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Consolidation of Cannington mine tailing at its liquid limit

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ABSTRACT

Mining activities need to take place for the economic survival of countries. Mine tailings, which are the residue of mining activities, need to be disposed carefully to reduce their environmental impact.
Millions of tonnes of mine tailings are disposed every year in Australia through underground mines and surface tailing dams. It is generally not possible to dispose all the tailings underground, due to the space limitations, therefore the remainder is sent to the surface tailing dams. For ease of transport over long distance, these tailings are often placed in the form of slurry with initial solid content of 50 to 60%.
To simulate the field condition in this study, the tailing slurry is placed in the settlement columns to settle under its own weight. Then a sample is taken for conventional one-dimensional oedometer consolidation from the base of the column to investigate the consolidation behaviour of the deepest sediments after self-weight consolidation has completed. The moisture content of location at which the sample for oedometer is taken, is determined to be 21% which is the liquid limit of the tailing.
It can be concluded that self-weight consolidation of the tailing finished at its liquid limit and application of surcharge is required for further consolidation. Study on the consolidation parameters of the tailing at this moisture content suggests large coefficient of consolidations with each loading increments.

Keywords: mine tailings, sedimentation, settlement columns, compression, consolidation at liquid limit

1 INTRODUCTION

The processing of minerals in mine tailings produces a large amount of by-product known as tailings. The Cannington mine is a metal-based mine that contains silver, zinc and lead. It is the largest silver mine in the world, and produces approximately 25 million ounces of silver per year and produces large amount of tailings. These tailings are usually used as pastefill, used for backfilling, disposed near a river, sea or in storage facilities such as tailing dams.

When the ore is removed from the ground very large voids are created. These are generally backfilled by the crushed waste rock or tailings that remain after the valuable minerals are removed from the ore. Millions of tonnes of mine tailings are disposed every year in Australia through underground mines and surface tailing dams. For ease of transport over long distance, these tailings are often placed in the form of slurry. It is generally not possible to dispose all the tailings underground, and the remainder is sent to the surface tailings dams (Figure 1). The underground mines have access drives at different levels that have to be barricaded to isolate the voids before filling with the tailing slurry. Failure of underground mine barricades and surface tailing dams during the early days of filling has been a common problem faced by the mining industry for years. To mitigate the problem it is necessary to understand the sedimentation-consolidation process of mine tailings. The mine tailings can have large fraction of fines, making the sedimentation-consolidation process relatively slow. Especially when placing the slurries underground, even if the clay content in the tailings is low, the consolidation process can be slow due to the very large depth of the voids exceeding 200 m sometimes. To understand the self-weight consolidation of the tailings followed by the sedimentation process, and to model the problem numerically, it is necessary to evaluate the coefficient of consolidation of the tailings at different stress levels. In this paper, an attempt is made to carry out some one-dimensional consolidation tests on mine tailings obtained from Cannington mine.

Figure 1. Discharge of the tailings into the storage facility, Cannington mine (Lottermoser 2003)

There are different factors that affect the consolidation settlement of soils. These factors are temperature, salinity, light, concentration of soil particles, solid content, mineralogy of the soil, amount of organic matters, filling rate, head pressure, particle size distribution. Changes of these parameters can change the settlement behaviour of the soils. Therefore each type of soil behaves differently, if its amount of salinity, minerals, and ionic concentration changes significantly. The presence, amounts and types of the elements in mine tailings depend on the type of extracted metal. For instance, the tailings of Cannington mine have significant amounts of silver as its principle commodity. As well as the presence of metal elements and affecting the mentioned factors, the angularity and orientation of particles can influence the settling behaviour of the tailings. Therefore, due to these differences, the behaviour of the mine tailings needs to be investigated. Specifically, consolidation behaviours such as compressibility and rate of consolidation are important to be investigated for land reclamation and estimation of the dyke storage capacity.

The objective of this study is to examine the sedimentation and consolidation behaviour of the Cannington mine tailings at its liquid limit. Liquid limit is the transition point at which the slurry is transiting to soil and start to develop small shear strength. This is a temporary stage, however, initial water content affect the initial void ratio, the soil fabric developed and hence the consolidation parameters. Another objective of this study is to determine whether oedometer testing is a proper method for investigating the consolidation parameters of the tailings.

