Tests for wide range of compressibility and hydraulic conductivity of flocculated tailings

J. D. Scott, S. Jeeravipoolvarn & R. J. Chalaturnyk
Department of Civil and Environmental Engineering – University of Alberta, Edmonton, AB, Canada

ABSTRACT

In order to evaluate tailings consolidation behaviour, a large strain consolidation test is generally used to obtain effective stress-void ratio and void ratio-hydraulic conductivity relationships for consolidation analysis. This test, however, is only able to perform at low void ratios where an application of stresses is possible. At higher void ratios, where most of the settlement takes place, the relationships are more important to the tailings settlement prediction. To capture a wider range of compressibility and hydraulic conductivity, test procedures must be developed. This paper presents a combination of three sub-tests which are large strain consolidation test, compression standpipe test and hindered sedimentation test. The tests were successfully performed on flocculated Syncrude Aurora tailings. The results show that the combination of the tests gives continuous measurements over a wide range void ratios from 0.39 to 29.1 for hydraulic conductivity while effective stresses could be measured at a void ratio of 2.30 and below.

RÉSUMÉ

Afin d'évaluer le comportement de consolidation de produits de queue, un grand essai de consolidation de contrainte est généralement employé pour obtenir le rapport soumettre à une contrainte-vide efficace et pour vider des rapports rapport-hydrauliques de conductivité pour l'analyse de consolidation. Cet essai, cependant, peut seulement exécuter à de bas rapports vides où une application des efforts est possible. À des rapports vides plus élevés, où la majeure partie du règlement a lieu, les rapports sont plus importants pour la prévision de règlement de produits de queue. Pour capturer un éventail de compressibilité et de conductivité hydraulique, des méthodes d'essai doivent être développées. Cet article présente une combinaison de trois secondaire-essais qui sont grand essai de consolidation de contrainte, essai de colonne de compression et essai gêné de sédimentation. Les essais ont été avec succès réalisés sur les produits de queue floculés Aurora Syncrude. Les résultats prouvent que la combinaison des essais donne des mesures continues au-dessus des rapports d'un vide d'éventail de 0.39 à 29.1 pour la conductivité hydraulique tandis que des efforts efficaces pourraient être mesurés à un rapport vide de 2.30 et ci-dessous.

1 INTRODUCTION

In geotechnical engineering, tailings consolidation behaviour is normally evaluated through two important relationships which are effective stress-void ratio and hydraulic conductivity-void ratio relationships. Directly obtained through a large strain consolidation test, these two relationships are used in a finite strain consolidation model to predict the rate and amount of settlement of a tailings material under self-weight and imposed stresses. The large strain consolidation test, however, is only able to perform at low void ratios where an application of stresses is possible. At higher void ratios, where most of the settlement takes place, the relationships are much more important to the settlement prediction of tailings.

To obtain hydraulic conductivity at higher void ratios than that possible in a large strain consolidation test, Pane and Schiffman (1997) proposed that a hindered settling test can be used to get a hydraulic conductivity corresponding to an initial void ratio of the tested material via Equation 1 (Been 1980, Pane and Schiffman 1997).

$$v_s = -\left(\frac{\gamma_s}{\gamma_w} - 1\right)\frac{k}{1+e} \qquad [1]$$

Where v_s is initial settling velocity, γ_s is unit weight of solids, γ_w is unit weight of water, k is hydraulic conductivity and e is an initial void ratio.

This test is well accepted when slurry is undergoing hindered sedimentation but it is generally believed that during consolidation this method can not be used. Pane and Schiffman (1997) stated that this equation is valid only when there is suspension of the initial void ratio at the sediment water interface or as long as the settling velocity is constant. Toorman (1999) strictly indicated that the initial settling rate of self-weight consolidation can be used to estimate hydraulic conductivity where diffusive effects are negligible. This is theoretically identical to a one dimensional finite strain consolidation theory which will also give a constant initial settling velocity for high initial void ratios. Thus the use of Equation 1 during consolidation phase will give an acceptable hydraulic conductivity value associated with the initial void ratio. In a real situation, however, piping can occur (Edil and Fox 2000) and the void ratio at the interface could be altered as well as the settling velocity. One would expect that Equation 1 will only hold true through a certain void ratio until the influence of compressibility becomes large. This problem can easily be handled by a direct measurement of hydraulic conductivity during a large strain consolidation test.

