BTA/GE/11-03 **Sedimentation of Oil Sands Tailings**

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1. Abstract

In Alberta (Canada) bitumen is extracted from the mined oil sands ore by a process that uses hot water. This process produces large amounts of tailings, which is a mixture of water and sediment particles. These tailings are stored in large ponds to allow the sediments to settle out of suspension. The water is recycled in the hot-water process and the solids are used for land reclamation in the mine site areas that have been mined out. The fine particles in the tailings settle very slowly so companies are trying to find ways to accelerate the dewatering process. A dewatering process consists of three phases: sedimentation, consolidation and ripening when the sediment layer is exposed to air. Samples of the tailings were shipped to Delft University of Technology to perform dewatering experiments. From one of the first experiments it was suspected that the moisture content of the samples was already too low for the sedimentation phase to precede the consolidation phase. The goal of this project was to find out if there is a relation between the moisture content at the transition between the sedimentation and consolidation phases and the liquid limit and liquidity index of the soil. To be able to compare the results with another type of soil, the same tests were performed on river clay.

Three sedimentation columns with different moisture contents were prepared for each of the materials and standard tests (BS 1377) were performed on the soils to determine the liquid and plastic limit from which the liquidity index was derived. To further characterize the materials, hydrometer tests were performed. From the British soil classification chart was deduced that the thickened tailings were to be classified as an intermediate plasticity clay and the river clay as a high plasticity clay.

The major conclusion that may be drawn from the test results is that the liquidity index at the boundary between sedimentation and consolidation for both materials is around 18 and 19 for both soils. Furthermore the moisture content at the transition from the sedimentation phase to the consolidation phase is around ten times higher than the liquid limits of the materials. Another conclusion is that the consolidation phase shows no acceleration on a logarithmic time scale when it is preceded by the sedimentation phase, where this acceleration is visible when the sedimentation phase does not occur.

2. Introduction

2.1 General problem of dewatering of tailings

In Alberta (Canada) oil sands are mined in large scale open pit operations using large mechanical equipment. After the ore is excavated, the thick bitumen is washed off the sand and clay with hot water. The sediment particles form a slurry with water. This slurry is called tailings and it is deposited in large ponds where the sand and clay particles are allowed to settle to separate the water from the sediments. A dewatering process is characterized by three phases: sedimentation, consolidation and ripening. The separated water is used again in the hot-water process and the solids are, if suitable, used for land reclamation purposes in the mined-out areas at the mine site.

The so-called hot-water process produces a big amount of tailings, for every barrel of bitumen that is produced, more than 3 m^3 of tailings are generated (Xu, Dabros, & Kan, 2008). Since mining operations are expanded more space is needed for ponds. However companies encounter stricter regulations concerning the construction of new tailings ponds. Therefore these companies are looking for ways to shorten the residence time of tailings in the pond to use the pond area in a more efficient way.

2.2 Scope of this project

Dewatering tests were performed at Delft University of Technology to get a first estimation of the time it takes for the tailings to dewater. From the results of this test it is presumed that the water content of these tailings is too low for the first phase of dewatering (sedimentation) to occur. This raised the question at which moisture content the boundary between the sedimentation and consolidation phases is. And how this moisture content can be related to soil classification properties like the Atterberg limits (liquid and plastic) and the plasticity and liquidity indices that are derived from the Atterberg limits. To be able to compare the results of these tests for the tailings with a different type of soil, the same tests are performed on river clay.

2.3 Literature

2.3.1 Dewatering of soil

As mentioned in paragraph 2.1 three phases in dewatering of soil can be distinguished: sedimentation, consolidation and ripening. This project only deals with the first two phases, sedimentation and consolidation. Because the soil is not exposed to air after the consolidation phase, the phase of ripening does not occur.

During the sedimentation phase in a stagnant liquid, solid particles settle out of the suspension in which they are entrained under the influence of their density, which is higher than the density of the fluid. Stoke's law (Equation 2.1) gives the stationary fall velocity for a single spherical particle in a fluid (Boggs, 2006).

Equation 2.1

$$v = \frac{2}{9}\frac{(\rho_s - \rho_f)}{\mu} g R^2$$

In which:
v = velocity [m/s]
ρ_s = density of solid particle [kg/m^3]
ρ_f = density of fluid [kg/m^3]
g = gravitational acceleration [m/s^2]
R = radius of particle [m]

After sedimentation a lot of water is still trapped in the sediment layer. Consolidation is the process during which this water is squeezed out of the sediment layer because of the weight of the overlying sediment.

In a previous study (Azam, Jeeravipoolvarn, & Scott, 2009) from the relation between the void ratio and effective stress the void ratio was determined at which the sedimentation phase of some specific tailings material ended, namely 8.0. The tailings consisted mainly of heavy iron oxides (specific gravity of 3.15) and 93% of the grains were smaller than 0.075 mm and 35% smaller than 0.002 mm.

2.3.2 Atterberg limits

The Atterberg limits were developed by Albert Atterberg (1911) to determine the behavior of silts and clays at different moisture contents. Atterberg distinguished four different states: liquid, plastic, semi-solid and solid (Liu & Evett, 1984). The liquid limit (W_{LL}) of a soil is the moisture content at the boundary between plastic and liquid behavior. The plastic limit (W_{PL}) is the moisture content at the transition between the semisolid and the plastic state. The shrinkage limit (W_{SL}) forms the boundary between solid and semisolid behavior, this Atterberg limit is not further used in this project. Figure 2.1 provides an overview of the Atterberg limits and the different states of soils with the moisture content W increasing to the right.

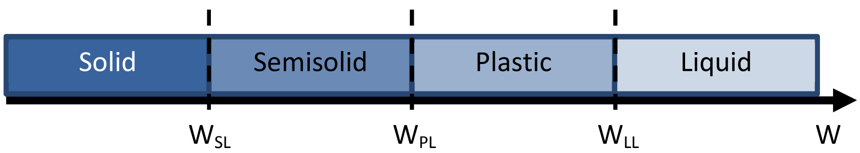

Figure 2.1 Schematic overview of the Atterberg limits and the different states of soils

There are two tests that are generally used to determine the liquid limit: the Casagrande cup test and the cone penetrometer test. The plastic limit is reached when a sample of the soil starts to crumble as it is rolled to form a thread of 3 mm diameter in British Standard or 3.2 mm (1/8 inch) in American standard. (Day, 2001). The plasticity index is the difference between the liquid and plastic limit (Liu & Evett, 1984). The liquidity index is the difference between the natural moisture content and the plastic limit divided by the plasticity index (Wesley, 2010).

3. Materials and Methods

This chapter contains information on the origin of the soils. It explains which tests were performed to characterize the material and it gives the set-up of the dewatering experiments

3.1 Origin of the soils

3.1.1 Tailings

The oil sands tailings used in the tests are from Albian Sands Muskeg River Mine at Fort McMurray in Canada. Here hydro cyclones separate the tailings and the overflow is thickened. This is called thickened tailings, often referred to as TT. Four oil drums of thickened tailings sludge were shipped from Canada to Delft University of Technology. In Delft the drums were rolled for several minutes before samples were transferred into buckets. The tailings are a mixture of sand, silt, clay, water and approximately 1 to 2% bitumen (Yao, van Tol, van Paassen, Everts, & Mulder, 2010). Since the further sample preparation differs for every test, this is described per test.

3.1.2 River Clay

The river clay is bought as a cube of 10 kg at Firma van Emmerik in Delft. It is produced by Ve-Ka industrie keramische grondstoffen[1] located in Dreumel (The Netherlands).

