THE EFFECT OF FLOCCULANT ON THE GEOTECHNICAL PROPERTIES OF MATURE FINE TAILINGS: AN EXPERIMENTAL STUDY

Yutian Yao, Frits van Tol and Leon van Paassen
Section Geo-engineering, Department of Geoscience and Engineering, Delft University of Technology, The Netherlands

ABSTRACT

When oil sands tailings are deposited in a tailing pond, they settle and segregate to create a layer of stagnant water on top that is reused in oil extraction and a dense mixture of clay, silt and water on the bottom which is referred to as mature fine tailings (MFT). Dewatering of MFT is a problem due to its very high fines content and relatively low solid content. Atmospheric drying offers a possible solution to this problem. In this technique, MFT are pumped or dredged out of the pond and mixed with polymers that helps to accelerate the release of water from the fines, and then placed on a sloped drying area in a thin layer. When the released water runs off the remaining flocculated MFT will dry to the desired moisture content for removal and replacement in the mine or for subsequent lifts. This paper presents a laboratory study on the flocculated MFT. With a series of tests the basic properties and consolidation and desiccation behavior of flocculated MFT are assessed. The results were compared with original untreated MFT, which confirmed that in case flocculants are properly mixed with MFT, they have a positive effect on the dewatering rate of the MFT. However, the final volume of the consolidated flocculated MFT when exposed to atmospheric drying can be significantly larger than the untreated MFT. The results provide a useful reference for future pilot-scale tests and commercial implementation of the atmospheric drying method on flocculated MFT.

INTRODUCTION

Oil sands tailings are a byproduct from the oil extraction process used in mining operations. Normally, the produced tailings are discharged directly into a tailings pond for storage. In tailings ponds, tailings segregate relative to the grain size distribution and settle further to create a layer of stagnant water on top that is drained and re-used in bitumen extraction process and a mixture of clay, silt and water on the bottom or the central part of the pond which is referred as mature fine tailings (MFT). Dewatering MFT forms a problem for engineers due to the very high fines content (about 80%-90%, fines are defined as the particle size <44 μm) and a relatively low solid content. In order to maximize the proportion of recycled water and to reduce the volume of fine tailings, a variety of tailings dewatering options are being investigated. Among these options, atmospheric drying is being tested by several companies and considered as a promising method in disposal of fine tailings. In this method, MFT is dredged from the tailings pond and mixed with flocculants - chemical agents that help to aggregate the fines clay particles in the MFT together and accelerate the release of water from the fines - before being placed in a relative thin layer on a sloped surface. The released water runs down the sloped surface to a collection area and is reused for extraction. The remaining deposits will dry under the influence of environmental factors (radiant heat, wind, humidity, and drainage) to the desired moisture content for removal and replacement in the mine, or subsequent lifts. Under ideal conditions, a significant amount of the water is recovered leading to large volume reduction of the tailings.

Knowledge regarding the basic physical properties of the tailings and their consolidation and desiccation behaviors is necessary to understand the material behavior of the tailings and to further improve the efficiency of disposal (Qiu and Sego 1998). This paper presents experimental research on flocculated MFT which aims to ascertain the basic properties of the material and to examine its consolidation and desiccation behavior. The obtained data are compared with that of the original MFT to evaluate the effects of flocculation on the behavior of tailings The data generated will provide necessary parameters for numerical simulation with models and a useful reference for future pilot-scale tests and commercial implementation of the atmospheric drying method.