To obtain an effective stress-void ratio relationship at high void ratios, pore pressure measurements are coupled with density measurements to obtain effective stresses. Different methods available to obtain density profiles include X-ray or γ-ray density measurements (Been and Sills 1981, Shih et al. 1986, Bergström 1992, Bartholomeeusen et al. 2002, Alexis et al. 2004), a pressurized sampling method (Jeeravipoolvarn 2005) and a pipette sampling method (Shirato et al. 1970).

In order to capture a wider range of compressibility and hydraulic conductivity, test procedures must be developed. This paper presents a combination of three sub-tests which are a large strain consolidation test, a compression standpipe test and a hindered sedimentation test. Flocculated oil sands tailings are chosen for this study and the objectives of the combination of the tests are three fold. First, is to determine the void ratio at which effective stresses start to develop during the thickening process. This void ratio would be the boundary when sedimentation ends and consolidation begins. Secondly, is to determine the change in hydraulic conductivity as the void ratio decreases. Lastly, is to obtain the effective stress-void ratio and the void ratio-hydraulic conductivity relationships from very low effective stresses to high effective stresses for finite strain consolidation modeling.

2 EXPERIMENTAL PROGRAM

Three types of tests were performed; a large strain consolidation test, a compressibility standpipe test and a number of hindered sedimentation standpipe tests. All the tests are listed in Table 1.

A large strain consolidation test is performed at moderate to low void ratios where application of stresses is possible. The compressibility standpipe is performed to obtain an effective stress-void ratio relationship at high void ratios and the hindered sedimentation test is utilized for determining hydraulic conductivity at high void ratios. The results from all the tests were combined to determine the parameters in the above objectives.

Table 1. Tests performed

Type of test	Objectives	Number of test
Hindered sedimentation test	determine hydraulic conductivity during hindered settling stage	6
Compressibility standpipe test	determine compressibility and hydraulic conductivity	1
Large strain consolidation test	determine compressibility and hydraulic conductivity	1

3 TAILNGS MATERIALS

The tailings materials selected for this study was Syncrude Aurora cyclone overflow tailings with a solids content of about 10% (by mass) and a fines content (<45 μm) of about 50% (by mass) or a sand-fine ratio (SFR) of 1. This material was chosen because it is being flocculated and thickened in large experimental thickeners. The solids content increases to 47% to 52% in the thickener. Modeling of the thickener process requires knowledge of the change in hydraulic conductivity and the development of effective stress during the thickening process. Modeling also requires knowledge of the solids content at which the thickening process changes from sedimentation to consolidation.

Cyclone overflow samples were obtained from the Syncrude Aurora Stacker Site on December 6, 2004. Eight 20 L pails of cyclone overflow and one 20 L pail of cyclone underflow sand were brought to the University of Alberta on December 8, 2004. The overflow pails were generally quite high in fines. Five of the pails were mixed together in a 200 L barrel and sampled for solid and fines contents. The sand pail was also sampled for solids and fines. The cyclone overflow in the barrel, the sand and process water on top of the remaining pails were combined to make samples with solids contents prior to flocculation from 8% to 22% and a SFR of about 1.

Flocculent, CIBA alcloflood 1235, at 80 g/T was used to produce flocculated tailings for all experiments. Cyclone overflow was mixed with the flocculent in a 20 L pail by a variable speed mixer to obtain a homogeneous mix. Details on the mixing method are presented in the next section.

It is observed that the flocculated cyclone overflow has three void ratios. They are a void ratio of an individual floc - a floc void ratio, a void ratio of a group of flocs - an aggregate void ratio and a network void ratio of aggregated flocs - a network void ratio. From visual observations, at low effective stresses a network is formed between the aggregated flocs and the compression is due to the change in this structure rather than the change in aggregated void ratios. The pore water flow behaviour is also mostly through the network void ratios. As the network compressed, the behaviour is likely controlled by an aggregate void ratio and finally after the aggregates are compressed at higher effective stresses, the floc void ratios dominate. It has not been possible to quantify these void ratios for the current experimental setup and only the average void ratio of the total sample is used. The use of term void ratio in this paper is strictly indicating an average void ratio.

4 LARGE STRAIN CONSOLIDATION TEST

A large strain consolidation is performed on slurry that undergoes a large volume change. Due to the large deformation, a conventional odometer is inappropriate to use and a large strain consolidation apparatus is required.