3.2 Material Characterization

3.2.1 Grain size distribution

The hydrometer test is designed to determine the particle size distribution of the fine fraction (<63 µm). For both thickened tailings and river clay the test was performed according to BS 1377. Because an amount of about 50 g of dry soil is needed to perform the test, samples of the thickened tailings and the river clay were dried in the oven at respectively 50 °C and 105 °C. After grinding, 100 ml of the dispersing agent sodium hexametaphosphate solution was added to around 50 grams of both materials. These mixtures were allowed to soak during the weekend. After the weekend the mixtures were stirred for half an hour with a high speed stirrer. A 63 µm sieve was used to separate the coarser fraction from the fines. The remaining slurry with fines was transferred into a 1000 ml cylinder and immediately after shaking it, the hydrometer was inserted. The first density reading was performed as soon as possible. Then after 1, 2, 3, 4, 8 and 30 minutes and after 1, 2, 4, 8 and 24 hours density readings were logged. With help of Stoke's Law (Equation 2.1) these density readings are converted into grain sizes. The fraction coarser than 63 µm was dried and sieved with 600, 300 and 150 µm sieve. Together with the hydrometer test results this gives a curve for the particle size distribution. The fraction smaller than 2 µm is called clay, the silt fraction is between 63 µm and 2 µm and the fraction of the soil that is larger than 63 µm is called sand (Verruijt & van Baars, 2004). Further d_{10}, d_{50}, d_{60} and the uniformity coefficient $C_u = d_{10}/d_{60}$ are given which are often used to characterize soil (Verruijt & van Baars, 2004).

3.2.2 Atterberg Limits

The Atterberg Limits can be determined with basic tests and are usually performed on fine-grained soils to distinguish between silt and clay en different types of silt and clay. Here the liquid limit (W_{LL}) and plastic limit (W_{PL}) of thickened tailings and river clay are determined according to BS 1377. Because it takes a lot of time for the thickened tailings to lose a enough water to be able to perform

[1] See www.ve-ka.nl

the tests on this material, the tailings samples used are oven-dried and grinded with a mortar afterwards. Water was added to the grinded material and allowed to soak over a few days. The river clay already had a moisture content of 35%, so in this state it was ready to use for the tests.

Liquid Limit Tests

There are two basic tests available at TU Delft to determine the liquid limit, the cone penetrometer test and the Casagrande cup test. Both tests were performed on river clay. The liquid limit of thickened tailings could only be determined with the cone penetrometer test.

The basic principle of the cone penetrometer test is that, as the moisture content is increased by adding more water to the soil, a standard cone of 80 grams penetrates deeper into the soil when it is released from just above the surface of the soil sample which is in the sample cup. A penetration of 2 cm corresponds to the liquid limit. For several moisture contents the penetration is measured and the geotechnical moisture content is calculated according to Equation 3.3.

With the Casagrande cup test a sample of soil is placed in the cup. A grooving tool is used to cut a groove along the diameter. The moisture content at which it takes 25 blows to close the groove over a distance of 12 mm (the width of the other end of the grooving tool) matches the liquid limit. For several samples the number of blows is counted and the geotechnical moisture content is again determined using Equation 3.3. For the thickened tailings it was not possible to cut a decent groove along the diameter of the cup. Therefore the Casagrande cup test was only performed on river clay.

Plastic Limit Test

The plastic limit test starts with a ball of around 20 g of soil. This ball is divided into two sets of 4 small balls of equal size. Each ball is rolled by hand on a glass plate and by applying some pressure a thread is formed. As long as a 3 mm diameter thread can be rolled without cracks appearing, the moisture content is too high. As soon as the thread starts to crumble at a diameter of 3 mm, the plastic limit is reached. This is performed on 4 balls that form a set. The crumbled pieces of these 4 balls are placed in an evaporating dish together and are dried in an oven for a day. Once more the geotechnical moisture content is calculated with Equation 3.3. The same is done with the other 4 balls. The average moisture content of these two sets is the plastic limit.

Plasticity and Liquidity Indices

The plasticity index (PI) is derived from the liquid and plastic limit, it is actually the difference between these two Atterberg limits, see Equation 3.1 (Liu & Evett, 1984).

Equation 3.1

$$\boldsymbol{PI = W_{LL} - W_{PL}}$$

The liquidity index (LI) is defined as the difference between the natural moisture content (W_n) and the plastic limit divided by the plasticity index, see Equation 3.2 (Wesley, 2010).

Equation 3.2

$$\boldsymbol{LI = \frac{W_n - W_{PL}}{PI}}$$

The relation between the moisture content of a soil and the liquidity index is illustrated in Figure 3.1. On the upper axis the moisture content increases to the right. The plasticity index on the moisture content axis matches with one unit on the liquidity index axis. Suppose the natural moisture content (W_n)of a soil is represented by the blue dot on the moisture content axis, then its liquidity index is indicated by the red mark on the lower axis.

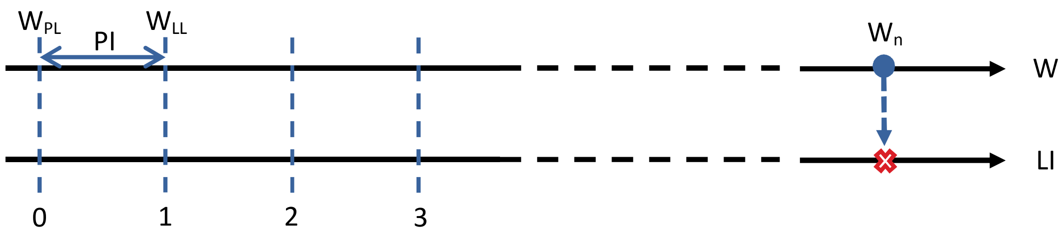

Figure 3.1 Illustration of the relation between moisture content and liquidity index

3.2.3 Soil Classification

In the British soil classification system (BS 5930: 1999 section 6), soil is classified based on its liquid limit and plasticity index according to Figure 3.2 below

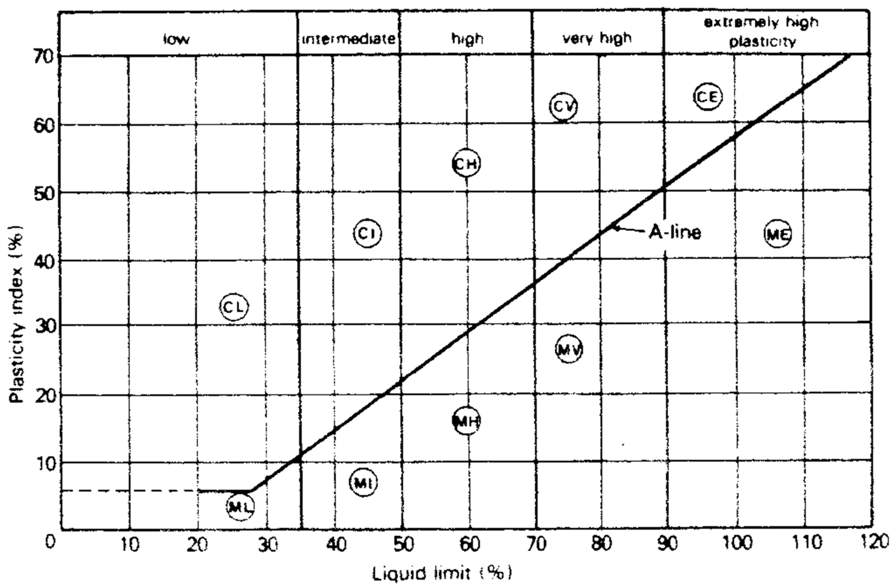

Figure 3.2 Chart of the British Soil Classification System

In which:

C = Clay M = Silt

L = Low plasticity I = Intermediate Plasticity H = High Plasticity

V = Very high plasticity E = Extremely high plasticity

3.3 Dewatering Experiments

3.3.1 Thickened Tailings

Bucket 3.1 was stirred for 30 minutes, after this a 1000 ml cylinder was filled with TT. A second cylinder was filled with half TT and half tap water. A third cylinder was prepared with three parts (750 ml) TT and one part tap water (250 ml). The top of each cylinder was sealed with a plastic film to prevent evaporation of the water. The cylinders were placed in a climate room (15°C) and at various points in time, the level at which the separation between sediment and water was, was logged. The three columns with thickened tailings are named 1, 2 and 3 with increasing moisture content.