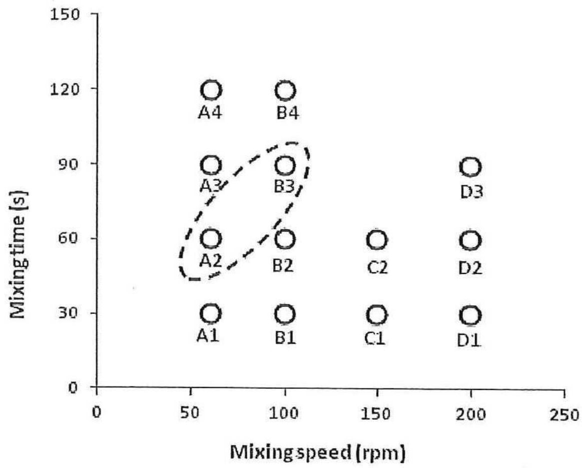
FLOCCULATION OF MATURE FINE TAILINGS

The MFT tailings used in this program originate from Shell Albian Sands Muskeg River Mine located in Fort McMurray, Canada. Several drums of tailings, 180 L each, were delivered for experimental research. The drums were agitated for about 30 minutes before the tailings were stored in 15L containers in an ambient environment away from direct sunlight.

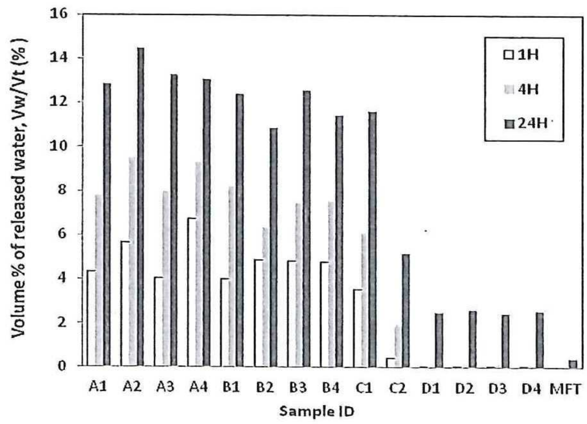
To produce the flocculated tailings for fast dewatering, one type of polymer provided by a commercial flocculent supplier was used to flocculate MFT in laboratory. The flocculent was prepared by mixing dry powder polymer with water decanted from tailings to form a solution at a concentration of 4 g/L as recommended by flocculent supplier. Flocculent solutions were then added to the MFT slurries at a dosage of 1g of dry flocculent to 1kg of dry solids. This relatively high flocculent dosage was suggested by the related research institutions based on the results of field tests. Actually, the real flocculent dosage used in engineering may vary with many factors such as the initial solid content, specific gravity, grain size distribution and pH etc. to obtain the optimum dewatering results. However, for the convenience of this research, all the tests presented in this paper were carried out on the flocculated MFT at the dosage of 1g/kg.

Several researchers (Jeeravipoolvarn, 2010; Munoz et al, 2011) found that the mixing conditions (mixing speed and mixing time) also play an important role on the results of flocculation. As stated by Munoz et al., there is a critical balance between the amount of polymer and the mixing conditions that dictate the effectiveness of the ability to release water from tailings. When the mixing conditions are ideal, water release is maximized. Munoz et al, further pointed out that the optimum mixing conditions produce large flocs with connected "macropores" which act as water channels and help to dewater the mixture. When the MFT-polymer mixture is "over mixed" there is breakdown in the flocs structure and a reduction or elimination of the water channels.

In order to evaluate the optimum mixing conditions with respect to the MFT with an initial solid content of 35%, a sands fines ratio (SFR) of 1:4 (80% fines) and a flocculent dosage of 1g/kg, a series of sedimentation tests were performed. The optimum was defined as the conditions that ensured maximum water recovery and minimized turbidity of filtrate. MFT stored in containers were agitated for several minutes with mixer before transferring to 500 ml beakers. Flocculent solutions of required volume were added to MFT when mixing started. The flocculated tailings were filled into a group of 250 ml cylinders for observation. See Figure 1a, the mixing conditions varied from 60 to 200 rpm with mixing speed and 30s to 120s of mixing time for different samples. The initial settling rate and volume of water released till 24 hours were monitored (see Figure 1b). The clarity of the filtrate was observed visually.



(a)



(b)

Figure 1. (a). Mixing conditions for different samples. (b). Observed volume percentage of released water (i.e. ratio between water volume and total sludge volume) changing with time.

