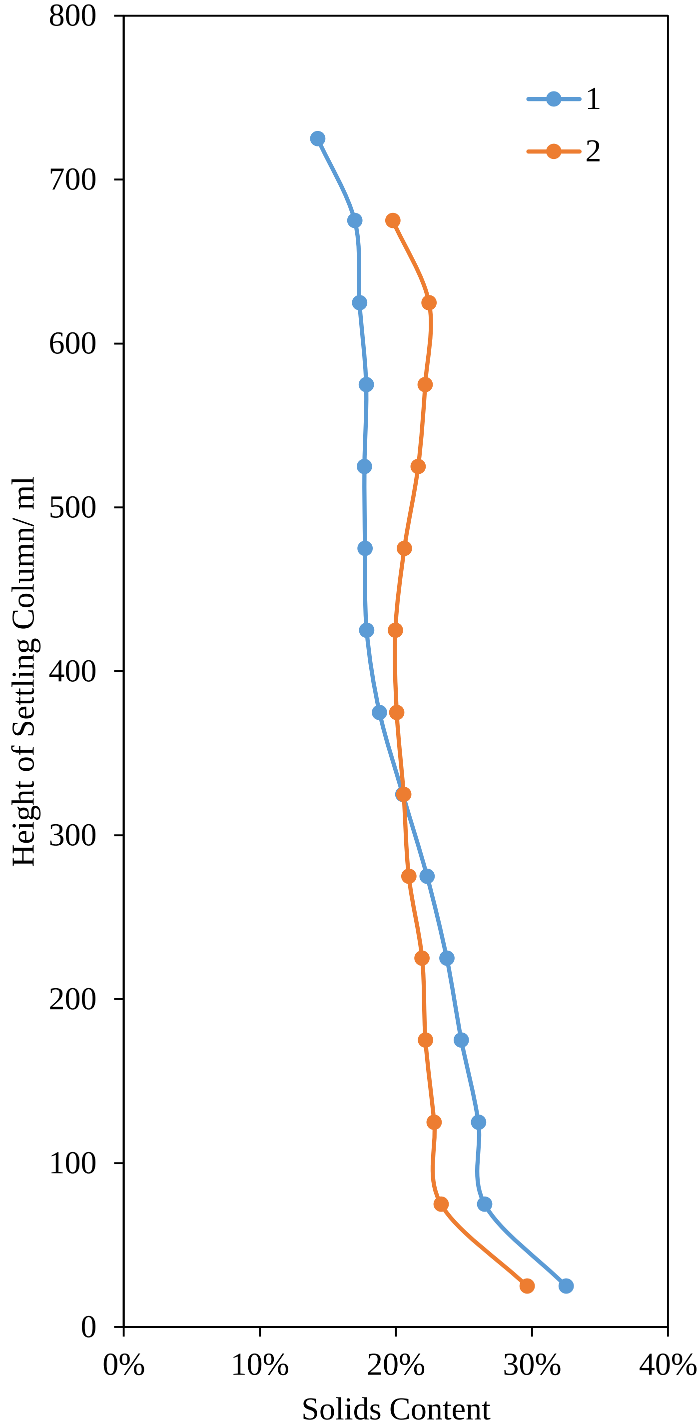

Figure 4.26 Distribution of solids content of kaolin with an initial solids content of 20%

The distribution of the solids content curve cannot be explained by Kynch theory since the interactions of the forces between kaolin particles cannot be ignored as the particles are too fine.

4.5.2 Results of Column Settling Tests with Sample Collection on Fine Tailings with Dispersant

The dispersion of fines samples provides one way to further decrease the segregation effects observed in the column settling test. Dry fines samples were mixed with sodium hexametaphosphate solution (40 g/L), resulting in a mixture with a solids content of 40%. A column-settling test with a sample-collection (Test 4.1) was carried out on this mixture. Results are shown in Figure 4.27, and compared with the results of fines without dispersant.