2 MATERIAL AND METHOD

2.1 Mine tailings

2.1.1 Mineralogy

The tailings used in this study were obtained from Cannington mine that is located in north-west of Queensland, near township of McKinley, Australia. The samples are transported to the James Cook University geo-mechanics laboratory in large closed drums. The Mineralogy of the mine tailings is presented by Lottermoser et al. (2009) demonstrated in table 1.

Table 1: Mineralogy of Cannington mine tailings (Lottermoser et al. 2009)

Minerals	**Concentration**
Quartz	>10%
Amphibole, Plagioclase	<10%
Anglesite, Bassanite, Biotite, Brucite, Calcite, Chlorite, Dolomite, Fayalite, Fluorite, Galena, Garnet, Gypsum, Halite, Hedenbergite, Hornblende, HFO phases, K-feldspar, Laumontite, Magnetite, native Sulphur, Natrojarosite, Plumbojarosite, Pyrite, Sphalerite, Szomolnokite, Talc	<1%

2.1.2 Specific gravity and Consistency limits, and particle size distribution

Specific gravity or density of the mine tailings is determined according to the AS 1289.3.5.1. The density of the tailings tends to be much higher than soils depending on the amount of heavy metals presenting in the soil. Higher amount of heavy metals result in higher specific gravity of tailings. The density of the tailings can vary between 2.65 to 4.4 depending on the type and amount of metals.

According to the reported specific gravities (Bowles 1986; Day 2001; Lambe and Whiteman 1979), the ranges of specific gravities for soils containing Chlorite is between 2.6 to 2.9. If the soil contain significant amount of mica and iron its specific gravity can varies between 2.75 to 3.00, and if it has Muscovite and Biotite it can have specific gravity up to 3.2. The tailing of Cannington mine has specific gravity of 2.89.

The liquid limit of the tailings has been determined with the use of fall cone method. The liquid limit is performed according to AS 1289.3.9.1 and the plastic limit is determined according to AS 1289.3.2.1. A smooth cone made of stainless steel with total weight of 80±0.05 g and 30±1° is released in 5±0.5s and the liquid limit is defined which the depth of penetration is 20 mm. The fall cone method is widely preferable to be used than Casagrande method due to the better repeatability and less variations in measurement caused by human error. Liquid limit of the tailing is determined to be 21%, and its plasticity index is obtained as 5.6%. Therefore the tailings can be classified as silty to clayey soil with very low plasticity according to Casagrande soil classification chart. Figure 2 shows the particles size distribution that has been performed in Advanced Analytical Center at James Cook University, according to which the tailing has 30% clay, 40% silt, and 30% sand therefore about 70% of the tailing is fine grained soil.

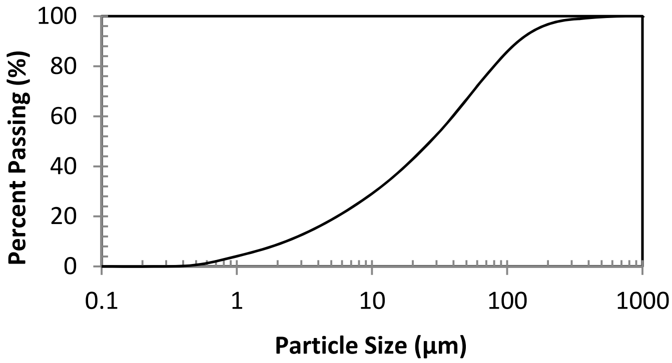

Figure 2. Particle size distribution of the Cannington mine tailings

2.2 Method

To prepare the slurries with specific solid content, the dried and powdered mine tailings were mixed with distilled water. Mixing the tailings with distilled water can reduce the concentration of the metal elements thus closer behaviour to soils might be expected. However, further investigation is required to investigate the effect of ions and metal concentrations on the consolidation parameters of the tailings. Then the mixture was left overnight to soak for 24 hours to ensure the homogeneity of the mixtures. Each settlement column has a diameter of 100 mm and a height of 1000 mm. According to Coulson et al. (1990), the size of the settlement column does not significantly affect the sedimentation and consolidation results if the ratio of the column diameter over diameter of the particles is higher than 100. The bottom of the settlement columns are perforated to allow the drainage of the water from the bottom. To avoid the blockage of the perforated holes filter paper is used at the bottom of the column. When the settlement columns are filled with slurries, they are left to drain and settle with time.