It can be seen from Figure 1b that sample A2 (60 rpm×60s) was leading in settling rate and the amount of water released. On the other hand, B3 (100 rpm×90s) was superior to the samples of Group A from the aspect of turbidity of filtrate. For overall consideration, the optimal conditions for this particular bench scale experiment should fall into the area shown in Figure 1a, thus a balanced condition— mixing time is between 70 and 90 seconds coupled with a mixing speed of 70 to 90 rpm. In this paper a mixing time of 80 seconds with a mixing speed of 60 rpm was used for all experiments. We can also see that there was only 1 ml water released after 24 hours for untreated MFT, which proved the effectiveness of this type of flocculent in speeding up the settling rate. After mixing, the flocculated MFT were stored in containers and allowed to settle. After settling, the stagnant water on top was removed and the remaining tailings were used for further experiments which are described in the following chapters.

BASIC PHYSICAL PROPERTIES

A series of laboratory tests including the solid density, Atterberg limits, and particle size distribution etc. were performed to obtain the basic physical properties of original MFT and thickened tailings (TT) (Yao et al, 2010,2012). In this paper, in order to evaluate the effect of flocculent on the basic properties of MFT, Atterberg limits were re-determined for both MFT and flocculated MFT using the method described in ASTM Standard D4318 (2002). The results are presented in Table 1. The liquid limit of original MFT was 47.2%. After flocculation the liquid limits increased to 65.3%, 66.5% and 68.5% with respect to the varying flocculent dosage at 0.5g/kg, 1 g/kg and 1.5 g/kg. For untreated MFT the plastic limit was 21.5% which is close to that of flocculated tailings. These results suggest that flocculation of tailings will increase the liquid limit and an increase of the flocculant dosage results in a higher plasticity index. Comparing the MFT and flocculated MFT tested in this paper with data from earlier work by Yao et al (2010, 2012) on MFT, originating from the same stock barrel, but sampled at different times, shows that each batch of MFT can differ in basic properties, so properties from one MFT cannot be generalized for all MFT or other types of oil sand tailings.

SHRINKAGE LIMIT AND SHRINKAGE CURVE TESTS

For mine tailings that swell and shrink under the influence of environmental factors during deposition, the relationship between their changes in bulk volume and changes in water content is a necessary parameter for the geotechnical engineer to predict the tailings behavior. To obtain a quantitative indication of the amount of volume changes that occur due to sub-aerial drying of the tailings, a shrinkage limit test and a shrinkage curve test are necessary. The shrinkage limit of a soil is defined as the water content corresponding to the minimum volume that a soil can attain upon drying to zero water content. It can be used to evaluate the shrinkage potential, crack development potential, and swell potential of cohesive soils. The mercury immersion method was originally used to determine the shrinkage limit in the laboratory, however, this method is no longer considered acceptable in most countries due to health safety concerns.

Table 1. Basic Properties of the Tailings.

Property Index	MFT*	MFT	Flocculated MFT		
			0.5g/kg	1.0 g/kg	1.5g/kg
Density of solids (g/cm3)	2.31	—	—	—	—
Liquid limit (%)	57	47.2	65.3	66.5	68.5
Plastic limit (%)	27	21.5	22.9	22.7	21.1
Plasticity index (%)	30	26.4	42.4	43.8	47.4
Shrinkage limit (%)	—	14.1	—	15.3	—
Fines content (<44 μm; %)	80	—	—	—	—
Sand content (>44 μm; %)	20	—	—	—	—

*Data from Yao et al (2012)

Another method introduced by the ASTM standard D4943 (2002) is widely accepted as an alternative to the mercury method. In this method, wax is used for the measurement of the volume of the soil specimen instead of mercury. In this research, shrinkage limit tests were performed on the tailings using a wax method, the results are shown in Table 1.