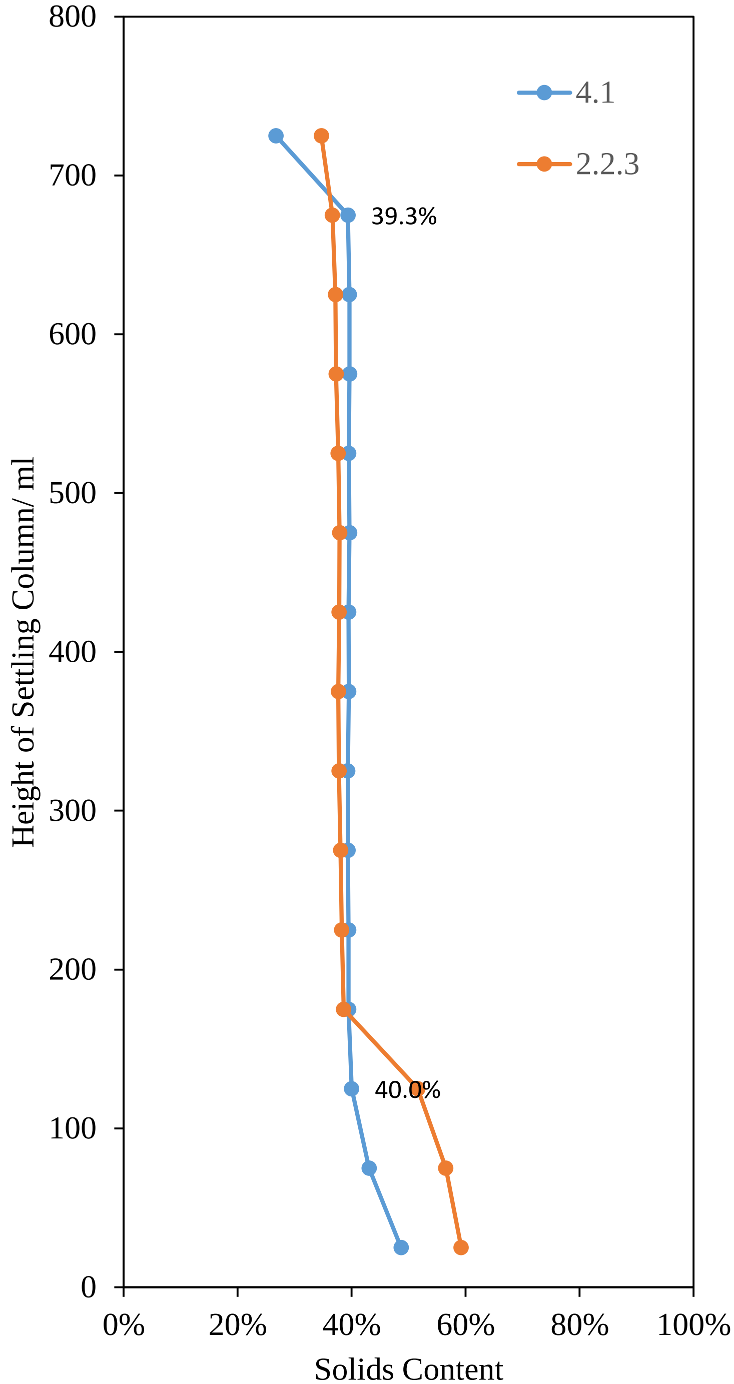

Figure 4.27 Distribution of the solids content of the test with dispersant

As a result of dispersing the material, the forces of interaction between particles was changed. One obvious effect would be the enhancement of the repulsive forces between particles, leading to the prevention of particles from getting together and forming clusters with a larger particle size. The repulsive forces also prevented the particles from settling. Thus, a much slower falling velocity was obtained in the test. It took around 12 days for the interface to drop 50 ml along the settling column (1 hour in the tests without dispersant). A comparison of the results with those of the column settling test with sample-collection shows that the use of dispersant also weakened the effects of segregation since the solids content of the top part was around 39.5%, which is extremely close to the initial solids content.

Chapter 5: Conclusions and Recommendations

5.1 Conclusions

The primary objective of this research is to gain a better understating of the relationship between sedimentation and some of its physical properties. Particle size and solids content are two main factors in the sedimentation of tailings. In order to achieve this objective, a series of column settling tests and column settling tests with sample-collection were conducted on copper tailings, and the results were analyzed using the Kynch theory. The conclusions of this research can be summarized as follows:

- The new apparatus designed and constructed for this research provides an effective tool by which samples of the suspension can be removed in the column-settling test without disturbing the local conditions. The collection of the samples makes it possible to further investigate the particle size and solids contents of the material.
- In the column settling tests, it was found that the development of the interface between supernatant water and suspension for copper tailings is effected by both solids content and particle size. The form of the interface occurs when the solids content of the suspension of total copper tailings is larger than 25%. Suspensions with lower solids contents may not form a clear interface during the sedimentation process. Particles with a particle size larger than 37 μm in copper tailings settle individually in the column-settling test, and this is defined as discrete settling.
- The two mixing methods for column settling tests involved in this research led to the same results, signifying that copper tailings can be fully mixed by shaking.

- From the results of column settling tests on total copper tailings and fine copper tailings, the fact that the interface of the suspensions with high solids contents (hindered settling) reduces in height at a constant velocity at the beginning, and is not affected by the particle size distribution of the material.
- A column settling test with sample collection is an effective method to measure the physical properties of sediment inside the settling column. By repeating the column-settling test with a sample-collection, the same results were obtained, indicating that high repeatability of this test method.
- Because of segregation, Kynch theory cannot be fully applied to the results of the sedimentation of total copper tailings. Coarse particles settle individually at the beginning of the column settling test, leading to two negative results regarding the application of Kynch theory. First, the accumulation of coarse particles affects the movement of the propagation of the wave from the bottom of the settling column. However, we know that the movement of the specific wave is essential in the calculation of Kynch theory. Second, the lack of coarse particles leads to a decrease in the solids content for the upper section in the suspension. Based on Kynch theory, this has a large influence on the reduction in height of the interface even though the solids content of the upper section remained constant from the very beginning.
- In the column settling tests and the column settling tests with sample collection, the influence of segregation was found to have decreased due to the removal of coarse particles. The propagation of a wave with a specific solids content from the bottom of the settling column, as described in Kynch theory, has been obtained. This result indicates that a decrease in the effect of segregation increases the applicability of Kynch theory.

- The first part of the prediction curve, calculated from the experimental data of column settling tests with sample-collection on fine copper tailings, and based on Kynch theory, matches the results of the column settling tests. Fine copper tailings settle at a constant velocity at first, this being determined by the movement of the interface.
- There exists a large disparity between the actual final height and the predicted final height of the sediment. The settling curve plotted with the results of the column settling tests shows that there exists an acceleration process before the falling velocity slows down. One explanation for this is changes in some of the attractive forces between particles. Kynch theory ignores, or rather does not consider, the forces between particles. With the fall of the interface, the distance between particles is decreased, and the decrease of distance increases some of the attractive forces between the particles, thus leading to an acceleration of the sedimentation.
- Compression settling occurred in the column settling tests in this research despite the main process hindering settling. The compression of the whole structure of the sediment leads to a decrease in volume, which can also be viewed as a decrease of the final height. Kynch theory's disregard for compressibility might therefore result in inaccurate estimations of the final height.
- Changes in the forces between particles lead to changes in the movement of the interface and the propagation of the solids content wave. However, the influence of applicability of Kynch theory that results from this change remains unknown.

5.2 Recommendations

The recommendations for further studies are summarized as follows:

- In order to get a more precise curve of the distribution of solids contents on the settling of the suspension, more samples at closer intervals can be taken from the suspension in the column-settling test. With more precise information on the distribution of solids contents, the accuracy of the calculation of $v_p(\rho_0)$ can be improved.
- In our study, because of equipment (sieve size) restrictions, the fine copper tailings with a particle size smaller than 37 µm could not be divided into more fractions. Further research could focus on dividing the fines into more fractions with narrow particle size ranges. These testing conditions could be considered to be more ideal with respect to Kynch theory.
- Column settling tests with sample-collection and longer settling times (after compression settling starts) should be conducted to investigate changes that occur in the bottom section. With more experimental data, the influence of compression settling on Kynch theory might be more accurately summarized.
- The compressibility of test samples should be studied to minimize the influence of compression settling. Column settling tests with sample-collection on materials with low compressibility might capture the propagation of the solids content wave with the “final solids content.”

References

ASTM., D. (2010). Standard specification for ASTM hydrometers.

ASTM., D. (2010). Standard test method for particle-size analysis of soils.

Arkell, N. P. (2012). Accelerated dewatering of oil sands tailings by microbially induced chemical changes. (Doctoral dissertation, University of Alberta)

Baruah, A. (1984). The settling behaviour of clay mixture suspension. (Masters dissertation, McGill University)

Been, K. (1981). Stress strain behaviour of a cohesive soil deposited under water. (Doctoral dissertation, University of Oxford)

Been. K., & Sills, G. C. (1981) Self-weight consolidation of soft soils: An experimental and theoretical study. *Geotechnique*, 31(4), 519-535.

Bhatti, A. S., Dollimore, D., Davies, L., & Bhatty, J. I. (1985). The application of interface settling rates in hindered settling to the determination of the mean particle radii. *Surface Technology*, 26(3), 287-293.

Biodiversity Heritage Library. *Proceedings of the Royal Society of Edinburgh* (vol. 13). The Society.

Brierley, C. L. (1993). *Mine waste management*. Elsevier Ltd.

