FINE TAILINGS DECREASE IN VOLUME BY CREEP COMPRESSION

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ABSTRACT
Self weight consolidation tests in 10 meter high by 0.9 meter diameter standpipes were commenced in 1982 at the University of Alberta to evaluate the long term consolidation behaviour of the oil sands fine tailings in the tailings ponds. Three standpipe tests have been performed, one standpipe of the oil sand fine tailings and two with sand added to the fine tailings. The standpipe test with the fine tailings is still under observation and is the only test discussed in this paper. At the present time, the standpipe has settled three meters and the average void ratio has decreased from 5.18 to 3.33 but the pore pressures have remained approximately equal to the total stress, that is, zero or very little effective stress has developed. The volume decrease appears to be by creep. The equipment, material and testing methods are described and typical test results are shown. The measurements of rate of settlement, pore pressure dissipation and void ratio decrease over the past twenty-one years are providing valuable data to analyze the long term consolidation behavior of oil sands fine tailings.

RÉSUMÉ
Des essais de consolidation de poids d'individu en 10 mètres de haut par des colonnes de diamètre de 0.9 mètre ont été débutés en 1982 à l'université d'Alberta pour évaluer le comportement à long terme de consolidation des produits de queue de sables d'huile très bien dans les étangs de produits de queue. Trois essais de colonne ont été réalisés, une colonne des produits de queue d'amende de sable d'huile et deux avec le sable ont été ajoutés aux produits de queue fins. L'essai de colonne avec les produits de queue fins est toujours sous l'observation et est le seul essai discuté en cet article. À l'heure actuelle, la colonne a arrangé trois mètres et le rapport vide moyen a diminué de 5.18 à 3.33 mais les pressions de pore sont demeurées approximativement égales à tout le effort, zéro ou très peu effort efficace s'est développé. L'équipement, les matériels et des méthodes d'essai sont décrits et des résultats d'essai typiques sont montrés.

1. INTRODUCTION

The oil sand mining operations in Northern Alberta using the Clark Hot Water Extraction process produce large volumes of tailings composed of sand, silt, clay and a small amount of bitumen. During deposition, the tailings segregate with the sand dropping out to form dykes and beaches and about one-half of the fines and the bitumen running into the tailings pond as fine tailings. After deposition, the fine tailings settle to about 30% solids within 2 years. Early in the mining operations it was apparent that the fine tailings in the ponds at this point were consolidating very slowly and the pore water pressures were remaining very high. The need to understand the consolidation behaviour of the fine tailings resulted in the establishment of long term, large scale self-weight consolidation tests at the University of Alberta.

To investigate these phenomena, two 10 m high, and 0.9 m diameter standpipes were filled in 1982 with the oil sands fine tailings in one standpipe and a mix of the fine tailings and sand in the second standpipe. The fine tailings standpipe has been monitored for over 20 years and although the fine tailings has compressed 3 m by self weight, little to no effective stresses have developed. Pore water pressures throughout the height of the standpipe are approximately equal to the total stress. The fine tails settlement in the tailings ponds show similar behaviour although monitoring of these deposits is complicated by many changes in the fine tails material and pore water chemistry over the years. Geotechnical analyses such as finite strain consolidation theory (Pollock, 1988), coupled sedimentation-consolidation theory (Masala, 1998), and an extension of finite strain consolidation theory incorporating creep have been used to model the consolidation of the fine tails. None of these theories can predict the long term consolidation and pore water pressures in the tailing pond deposits containing this cohesive slurry.

The objective of this paper is to document 21 years of a successfully operating standpipe, its performance and the response of the oil sands fine tailings over this period. The objective of this research program is to use the ten meter standpipe results to develop a theory which can be used to model the behaviour of the fine tailings in the ponds.