The settlement analysis of soils can be different when the investigations are based on field testing or laboratory experiments. Different factors such as the rate at which the tailing dams are filled, the height and distance of pumping, method of filling materials, size of the pump, environment at which the tailing is poured into, can change the behaviour of the tailings. Filling rate is one of the actions that cause a huge difference between field and laboratory investigations. Variations in filling rate change the result of the settlement due to its impact on stress history of particles. These changes in stress history of particles can also affect the compaction parameters. Therefore, how slurries would pour into the settlement columns can affect the overall sedimentation and consolidation of the soils. There are different methods used for filling the columns in laboratory studies and in field applications (filling the tailing ponds). Filling can either be layer by layer within time intervals, or it can be instantaneous where all tailings are placed at once and assuming that the lag time between pouring the slurry and the start of settling is zero, filling can take place by continuously pumping into the area. In this study, the instantaneous placement method is used and the prepared slurry of 1.7 times liquid limit was poured into the settlement column in at once and it is assumed that there would be no lag time from the start of the test.

To study the settling and sedimentation of the soil by oedometer a sample of 63 mm diameter is taken from the bottom of the column where the soil experiences the maximum compression due to the weight of upper layers. During the sampling process, samples were taken to obtain the water content of the tailing at which the specimen for oedometer testing was taken. It was found that the initial water content of the tailings was at the liquid limit which is 21% water content. Then the sample went through consolidation under oedometer and its consolidation behaviour is studied.

3. Consolidation settlement

The purpose of the consolidation test is to determine the consolidation behaviour of the Cannington mine tailings. Although it can be classified as ML (silt with low plasticity), due to the angularity of the particles and the presence of metal elements, its behaviour is different from soils that geotechnical engineers normally deal with. The analysis of the results obtained from the oedometer test clearly shows this deviation (Figure 3).

3.1 Coefficient of consolidation

The determination of coefficient of consolidation is normally based on the time at which a specific degree of consolidation has occurred. Based on different theories, considered degree of consolidation to determine the coefficient of consolidation varies. For example, Casagrande (1940) considers 50% completion of the consolidation and uses t_{50} for determination of its coefficient. This method is known as Casagrande log-time method. In case of Taylor (1948) theory, the completion at 90% of the consolidation is considered to be $t_{90,}$ and the time factor that is determined based on the dissipation of pore pressure is 0.848. These two methods are the most popular methods. Another method is Cour method (1971) that is based on inflection point of the settlement versus log-time at which 70% of consolidation is completed.

At the beginning of each loading increments abrupt initial compression was observed. This initial compression is not taken into account in any of the mentioned models. It is suggested by Craig (1974) that the initial compression should rather be ignored. Point a_s is corresponding to U=0 where the curve for primary consolidation starts and finishes at a_{100} corresponding to U=100 (Figure 4 a).

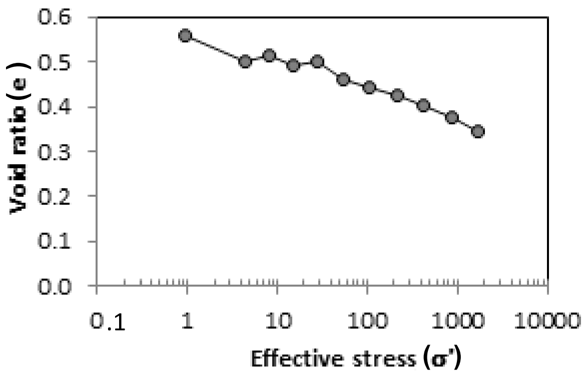

Figure 3. Void ratio versus effective stress logarithmic scale

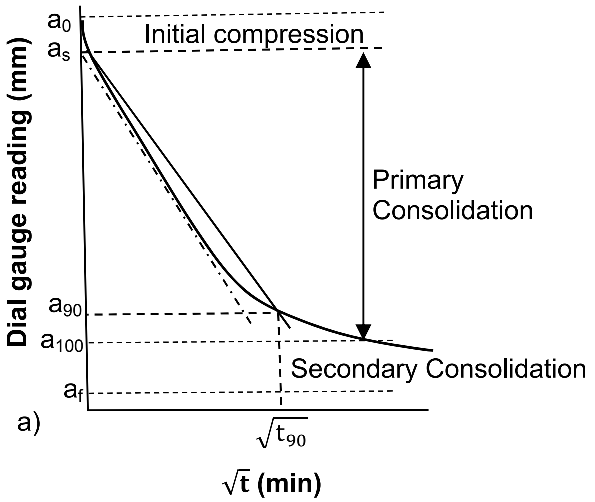

Figure 4. a) Root time method in case of initial compression (Craig 1974); b) Using Taylor root time method to determine t_{90} for Cannington mine tailing, typical shape of the strain versus root time of Cannington tailings