Moreover the application of the large strain consolidation test is to directly measure two important characteristics which are compressibility and hydraulic conductivity of the slurry. The large strain consolidation test used in this program was a multi-step loading test.

The large strain consolidation test is shown in Figure 1. The cell is 140mm inside diameter and can accommodate samples up to 200mm high. The wall friction is minimized by choosing the appropriate initial height of the samples so that the diameter to height ratio is acceptable when effective stresses develop.

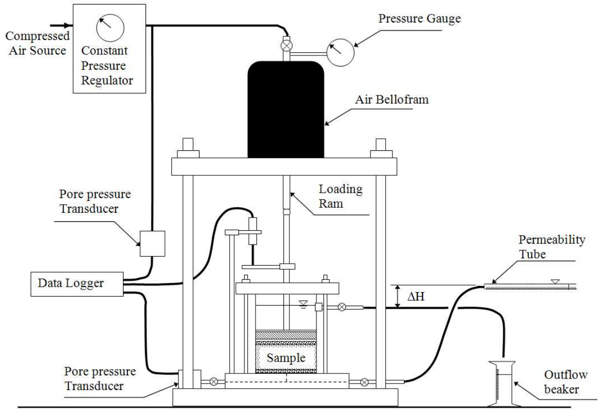

Figure 1. University of Alberta large strain consolidation test

4.1 Sample Preparation and Test Procedure

Approximately 15 L of cyclone overflow at a solids content of 7.0% and a SFR of about 1 was mixed for the large strain consolidation test. Two subsamples were taken for solids contents and two for fines contents. Table 2 shows the average values obtained. The solids contents were used to calculate the amount of flocculent to add. It was found that fines subsamples were not representative of this low solids content due to segregation of the mix. Fines subsamples of the nonsegregating flocculated cyclone overflow were representative and used to check the SFR of the mix.

Table 2. Sample preparation for a large strain consolidation test

Sample Condition	Solids content (%)	Fines content (%)	Sand-Fine Ratio (SFR)
Mixed	7.00	47.2	1.12
Flocculated	50.6	52.6	0.90

Experimentation was performed to develop a technique for mixing the flocculent into such a large sample of cyclone overflow to obtain optimum flocculation. A mixing time and mixing energy was developed which produced large flocs in the entire 15 L of cyclone overflow. The flocculated mixture was allowed to settle for one minute, the release water was decanted and the resulting flocculated material was poured into the consolidation cell. Two subsamples were taken for solids content and two for fines contents. Table 2 shows the average values obtained. The starting solids content of the flocculated cyclone overflow in the large strain consolidation test was 50.6% (*e* = 2.44) and the SFR was 0.90. The initial height was 95.5 mm.

4.2 Results

Twelve load steps and three unload steps were performed. The first load was the self-weight effective stress at the mid-height of the sample which was 0.18 kPa. The loads were approximately doubled for each subsequent load step to a maximum of about 800 kPa. Figure 2 shows the effective stress vs void ratio. A constant head, upwards flowing permeability step was performed after each load step. The void ratio vs. hydraulic conductivity is shown in Figure 3.

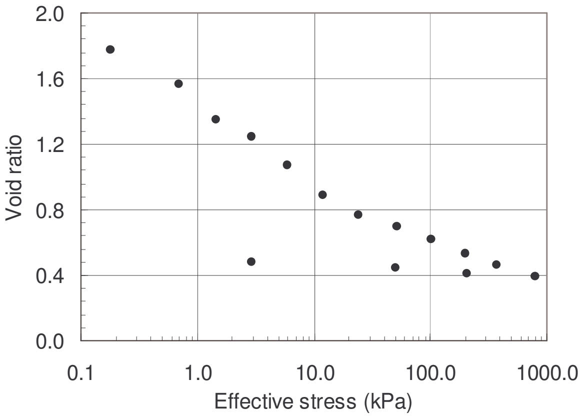

Figure 2. Effective stress vs. void ratio from the large strain consolidation test