2. THE TEN METER STANDPIPE

The ten meter standpipe is made of high density polyethylene with a wall 25 mm thick, 914 mm inside diameter and is 10.5 m in height. The bottom 0.5 m of the standpipe is encircled by a series of steel bands covered in fiberglass reinforcement to prevent any bulging of the plastic due to creep. The base of the standpipe is a 13 mm thick HDPE plate which is welded to the sides of the standpipe. The pore water pressure monitoring ports and sample ports are aligned at 0.5 m spacing down the side of the standpipe. The ten meter standpipe diagram (Figure 1) shows the alignment of all the measurement ports. The standpipes are located in a large building which has a fairy consistent temperature around 21°C.

The depth of the interface has been frequently measured to determine the amount of volume change of the tailings. Pore water pressures are measured at the piezometer ports usually at 1 m intervals. A pore pressure transducer is calibrated with a riser tube every time measurements are taken.

Sample ports are used to obtain solid content and bulk density measurements on the material. Sampling is conducted with both a solids content sampler and a density sampler. The density sampler allows the soil density to be measured under insitu pore pressure conditions to prevent gas coming out of solution or gas bubbles to increase in volume. The degree of saturation determined from this sampler down the depth of the standpipe is found to be between 99% and 100% which indicates that there are no gas bubbles in these fine tailings.

3. MATERIAL PROPERTIES

The ten meter standpipe contains 6.57 m^3 of fine tailings which was pumped from the Mildred Lake tailings pond and transported to Edmonton and pumped into the standpipe in October 1982. The fine tailings initially contained 2.7% bitumen, 28% minerals and 69.3% water by mass. The fine tailings has about 10% fine sand (>45μm), 40% silt-size and 50% clay-size (<2μm). The material properties are described in the following sections.

3.1 GRAIN SIZE DISTRIBUTION

The average grain size distribution of the fine tailings is shown in Figures 3 and 4 which are the grain sizes measured in 1985 and 2003 respectively. No significant change in grain size distribution has occurred during this period. Due to the bitumen content, the ASTM standard for the hydrometer-sieve test can not be performed effectively and a modified hydrometer test is conducted. Extraction of bitumen and drying of the samples is avoided as heavy hydrocarbons left in the sample tend to cement the finer particles together resulting in smaller measurements of clay-size material. Wet weights are chosen based on the solids contents and dry weights are measured after sieving. Excess bitumen is skimmed off the sample after mixing.

Segregation or settling of the sand through the fines matrix is evaluated in Figure 5. Three particle size fraction profiles at 850 days (1985) and 7507 days (2003) are shown. The fraction profiles do not show a significant change in particle size or migration of coarse grain particles and are within the range of experimental error.

Another common method used in the oil sands mining industry for determining clay size fraction is the methylene blue test. Methylene blue is a cationic dye that can be adsorbed on the exposed negatively charged surfaces of clays and is a standard used to measure exposed surface area of clays in soils. The quantity of exposed clay mineral can be calculated using an empirical relationship developed for the oil sands tailings (Tang, 1997) given as:

$$CMF\ (\%) = \{(0.006) \times (\text{MB value}) + 0.04\} / 0.14 \qquad [1]$$

where CMF = clay mineral fraction (%)
MB value = methylene blue number

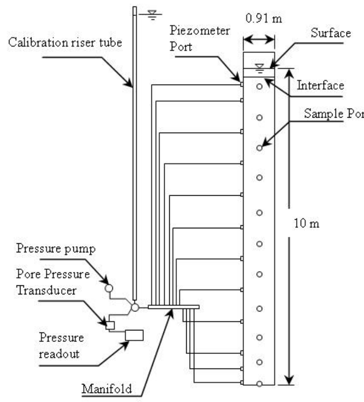

Figure 1. Ten meter self-weight consolidation standpipe diagram

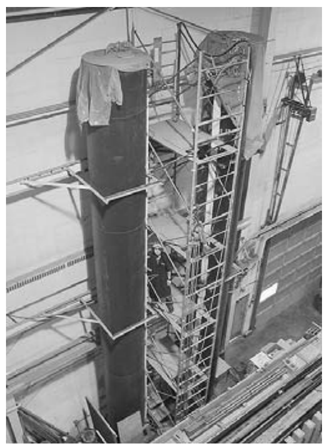

Figure 2. The ten meter standpipes

The standard methylene blue test procedure specifies the use of bitumen extracted and dried tailings samples. A dispersed methylene blue test should give similar results to those of a dispersed hydrometer test and represents the total amount of clay-size material existing in the fine tailings. Methylene blue test results showed that the clay fraction at depths of 4.5 m and 6.5 m are 50% and 53% respectively while the hydrometer tests measured 48% and 49% for the same depths. These results indicate that the modified hydrometer test procedure works effectively.