Caughill, D. L. (1992). Geotechnics of non-segregating oil sand tailings. (Masters dissertation, University of Alberta)

Chang, D., Lee, S., Lee, T., Jang, Y., & Kim, M. (1997). Non-colloidal sedimentation compared with Kynch theory. *Powder Technology*, 92(1), 81-87.

Chen, W. (1986). Sedimentation and thickening. (Doctoral dissertation, University of Houston).

Coe, H. S., & Clevenger, G. H. (1916). Methods for determining the capacity of slimesettling tanks. *Trans. AIME* 55, 356-385. (Referenced by Concha and Bürger)

Concha, F., & Bürger, R. (2003). Thickening in the 20th century: A historical perspective. *Minerals & Metallurgical Processing*, 20(2), 57-67.

Concha, F., & Bürger, R. (2002). A century of research in sedimentation and thickening. *Kona Powder and Particle Journal*, 20(0), 38-70.

Concha, F. (2009). Settling velocities of particulate systems. *Kona Powder and Particle Journal*, (27), 18-37.

Concha, F., & Bustos, M. C. (1991). Settling velocities of particulate systems, 6. kynch sedimentation processes: Batch settling. *International Journal of Mineral Processing*, 32(3), 193-212.

Concha, F., & Bustos, M. (1987). A modification of the Kynch theory of sedimentation. *AICHE Journal*, 33(2), 312-315.

Dick, R. (1986). *Wastewater sedimentation and thickening*. Environmental Sciences and Pollution Management.

Estepho, M. (2011). Seepage Induced Consolidation Test: Characterization of Mature Fine Tailings. (Masters dissertation, University of British Columbia)

Imai, G. (1980). Settling behavior of clay suspension. *Soils and Foundation*s, 20(2), 61-77.

Imai, G. (1981). Experimental studies on sedimentation mechanism and sediment formation of clay materials. *Soils and Foundations,* 21(1), 7-20.

Kynch, G. J. (1952). A theory of sedimentation. *Transactions of the Faraday Society,* 48, 166.

Lighthall, P.C., B.D. Watts and S. Rice. (1989). Deposition Methods for Construction of Hydraulic Fill Tailings Dams. Tailings Dams. *Geotechnical Aspects of Tailings Disposal and Acid Mine Drainage*. The Vancouver Geotechnical Society.

Lottermoser, B. (2010). *Mine wastes: Characterization, treatment and environmental impacts*. Springer.

Michaels, A. S., & Bolger, J. C. (1962). Settling rates and sediment volumes of flocculated kaolin suspensions. *Industrial & Engineering Chemistry Fundamentals*, 1(1), 24-33.

Mittal, H. K. (1974). Design and performance of tailings dams. (Doctoral dissertation, University of Alberta)

Moussavi, N. R. (2013). Application of dewatering technologies in production of robust non-segregating tailings. (Doctoral dissertation, University of Alberta).

Nixon, J. F., & McRoberts, E. C. (1976). A theory of soil sedimentation. *Canadian Geotechnical Journal*, 13(3), 294-310.

Ozturgut, E., & Lavelle, J. (1986). Settling analysis of fine sediment in salt water at concentrations low enough to preclude flocculation. *Marine Geology*, 69(3), 353-362.

Palermo, M., & Thackston, E. L. (1988). Refinement of column settling test procedures for estimating the quality of effluent from confined dredged material disposal areas. (No. TR-D-88-9)

Pane, V. (1985). Sedimentation and consolidation of clays (suspension, permeability, effective-stress, settling, fluidization). (Doctoral dissertation, University of Colorado at Boulder).

Pise, C. P., & Halkude, S. A. (2011). A Modified Method for Settling Column Data Analysis. *International Journal of Engineering & Science Technology*, 3(4), 3177-3183.

Richardson, J. F., Backhurst, J. R., Harker, J. H., & Knovel Chemistry & Chemical Engineering Library - Academic Collection. (2002). *Coulson and richardson's chemical engineering: Particle technology and separation processes*. San Diego: Butterworth-Heinemann

Robertson, W. (1994). The physical hydrology of mill-tailings impoundments. Short Course Handbook on Environmental Geochemistry of Sulfide Mine Wastes, Mineralogical Association of Canada, *Short Course Handbook*, 22, 1-17.

Shamsai, A., Pak, A., Bateni, S. M., & Ayatollahi, S. A. H. (2007). Geotechnical characteristics of copper mine tailings: A case study. *Geotechnical and Geological Engineering*, 25(5), 591-602.

Tan, T. (1995). Sedimentation to consolidation: A geotechnical perspective. *Compression and Consolidation of Clayey Soils*, 937-948.

Tarleton, E. S., Wakeman, R. J., & Institution of Chemical Engineers (Great Britain). (2007). *Solid/liquid separation: Equipment selection and process design*. Butterworth-Heinemann.

Tchobanoglous, G., & Metcalf and Eddy, B. (1979). *Wastewater engineering: Treatment, disposal, reuse*. New York: McGraw-Hill.

Treweek, G. P., & Morgan, J. J. (1977). Size distributions of flocculated particles: Application of electronic particle counters. *Environmental Science & Technology*, 11(7), 707-714.

Wang, R. F. T., Brooks, N. H. & Koh, R. C. (1989). *Laboratory analysis of settling velocities of wastewater particles in seawater using holography*. Environmental Quality Laboratory

Wang, X. (2012). Generic decision-making on the retreatment of copper tailings dams. (Masters dissertation, University of British Columbia).

Yao, K. M. (1979). Column settling test and tube settling. *Journal (American Water Works Association)*, 71(2), 109-112.

Appendices

Appendix A Experimental Data of Column Settling Tests on Total Copper Tailings

A.1 Results of Column Settling Test 1.1.1

Test No.		1.1.1
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	7.8
3	775	16.3
4	762.5	24.6
5	750	32.7
6	737.5	40.2
7	725	47.9
8	712.5	55.3
9	700	62.7
10	687.5	70.9
11	675	79.9
12	662.5	89.0
13	650	97.1
14	637.5	104.5
15	625	112.0
16	612.5	118.4
17	600	124.0
18	587.5	128.7
19	575	133.5
20	562.5	142.0
21	550	163.9
22	537.5	192.4
23	525	235.4
24	512.5	281.4
25	500	349.2
26	487.5	432.2

Test No.		1.1.1
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
27	475	524.3
28	462.5	642.4
29	450	812.9
30	430	1223.7

A.2 Results of Column Settling Test 1.1.2

Test No.		1.1.2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	7.8
3	775	15.0
4	762.5	20.9
5	750	28.2
6	737.5	34.5
7	725	40.9
8	712.5	46.6
9	700	52.5
10	687.5	60.4
11	675	67.5
12	662.5	74.8
13	650	82.4
14	637.5	88.9
15	625	95.9
16	612.5	101.1
17	600	106.9
18	587.5	112.4
19	575	117.4
20	562.5	122.1
21	550	126.5
22	537.5	131.8
23	525	149.6
24	512.5	171.7
25	500	210.1
26	487.5	247.9
27	475	306.7
28	462.5	380.2
29	450	489.4