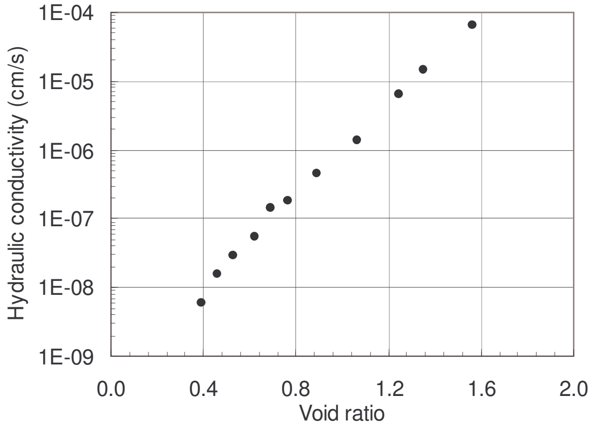

Figure 3. Void ratio vs. hydraulic conductivity from the large strain consolidation test

To evaluate the homogeneity of the large strain consolidation sample, at the end of the test it was sliced horizontally into 4 layers and two solids contents were determined for each layer. Results indicate that the sample was homogeneous in solids content which also indicates that the SFR was consistent throughout the depth. The average void ratio from these measurements was 0.46 and average solids content was 84.4%. The final void ratio and solids content calculated from the initial values and the measured changes in height are 0.48 and 84.0% respectively. This good agreement verifies the initial values and the measured compressibility.

5 COMPRESSIBILITY STANDPIPE TEST

To determine the effective stress-void ratio relationship at very low effective stresses, a large diameter standpipe is filled with tailings, allowed to consolidate under self-weight and when consolidation is complete, sampled in layers to determine the effective stress and void ratio with depth. The compressibility standpipe test is shown in Figure 4.

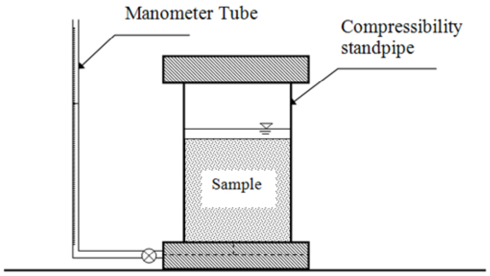

Figure 4. Compressibility standpipe test

5.1 Sample Preparation and Test Procedure

The compressibility standpipe used was 14 cm in diameter and was filled to a height of 26 cm. It was intended to fill the cylinder to a smaller height to have a better diameter-height ratio but observing the large voids in the flocculated cyclone overflow it was assumed that the a wall friction would be small and a greater height would result in larger effective stresses for overlap with the large strain consolidation test applied effective stresses.

Approximately 35 L of cyclone overflow was mixed in two batches to a solids content of about 10% and a SFR about 1. Two solids content subsamples and two fines content subsamples were taken from each batch. Table 3 shows the values obtained. As for the consolidation test subsampling, the fines content was better determined from the flocculated material. Each batch was mixed with the flocculent with the same mixing time and mixing energy about one minute apart. The flocculated mixtures were allowed to settle for one minute, the release water was decanted and the resulting flocculated material was poured into the compressibility standpipe cylinder in two layers. Two subsamples were taken from each layer for solids contents and two for fines contents. Table 3 shows the values obtained. The starting average solids content of the flocculated cyclone overflow in the compression standpipe test was 49.6% and the SFR was 0.92. These values are similar to the initial values in the flocculated sample in the large strain consolidation test.

Table 3 Sample preparation for a compressibility standpipe test

Sample Condition	Solids content (%)	Fines content (%)	Sand-Fine Ratio (SFR)
Mixed	10.4	52.5	0.91
Flocculated layer 1	46.4	51.3	0.95
Flocculated layer 2	52.9	52.8	0.89
Flocculated (average)	49.6	52.1	0.92

5.2 Test Results

The sample was allowed to settle under self-weight and pore pressures were monitored at the base. Consolidation was considered complete when the excess pore pressure at the base had fully dissipated. Figures 5 and 6 show the settlement and excess pore pressure with time. Settlement and pore pressure dissipation where rapid due to the large voids around the flocs (Figure 7). The initial hindered sedimentation immediately after placing gave a hydraulic conductivity of 4.3 x 10^{-3} cm/s at an initial void ratio of 2.54.

The sample settled rapidly from an initial height of 26.0 cm to a height of 20.6 cm and at this height the excess pore pressures had fully dissipated. After one week the sediment height had only decreased to 20.2 cm and the large voids around the flocs had not changed (Figure 7).