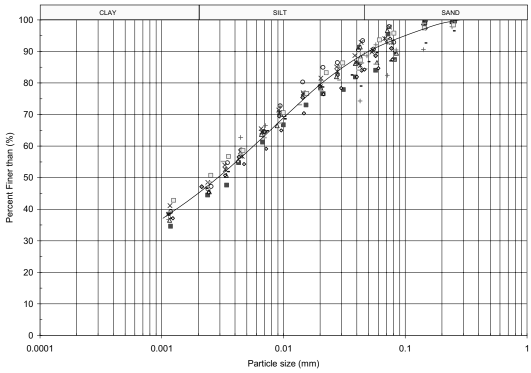

Figure 3. Grain size distribution in 1985

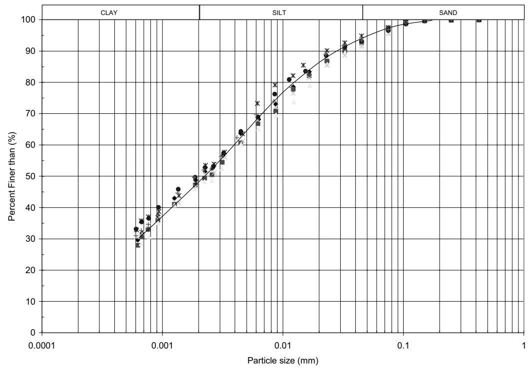

Figure 4. Grain size distribution in 2003

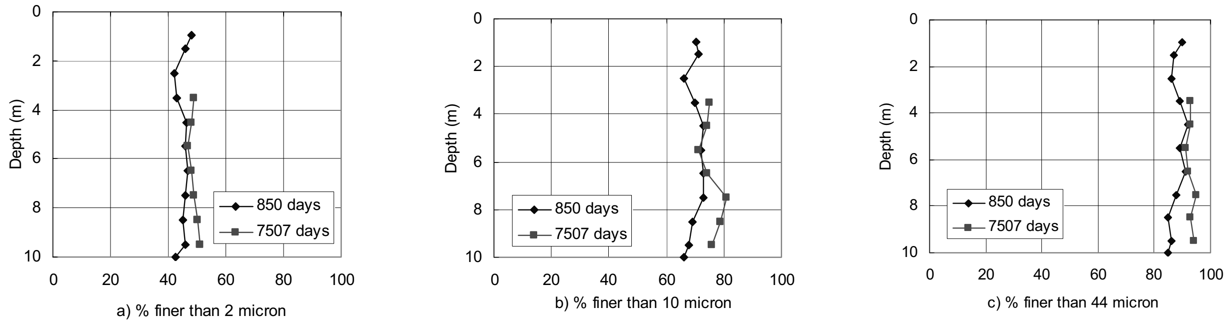

Figure 5. Particle size fraction profiles for a) % finer than 2 μm, b) % finer than 10 μm and c) % finer than 44 μm

3.2 MINERALOGY

Soil behaviour is directly related to the mineralogy of soils. Soil particles and interaction between the particles controls the compressibility as well as the hydraulic conductivity of a soil. The clay minerals of the fine tailings typically consist of 80% kaolinite, 15% illite, 1.5% montmorillonite, 1.5% chlorite and 2% mixed clay layers (FTFC, 1995). The fines in the tailings result from the dispersion of clay-shale stringers and layers in the ore during mining and extraction.

Bulk and clay X-Ray diffraction analysis performed on clay samples from the ten meter standpipe has confirmed the clay mineralogy of the fine tailings in the standpipe. Table 1 shows the major minerals of the fine tailings samples at depths of 6.5 m and 9.5 m.