A.3 Results of Column Settling Test 1.1.3

Test No.		1.1.3
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	8.6
3	775	17.1
4	762.5	26.2
5	750	34.1
6	737.5	41.1
7	725	50.0
8	712.5	57.5
9	700	64.9
10	687.5	73.5
11	675	82.5
12	662.5	91.9
13	650	101.0
14	637.5	108.6
15	625	114.6
16	612.5	120.4
17	600	125.6
18	587.5	130.8
19	575	135.7
20	562.5	143.9
21	550	166.4
22	537.5	203.1
23	525	250.7
24	512.5	304.4
25	500	373.9
26	487.5	446.9
27	475	541.3
28	462.5	685.8
29	450	848.3
30	432	1220.7

A.4 Results of Column Settling Test 1.2.1

Test No.		1.2.1
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	11.2
3	775	24.9
4	762.5	38.6
5	750	50.3
6	737.5	61.9
7	725	72.9
8	712.5	87.3
9	700	99.1
10	687.5	110.2
11	675	121.9
12	662.5	132.5
13	650	142.1
14	637.5	150.8
15	625	158.1
16	612.5	163.3
17	600	168.5
18	587.5	179.6
19	575	204.9
20	562.5	249.9
21	550	308.6
22	537.5	375.5
23	525	458.2
24	512.5	573.8
25	500	725.4
26	487.5	911.9
27	475	1216.5

A.5 Results of Column Settling Test 1.2.2

Test No.		1.2.2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	9.5
3	775	27.3
4	762.5	40.5
5	750	51.8
6	737.5	62.9
7	725	74.5
8	712.5	89.2
9	700	101.9
10	687.5	113.9
11	675	124.7
12	662.5	134.0
13	650	142.3
14	637.5	150.6
15	625	157.2
16	612.5	162.2
17	600	167.9
18	587.5	183.1
19	575	211.9
20	562.5	260.5
21	550	316.2
22	537.5	402.4
23	525	502.0
24	512.5	650.4
25	500	857.6
26	487.5	1124.2
27	475	1494.0

A.6 Results of Column Settling Test 1.2.3

Test No.		1.2.3
Sample		Total tails of copper tailings
Solids Content		40%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	15.6
3	775	29.3
4	762.5	42.2
5	750	54.5
6	737.5	65.6
7	725	77.2
8	712.5	90.6
9	700	101.9
10	687.5	114.0
11	675	125.0
12	662.5	135.3
13	650	144.8
14	637.5	152.0
15	625	158.2
16	612.5	163.8
17	600	178.5
18	587.5	206.5
19	575	253.1
20	562.5	310.1
21	550	392.2
22	537.5	477.4
23	525	594.3
24	512.5	732.6
25	500	934.3
26	487.5	1215.6

A.7 Results of Column Settling Test 1.1.1-2

Test No.		1.1.1-2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	10.2
3	775	20.5
4	762.5	29.7
5	750	37.2
6	737.5	45.8
7	725	53.5
8	712.5	61.2
9	700	70.0
10	687.5	79.8
11	675	88.3
12	662.5	97.3
13	650	105.8
14	637.5	114.0
15	625	121.1
16	612.5	127.1
17	600	132.9
18	587.5	138.9
19	575	144.4
20	562.5	153.5
21	550	177.6
22	537.5	212.0
23	525	258.3
24	512.5	315.8
25	500	390.9
26	487.5	485.2
27	475	622.9
28	467	725.8
29	459	820.0
30	447	1035.6
31	432	1514.4
32	419	2161.7

Test No.		1.1.1-2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
33	413	2640.5
34	412	3177.4

A.8 Results of Column Settling Test 1.1.2-2

Test No.		1.1.1-2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	9.5
3	775	20.0
4	762.5	29.4
5	750	37.9
6	737.5	45.9
7	725	53.7
8	712.5	61.7
9	700	70.4
10	687.5	80.7
11	675	88.7
12	662.5	98.2
13	650	106.2
14	637.5	114.0
15	625	121.2
16	612.5	127.4
17	600	133.4
18	587.5	139.8
19	575	145.3
20	562.5	153.9
21	550	178.8
22	537.5	221.4
23	525	270.0
24	512.5	340.9
25	500	420.2
26	487.5	528.5
27	478	627.3
28	470	724.8
29	462.5	818.4
30	450	1034.9
31	437.5	1372.3

Test No.		1.1.1-2
Sample		Total tails of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
32	434	1513.6
33	420	2160.4
34	415	2639.7
35	414	3176.2

A.9 Results of Column Settling Test 1.2.1-2

Test No.		1.2.1-2
Sample		Total tails of copper tailings
Solids Content		40%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	12.5
3	775	27.4
4	762.5	40.0
5	750	51.6
6	737.5	63.8
7	725	74.8
8	712.5	87.5
9	700	100.4
10	687.5	112.9
11	675	124.4
12	662.5	134.2
13	650	143.1
14	637.5	150.0
15	625	155.8
16	612.5	161.7
17	600	169.7
18	587.5	195.9
19	575	229.7
20	562.5	284.7
21	550	356.0
22	537.5	446.5
23	525	556.8
24	513	687.0
25	500	947.6
26	476	1573.4
27	462	3236.6

A.10 Results of Column Settling Test 1.2.2-2

Test No.		1.2.2-2
Sample		Total tails of copper tailings
Solids Content		40%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	12.3
3	775	27.9
4	762.5	40.4
5	750	51.8
6	737.5	65.1
7	725	75.9
8	712.5	89.5
9	700	102.3
10	687.5	114.8
11	675	126.2
12	662.5	135.9
13	650	144.3
14	637.5	151.9
15	625	157.7
16	612.5	163.9
17	600	174.9
18	587.5	202.8
19	575	238.3
20	562.5	291.8
21	550	367.5
22	537.5	457.3
23	525	579.3
24	516	685.6
25	502	946.8
26	478	1572.2
27	463	3235.0

Appendix B Experimental Data of Column Settling Test with Sample Collection on Total Copper Tailings

B.1 Results of Column Settling Test with a Sample Collection 1.1.4

Test No.		Test 1.1.4	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.3	190.7	146.7	12.70%
2	675	140.3	190.7	146.7	12.70%
3	625	138.5	191	145.2	12.76%
4	575	135.6	189.8	142.6	12.92%
5	525	141.6	198.6	149.4	13.68%
6	475	141.5	194.1	148.4	13.12%
7	425	140.4	196.6	147.9	13.35%
8	375	121.4	177.3	128.9	13.42%
9	325	120	172.2	127	13.41%
10	275	123.6	177.2	132	15.67%
11	225	121.9	176.2	137.6	28.91%
12	175	122.4	203.3	171.5	60.69%
13	125	124.9	198.7	176.2	69.51%
14	75	101.9	197.8	172	73.10%
15	25	162.2	255	233.8	77.16%