Shrinkage characteristics curve describes the relationship between bulk volume and water content which is normally expressed by void ratio (i.e. the ratio between the void volume and the solid volume) versus gravimetric water content (i.e. the ratio between the water mass and the total mass). To determine the shrinkage characteristics curve, continuous measurement of bulk volume of the soil specimen during drying is required. In this paper, the balloon method described by Tariq & Durnford (1993) was selected to determine this curve. The advantage of this method is that the setup (see figure 2) is easily constructed and the whole test can be completed for the full moisture range in a short period (3-4days) with an air pump which passes air with low pressure (100L per hour) over the sample. With this method, the balloon can be filled with MFT as slurry with a high water content before applying air flow to dry the tailing. At regular time intervals, the specimen was weighed and the volume was determined by submerging the balloon into the water and measuring the mass of water replaced by the soil using Archimedes principle. A small vacuum was applied to ensure a perfect fitting of the balloon to the soil sample before the above procedures. Figure 3 presents the shrinkage curves of flocculated MFT and non-flocculated MFT.

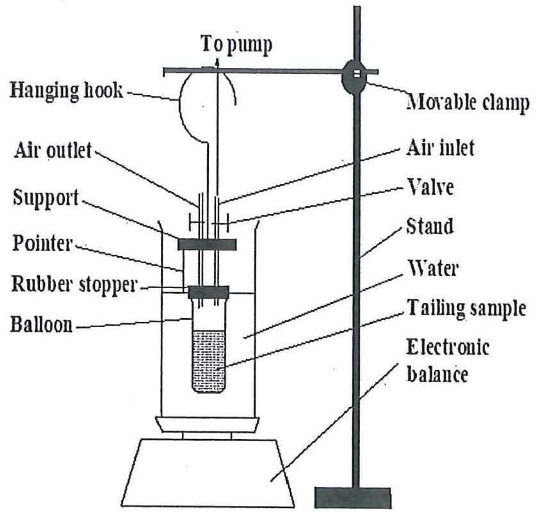


Figure 2. Setup used to determine soil shrinkage characteristic curve using Tariq & Durnford balloon method.

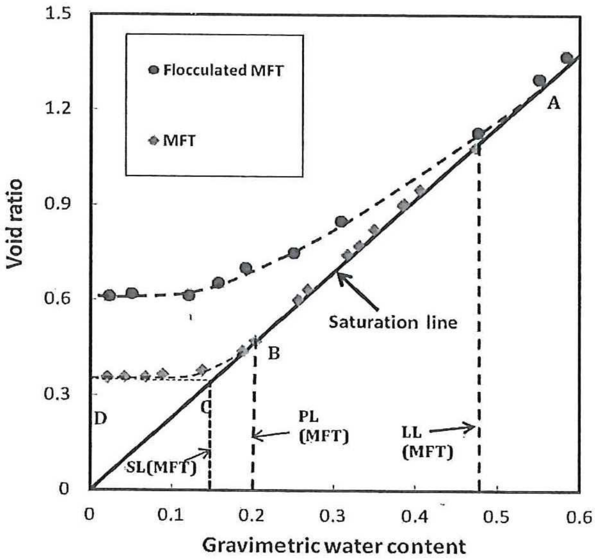


Figure 3. Shrinkage curves of the tailings determined with balloon method.

From the graph provided in Figure 3, three shrinkage stages can be identified based on the theories related to unstructured clay during drying (Bronswijk, 1991). Take the shrinkage curve of MFT as an example, the first stage (from A to B, in figure 2) is called normal shrinkage or basic shrinkage that is characterized by the equal decrease in water volume and in bulk soil volume. The second stage is called residual shrinkage starting from point B where the soil begins to desaturate. Generally, this point is close to the plastic limit of the soil. In this test the water content of MFT at point B is about 20% and the measured plastic limit is of 21.5%.

Upon further drying, point C is reached where the final stage of zero shrinkage starts. In this stage the soil particles have reached their densest configuration and the volume of the aggregates stays constant as the water volume further decreases. This can be referred to as the true shrinkage limit of the soil and the gravimetric water content appears to approximately correlate with residual soil conditions (Fredlund, 2011). The water content of MFT at point C is about 14% while the measured shrinkage limit is 14.1%. For flocculated MFT, the water content at the desaturation point is more than twice the measured plastic limit. This phenomenon is related to flocculation which changes the clay structure and properties. Finally, the comparison between the MFT with and without flocculent indicates that for the final void ratio of MFT when completely dried out was almost half the final void ratio of flocculated MFT. Apparently, flocculated MFT requires considerably more volume after complete drying than untreated MFT.