It appears that the major mineralogy of the fine tailings is generally kaolinite followed by quartz and illite respectively. From Table 1 it appears that the clay particles are not fully dispersed, some of the kaolinite forms peds and booklets which have a large particle size and appear as silt size particles. Kaolinite, which is the major clay mineral in the fine tailings, is typically one of the least active clay minerals in thixotropic gain in strength. However, an addition of a dispersing agent to kaolinite can make kaolinite very thixotropic (Mitchell, 1960).

Table 1. Major minerals of the fine tailings in the ten meter standpipe.

Minerals (%)	Sand size (>45μm)		Silt size (45μm-2μm)		Clay size (<2μm)		Total mineral in mineral category	
Depth in standpipe (m)	6.5	9.5	6.5	9.5	6.5	9.5	6.5	9.5
Quartz and other minerals	5	7	29	31	0	0	34	38
Kaolinite	0	0	19	9	25	28	44	37
Illite	0	0	0	0	22	25	22	25
Total minerals in size range	5	7	48	40	47	53	100	100

3.3 WATER CHEMISTRY

Several investigations have found that the pore water chemistry has a major influence on the fine tailings structure. Tang et al. (1997) showed that the bicarbonate and sodium hydroxide in the tailings water are the dominant agents which cause the card-house floc structure of kaolinite clay-water systems as in the CHWE tailings. The sodium hydroxide is added during the extraction process as a dispersing agent and the bicarbonate comes from the connate water in the oil sands and from the adsorption of CO_2 during aeration processes. Similarly, FTFC (1995) studies on the effect of the compositions of the tailings water concluded that the repulsive and attractive forces between the clay particles dominate the behaviour of the fine tailings-water structure and that the electro-kinetic behaviour is mainly caused by the presence of bicarbonate ions. Major ions in the fine tailings pore water samples from five different depths in the ten meter standpipe are shown in Table 2. The significant presence of bicarbonate (HCO_3^-) is shown. Conductivity and pH measurements at different depths taken in 2000 are shown Figures 6 and 7 respectively. The values are similar to those in the Syncrude and Suncor tailings ponds in 1992 and indicate that no significant changes in water chemistry in the ten meter standpipe occurred from 1982 to 2000.

Table 2. Compositions of pore water in ppm of the fine tailings from the ten meter standpipe.

Depth (m)	Na	K	Mg	Ca	F	Cl	SO_4	CO_3	HCO_3	NH_4	IC_{50}	IC_{20}	Nap Acid
4.5	258	7.5	4.1	5.9	5.0	87.0	BDL	24.6	864	8.7	23	7	41
6.5	260	7.9	4.3	6.0	9.0	97.0	3.0	25.8	878	9.4	N/A	N/A	N/A
7.5	260	7.8	4.0	5.7	6.0	90.0	3.0	67.2	775	9.3	20	5	45
8.5	254	7.7	4.0	5.7	12.0	100.0	5.0	13.8	873	8.6	N/A	N/A	N/A
9.5	257	7.9	4.1	6.0	9.0	96.0	8.0	33.0	839	8.1	25	8	42

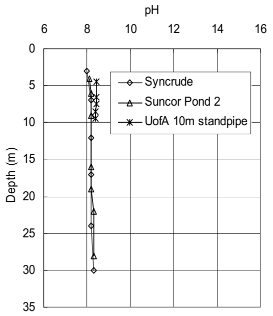

Figure 6. pH profiles

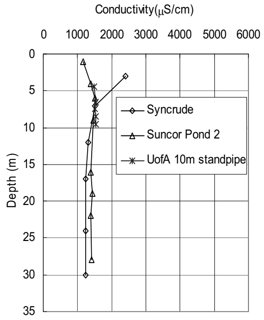

Figure 7. Conductivity profiles

3.4 BITUMEN CONTENT

Bitumen exists in the tailings as free and adsorbed bitumen. The amount of bitumen in the ten meter standpipe averages around 8% of the dry mass which is higher than the present bitumen content in the tailings ponds. It is typically greater in finer tailings than coarser tailings (Scott, Dusseault, and Carrier, 1985).