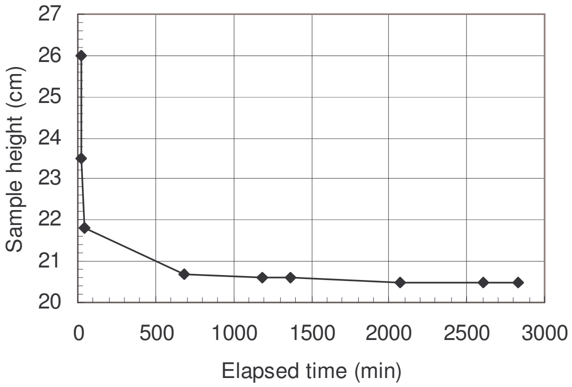

Figure 5. Interface settlement vs. time

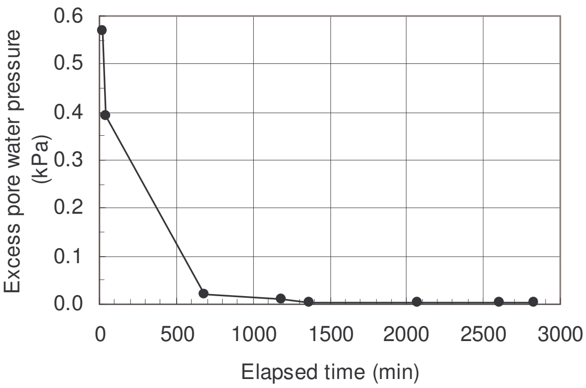

Figure 6. Excess pore pressure vs. time

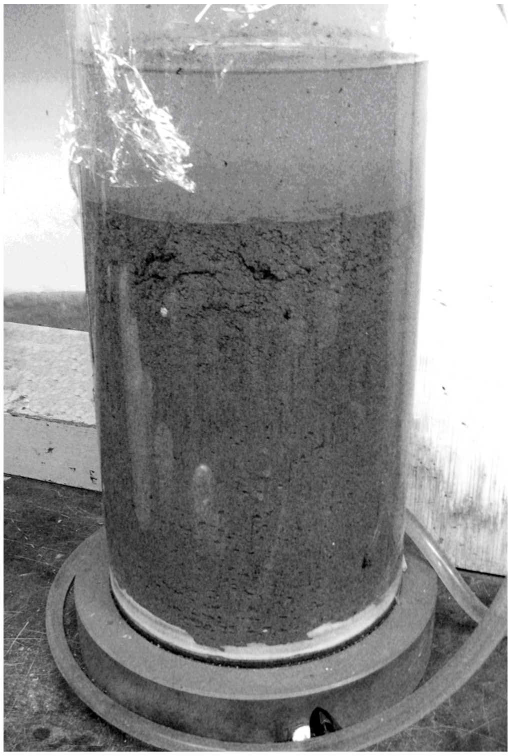

Figure 7. Flocculated tailings in the compressibility standpipe test

The standpipe was sampled in 15 layers. From the solids content of each layer, the void ratios and total stresses were calculated. As hydrostatic pore pressure existed in the sample, the effective stress at the mid-height of each layer can be calculated.

Figures 8 and 9 show void ratio and accumulative effective stress profiles from the compressibility standpipe test respectively. The fairly smooth curves with no breaks indicate the initial sample was quite uniform in solids and SFR with depth. The data in Figures 8 and 9 gives compressibility of the tailings at low effective stresses which are combined with the large strain consolidation results in Section 7.