3.3.2 River Clay

Also three cylinders were filled with a mixture of river clay and tap water. 2.5 kg of river clay was put into the container of a stirrer and tap water was added. Three 1000 ml columns of a different moisture content were prepared, covered with a plastic film and placed in the climate room. The sedimentation level was logged at various points in time. The three columns with river clay are numbered 4, 5 and 6 with increasing water content.

3.3.3 Moisture content

To determine the moisture content of each of the columns, samples were taken at the start of the experiments. These samples were weighed in a petri dish of which the mass was known and placed in a drying oven at about 105 °C to dry for at least 24 hours. After drying they were weighed again. The (geotechnical) moisture content in percentage can be calculated with Equation 3.3 (Day, 2001)

Equation 3.3

$$W = \frac{m_w}{m_d} \cdot 100 = \frac{m_{wc} - m_{dc}}{m_{dc} - m_c} \cdot 100$$

In which:

W = Moisture content [%]
m_w = mass of water [g]
m_d = mass of dried sample [g]
m_{wc} = mass of wet soil + mass of container (petri dish)[g]
m_{dc} = mass of dried soil + mass of container (petri dish)[g]
m_c = mass of container (petri dish)[g]

4. Results

4.1 Material characterization

4.1.1 Grain size distribution

The grain size distribution curves of both tailings and river clay are presented in Figure 4.1. The orange arrows in this figure indicate on the vertical axis the percentage of the material which is smaller than 2 µm (0.002 mm). This fraction is called clay according to the Udden-Wentworth classification. The green arrows indicate the 63 µm (0.063 mm) boundary which is the upper limit of the silt fraction. For the tailings d_{10}, d_{50} and d_{60} are indicated by purple arrows. Since the intention to perform the hydrometer tests was to find out what percentage of the material is smaller than 2 µm, the experiment was stopped after this particle size was reached. This means that for river clay d_{10} could not be determined. However d_{50} and d_{60} are indicated by purple arrows. These numbers are listed in Table 4.1 together with the uniformity coefficient C_u. The density readings of the hydrometer tests can be found in Appendix A: Hydrometer test results

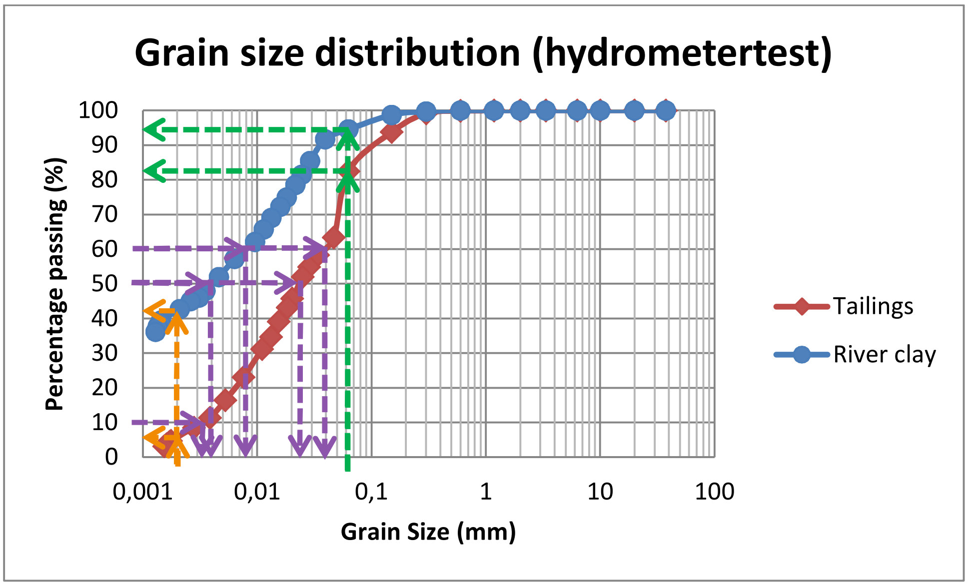

Figure 4.1 Grain size distribution of tailings and river clay

	Thickened Tailings	River Clay
Sand (>0.063 mm)	17.5 %	5.5 %
Silt (0.002 mm, 0.063 mm)	76.5 %	42.5 %
Clay (<0.002 mm)	6 %	42 %
d_{10} (mm)	0.0034	-
d_{50} (mm)	0.0235	0.0041
d_{60} (mm)	0.0383	0.0082
d_{10}/d_{60} (-)	0.0876	-

Table 4.1 Grain size distribution of tailings and river clay resulting from hydrometer tests

4.1.2 Atterberg Limits

Table 4.2 below lists the results of the Atterberg limit tests for both tailings and river clay. The liquidity indices are calculated use the natural moisture contents (W_n) of the different columns that were prepared for the dewatering experiments. These water contents can be found in paragraph 4.2.3. All test results can be found in Appendix B: Atterberg Limit tests

	Thickened Tailings	River Clay
W_{LL}	38.1	57.2
W_{PL}	21.0	21.7
PI	17.1	35.5
LI column 1	11.1	-
LI column 2	20.5	-
LI column 3	27.4	-
LI column 4	-	3.4
LI column 5	-	8.5
LI column 6	-	29.9

Table 4.2 Atterberg limits of tailings and river clay

4.1.3 Soil Classification

Now that we know the liquid limit and the plasticity index of both soils, we are able to plot them in the British soil classification system chart that was introduced in paragraph 3.2.3. In Figure 4.2 one can see that the tailings can be classified as ***intermediate plasticity clay*** (red dot) and the river clay as ***high plasticity clay*** (blue dot).

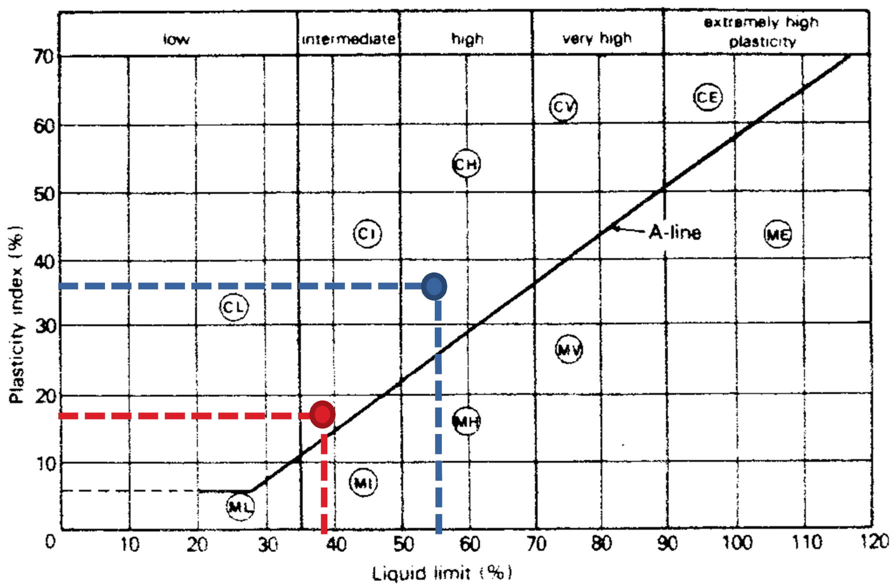

Figure 4.2 Tailings (red) and river clay (blue) plotted in the British soil classification system chart

4.2 Dewatering Experiments

On a linear time scale a sedimentation process gives a characteristic 'S-shaped curve'. Since a consolidation process takes significant more time, this is best represented on a logarithmic time scale. The results below are displayed on a logarithmic time-axis for all three columns . If the water content of the column is high enough for the sedimentation phase to occur, also the sedimentation part is shown on a linear time axis graph. All the logged values for the dewatering experiments can be found in Appendix C: Dewatering Experiments.