Bitumen content can be defined by two definitions which are bitumen content in geotechnical terms and mining terms. The geotechnical and mining bitumen contents are expresses in Equations 2 and 3 respectively.

$$b_g = \frac{w_b}{w_{b+s}} \qquad [2]$$

$$b_m = \frac{w_b}{w_{w+b+s}} \qquad [3]$$

where b_g = geotechnical bitumen content
b_m = mining bitumen content
w_b = weight of bitumen
w_{b+s} = weight of bitumen and solids
w_{w+b+s} = weight of water, bitumen, and solids

While the geotechnical definition of bitumen content means that the parameter is fixed with the amount of solids, the mining definition means that the bitumen content will change with the amount of solids. In geotechnical analyses, the geotechnical definition is preferred.

Scott et al. (1985) suggest that bitumen has a significant influence on the consolidation process. The clay adsorbed organic layers and bitumen's affinity for water are a factor in decreasing the tailings hydraulic conductivity which controls the rate of consolidation. It also appears that the bitumen acts like a very viscous solid which at particle contacts can affect water flow through pore throats. Under high hydraulic gradients, such as in large strain consolidation tests, the bitumen tends to flow and block the pore throats resulting in a lower measured hydraulic conductivity.

3.5 SPECIFIC GRAVITY

Specific gravity of the fine tailings was measured initially in 1982 and in 2003 and the value in both cases was 2.28, low compared to natural clay soils. The low specific gravity value of the fine tailings is caused by the amount of bitumen attached to the fine particles. The bitumen which has a specific gravity of 1.03 is considered part of the solids and results in this low specific gravity of the mineral solids.

3.6 ATTERBERG LIMIT

The Atterberg limits of the oil sand fine tailings are shown in Figure 8. The liquid limit of the tailings ranges from 44% to 53% and the plasticity index is in the range of 23% to 32%. The tailings with more bitumen (usually finer tailings) tends to have higher liquid limits. Studies have indicated a consistently lower plasticity index value for bitumen-free tailings (Scott et al. 1985). Thus bitumen has an effect on the clay-water interaction which affects both hydraulic conductivity and compressibility of the fine tailings. Table 4 shows index properties of the fine tailings in 1982 and

2003. There does not appear to have been a significant change in the index properties throughout the 21 years of the standpipe operation.

Because of the rapid thixotropic gain in strength of the fine tailings, liquid limit samples have to be mixed thoroughly and tested quickly or high values of liquid limit will be measured as the material gains strength rapidly after mixing.

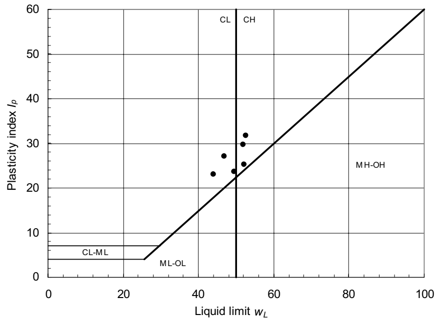

Figure 8. Plasticity of oil sand fine tailings

Table 4. Index properties of the fine tailings.

Year	1982	2003
Average Water Content (%)	227	146
Liquid Limit (%)	46	52
Plastic Limit (%)	21	21
Plastic Index (%)	25	31
Liquidity Index	8.24	4.03
Activity	0.53	0.65
Specific Gravity	2.28	2.28

3.7 THIXOTROPY

Thixotropy is defined as an isothermal, reversible time dependent process occurring under conditions of constant composition and volume whereby material stiffens while at rest and softens or liquefies by remolding (Mitchell, 1993). For geotechnical engineering, the thixotropic phenomenon can be generally described as a continuous decrease of shear strength or softening cause by remolding, followed by a time-dependent return to the original harder state at a constant water content and constant porosity. This phenomenon takes place in the majority of clay-water systems. As the consolidation process in clays is related to time and thixotropic is a time dependent effect, Mitchell (1960) argues that it would seem reasonable that thixotropic effects during consolidation lead to a smaller compression index. As a result thixotropic gain in strength will retard the consolidation process by building up bond strength and not allowing the soil to compress.