B.2 Results of Column Settling Test with a Sample Collection 1.1.4-2

Test No.		Test 1.1.4-2	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	121.4	181.4	127.9	10.8%
2	675	120	173.5	126.9	12.9%
3	625	123.6	179	130.8	13.0%
4	575	121.9	177.4	129.2	13.2%
5	525	122.4	175.9	129.3	12.9%
6	475	124.9	182.6	132.7	13.5%
7	425	101.9	153.6	109	13.7%
8	375	103.9	157.6	111.3	13.8%
9	325	121.1	177	128.9	14.0%
10	275	168.3	223.5	177.5	16.7%
11	225	164.8	223	185.6	35.7%
12	175	148.2	232.6	203.8	65.9%
13	125	165	240.1	218	70.6%
14	75	165.5	260.8	237.3	75.3%
15	25	160	246.6	227.5	77.9%

B.3 Results of Column Settling Test with a Sample Collection 1.1.5

Test No.		Test 1.1.5	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	140.4	176.6	144.4	11.0%
2	625	140.3	191.4	146.9	12.9%
3	575	101.1	153.3	107.4	12.1%
4	525	140.2	193.2	146.5	11.9%
5	475	103.1	153.4	108.9	11.5%
6	425	140.3	194.5	146.7	11.8%
7	375	138.5	195.1	146.4	14.0%
8	325	135.6	185.8	145.3	19.3%
9	275	141.6	196.8	154.4	23.2%
10	225	141.5	201.6	165.6	40.1%
11	175	140.4	217.9	192.9	67.7%
12	125	162.2	248.3	223	70.6%
13	75	163.4	253.1	230.9	75.3%
14	25	165.9	239	223.9	79.3%

B.4 Results of Column Settling Test with a Sample Collection 1.1.5-2

Test No.		Test 1.1.5-2	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	140.4	195.6	146.2	10.5%
2	625	140.3	192.5	146.4	11.7%
3	575	101.1	157	108	12.3%
4	525	140.2	193.3	146.5	11.9%
5	475	103.1	159.2	110	12.3%
6	425	140.3	194	146.9	12.3%
7	375	138.5	194	146.4	14.2%
8	325	135.6	191.4	145.8	18.3%
9	275	141.6	198	154.1	22.2%
10	225	141.5	208.9	168.9	40.7%
11	175	140.4	222.9	195	66.2%
12	125	136.6	226.1	199.9	70.7%
13	75	162.2	255	231.7	74.9%
14	25	163.4	247.3	228.2	77.2%

B.5 Results of Column Settling Test with a Sample Collection 1.1.6

Test No.		Test 1.1.6	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 650 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	625	136.6	190.8	141.8	9.6%
2	575	121.4	174.1	127	10.6%
3	525	120	177.3	126.4	11.2%
4	475	123.6	178.1	130.9	13.4%
5	425	121.9	178	130.9	16.0%
6	375	122.4	176.5	132.1	17.9%
7	325	124.9	184	137	20.5%
8	275	101.9	158.5	115.8	24.6%
9	225	103.9	171.7	131.7	41.0%
10	175	121.1	199.7	172.3	65.1%
11	125	158.9	244.2	219.3	70.8%
12	75	168.3	260.5	236.7	74.2%
13	25	164.8	250.5	230.8	77.0%

B.6 Results of Column Settling Test with a Sample Collection 1.1.7

Test No.		Test 1.1.7	**Sample**	Total tails of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 600 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	575	123.6	176.9	128.1	8.4%
2	525	121.9	175.8	129.3	13.7%
3	475	122.4	181.2	131.6	15.6%
4	425	124.9	180.8	134.7	17.5%
5	375	101.9	155.4	112.2	19.3%
6	325	103.9	161.8	116.5	21.8%
7	275	121.1	179.7	136.4	26.1%
8	225	165.9	230.4	192.3	40.9%
9	175	158.9	239	209.4	63.0%
10	125	168.3	254.1	227.8	69.3%
11	75	164.8	260.1	235.7	74.4%
12	25	148.2	238.4	218.3	77.7%

B.7 Results of Column Settling Test with a Sample Collection 1.2.4

Test No.		Test 1.2.4	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.4	203.6	147.1	10.60%
2	675	140.3	193.4	146.1	10.92%
3	625	101.1	155.9	108	12.59%
4	575	140.2	194.5	147	12.52%
5	525	103.1	156.1	109.7	12.45%
6	475	140.3	195.6	147.4	12.84%
7	425	138.5	192.2	145.4	12.85%
8	375	135.6	190.1	142.7	13.03%
9	325	141.6	194.5	148.7	13.42%
10	275	141.5	196	153.9	22.75%
11	225	140.4	205.8	172.5	49.08%
12	175	136.6	216.8	190.9	67.71%
13	125	121.4	209.2	184.7	72.10%
14	75	162.2	254.6	232.8	76.41%
15	25	163.4	239.5	223.1	78.45%

B.8 Results of Column Settling Test with a Sample Collection 1.2.4-2

Test No.		Test 1.2.4-2	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.4	194.9	147.6	13.2%
2	675	140.3	194.9	148.4	14.8%
3	625	101.1	155	109.3	15.2%
4	575	140.2	197.7	148.8	15.0%
5	525	103.1	158.6	111.5	15.1%
6	475	140.3	197.3	148.9	15.1%
7	425	138.5	193.1	146.7	15.0%
8	375	135.6	190.7	144	15.2%
9	325	141.6	196.6	151	17.1%
10	275	141.5	201.7	160.7	31.9%
11	225	140.4	216.3	187.1	61.5%
12	175	136.6	220.6	195.2	69.8%
13	125	162.2	247.5	224.4	72.9%
14	75	163.4	259.7	236.8	76.2%
15	25	165.9	254.5	235.1	78.1%

B.9 Results of Column Settling Test with a Sample Collection 1.2.5

Test No.		Test 1.2.5	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	140.4	198	147.4	12.2%
2	625	140.3	191.2	146.8	12.8%
3	575	101.1	158.8	108.8	13.3%
4	525	140.2	194.6	147.6	13.6%
5	475	103.1	159	111.8	15.6%
6	425	140.3	195.6	151.1	19.5%
7	375	138.5	196.6	151.9	23.1%
8	325	135.6	193.9	152	28.1%
9	275	141.6	208.7	172	45.3%
10	225	141.5	220.3	191.9	64.0%
11	175	140.4	230.9	203.2	69.4%
12	125	136.6	226.3	201.2	72.0%
13	75	162.2	250.2	229.1	76.0%
14	25	163.4	243.9	227	79.0%