4.2.1 Thickened Tailings

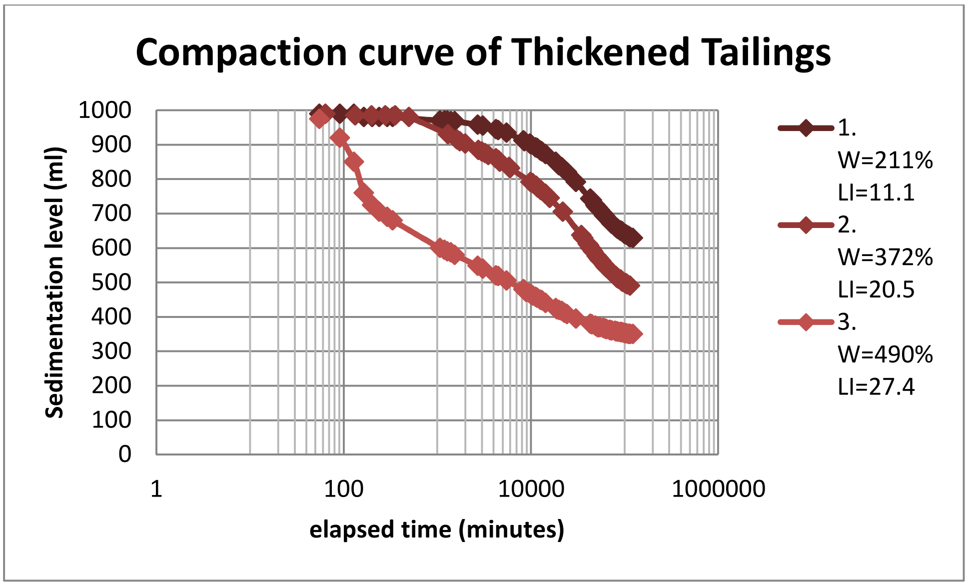

Figure 4.3 Results of dewatering experiments on three thickened tailings columns

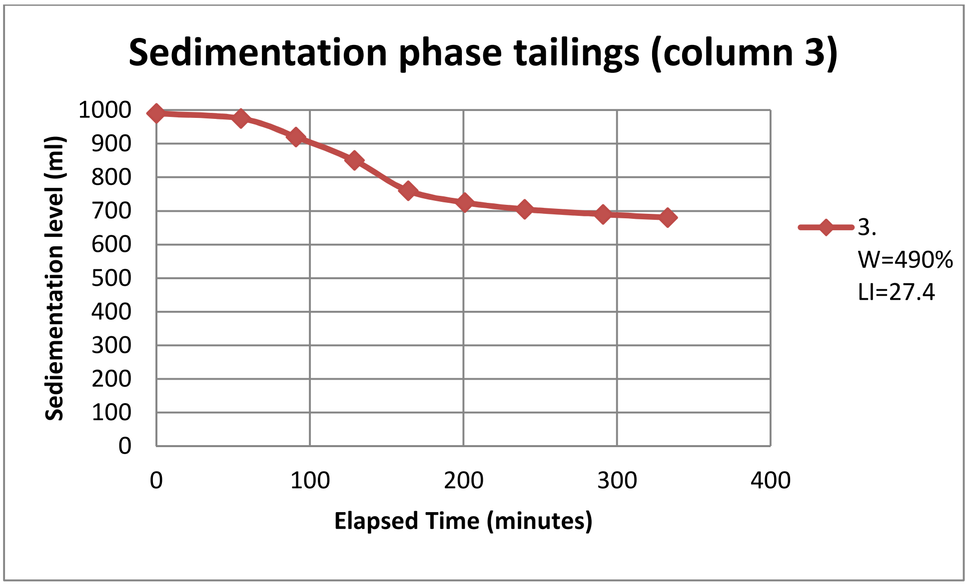

Figure 4.4 Sedimentation curve of thickened tailings column 3

4.2.2 River Clay

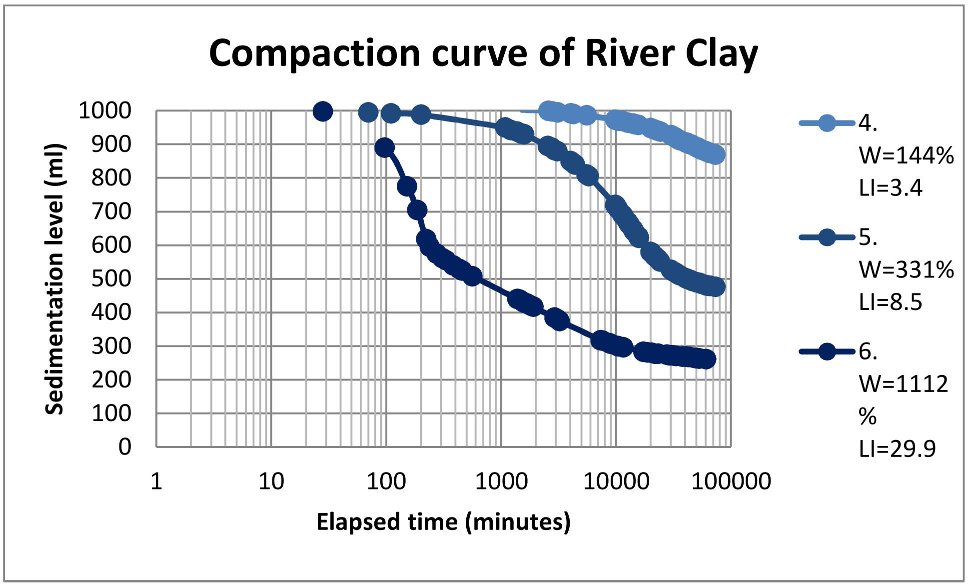

Figure 4.5 Results of dewatering experiments on three columns of river clay slurry

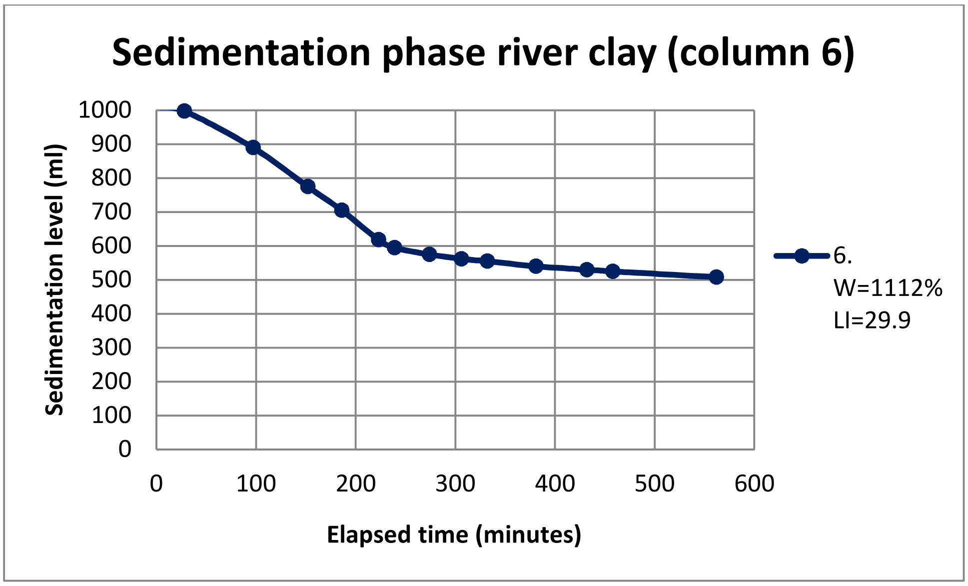

Figure 4.6 Sedimentation curve of river clay column 6

4.2.3 Moisture content

Moisture contents are calculated according to Equation 3.3. Table 4.3 and Table 4.4 present the results.