In general, kaolinite has miner thixotropic behaviour compared to bentonite and illite but the fine tailings, in which kaolinite is the main clay mineral, exhibits a very high thixotropic gain in strength. As discussed, above the mineralogy is not the main factor of this phenomenon but the addition of sodium hydroxide as a dispersing agent during the oil sands extraction process and the presence of bicarbonates and organic matter (bitumen) give the material its thixotropic behaviour.

In order to evaluate this phenomenon for geotechnical applications, thixotropic strength tests on fine tailings samples have been performed by several researchers at the University of Alberta. The objective of the thixotropic shear strength tests performed on the fine tailings was to investigate the absolute and relative gain in strength of the material with time. The increase in strength of the fine tailings in the experimental programs was due both to the thixotropic behaviour of the material and to a decrease of void ratio due to self weight consolidation. The strength values were then corrected for the change in void ratio (Miller, 1996). Thixotropic strength tests on the fine tailings were conducted by both the cavity expansion test and the vane shear test. Here only the results of the cavity expansion test are presented.

The cavity expansion test procedure uses a cavity expansion theory to calculate the undrained shear strength of a soil from applied pressure in an expanding sphere. The initial cavity expansion test procedure was established by Banas (1991), who refined Elder's (1985) work and which became the procedure presently used at the University of Alberta. Figure 9 shows thixotropic strengths measured from the cavity expansion test at void ratios of 4.63 and 3.42 or solids contents of 33% and 40% (Miller, 1996). The initial strengths after remolding were small, 18 Pa and 165 Pa respectively. Within 2 days the strength had increased to 182 Pa and 702 Pa respectively. At 350 days the strengths were 635 Pa and 1941 Pa respectively and still increasing.

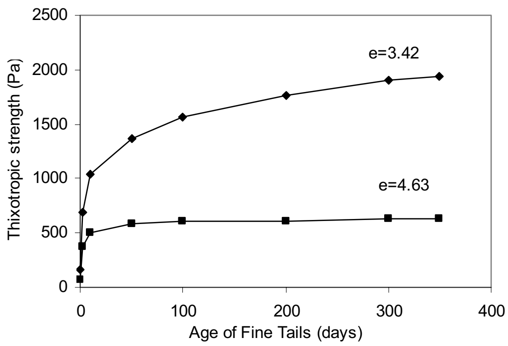

Figure 9. Thixotropic strength with time

3.8 BIOLOGICAL GAS

Biological gas generation can cause a process of rapid consolidation by opening up water flow channels by gas bubble migration towards the surface of the deposit. To investigate this effect, the presence of methanogens (methane producing microorganisms) and sulfate reducing bacteria (SRB) (inhibiting methane generation microorganisms) is determined. Figures 10 and 11 show profiles of methanogen and SRB maximum possible numbers (MPN) respectively in the ten meter standpipe. The MPN values are determined by the standard five-tube MPN method (American Public Health Association, 1985). The lack of methanogens indicates gas generation should be negligible and no gas bubbles have been observed in the standpipe. The measured degree of saturation varies from 99% to 100% throughout the depth. Therefore gas generation has not affected the consolidation process in this standpipe test. Details about effects of sulfate on methanogens and SRB can be found elsewhere (Holowengo et al. 2000) and the influence of gas generation in parts of the Syncrude tailings pond is discussed by Guo et al. (2004).

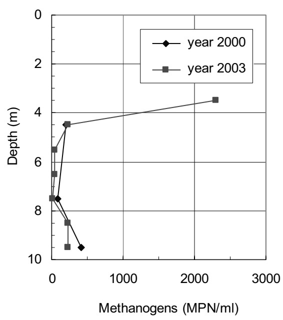

Figure 10.Methanogen profiles

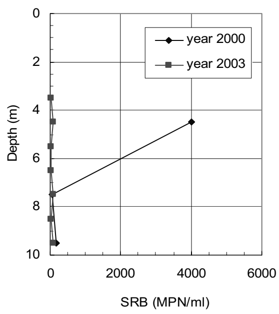

Figure 11. SRBS profiles

3.9 SCANNING ELECTRON MICROGRAPHS (SEM)

Studies on SEM images have shown that the fine tailings card-house floc structure is directly related to the pore water chemistry (Tang et al. 1997).