Therefore in this study the initial compression is rather ignored for calculation of the coefficient of consolidation but it is taken into account for determination of the compressibility parameters.

Due to the elimination of the initial compression, it is not advisable to use Casagrande and Cour method as these methods are based on the completion of the primary consolidation, whereas, Taylor's root-time method depends on the initial behaviour of the soil. Thus, Taylor method is used in this study for calculation of coefficient of consolidation.

Figure 5 shows the variation of coefficient of consolidation for each loading increment. During the first five loading increments, coefficient of consolidation increases as the loading increment increase. Afterward once the void ratio reduces dissipation of pore water pressure reduces and this result in a more stable values of coefficient of consolidation. The ranges of c_v obtained in this study is in harmony with what Aubertin et al. (1996) for Quebec tailings as 0.005 – 2.8 (m^2/yr), the Quebec tailing has 75% fine grains which might be comparable to Cannington mine tailing to some extent. However, each type of tailings can behave differently due to the type and concentration of metal ions. Due to the initial compression of the soil it is difficult to determine the coefficient of consolidation as it is not clear where the primary consolidation actually starts to occur.

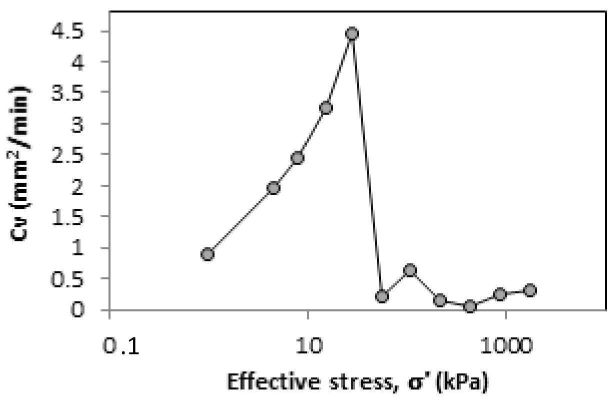

Figure 5. Variation of coefficient of consolidation for each loading increment.

3.2 Coefficient of volume change and compressibility

Coefficient of volume change is the measurement of the compressibility of the soil. It is a value which shows how much a soil can be compressed when a specific amount of load is applied. Therefore it is dependant of the changes in volume (ε_{vol}) and effective stress ($\Delta\sigma'$) that caused the volume change.

$$m_v = \frac{\varepsilon_{vol}}{\Delta\sigma'} \quad (1)$$

Figure 6 shows the variation of m_v with effective stress. The effective stress and the coefficient of volume change is correlated using bi-power fit with 99 %. Therefore, coefficient of consolidation as a function of effective stress is:

$$m_v = 15.85\ \sigma'^{-0.678} \quad (2)$$

As the applied pressure increases the m_v reduces and this shows that the compressibility of the soil reduces during application of heavy loads. The coefficient of compressibility (compression index) of the studied mine tailing can be determined from the slope of the void ratio versus logarithm of effective stress (Figure 3).
The ranges of compression index for different mine tailings is studied by many researchers. Barnekow et al. (1999) presented the ranges of the compression indices based on the type of tailings (Table 2). He divided the tailings into three types, fine mine tailings, intermediate fine tailings, and sandy tailings. His classification is based on how close the behaviour of the tailings is to soils. Soils with moderate to high plasticity are classified as intermediate fine tailings. Cannington tailings is more likely to be classified as intermediate fine tailings, based on its compression index. The compression index of the tailing reported herein is 0.56, which is close to the upper limit reported by Barnekow et al. (1999) as 0.55 for intermediate fine tailings. Therefore, the Cannington tailings can be classified as fine to intermediate fine tailing according to its value of compression index.