Tailings	m_c [g]	m_{wc} [g]	m_{dc} [g]	W [%]
Column 1	44.62	68.73	52.38	210.70
Column 2	48.58	70.86	53.30	372.03
Column 3	45.12	61.98	47.98	489.51

Table 4.3 Moisture content of Thickened Tailings columns

River Clay	m_c [g]	m_{wc} [g]	m_{dc} [g]	W [%]
Column 4	34.04	52.52	41.60	144.44
Column 5	34.15	49.61	37.74	330.64
Column 6	45.05	62.74	46.51	1111.64

Table 4.4 Moisture content of River Clay columns

5. Discussion

Looking at the consolidation curves in Figure 4.3 and Figure 4.5 one can see that there is a clear difference in the consolidation behavior between the columns that show a sedimentation phase (3 and 6) and the columns that only show a consolidation phase (1, 2, 4 and 5). If there is only consolidation, it takes a while before the level that forms the boundary between water and soil starts to drop, but after this there is clear acceleration visible on a logarithmic time scale. Whereas after a period of sedimentation, the consolidation curves for both thickened tailings and river clay are more or less straight lines and show no acceleration on a logarithmic scale. An explanation for this difference in behavior could be that when the consolidation phase starts there is still an amount of particles in suspension, in other words, there is no clear boundary between the sedimentation and consolidation phases. Because it takes some time before all particles participate in the consolidation process there is no acceleration visible on the logarithmic time axis just after the sedimentation phase. Moreover the columns 3 and 6 contain the smallest amount of solids and since consolidation is the process in which water is squeezed out of the soil under the influence of the weight of the soil itself, it is not strange that the consolidation process proceeds the slowest in these columns.

Now that we have the test results it's time to return to the original question if there is a relation between the moisture content at which sedimentation phases passes into the consolidation phase and the liquid limit and liquidity index. First a point needs to be determined in the dewatering curves of both materials. In Figure 4.3 this point is determined to be at a sedimentation level of 725 ml after 201 minutes for thickened tailings and in Figure 4.5 the chosen point is 618 ml after 223 minutes.

Moisture content can also be defined as the ratio of the mass of water and the total mass (water plus solids) multiplied by a hundred as in Equation 5.1 below.

Equation 5.1

$$\boldsymbol{W^* = \frac{m_{wc} - m_{dc}}{m_{wc} - m_c} \cdot 100}$$

This way to calculate the moisture content differs from the way to calculate the geotechnical moisture content W (see Equation 3.3), for this reason it is called W* here. We need this W* in Equation 5.2 to determine the moisture content that is the boundary between the sedimentation and the consolidation phase.

Equation 5.2

$$\boldsymbol{W_b = \frac{m_t - \rho_w(V_t - V_b) - m_t\left(1 - \frac{W^*}{100}\right)}{m_t\left(1 - \frac{W^*}{100}\right)}}$$

In which:
W_b = Moisture content at the boundary between the sedimentation and the consolidation phase [%]
m_t = total mass of the slurry [g]
V_t = total volume of slurry at the start of the experiment][ml]
V_b = Sedimentation level at the boundary [ml]
ρ_w = Density of water [g/ml]
W* = Moisture content with respect to total mass of the slurry. [%]

The values that are used for these quantities are listed in Table 5.1

	Thickened Tailings	River Clay
m_t (g)	1089	1040
V_t (ml)	990	1010
V_b (ml)	725	618
ρ_w (g/ml)	1	1
W* (%)	0.83	0.917
W_b (%)	345	651
W_{LL} (%)	38.1	57.2
W_b/W_{LL} (-)	9.05	11.38
LI_b (-)	18.95	17.72

Table 5.1 Calculation of W_b

From the results in Table 5.1 one can see that the values W_b for these materials are around ten times higher than their liquid limits. When the values for W_b are used to calculate the liquidity index at the boundary (W_n is replaced by W_b in Equation 3.2), we find liquidity indices that are very close to each other (18.95 and 17.72 for tailings and river clay respectively, see last line of Table 5.1).

The above seems a rather complicated way to calculate W_b. Another way is to use the void ratio which is calculated with Equation 5.3 (Verruijt & van Baars, 2004).

Equation 5.3

$$e = \frac{V_V}{V_S} = \frac{V_W}{V_S}$$

In which
e = Void ratio (-)
V_V = Void space volume (ml)
V_S = Volume of solids (ml)
V_W = Volume of water (ml)

From the second part of Equation 5.3 it can be seen that it is assumed that all void space is substituted by water. Since all moisture contents we know are expressed as mass percentages, we can't work with volumes immediately. But when we take for ρ_W = 1.0 (g/ml), ρ_S = 2.29 (g/ml) for thickened tailings (Yao, van Paassen, van Tol, Everts, & Mulder, 2010), ρ_S = 2.65 (g/ml) for river clay and we take the following steps we find values for W_b that approximate the same values as calculated above.

$e = \frac{m_W}{m_S}\frac{\rho_S}{\rho_W} = \frac{W}{100}\frac{\rho_S}{\rho_W}$ and $V_S = \left(\frac{1}{(1+e)}\right)V_t$ leads to $m_S = V_S \cdot \rho_S$

Now $m_W = (V_b - V_S)\rho_W$ gives $W_b = \frac{m_W}{m_S} \cdot 100$ and $e_b = \frac{V_b - V_S}{V_S}$

Table 5.2 lists the values that were used for the different quantities in the steps above for both materials. The numbers in italics are results from a calculation in one of the steps.

	Thickened Tailings	River Clay
W (-)	490	1112
ρ_S (g/ml)	2.29	2.65
ρ_W (g/ml)	1.00	1.00
e (-)	*11.21*	*29.46*
V_t (ml)	990	1010
V_s (ml)	*81.08*	*33.16*
m_s (g)	*185.68*	*87.87*
V_b (ml)	725	618
m_W (g)	*643.92*	*584.84*
W_b (%)	*346.79*	*665.55*
e_b (-)	*7.94*	*17.64*
LI (-)	*19.05*	*18.14*

Table 5.2 Values used to calculate W_b with help of the void ratio

In the last line of Table 5.2 the liquidity indices are calculated with the new values of W_b. We see that these values are even closer to each other compared to the results in Table 5.1 in which the difference is more than 1, where it is less than 1 now. Between the two values of W_b we have for tailings is a difference of 1.79 ml. For River clay this difference is larger (14.55 ml), which may be a result from the assumption of the density of 2.65. A lower density results in a lower value for W_b. But compared to the total volume on which the test was performed (1010 ml) the difference of 14.55 ml is only a deviation of 1.4 %.

Comparing the result of the void ratio at the boundary for the oil sands tailings (7.94) with the result from the previous study (Azam, Jeeravipoolvarn, & Scott, 2009) on heavy iron oxide tailings (8.0), we see that the values are very close to each other.

Finally it should be noted here that for both thickened tailings and river clay there is only one column in which the transition from sedimentation to consolidation is visible in the results. It would be better if there were two columns with different moisture contents to see if the calculated values for W_b are the same.

6. Conclusions and Recommendations

After having discussed the results of the different tests and the relation between the results, the major conclusion that may be drawn is that the liquidity index that is calculated from the moisture content at which the sedimentation phase passes into the consolidation phase is around the numbers 18 and 19 (depending on the way W_b is calculated). Furthermore this moisture content is around ten times higher than the liquid limit. Since this is established for only two different soils, research should be continued on other types of soils to see if this conclusion holds for other materials.