B.10 Results of Column Settling Test with a Sample Collection 1.2.5-2

Test No.		Test 1.2.5-2	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	121.4	175.6	128.7	13.5%
2	625	120	175	127.9	14.4%
3	575	123.6	180.8	131.9	14.5%
4	525	121.9	176.5	129.9	14.7%
5	475	122.4	175.9	130.3	14.8%
6	425	124.9	181.3	134.9	17.7%
7	375	101.9	159.6	114.8	22.4%
8	325	103.9	163.8	120.2	27.2%
9	275	121.1	190.2	153.5	46.9%
10	225	158.9	240.6	212.4	65.5%
11	175	168.3	250.7	226	70.0%
12	125	164.8	252.1	228.4	72.9%
13	75	148.2	239.2	218.1	76.8%
14	25	165	243.7	227.3	79.2%

B.11 Results of Column Settling Test with a Sample Collection 1.2.6

Test No.		Test 1.2.6	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 650 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	625	121.4	170.1	126.1	9.7%
2	575	120	174.2	126.4	11.8%
3	525	123.6	179.8	132.5	15.8%
4	475	121.9	180.7	132.9	18.7%
5	425	122.4	179.6	134.7	21.5%
6	375	124.9	183.9	139.4	24.6%
7	325	101.9	163.2	119.7	29.0%
8	275	103.9	170.3	133	43.8%
9	225	121.1	202	171.9	62.8%
10	175	165.9	251.7	224.5	68.3%
11	125	158.9	250.3	224.5	71.8%
12	75	168.3	263.5	239.9	75.2%
13	25	164.8	246.2	229.2	79.1%

B.12 Results of Column Settling Test with a Sample Collection 1.2.7

Test No.		Test 1.2.7	**Sample**	Total tails of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 600 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	575	121.4	176.2	129.6	15.0%
2	525	120	177.7	130	17.3%
3	475	123.6	181.9	135	19.6%
4	425	121.9	177.7	133.9	21.5%
5	375	122.4	182.6	136.8	23.9%
6	325	124.9	186	142.9	29.5%
7	275	101.9	168.5	131.2	44.0%
8	225	103.9	182.9	152.9	62.0%
9	175	121.1	205.3	178.5	68.2%
10	125	165.9	252.4	227.8	71.6%
11	75	158.9	255.6	231.2	74.8%
12	25	168.3	260	239.5	77.6%

Appendix C Experimental Data of Column Settling Tests on Fines of Copper Tailings

C.1 Results of Column Settling Test 2.1.1

Sample		Fines of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	8.2
3	775	18.7
4	762.5	29.2
5	750	39.6
6	737.5	50.3
7	725	61.5
8	712.5	71.8
9	700	82.0
10	687.5	92.7
11	675	103.4
12	662.5	114.5
13	650	124.0
14	637.5	134.8
15	625	145.3
16	612.5	155.2
17	600	165.7
18	587.5	177.4
19	575	188.0
20	562.5	198.1
21	550	207.9
22	537.5	215.5
23	525	223.4
24	512.5	233.2
25	500	241.2
26	487.5	245.4
27	475	251.9
28	462.5	256.0
29	450	269.7
30	437.5	292.5
31	425	333.4
32	412.5	395.0

Sample		Fines of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
33	400	513.5
34	387.5	880.8
35	380	1429.0

C.2 Results of Column Settling Test 2.1.2

Test No.		2.1.2
Sample		Fines of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	8.3
3	775	19.0
4	762.5	30.4
5	750	41.3
6	737.5	52.8
7	725	64.3
8	712.5	75.3
9	700	86.9
10	687.5	97.7
11	675	108.1
12	662.5	118.8
13	650	130.7
14	637.5	142.4
15	625	153.9
16	612.5	164.7
17	600	175.5
18	587.5	186.2
19	575	196.5
20	562.5	207.3
21	550	215.7
22	537.5	224.6
23	525	232.9
24	512.5	241.4
25	500	248.9
26	487.5	255.7
27	475	262.4
28	462.5	268.9
29	450	284.9
30	437.5	310.7
31	425	351.0
32	412.5	403.7
33	400	480.5

Test No.		2.1.2
Sample		Fines of copper tailings
Solids Content		35%
No.	**Height/ ml**	**Settling Time/ mins**
34	387.5	700.2
35	375	1430.0

C.3 Results of Column Settling Test 2.2.1

Test No.		2.2.1
Sample		Fines of copper tailings
Solids Content		40%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	18.6
3	775	38.2
4	762.5	57.5
5	750	78.0
6	737.5	96.3
7	725	115.2
8	712.5	132.4
9	700	151.6
10	687.5	169.1
11	675	189.7
12	662.5	208.5
13	650	227.0
14	637.5	244.5
15	625	263.0
16	612.5	280.6
17	600	296.7
18	587.5	312.3
19	575	328.2
20	562.5	345.0
21	550	359.2
22	537.5	374.4
23	525	386.5
24	512.5	398.8
25	500	409.0
26	487.5	419.4
27	475	429.4
28	462.5	446.3
29	450	503.8
30	437.5	613.9
31	425	865.5
32	417	1440.0

C.4 Results of Column Settling Test 2.2.2

Test No.		2.2.2
Sample		Fines of copper tailings
Solids Content		40%
No.	**Height/ ml**	**Settling Time/ mins**
1	800	0.0
2	787.5	17.9
3	775	36.3
4	762.5	56.4
5	750	76.5
6	737.5	95.9
7	725	115.2
8	712.5	133.7
9	700	150.0
10	687.5	167.0
11	675	184.7
12	662.5	203.1
13	650	221.5
14	637.5	238.1
15	625	254.2
16	612.5	269.9
17	600	283.2
18	587.5	297.7
19	575	311.4
20	562.5	326.0
21	550	340.3
22	537.5	351.3
23	525	360.3
24	512.5	371.5
25	500	380.9
26	487.5	407.4
27	475	467.2
28	462.5	555.3
29	450	741.2
30	437.5	1030.6
31	432	1429.0

Appendix D Experimental Data of Column Settling Tests with Sample-collection on Fine Copper Tailings

D.1 Results of Column Settling Test with a Sample Collection 2.1.3

Test No.		Test 2.1.3	**Sample**	Fines of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.4	202.6	158.9	29.74%
2	675	140.3	202.2	159.9	31.66%
3	625	101.1	165.7	121.9	32.20%
4	575	140.2	201.9	160.1	32.25%
5	525	103.1	166	123.5	32.43%
6	475	140.3	205.2	161.3	32.36%
7	425	138.5	199.2	158.2	32.45%
8	375	135.6	199.5	156.4	32.55%
9	325	141.6	203.3	161.7	32.58%
10	275	141.5	203.8	161.9	32.74%
11	225	140.4	201.4	160.5	32.95%
12	175	136.6	198.6	157.2	33.23%
13	125	162.2	227.1	187.8	39.45%
14	75	163.4	238.8	204.6	54.64%
15	25	165.9	239.4	209.2	58.91%