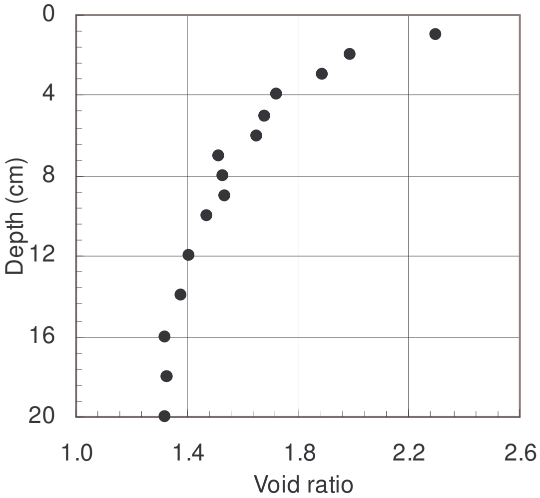

Figure 8. Void ratio measurement with depth at the end of consolidation

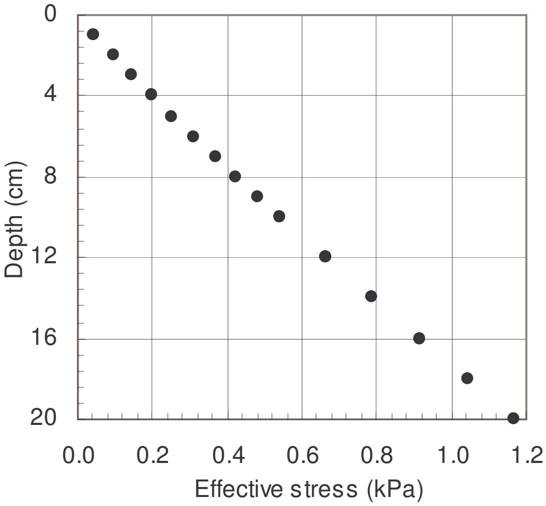

Figure 9. Effective stress with depth at the end of consolidation

6 HINDERED SEDIMENATION TEST

The hindered sedimentation standpipe tests were used to measure hydraulic conductivity at large void ratios. A number of samples of cyclone overflow were mixed at different initial solids contents but with a SFR of approximately 1. Subsamples were taken to measure solids content and fines content. The solids contents were then corrected for the amount of water in the flocculent. The solids and fines contents of the hindered sedimentation tests are listed in Table 4.

Table 4 Hindered sedimentation test results

Test	S (%)	F (%)	e	SFR	v_s (cm/s)	k (cm/s)
1	7.90	50.0	29.1	1.00	2.68	53.8
2	7.90	50.0	29.1	1.00	1.86	37.6
3	14.4	46.9	14.8	1.13	0.85	8.99
4	21.0	54.4	9.40	0.84	0.06	0.39
5	22.1	55.3	8.83	0.81	0.14	0.89
6	10.3	47.9	21.7	1.09	0.64	9.77

The samples were then flocculated with a controlled flocculent dose, mixing time and mixing energy and immediately poured into a 2 L standpipe. Interface settlements with time are shown in Figure 10. Initial interface settlement was monitored. For the 8% solids mix, hindered sedimentation was over in about 20 seconds. For the higher solids mixes, hindered settlement only lasted several minutes. Several tests were duplicated to check the test procedure. The initial constant settlement velocity is a function of the hydraulic conductivity at the initial void ratio (*e*). The hydraulic conductivity (*k*) can be calculated with Equation 1.

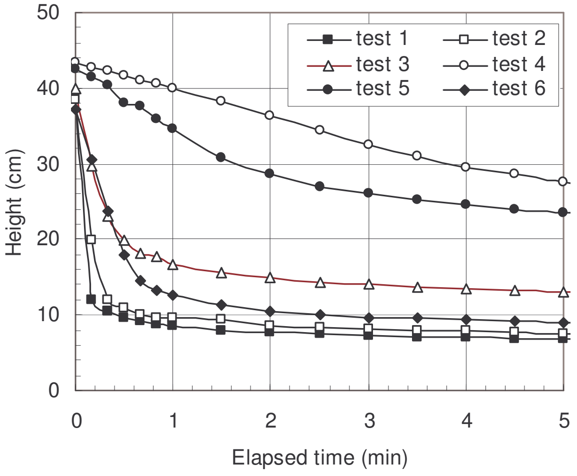

Figure 10. Hindered sedimentation test results

7 COMBINED TEST RESULTS

Figures 11 and 12 include the combined compressibility test results. Figure 11 shows the relationship between void ratio and effective stress over an effective stress range from 0.02 kPa to 800 kPa. This relationship is better visualized in Figure 12 where effective stress is plotted on an arithmetic scale from 0 kPa to 6 kPa. This figure shows that a significant effective stress only starts to develop at a void ratio of about 2 and only reaches about 1 kPa at a void ratio of about 1.3.

The data in Figures 11 and 12 is used in finite strain consolidation modeling by fitting a mathematical equation to the data points. It is found that a power law model (Figure 11) can be utilized with a high coefficient of determination for these flocculated tailings.