A conclusion that may be drawn from the dewatering experiments is that the consolidation behavior of soils was different when the sedimentation phase had first occurred. On a logarithmic time scale this is visible as a straight line. When only the consolidation phase occurred, there was a clear acceleration visible on a logarithmic time scale. The fact that this acceleration is not there when the consolidation phase is preceded by the sedimentation phase is due to particles that are still in suspension when the consolidation phase starts. These particles do not contribute to the weight of soil that makes water come out of the layer of sediment. Further the columns that show a sedimentation phase have the highest water contents, so the least amount of solid particles. This causes a slower consolidation, simply because there is less weight.

As discussed in chapter 5 it would also have been better to have two columns for every material with different water contents that is high enough for the sedimentation phase to take place. In this way it is possible to check if the values of W_b match for both columns of the same material.

7. References

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8. Appendices

Appendix A: Hydrometer test results

Input Parameters		Sieving Analysis	
Sample	**Tailings**	**Sieve (mm)**	**Mass retained (g)**
Temperature (°C)	15.5	1.18	0
Particle density (Mg/m³)	2.65	0.6	0.08
Density reading R_0 (-)	1.0030	0.3	0.36
Start mass sample (g)	50.92	0.15	2.72
Meniscus correction	0.5	0.063	5.77

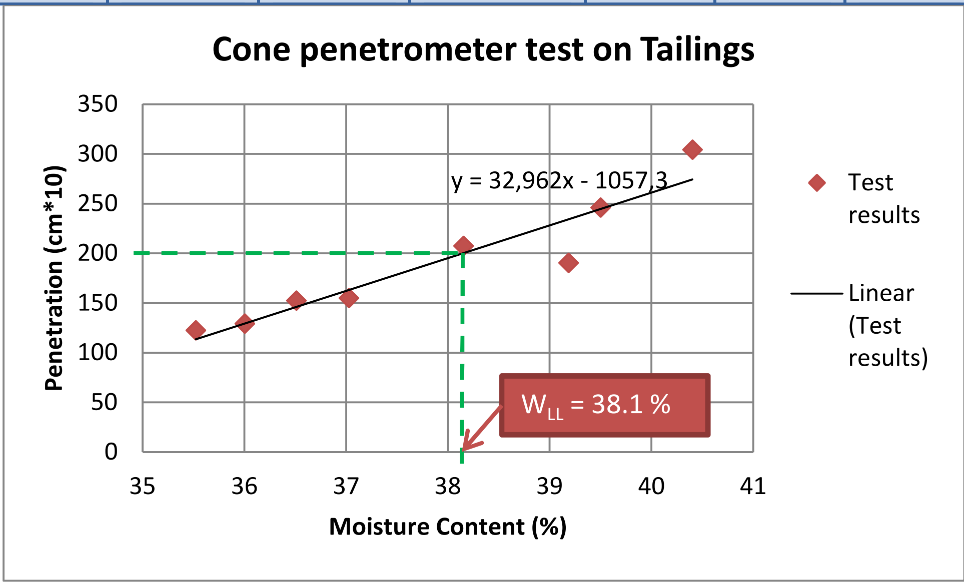
Hydrometer Analysis					
hr	**min**	**Density reading**	**hr**	**min**	**Density reading**
0	1	1.0231	0	57	1.0103
0	2	1.0215	2	5.5	1.0082
0	3	1.0204	4	0	1.0066
0	4	1.0195	7	49	1.0057
0	6.5	1.0175	20	25.5	1.0045
0	8	1.0167	21	25	1.0044
0	12	1.0154	24	2	1.0042
0	17	1.0140	27	3.5	1.0040
0	25	1.0129			

Input Parameters		Sieving Analysis	
Sample	**River Clay**	**Sieve (mm)**	**Mass retained (g)**
Temperature (°C)	15.5	1.18	0
Particle density (Mg/m³)	2.65	0.6	0.01
Density reading R_0 (-)	1.0030	0.3	0.14
Start mass sample (g)	48.9	0.15	0.48
Meniscus correction	0.5	0.063	2.05

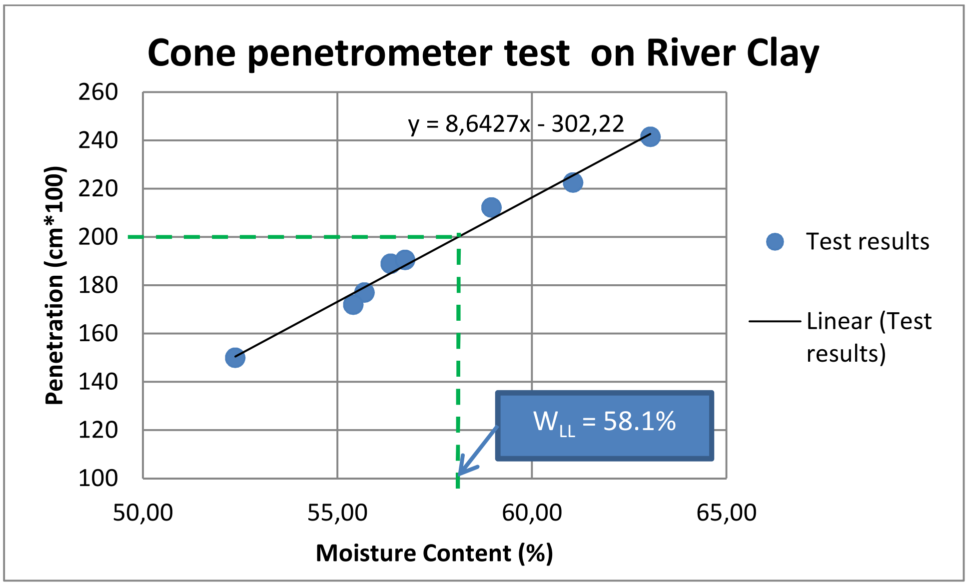
Hydrometer Analysis					
hr	**min**	**Density reading**	**hr**	**min**	**Density reading**
0	1	1.0309	2	0	1.0188
0	2	1.0290	3	35	1.0176
0	3	1.0278	4	43	1.0170
0	4	1.0269	6	38	1.0167
0	6	1.0258	10	27	1.0160
0	8	1.0250	23	3	1.0150
0	12	1.0240	24	0	1.0148
0	17	1.0230	26	40	1.0145
0	25	1.0219	29	41.25	1.0140
1	0	1.0204			

Appendix B: Atterberg Limit tests

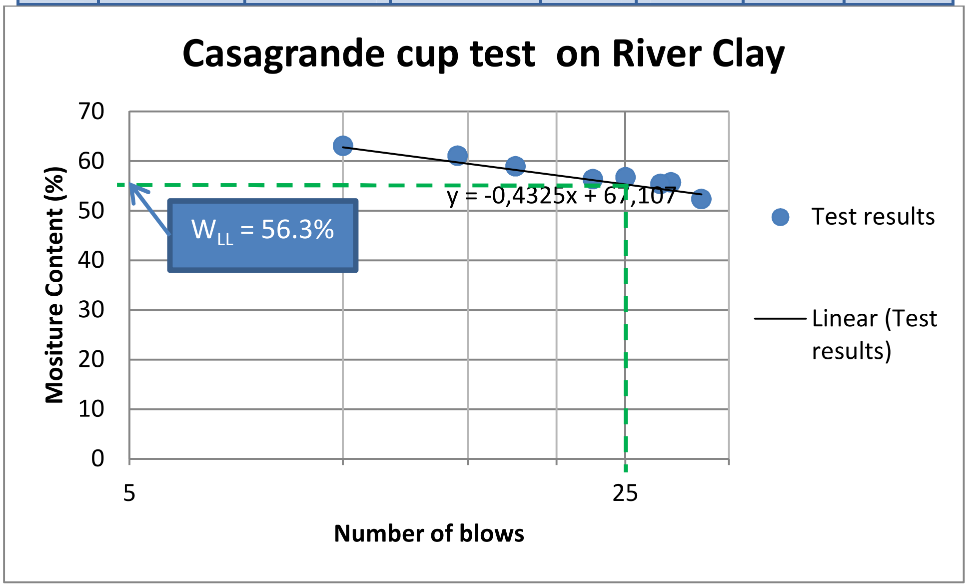
Cone penetrometer test on tailings								
No.	**Reading 1**	**Reading 2**	**Reading 3**	**Average reading**	**M_c (g)**	**M_{wc} (g)**	**M_{dc} (g)**	**W (%)**
1	121	128	118	**122.3**	47.57	72.33	65.84	**35.52**
2	128	133	126	**129.0**	46.62	76.31	68.45	**36.01**
3	148	154	155	**152.3**	45.44	70.79	64.01	**36.51**
4	160	150	155	**155.0**	48.67	79.57	71.22	**37.03**
5	195	188	188	**190.3**	43.96	74.08	65.60	**39.19**
6	241	249	248	**246.0**	34.42	71.22	60.80	**39.50**
7	211	199	212	**207.3**	49.02	84.94	75.02	**38.15**
8	303	309	300	**304.0**	45.10	78.60	68.96	**40.40**