D.2 Results of Column Settling Test with a Sample Collection 2.1.4

Test No.		Test 2.1.4	**Sample**	Fines of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	140.4	197.5	156.2	27.7%
2	625	140.3	201.5	158.1	29.1%
3	575	101.1	163.5	119.1	28.8%
4	525	140.2	202.5	158.3	29.1%
5	475	103.1	163.7	120.9	29.4%
6	425	140.3	200.7	158.1	29.5%
7	375	138.5	200.4	156.8	29.6%
8	325	135.6	192.8	152.6	29.7%
9	275	141.6	204.4	160.6	30.3%
10	225	141.5	202.7	163.3	35.6%
11	175	140.4	215.1	178.9	51.5%
12	125	136.6	212.6	178.8	55.5%
13	75	162.2	239.2	207.3	58.6%
14	25	163.4	234.2	205.9	60.0%

D.3 Results of Column Settling Test with a Sample Collection 2.1.5

Test No.		Test 2.1.5	**Sample**	Fines of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 650 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	625	121.4	181.3	136.2	24.7%
2	575	120	180.6	136	26.4%
3	525	123.6	185	140.1	26.9%
4	475	121.9	181.9	138.2	27.2%
5	425	122.4	183.1	138.9	27.2%
6	375	124.9	185.3	141.4	27.3%
7	325	101.9	161.1	118.3	27.7%
8	275	103.9	167.4	128.5	38.7%
9	225	121.1	192.2	157.2	50.8%
10	175	165.9	240.3	205.9	53.8%
11	125	158.9	237	203.3	56.9%
12	75	168.3	250.8	217.2	59.3%
13	25	164.8	235.6	207.6	60.5%

D.4 Results of Column Settling Test with a Sample Collection 2.1.6

Test No.		Test 2.1.6	**Sample**	Fines of copper tailings	
Solids Content		35%			
Description		Samples collected when interface reached 550 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	525	121.4	178.6	131.7	18.0%
2	475	120	175.2	131.5	20.8%
3	425	123.6	180.6	135.8	21.4%
4	375	121.9	183.3	141.7	32.2%
5	325	122.4	186.8	152.8	47.2%
6	275	124.9	197.8	163.8	53.4%
7	225	101.9	173.4	142.4	56.6%
8	175	103.9	180	148.1	58.1%
9	125	121.1	197	166.5	59.8%
10	75	158.9	243.5	210.8	61.3%
11	25	168.3	243.3	216.3	64.0%

D.5 Results of Column Settling Test with a Sample Collection 2.2.3

Test No.		Test 2.2.3	**Sample**	Fines of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.4	201.8	161.7	34.69%
2	675	140.3	206.4	164.5	36.61%
3	625	101.1	164.1	124.5	37.14%
4	575	140.2	207.8	165.4	37.28%
5	525	103.1	168.2	127.6	37.63%
6	475	140.3	206.3	165.3	37.88%
7	425	138.5	204.9	163.6	37.80%
8	375	135.6	200.4	160	37.65%
9	325	141.6	207	166.3	37.77%
10	275	141.5	209.3	167.3	38.05%
11	225	140.4	204.7	165	38.26%
12	175	136.6	202.7	162.1	38.58%
13	125	162.2	234.7	199.6	51.59%
14	75	163.4	238.6	205.9	56.52%
15	25	165.9	230.6	204.2	59.20%

D.6 Results of Column Settling Test with a Sample Collection 2.2.4

Test No.		Test 2.2.4	**Sample**	Fines of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 700 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	675	121.4	180.2	139.8	31.3%
2	625	120	185.3	141.6	33.1%
3	575	123.6	186.8	144.8	33.5%
4	525	121.9	186.3	143.7	33.9%
5	475	122.4	186.7	144.2	33.9%
6	425	124.9	187.4	146.3	34.2%
7	375	101.9	167.1	124.4	34.5%
8	325	103.9	165.5	125.3	34.7%
9	275	121.1	188.1	149.4	42.2%
10	225	158.9	227.8	194.8	52.1%
11	175	168.3	245.1	210.5	54.9%
12	125	164.8	239.9	207.5	56.9%
13	75	148.2	227.1	194.2	58.3%
14	25	165	236	208	60.6%

D.7 Results of Column Settling Test with a Sample Collection 2.2.5

Test No.		Test 2.2.5	**Sample**	Fines of copper tailings	
Solids Content		40%			
Description		Samples collected when interface reached 650 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	625	140.4	203.8	158.7	28.9%
2	575	140.3	203	159.8	31.1%
3	525	101.1	163	120.5	31.3%
4	475	140.2	202.5	159.9	31.6%
5	425	103.1	165	122.8	31.8%
6	375	140.3	205	161.1	32.1%
7	325	138.5	203.2	165.8	42.2%
8	275	135.6	210.5	176	53.9%
9	225	141.6	212.8	182	56.7%
10	175	141.5	221.1	187.4	57.7%
11	125	140.4	215.5	184.8	59.1%
12	75	136.6	221.1	187.5	60.2%
13	25	162.2	234.7	207.4	62.3%

D.8 Results of Column Settling Test with Sample Collection Ending 4.1

Test No.		Test 4.1	**Sample**	Fines + Dispersant	
Solids Content		40%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	121.4	196.3	142.9	26.70%
2	675	120	187.6	148.1	39.35%
3	625	123.6	191	151.8	39.61%
4	575	121.9	191.3	150.9	39.63%
5	525	122.4	191.3	151.1	39.48%
6	475	124.9	193.8	153.7	39.62%
7	425	101.9	167.8	129.4	39.45%
8	375	103.9	170	131.5	39.49%
9	325	121.1	190.3	149.8	39.31%
10	275	162.2	232.6	191.4	39.35%
11	225	163.4	232.1	192	39.45%
12	175	165.9	232.8	193.8	39.46%
13	125	158.9	227.4	187.8	40.00%
14	75	168.3	238.9	200.2	43.06%
15	25	164.8	225.4	195.8	48.68%

Appendix E Experimental Data of Column Settling Tests on the Mixture of Kaolin and Concrete Sands

E.1 Results of Column Settling Test 3.1

Test No.		3.1
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
1	1000	0.0
2	995	6.9
3	990	11.9
4	985	15.8
5	980	19.2
6	975	23.5
7	970	26.4
8	965	29.7
9	960	32.5
10	955	35.1
11	950	38.1
12	945	42.2
13	940	44.7
14	935	47.9
15	930	51.1
16	925	54.7
17	920	57.6
18	915	61.1
19	910	63.4
20	905	66.7
21	900	69.5
22	895	73.1
23	890	76.3
24	885	80.7
25	880	83.7
26	875	88.9
27	870	91.4
28	865	95.9
29	860	98.6