CONSOLIDATION TESTS

The purpose of the consolidation tests was to determine the consolidation behavior of tailings over the effective stress range of 1-100 kPa which is operative in the majority of tailings management facilities. One-dimensional consolidation tests were performed in accordance with the procedure described in ASTM D2435 (2004). Samples were prepared by air drying the tailings to the required moisture content in a controlled environment. Load increments that applied stresses of 2.3, 4.6, 9, 18, 36, 72 and 144 kPa were used for both MFT and flocculated MFT specimens. Each stress increment was maintained for at least 24 hours until the primary consolidation was finished. At least three specimens were tested for each type of tailings and one group of results is presented in this paper. Figure 4 provides the relationship between void ratio (*e*) and logarithm of effective stress (e-log p curve) for both tailings. The initial values of water content for flocculated MFT and MFT were 54% and 49%, which are close to the liquid limits. It can be seen that over the stress range of 4 to 150 kPa, the data points for each tailings formed a straight line. The slope of this line is denoted as the compression index c_c in soil mechanics theory which reflects the compressibility of the soil. A highly compressible soil will have large value of c_c. Other consolidation parameters such as coefficient of consolidation (c_v) and coefficient of volume compressibility (m_v) were calculated from the test results from each load increment. Moreover, the saturated hydraulic conductivity of the soil specimen from each load increment was calculated using the consolidation parameters obtained. The main results of the consolidation tests and calculated hydraulic conductivity are shown in Table 2.

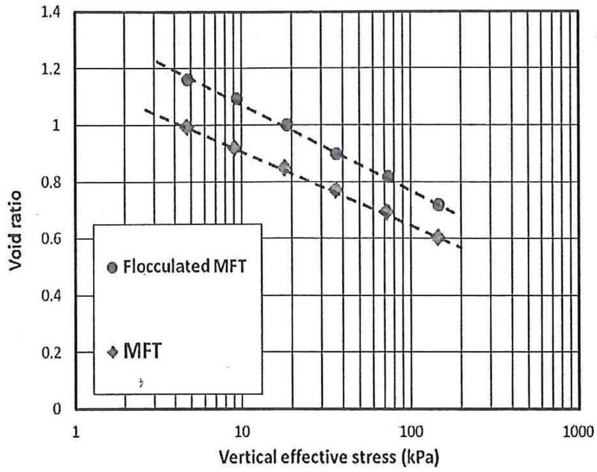


Figure 4. The compressibility of oil sands tailings.

Compared with the original MFT, the flocculated MFT have slightly higher values in the compression index c_c and an almost three times higher saturated hydraulic conductivity. The results of these tests suggest that flocculation of fine particles of MFT used in this paper, doesn't have a significant effect on the compressibility and a limited effect on the saturated hydraulic conductivity.

Table 2. Consolidation Tests and Calculated Saturated Hydraulic Conductivity of Oil Sands Tailings.

Property index	c_c	c_v (m^2/year)	m_v (m^2/MN)	k_s (m/s)
MFT	0.24-0.30	0.063-0.16	1.1-20	4.1×10^{-11} -6.9×10^{-10}
Flocculated MFT	0.27-0.32	0.07-0.16	1.4-14	4.9×10^{-11} - 5.0×10^{-10}

LABORATORY VANE SHEAR TESTS

The vane shear test is a relatively simple, quick, cost-effective geotechnical testing method used to estimate the undrained shear strength of soft to firm cohesive soils. This test can be carried out both in the field and in the laboratory. In this paper, a series of vane shear tests were performed in laboratory by following the procedure described in British Standard (BS 1377 (1990)) on the tailings specimens. Materials used for the vane tests were taken from the tailings storage which were contained in large buckets and placed in the controlled environment for air drying. At different time intervals, soil samples were taken from different positions and depths of the tailings with a sampler which is about 38mm in diameter and 80 mm in height. Besides the vane shear strength, water content and the density of each sample were also measured. Relationship between the void ratio and the undrained shear strength in each type of tailing was established through tests, shown in Figure 5.