Cone penetrometer test on river clay									
No.	**Reading 1**	**Reading 2**	**Reading 3**	**Reading 4**	**Average reading**	**M_c (g)**	**M_{wc} (g)**	**M_{dc} (g)**	**W (%)**
1	152	148			**150**	47.58	60.41	56.00	**52.38**
2	189	189			**189**	43.96	63.10	56.20	**56.37**
3	178	176			**177**	34.43	45.64	41.63	**55.69**
4	170	174			**172**	49.02	61.81	57.25	**55.41**
5	193	188			**190.5**	46.62	58.94	54.48	**56.74**
6	218	210	206	215	**212.3**	48.67	59.05	55.20	**58.96**
7	218	229	221		**222.7**	46.97	57.89	53.75	**61.06**
8	243	240			**241.5**	34.30	49.92	43.88	**63.05**



Casagrande cup test on river clay							
No.	**Reading 1**	**Reading 2**	**Average reading**	**M_c (g)**	**M_{wc} (g)**	**M_{dc} (g)**	**W (%)**
1	32	32	**32**	47.58	60.41	56.00	**52.38**
2	22	23	**22.5**	43.96	63.10	56.20	**56.37**
3	28	30	**29**	34.43	45.64	41.63	**55.69**
4	28	28	**28**	49.02	61.81	57.25	**55.41**
5	25	25	**25**	46.62	58.94	54.48	**56.74**
6	17	18	**17.5**	48.67	59.05	55.20	**58.96**
7	15	14	**14.5**	46.97	57.89	53.75	**61.06**
8	10	10	**10**	34.30	49.92	43.88	**63.05**



Plastic limit test on tailings				
Set no	M_c (g)	M_{wc} (g)	M_{dc} (g)	W_{PL} (%)
1	34.44	46.57	44.42	21.5
2	34.90	48.99	46.59	20.5
			Average W_{PL} (%)	**21.0**

Plastic limit test on river clay				
Set no	M_c (g)	M_{wc} (g)	M_{dc} (g)	W_{PL} (%)
1	34.1	48.4	45.83	21.9
2	45.4	57.8	55.60	21.6
			Average W_{PL} (%)	**21.7**

Appendix C: Dewatering Experiments

Dewatering Experiments Thickened Tailings					
Column 1		Column 2		Column 3	
Date and time	Level	Date and time	Level	Date and time	Level
4-1-2011 14:52	990	10-1-2011 11:28	990	4-1-2011 14:52	990
4-1-2011 15:47	990	10-1-2011 12:32	990	4-1-2011 15:47	975
4-1-2011 16:23	990	10-1-2011 13:41	985	4-1-2011 16:23	920
4-1-2011 17:01	990	10-1-2011 14:46	985	4-1-2011 17:01	850
4-1-2011 17:36	980	10-1-2011 16:07	985	4-1-2011 17:36	760
4-1-2011 18:13	980	10-1-2011 17:22	985	4-1-2011 18:13	725
4-1-2011 18:52	980	10-1-2011 19:44	980	4-1-2011 18:52	705
4-1-2011 19:43	980	11-1-2011 9:04	930	4-1-2011 19:43	690
4-1-2011 20:25	980	11-1-2011 14:21	915	4-1-2011 20:25	680
5-1-2011 8:35	970	11-1-2011 16:26	910	5-1-2011 8:35	600
5-1-2011 10:47	970	11-1-2011 20:32	903	5-1-2011 10:47	595
5-1-2011 12:07	970	12-1-2011 9:20	885	5-1-2011 12:07	590
5-1-2011 14:09	968	12-1-2011 13:27	880	5-1-2011 14:09	587
5-1-2011 16:26	968	12-1-2011 17:27	875	5-1-2011 16:26	580
6-1-2011 11:57	958	12-1-2011 21:49	870	6-1-2011 11:57	548
6-1-2011 17:54	955	13-1-2011 9:55	860	6-1-2011 17:54	540
7-1-2011 13:25	945	13-1-2011 14:42	855	7-1-2011 13:25	520
7-1-2011 17:11	942	13-1-2011 17:08	850	7-1-2011 17:11	518
8-1-2011 9:54	935	14-1-2011 13:03	835	8-1-2011 9:54	505
10-1-2011 9:51	912	14-1-2011 15:27	832	10-1-2011 9:51	480
10-1-2011 12:32	910	17-1-2011 8:51	792	10-1-2011 11:28	478
11-1-2011 9:04	903	17-1-2011 17:46	788	10-1-2011 14:46	476
11-1-2011 14:22	900	18-1-2011 9:45	780	10-1-2011 19:44	472
12-1-2011 9:20	892	18-1-2011 17:18	775	11-1-2011 9:04	468
12-1-2011 17:27	890	19-1-2011 9:48	767	11-1-2011 14:21	465
13-1-2011 9:55	883	20-1-2011 10:00	757	11-1-2011 20:32	462
13-1-2011 17:08	880	21-1-2011 11:33	745	12-1-2011 9:20	458
14-1-2011 13:03	872	25-1-2011 15:04	705	12-1-2011 17:27	455
17-1-2011 8:51	850	3-2-2011 10:00	637	13-1-2011 9:55	450
17-1-2011 17:46	846	4-2-2011 15:44	629	13-1-2011 17:08	448
18-1-2011 9:45	840	7-2-2011 11:13	612	14-1-2011 13:03	440
19-1-2011 9:48	834	8-2-2011 9:31	608	17-1-2011 8:51	425
20-1-2011 10:00	827	9-2-2011 9:55	600	17-1-2011 17:46	422
21-1-2011 11:33	820	10-2-2011 10:17	597	18-1-2011 9:45	420
25-1-2011 15:04	792	11-2-2011 11:47	590	19-1-2011 9:48	417
3-2-2011 10:00	743	14-2-2011 11:17	577	20-1-2011 10:00	411
4-2-2011 15:44	739	15-2-2011 11:26	572	21-1-2011 11:33	408
7-2-2011 11:13	725	16-2-2011 9:35	569	25-1-2011 15:04	395
8-2-2011 9:31	720	16-2-2011 19:27	568	3-2-2011 10:00	380
9-2-2011 9:55	717	17-2-2011 9:13	565	4-2-2011 15:44	378
10-2-2011 10:17	713	18-2-2011 10:27	562	7-2-2011 11:13	374
11-2-2011 11:47	710	21-2-2011 12:25	552	8-2-2011 9:31	372
14-2-2011 11:17	700	22-2-2011 11:34	548	9-2-2011 9:55	370
15-2-2011 11:26	695	23-2-2011 13:47	544	10-2-2011 10:17	370