Test No.		3.1
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
30	855	102.0
31	850	104.9
32	845	107.4
33	840	109.4
34	835	111.7
35	830	113.1
36	825	115.3
37	820	116.7
38	815	118.7
39	810	119.9
40	805	121.5
41	800	122.4
42	795	123.8
43	790	124.8
44	785	126.3
45	780	127.8
46	775	130.7
47	770	133.5
48	765	138.0
49	760	142.2
50	755	147.7
51	750	153.9
52	745	162.8
53	740	169.1
54	735	178.8
55	730	188.8
56	725	200.1
57	720	213.4

E.2 Results of Column Settling Test 3.2

Test No.		3.2
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
1	994	0.0
2	990	6.1
3	985	9.5
4	980	12.9
5	975	16.6
6	970	19.8
7	965	23.2
8	960	26.1
9	955	28.9
10	950	31.9
11	945	35.1
12	940	37.9
13	935	40.5
14	930	43.0
15	925	46.1
16	920	48.4
17	915	50.6
18	910	53.5
19	905	56.5
20	900	59.8
21	895	63.4
22	890	68.5
23	885	73.3
24	880	76.5
25	875	79.1
26	870	81.5
27	865	85.0
28	860	87.6
29	855	90.0
30	850	92.2
31	845	94.2
32	840	95.6
33	835	97.7

Test No.		3.2
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
34	830	98.7
35	825	99.8
36	820	101.0
37	815	101.9
38	810	102.8
39	805	104.0
40	800	105.8
41	795	108.3
42	790	111.5
43	785	115.2
44	780	119.4
45	775	124.1
46	770	129.5
47	765	135.5
48	760	142.2
49	755	149.9
50	750	158.9
51	745	167.2
52	738	181.4
53	726	208.2

E.3 Results of Column Settling Test 3.3

Test No.		3.3
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
1	1003	0.0
2	1000	3.7
3	995	7.7
4	990	12.9
5	985	16.6
6	980	19.5
7	975	22.5
8	970	25.5
9	965	28.2
10	960	31.2
11	955	34.4
12	950	36.9
13	945	40.1
14	940	42.3
15	935	45.2
16	930	47.8
17	925	50.3
18	920	53.3
19	915	55.2
20	910	57.4
21	905	61.1
22	900	64.3
23	895	66.6
24	890	69.0
25	885	72.7
26	880	76.5
27	875	79.7
28	870	82.9
29	865	85.9
30	860	88.6
31	855	91.4
32	850	94.0
33	845	96.4

Test No.		3.3
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
34	840	98.5
35	835	100.2
36	830	101.7
37	825	103.3
38	820	105.0
39	815	106.1
40	810	107.0
41	805	107.8
42	800	108.8
43	795	110.0
44	790	111.5
45	785	113.8
46	780	116.6
47	775	119.8
48	770	123.2
49	765	128.5
50	760	133.2
51	755	138.4
52	750	145.7
53	745	154.4
54	740	162.9
55	735	173.5
56	730	183.9

E.4 Results of Column Settling Test 3.4

Test No.		3.4
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
1	1004	0.0
2	1000	4.5
3	995	5.9
4	990	14.0
5	985	19.2
6	980	22.5
7	975	26.2
8	970	29.4
9	965	33.4
10	960	36.4
11	955	39.5
12	950	43.1
13	945	46.2
14	940	48.6
15	935	51.6
16	930	54.6
17	925	57.3
18	920	60.0
19	915	63.3
20	910	66.1
21	905	69.9
22	900	74.1
23	895	78.9
24	890	82.2
25	885	86.4
26	880	89.7
27	875	93.4
28	870	97.5
29	865	101.3
30	860	104.3
31	855	107.4
32	850	110.0
33	845	112.6

Test No.		3.4
Sample		Concrete Sands + Kaolin
Solids Content		30.0%
No.	**Height/ ml**	**Settling Time/ mins**
34	840	113.9
35	835	115.8
36	830	117.9
37	825	119.3
38	820	120.8
39	815	122.3
40	810	123.3
41	805	124.7
42	800	125.7
43	795	127.0
44	790	128.5
45	785	132.0
46	780	135.2
47	775	138.6
48	770	142.5
49	765	148.6
50	760	156.1
51	755	161.3
52	750	168.6
53	745	177.7
54	740	186.4
55	735	196.5
56	727	217.2

Appendix F Experimental Data of Column Settling Tests with Sample Collection on Kaolin

F.1 Results of Column Settling Test with a Sample Collection 1

Test No.		Test 1	**Sample**	Kaolin	
Solids Content		20%			
Description		Samples collected when interface reached 750 ml			
No.	**Height/ ml**	**Weight of Container/ g**	**Total Weight/ g**	**Dry Weight/ g**	**Solids Content**
1	725	140.4	194.4	148.1	14.26%
2	675	140.3	198	150.1	16.98%
3	625	101.1	155.9	110.6	17.34%
4	575	140.2	196.3	150.2	17.83%
5	525	103.1	159.6	113.1	17.70%
6	475	140.3	197.8	150.5	17.74%
7	425	138.5	192.8	148.2	17.86%
8	375	135.6	190.9	146	18.81%
9	325	141.6	199.1	153.4	20.52%
10	275	141.5	196.2	153.7	22.30%
11	225	140.4	196.4	153.7	23.75%
12	175	136.6	193	150.6	24.82%
13	125	162.2	222.8	178	26.07%
14	75	163.4	223.7	179.4	26.53%
15	25	165.9	223.4	184.6	32.52%

F.2 Results of Column Settling Test with a Sample Collection 2

Test No.		Test 2	Sample	Kaolin	
Solids Content		20%			
Description		Samples collected when interface reached 700 ml			
No.	Height/ ml	Weight of Container/ g	Total Weight/ g	Dry Weight/ g	Solids Content
1	675	121.4	175.5	132.1	19.78%
2	625	120	180.6	133.6	22.44%
3	575	123.6	180	136.1	22.16%
4	525	121.9	181.5	134.8	21.64%
5	475	122.4	176.7	133.6	20.63%
6	425	124.9	183	136.5	19.97%
7	375	101.9	159.7	113.5	20.07%
8	325	103.9	159.3	115.3	20.58%
9	275	121.1	175.5	132.5	20.96%
10	225	158.9	216.8	171.6	21.93%
11	175	168.3	225.1	180.9	22.18%
12	125	164.8	222.2	177.9	22.82%
13	75	148.2	206.5	161.8	23.33%
14	25	165	223	182.2	29.66%