It is well known that the undrained shear strength of a remolded clayey soil increases rapidly as the water content decreases (ref). In this test, for MFT with void ratio of 1.35 (about 60% in water content) the measured shear strength was about 1kPa, this value climbed up to 190 kPa when the void ratio decreased further to 0.48 (about 16% in water content). Comparing the undrained shear strength curves of untreated MFT and flocculated MFT, the latter curve was located slightly higher than the former one in the graph.

In other words, at the same void ratio the untreated MFT shows lower shear strength than flocculated MFT or at the same shear strength flocculated shows a higher void ratio than non-flocculated MFT.

In practice tailings produced from the extraction plant are normally adjusted to high water content slurries for the purpose of transport and deposition, however, for successful reclamation the excess water must be removed from the tailings and a minimum shear strength must be achieved. According to Directive 074, the minimum shear strength required for reclamation is 5 kPa. According to figure 5 an undrained shear strength of 5 kPa for MFT, flocculated MFT is obtained at void ratios of about 1.0, 1.1, respectively.

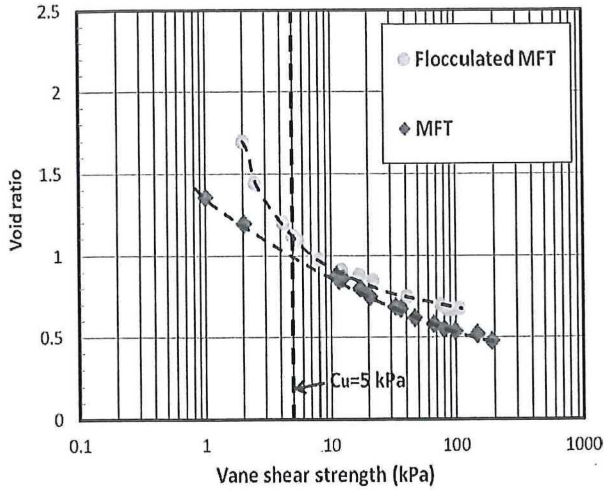


Figure 5. Vane shear strength of tailings.

WATER RETENTION CHARACTERISTIC TESTS

The water retention characteristics tests are used to determine the soil water characteristics curves (SWCC). The SWCC is an empirical relationship between soil suction stress and water content. Soil suction stress is one of the most important factors affecting the drying behavior of (unsaturated) soils. In atmospheric drying, the flocculated tailings are deposited in thin layers and allowed to desiccate and eventually desaturate under the influence of environmental factors (i.e. humidity, temperature, wind, etc.). The SWCC is used in numerical models to predict the change in volume and water content when water is evaporated from the soil surface.

The filter paper method, described in ASTM Standard D5298 (2002), was used to determine the water retention curves of fine tailings because of its advantages over other suction measurement methods. The working principle of this method is that the filter paper will come to equilibrium with the soil, and suction value of the filter paper and the soil will be the same at equilibrium. The filter paper needs to be calibrated before use. The purpose of calibration is to determine the relationship between soil suction stress (total suction or matric suction) and the measured moisture content of filter paper at equilibrium. ASTM D 5298 employs a single calibration curve that has been used to infer both total and matric suction measurements. However, Houston et al

(1994) proved that the total suction calibration curve and the matric suction calibration curve of one soil don't match thus should be determined separately. Bulut (1996, 2001) determined the calibration curves with Schleicher & Schuell No. 589-WH filter paper for both total and matric suction measurement. In this paper, the same type of filter paper was selected and the calibration curves were used. The determined water retention curves for non-flocculated MFT and flocculated MFT are shown in Figure 6. The figure shows that particularly in the low ranges of suction flocculated MFT shows significantly higher water content than MFT without flocculent. At a suction stress above 200 kPa (water content of about 25%) the SWCC of all three types of tailings are more or less equal.