3.3 Estimation of hydraulic conductivity from consolidation test

Indirect estimation of hydraulic conductivity of the soils can be determined from product of the coefficient of consolidation (c_v), coefficient of volume compressibility (m_v) and unit weight of water (γ_w). Especially in case of self-weight consolidation, hydraulic conductivity plays an important role, as changes of hydraulic conductivity change the rate of consolidation settlement and void ratio. It is based on the hydraulic conductivity of soils that pore fluid is able to move within pore and drag solutes with themselves. Therefore porosity and degree of saturation of soils are important factors that hydraulic conductivity depends on.

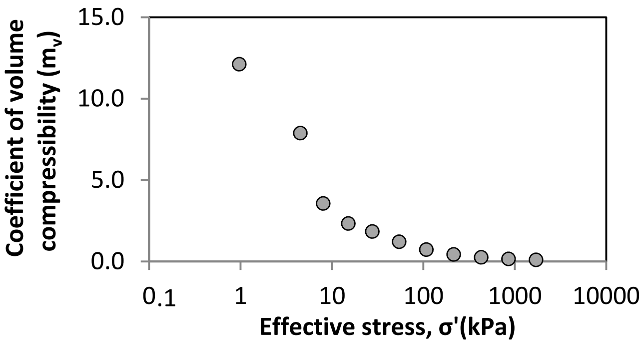

Figure 6. Variation of coefficient of volume compressibility for each loading increment.

Table 2: The ranges of compression index based on type of the tailings (After Barnekow et al. 1999)

Type of tailing	Ranges of Compression index Cc
Fine Tailings	0.60-0.82
Intermediate fine tailings	0.40 - 0.55
Sandy Tailings	0.02 - 0.08

Hydraulic conductivity can be defined as, the ease at which water flows through the pores. If a soil has low hydraulic conductivity, it may take years for consolidation to be completed. Hydraulic conductivity gives an indication of soil compressibility, and how well it may consolidate under each loading increment. The speed of consolidation settlement mainly depends on the hydraulic conductivity of the soils. Soils with higher hydraulic conductivity settle faster than soils with low hydraulic conductivity. For example sand has high hydraulic conductivity, therefore it settles quickly, whereas it may take years for clayey soils to consolidate. Clayey soils usually have very low hydraulic conductivity, and this hinders the dissipation of water through pores and makes them highly compressible.

Figure 7 shows the changes of hydraulic conductivity with void ratio. Accordingly, the hydraulic conductivity increases as the void ratio reduces. The best fit is found to be bi-power law function, and therefore hydraulic conductivity as a function of void ratio with 83% coefficient of determination can be written as:

$$k = 0.4994\ e^{0.0485} \quad (3)$$

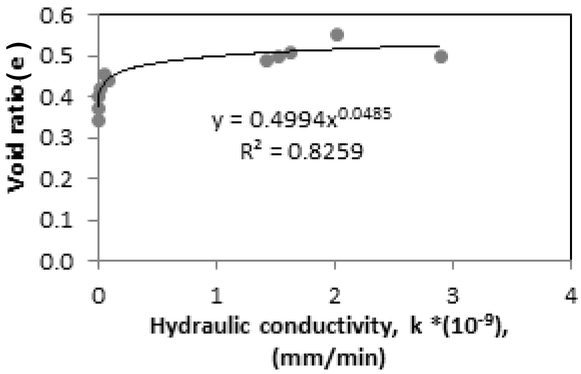

Figure 7. Void ratio versus hydraulic conductivity

4 CONCLUSION

This paper presented the consolidation behaviour of the Cannington mine tailings that has been investigated by the use of oedometer testing. The tailings is classified as silt with low plasticity with liquid limit of 21%. The compressibility of the tailing is found to be 0.56 and is classified as intermediate fine tailings which is in agreement with the grain size distribution of the soil that shows about 70% of the tailings is fine material and the rest is sandy. Determination of coefficient of consolidation by the existing methods is difficult due to the initial compression of the tailings and it is not very much clear where exactly the primary consolidation starts. This might lead to errors in finding the coefficient of consolidation by oedometer. Therefore, further study on analysis of how to obtain most accurate coefficient of consolidation is necessary. This can be done through analysis of self-weight consolidation. As the type and the concentration of metal elements can affect the behaviour of the tailings, further investigation of this can be helpful in estimating the behaviour of the tailings and their difference with soils.

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