To model the entire increase in solids content in a thickener the effective stress-void ratio relationship and the void ratio-hydraulic conductivity relationship must be known over the entire range of void ratios. The void ratios in the void-ratio hydraulic conductivity relationship has been determined over the full range from a void ratio of 29.1 (solids content of 8%) to a void ratio of 0.39 (solids content of 86%) but the largest void ratio in the effective stress-void ratio determination is only 2.30. However, at void ratios over 2.0, the effective stresses are so small and the hydraulic conductivity is so large that the void ratio-hydraulic conductivity relationship completely governs the finite strain consolidation analysis. The effective stress-void ratio relationship, therefore, can be extrapolated to a void ratio of 29.1 with little error.

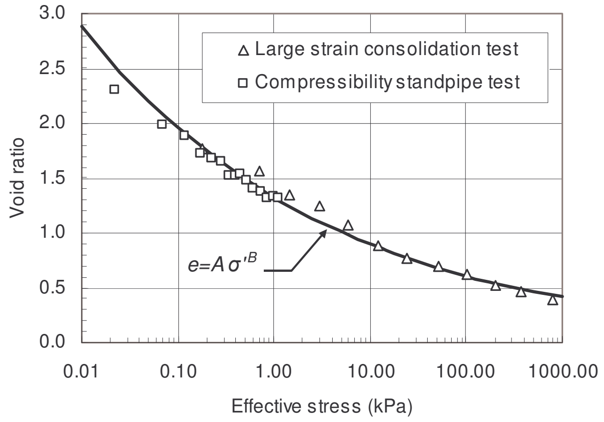

Figure 11. Combined effective stress - void ratio data (log scale)

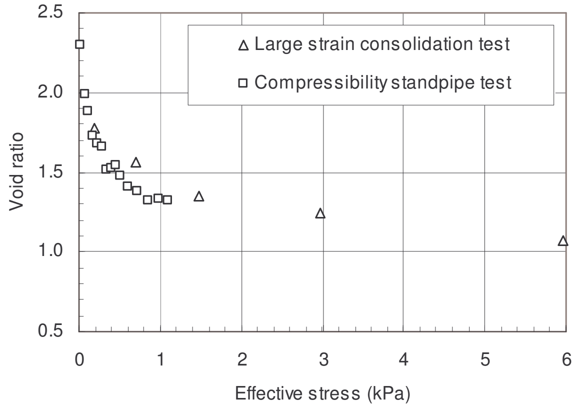

Figure 12. Combined effective stress - void ratio data (arithmetic scale)

Figure 13 includes all the hydraulic conductivity measurements from the different tests. A log-log scale is used as previous research has shown that the void ratio-hydraulic conductivity relationship is a straight line at large void ratios in this type of plot (Boratenec 2003). These test results are fairly linear at void ratios over 2. It would appear that the network void ratios govern the hydraulic conductivity at these large void ratios (Figure 7). When the flocculated tailings are consolidated to void ratios below 1, the average void ratio becomes the dominant void ratio. It was observed that in the large strain consolidation test at 200 kPa (*e* = 0.53), some larger voids are still visible in the sample but they are not continuous and may not have a significant influence on the hydraulic conductivity.

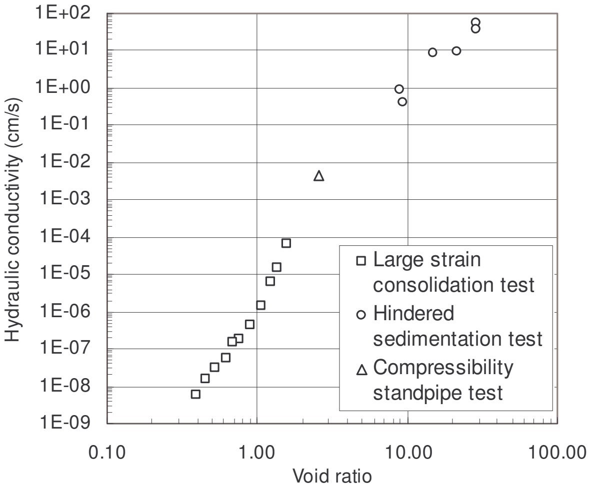

Figure 13. Combined void ratio - hydraulic conductivity data (log-log scale)