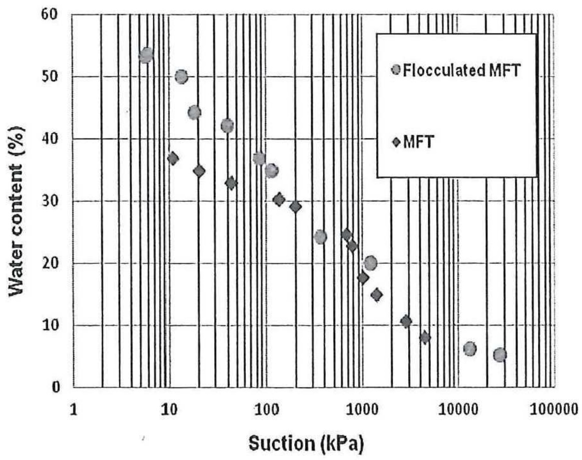


Figure 6. Water retention curves of the tailings.

DISCUSSION AND CONCLUSIONS

In this paper, the properties including basic physical properties, shrinkage characteristics, consolidation behavior, vane shear strength and soil water characteristics were compared between untreated MFT and flocculated MFT through laboratory tests. From the comparison the following conclusions could be drawn:

(1) The amount of flocculent and the mixing procedure (Mixing speed and duration) have great impact on flocculation results and thus control the dewatering behavior of the flocculated tailings. The optimum mixing condition for MFT with an initial solid content of 35% and SFR of 0.25 at the dosage of 1g/kg was determined in this paper at 70—90 seconds at a mixing rate of 70-90 rpm.

(2) Sedimentation tests on the flocculated MFT demonstrated the effectiveness of this type of flocculent in accelerating the settling rate and the release of water from the tailings.

(3) Regarding the Atterberg limits, the liquid limit of MFT increased from 47% to 67% while the plastic limit and shrinkage limit did not change much after flocculation.

(4) The shrinkage curves showed that flocculated MFT already started to desaturate at a high plastic index (i.e. a high water content compared to plastic and liquid limit.) in contrast to original MFT which started to desaturate close to the plastic limit. Also these curves showed that the void ratio of completely dried flocculated MFT was about 0.6 which is about twice the void ratio of completely dreied MFT.

(5) The one-dimensional consolidation tests showed that within the stress range of 2 to 150 kPa flocculated MFT and non-flocculated MFT tailings show similar compressibility, but flocculated MFT has a higher void ratio. The measured consolidation parameters (c_v, m_v and k_s) of the flocculated MFT are close to those of MFT.

(6) The minimum undrained shear strength of 5 kPa which is the requirement for successful reclamation is reached at a higher void ratio for flocculated MFT compared to original MFT.

(7) The SWCC shows a significantly higher water content for flocculated MFT at suction stresses below 200 kPa. Above 200 kPa differences between the three types of tailings are insignificant.

Combining the various experimental results it can be concluded that adding flocculants has a positive effect on the dewatering rate of the MFT (when properly mixed). The flocculated MFT settles faster and the permeability of the settled flocs is higher than the MFT without the flocculent. However, the high liquid limit, higher void ratio during one-dimensional compression and high water content at suction stresses below 200 kPa in the SWCC indicate that flocculated MFT binds more water that the MFT without flocculent, particularly under low stress conditions. The final volume of the consolidated flocculated MFT when exposed to atmospheric drying can be significantly larger than the MFT without flocculent. These findings seem to indicate that disposal of flocculated tailings requires larger tailing ponds. On the other hand the fact that the required shear strength is reached at a higher void ratio might allow earlier access on the reclaimed tailings to take additional measures which can further accelerate consolidation, like planting trees.

Although the results of the various tests seem to be consistent, they might differ for various types of tailings and should be validated based on field observations. For example the optimum mixing rate and duration are likely to be valid only for the mixing equipment used in our experimental program. Therefore the optimum mixing conditions should probably be redefined for different mixing equipment, sludge and flocculent types. Further investigation in the flocculation mechanism is required to explain the observed behavior. Secondly most tests were performed at stresses above 2 kPa, while significant volume change might occur in the relatively low stress range from 0-2 kPa. Large strain consolidation tests must be performed to evaluate the full consolidation and desiccation behavior as a result of atmospheric drying.

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