16-2-2011 9:35	692	24-2-2011 10:45	542	11-2-2011 11:47	370
16-2-2011 19:27	691	28-2-2011 10:41	532	14-2-2011 11:17	368
17-2-2011 9:13	690	1-3-2011 12:12	530	15-2-2011 11:26	367
18-2-2011 10:27	687	2-3-2011 12:41	528	16-2-2011 9:35	366
21-2-2011 12:25	678	3-3-2011 13:55	525	16-2-2011 19:27	365
22-2-2011 11:34	676	4-3-2011 13:41	523	17-2-2011 9:13	365
23-2-2011 13:47	673	7-3-2011 13:12	518	18-2-2011 10:27	364
24-2-2011 10:45	670	8-3-2011 13:35	515	21-2-2011 12:25	362
28-2-2011 10:41	662	9-3-2011 11:45	513	22-2-2011 11:34	361
1-3-2011 12:12	660	10-3-2011 15:50	512	23-2-2011 13:47	360
2-3-2011 12:41	659	11-3-2011 13:39	510	24-2-2011 10:45	360
3-3-2011 13:55	657	14-3-2011 10:54	508	28-2-2011 10:41	359
4-3-2011 13:41	655	15-3-2011 15:10	505	1-3-2011 12:12	358
7-3-2011 13:12	650	16-3-2011 15:56	503	2-3-2011 12:41	358
8-3-2011 13:35	650	18-3-2011 13:32	501	3-3-2011 13:55	358
9-3-2011 11:45	649	21-3-2011 16:16	498	4-3-2011 13:41	357
10-3-2011 15:50	648	22-3-2011 10:12	498	7-3-2011 13:12	356
11-3-2011 13:39	646	23-3-2011 13:35	496	8-3-2011 13:35	356
14-3-2011 10:54	642	24-3-2011 16:59	496	9-3-2011 11:45	356
15-3-2011 15:10	640	25-3-2011 11:26	494	10-3-2011 15:50	355
16-3-2011 15:56	640	30-3-2011 13:36	490	11-3-2011 13:39	355
18-3-2011 13:32	638			14-3-2011 10:54	353
21-3-2011 16:16	635			15-3-2011 15:10	353
22-3-2011 10:12	634			16-3-2011 15:56	352
23-3-2011 13:35	632			18-3-2011 13:32	352
24-3-2011 16:59	631			21-3-2011 16:16	350
25-3-2011 11:26	632			22-3-2011 10:12	350
30-3-2011 13:36	629			23-3-2011 13:35	350
				24-3-2011 16:59	350
				25-3-2011 11:26	350
				30-3-2011 13:36	350

Dewatering Experiments River Clay					
Column 4		Column 5		Column 6	
Date and time	Level	Date and time	Level	Date and time	Level
7-2-2011 14:59	1010	7-2-2011 15:29	1000	16-2-2011 10:05	1010
8-2-2011 9:31	1005	7-2-2011 16:39	995	16-2-2011 10:33	998
8-2-2011 16:25	1002	7-2-2011 17:19	992	16-2-2011 11:42	890
9-2-2011 9:55	1000	7-2-2011 18:50	988	16-2-2011 12:37	775
9-2-2011 13:18	998	8-2-2011 9:31	950	16-2-2011 13:11	705
9-2-2011 18:51	995	8-2-2011 11:36	943	16-2-2011 13:48	618
10-2-2011 10:17	992	8-2-2011 14:26	938	16-2-2011 14:04	595
10-2-2011 13:53	990	8-2-2011 16:25	932	16-2-2011 14:39	575
11-2-2011 11:47	986	8-2-2011 17:54	930	16-2-2011 15:11	562
14-2-2011 11:17	973	9-2-2011 9:55	895	16-2-2011 15:37	555
14-2-2011 21:35	970	9-2-2011 13:18	890	16-2-2011 16:26	0:00
15-2-2011 11:26	969	9-2-2011 15:54	883	16-2-2011 17:17	530
16-2-2011 9:35	965	9-2-2011 18:51	880	16-2-2011 17:43	525
17-2-2011 9:13	962	10-2-2011 10:17	850	16-2-2011 19:27	508
17-2-2011 17:53	960	10-2-2011 13:53	845	17-2-2011 9:13	440
18-2-2011 10:27	958	10-2-2011 16:47	840	17-2-2011 10:09	438
21-2-2011 12:25	948	11-2-2011 11:47	810	17-2-2011 11:39	433
22-2-2011 11:34	945	11-2-2011 15:51	806	17-2-2011 12:35	429
23-2-2011 13:47	941	14-2-2011 11:14	720	17-2-2011 14:01	427
24-2-2011 10:45	938	14-2-2011 13:02	718	17-2-2011 15:14	423
28-2-2011 10:41	927	14-2-2011 15:45	715	17-2-2011 16:51	419
1-3-2011 12:12	924	14-2-2011 21:35	708	17-2-2011 17:53	417
2-3-2011 12:41	920	15-2-2011 11:26	692	18-2-2011 10:27	385
3-3-2011 13:55	915	15-2-2011 14:40	689	18-2-2011 13:21	380
4-3-2011 13:41	912	15-2-2011 18:24	685	18-2-2011 15:49	375
7-3-2011 13:12	906	16-2-2011 9:35	670	21-2-2011 12:25	318
8-3-2011 13:35	905	16-2-2011 13:11	666	21-2-2011 17:08	317
9-3-2011 11:45	902	16-2-2011 15:11	663	22-2-2011 11:34	309
10-3-2011 15:50	900	16-2-2011 17:17	662	22-2-2011 16:10	307
11-3-2011 13:39	898	16-2-2011 19:27	660	23-2-2011 13:47	300
14-3-2011 10:54	891	17-2-2011 9:13	648	23-2-2011 16:38	299
15-3-2011 15:10	890	17-2-2011 11:39	645	24-2-2011 10:45	297
16-3-2011 15:56	887	17-2-2011 12:55	643	28-2-2011 10:41	283
17-3-2011 14:42	885	17-2-2011 16:51	640	1-3-2011 12:12	281
18-3-2011 13:32	884	18-2-2011 10:27	627	2-3-2011 12:41	280
21-3-2011 16:16	880	18-2-2011 13:21	625	3-3-2011 13:55	278
22-3-2011 10:12	878	18-2-2011 15:49	622	4-3-2011 13:41	278
23-3-2011 13:35	877	21-2-2011 12:25	580	7-3-2011 13:12	275
24-3-2011 16:59	875	21-2-2011 17:08	578	8-3-2011 13:35	273
25-3-2011 11:26	874	22-2-2011 11:34	570	9-3-2011 11:45	273
30-3-2011 13:36	869	22-2-2011 16:10	568	10-3-2011 15:50	272
		23-2-2011 13:47	560	11-3-2011 13:39	271
		23-2-2011 16:38	559	14-3-2011 10:54	269
		24-2-2011 10:45	552	15-3-2011 15:10	269
		28-2-2011 10:41	527	16-3-2011 15:56	269

		1-3-2011 12:12	522	17-3-2011 14:42	268
		2-3-2011 12:41	518	18-3-2011 13:32	268
		3-3-2011 13:55	514	21-3-2011 16:16	265
		4-3-2011 13:41	511	22-3-2011 10:12	265
		7-3-2011 13:12	502	23-3-2011 13:35	264
		8-3-2011 13:35	500	24-3-2011 16:59	263
		9-3-2011 11:45	498	25-3-2011 11:26	263
		10-3-2011 15:50	496	30-3-2011 13:36	261
		11-3-2011 13:39	494		
		14-3-2011 10:54	490		
		15-3-2011 15:10	489		
		16-3-2011 15:56	488		
		17-3-2011 14:42	486		
		18-3-2011 13:32	485		
		21-3-2011 16:16	481		
		22-3-2011 10:12	480		
		23-3-2011 13:35	480		
		24-3-2011 16:59	479		
		25-3-2011 11:26	479		
		30-3-2011 13:36	476		