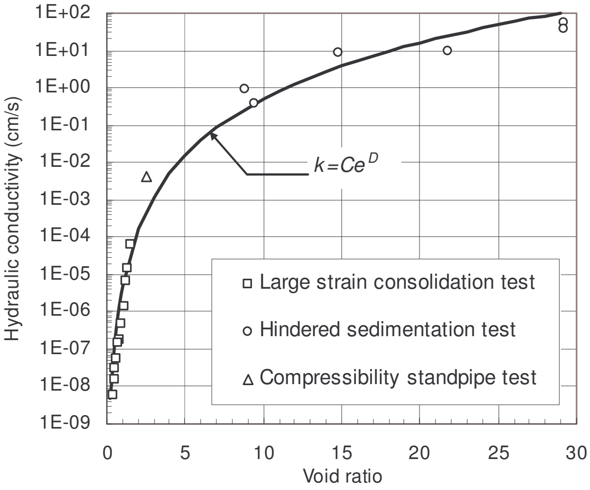

Figure 14. Combined void ratio - hydraulic conductivity data (arithmetic scale on x-axis)

Figure 14 is the same data with void ratio as an arithmetic scale. This plot more vividly shows how the hydraulic conductivity, thus the settling rate, increases as the void ratio increases or the initial solids of the thickener feed decreases. It would appear that a maximum hydraulic conductivity of about 100 cm/s is possible for this cyclone overflow material and flocculent as the thickener feed solids content decreases. A hydraulic conductivity of 100 cm/s results in a maximum floc settlement rate of about 4 cm/s. The increase of hydraulic conductivity from a void ratio of 15 (solids content of 14%) to the void ratio of 29.1 (solids content of 8%) is not major and indicates that this is the range of feed solids content for efficient settling in a thickener for this material and flocculent dosage.

For a finite strain consolidation analysis, a power law model can be used to obtain a void ratio-hydraulic conductivity relationship (Figure 14) of the data in Figures 13 and 14 with a high value of the coefficient of determination.

8 DISCUSSION AND CONCLUSIONS

The objectives of the testing program were met. It should be emphasized that the test results are only valid for cyclone overflow with the same mineralogy as the sample taken on December 6, 2004, a sand-fines ratio of about one and for the flocculent type and dosage used.

This flocculated cyclone overflow only has a significant effective stress starting at a void ratio of 2 (solids content of 60%). The effective stress is only about 1 kPa at a void ratio of 1.3 (solids content of 65%).

The flocculated cyclone overflow has small voids in the flocs and large voids around the flocs. The calculated void ratio is the average void ratio and this void ratio is used in the effective stress-void ratio relationship and the void ratio-hydraulic conductivity relationship.

At large void ratios over 2, the large voids around the flocs appear to dominate the hydraulic conductivity. However, as the large voids appear to contain most of the void space in the sample, their network void ratio may not differ greatly from the average void ratio. At void ratios below 1, not many large voids around the flocs still exist. Therefore the floc void ratios at these low void ratios dominate the hydraulic conductivity and may not differ greatly from the average void ratio. At void ratios between 2 and 1, the average void ratio may not truly represent the void ratio controlling the hydraulic conductivity.

The flocculated cyclone overflow prepared for the large strain consolidation test had a solids content of 50.6% similar to the experimental thickener underflow paste with solid contents from 47% to 52%. The consolidation test would model the consolidation of the paste in the field if the paste properties were not affected during field deposition. The paste, however, is sheared during pumping, pipelining and flowing into the depositional area. A more representative consolidation test would be to shear the consolidation sample with the same magnitude and duration shear forces after flocculation, one minute settling and decanting but before placing it in the consolidation cell.

The void ratio-hydraulic conductivity relationship of the cyclone overflow has been measured over the full range of void ratios occurring in a thickener to those in a consolidated paste deposit in the field, that is, from an initial void ratio of 29.1 (solids content of 8%) to a highly consolidated void ratio of 0.39 (solids content of 86%). The effective stress-void ratio relationship has been measured from a maximum void ratio of 2.30 (solids content of 52%) to the highly consolidated void ratio of 0.39. At void ratios over 2.30 the effective stresses are so small and the hydraulic conductivity is so large that the void ratio-hydraulic conductivity relationship dominates the results of finite strain consolidation analyses. The effective stress-void ratio relationship, therefore, can be extrapolated to a void ratio of 29.1 with little error.

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