In Figures 12, 13, and 14 the card-house floc structure is clearly shown. At 9.5 m depth close to the bottom of the standpipe the card-house structure is compressed while at the middle and at the top of the standpipe, the card-house structure is similar to that found in the tailings ponds (FTFC, 1995). An image analysis on the SEM micrographs has been performed based on a total of 60 images (20 images at each depth). This analysis was based on the blacking-in or out technique (Smart and Tovey, 1980) and the results are shown in Table 5.

Table 5. SEM photo analysis results.

Depth (m)	Measured void ratio	Estimated void ratio	Average floc spacing (μm)
3.5	3.43	3.50	7.43
6.5	3.88	3.58	6.62
9.5	2.65	2.52	3.70

The void ratio values calculated from the image analysis show a close agreement with the laboratory measurements.

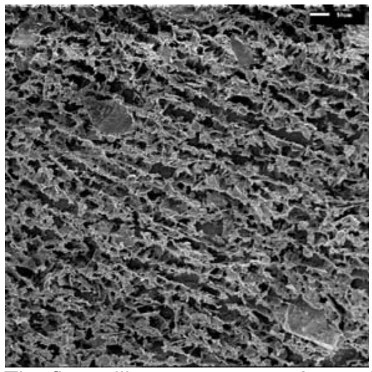

Figure 12. The fine tailings structure at 3.5 m depth.

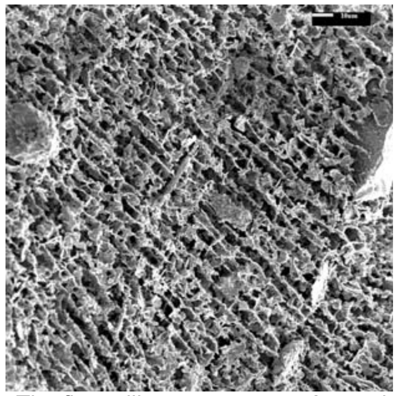

Figure 13. The fine tailings structure at 6.5 m depth.

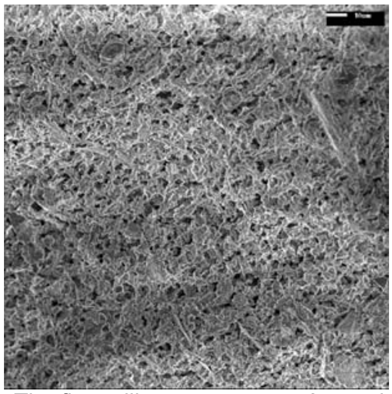

Figure 14. The fine tailings structure at 9.5 m depth.

4. STANDPIPE TEST RESULTS

The 10 m high standpipe was filled with fine tails from Syncrude's tailings pond in October, 1982 and monitoring of interface settlement, pore pressures, density and void ratio with depth have been conducted since that time. Only a few results are included in this short paper.

Figure 15 shows the interface settlement during the past 21 years. The settlement of the fine tailings has reached 3 m and has settled at a uniform rate during the last 10 years. The solids content appears to be changing fairly uniformly with depth and only the bottom meter appears to be consolidating (Figure 16). The average solids content has increased from its initial value of 30.6% to its present value of 40.6%.

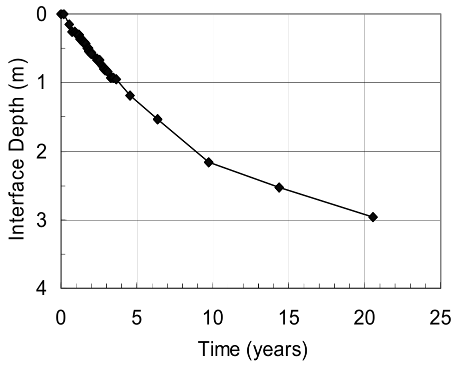

Figure 15. Interface settlement of the standpipe

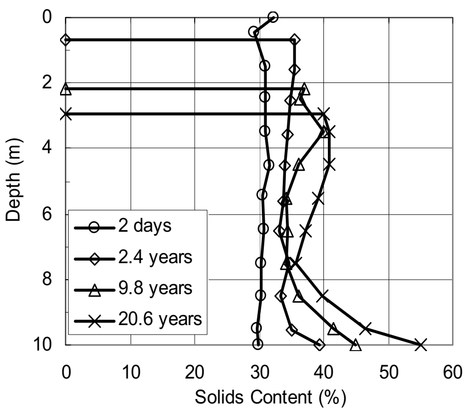

Figure 16. Solids content profiles of the standpipe

From Figures 17 and 18, total stresses, effective stresses and pore pressures at the initial time and at 20.6 years are shown. Pore water pressure measurements show that the pore pressure remains very high and close to the total stress. The effective stresses as shown are very low to no effective stress. Only the 1 m bottom part of the standpipe shows a small effective stress about 5 kPa at the bottom. The average void ratio at this time is about 3.33. During the last 10 years approximately zero effective stress has developed while the interface has settled about 80 cm. Therefore the decrease in void ratio throughout most of the depth of the standpipe is not due to consolidation, that is, a decrease in pore pressure with a subsequent increase in effective stress but is a creep phenomenon at a consistent effective stress of zero.

The increase of effective stress at the bottom of the standpipe as shown in Figure 18 is not due to segregation of coarse materials in the fine tailings. The fines content (<45μm) is consistent throughout the depth of the standpipe and is about 90% (Suthaker et al. 1997).

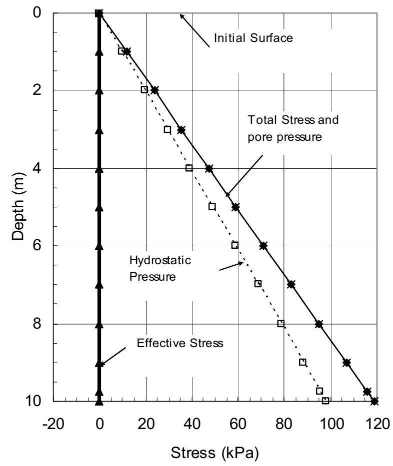

Figure 17. Initial total stress, pore pressure, and effective stress profiles of the standpipe

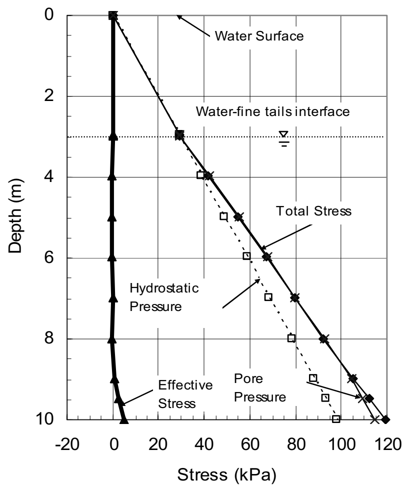

Figure 18. Total stress, pore pressure, and effective stress profiles of the standpipe after 20.6 years

5. DISCUSSION

Monitoring of the large scale self weight consolidation test will be continued for further evaluation of the consolidation behaviour of this class of materials. The 21 years of readings show that the fine tailings is still undergoing compression with approximately zero effective stress while the volumetric strain has reached 30%. The compression process appears to be a creep mechanism. The large thixotropic strength of the fine tails results in the soil structure being overconsolidated and pore pressure dissipation will not occur until effective stresses are sufficient to shear the interparticle bonds. Meanwhile, submerged self-weight is sufficient to result in slow bond yielding or creep.

The ten meter standpipe test results will be used to develop a theory for the settlement behaviour of large void ratio, thixotropic slurries.

6. ACKNOWLEDGEMENT

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