COMPRESSIBILITY AND HYDROCOMPRESSION SETTLEMENT OF MINE TAILINGS

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Abstract : Tailing dam as storage facility plays an important role in the waste management of mining industries but failure of this structure, while the mine tailings are still in slurry form, can result in a debris flow that poses a serious threat to life, property and the environment. It is therefore important to reduce the volume of tailings so that the risk to the exposed population and the environment can be reduced. One possible option is to utilize tailings that do not contain deleterious components as backfill or as embankment materials in the construction of tailing dams. This research study was conducted to have an understanding of the consolidation characteristics of tailing as this will help to devise both short and long term disposal options for this waste material and determine their suitability in geotechnical application. Tailings from concrete aggregate quarry in Cavite and gold mine sites in Davao and Masbate were subjected to consolidation tests to determine the consolidation parameters that describe the compressibility and the one-dimensional consolidation behavior of tailings when subjected to vertical stresses. Based from the values of consolidation parameters, tailings are classified as slightly compressible. Gold mine tailings from Davao were shown to be 40% more compressible than aggregate tailings and gold tailings from Masbate. The hydrocompression settlement of tailings was also investigated. Tests results revealed that tailings are only slightly susceptible to hydrocompression. Gold tailing from Davao was the least responsive to wetting. Gold tailings from Masbate was the most responsive to wetting with maximum hydrocompression strain, $_h$ of 0.98%. The plot of hydrocompression strain ($_h$) as a function of vertical effective stress was presented, and serves as a useful tool to predict settlement due to wetting for various depths of embankment. From the experimental data obtained, polynomial relationships were developed to estimate the hydrocompression settlement as a function of vertical stress.

Keywords: mine tailings; consolidation parameters; hydrocompression settlement

1. INTRODUCTION

Despite the economic benefits, mining operations often face strong opposition from affected communities because of its adverse environmental and social effects. Foremost of these is the generation of huge amounts of waste materials called mine tailings. Tailings are the materials left over after separating the valuable fraction from the worthless fraction of the ore. The volume of tailings produced by mining operations often exceeds the volume of the recovered minerals by several orders of magnitude. For example, the production of 10 g of gold results in more than 5 tons of solid and liquid wastes generated by mining and milling processes (Ripley, 1982). During the five-year period from 1988 to 1992, small-scale mining activity in the Philippines produced an estimated 38,230.63 kgs. of gold, 5.73 million metric tons of ore mined, and 14.32 million metric tons of tailings (Santellices, 1997). In an effort to protect the environment, it has been an integral part of most mining companies to undertake environmental protection measures in order to minimize if not completely eliminate negative environmental impacts. Some of these measures are the construction of tailing disposal systems. In tailing dams, the mine tailings are generally deposited in slurry form. Failure of the dam, while the mine tailings are still in slurry form, can result in a debris flow that poses a serious threat to life, property and the environment. It is therefore important to reduce the volume of tailings in tailings' impoundment so that the risk to the exposed population and the environment can be reduced. One possible option is to utilize tailings that do not contain deleterious components as backfill or as embankment materials in the construction of tailing dams. Use of mine tailings as fill or embankment materials would alleviate disposal problems and reduce impoundment cost. To evaluate its applicability as construction materials, consolidation parameters that describe the compressibility and the one-dimensional consolidation behavior of tailings when subjected to vertical stresses were determined. It is necessary to have an understanding of the consolidation characteristics of tailing as this will help to devise both short and long term disposal options for this waste material and determine their suitability as embankment or fill material. The hydrocompression settlement of tailings was also investigated to determine the response of mine tailings when exposed to wetting.

Tailing samples used in this study were obtained from three (3) mining sites in the Philippines namely concrete aggregate quarry in Cavite, gold processing plant in Davao del Norte, and gold mining site in Aroroy, Masbate. The first sample designated as TS#1 is obtained from wastes of concrete aggregate quarry in Sapang I, Ternate, Cavite. These are produced from washing crushed rocks in the siltation pond through the natural process of sedimentation. The second type of sample (TS#2) is tailing from a gold processing plant located at Barangay Magdum, Tagum City, Davao del Norte. The third sample (TS#3) is tailing from gold mine site in Aroroy, Masbate.

2. EXPERIMENTAL PROGRAM

A series of laboratory tests based on ASTM standard procedures were carried out to determine the physical properties and consolidation behavior of the mine tailing samples. The laboratory tests include grain-size analyses, Atterberg limits tests, specific gravity tests, maximum and minimum index density tests, compaction tests by Proctor method, scanning electron microscopy, and oedometer tests.

The consolidation properties to describe the compressibility of tailing samples were determined by oedometer test using the procedure described in ASTM D2435 Standard Test Method for One-Dimensional Consolidation Properties of Soils. Reconstituted specimens were prepared with a target relative density slightly closed to 90% to simulate the very dense condition of the embankment. Specimen was directly compacted in the consolidometer device by tamping or kneading to achieve the desired density. Specimens were subjected to load increments that applied stresses of 5, 10, 20, 40, 80, and 160 kPa. Tests runs were performed with sample in submerged condition to determine the consolidation parameters.

Test runs were also performed to evaluate the hydrocompression settlement of tailings. Four reconstituted specimens of each type of tailings were prepared at initial relative density closed to 90% with moisture content near its optimum. Preparation of samples was the same as the submerged condition but the saturation of specimen was delayed. Each specimen was consolidated under a series of vertical stress increments. Once a predetermined stress (10, 40, 80 and 160 KPa) was reached, the specimen was inundated after primary consolidation was attained.

Hydrocompression settlement was observed and recorded for 24 hours, after which, specimens were reloaded/unloaded to complete the consolidation process. The amount of hydrocompression settlement (_h) was measured from the plot of vertical strain versus time.

3. TEST RESULTS

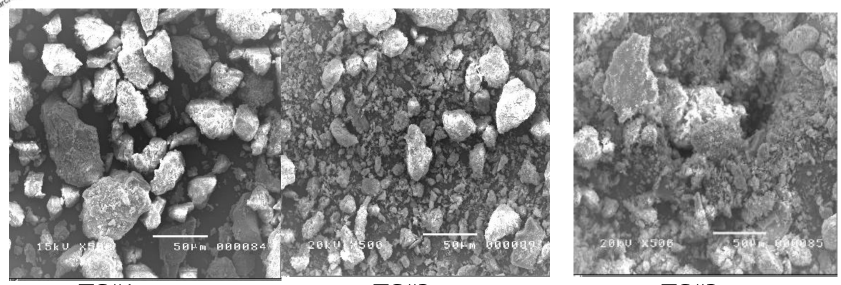
Physical Properties

The distribution of grain sizes of the three (3) types of tailing samples was determined using the combined method of sieve analysis and hydrometer test. For each type of tailing, 3 test runs were performed in accordance with ASTM D422. Tailings from concrete aggregate quarry (TS#1) primarily consisted of fine sands with very few silts. Based from Unified Soil Classification System (USCS), TS#1 is classified as poorly graded sand with silt and is given the symbol of SP-SM. Gold mine tailings from Davao (TS#2) and Masbate (TS#3) both exhibited an almost equal distribution of fine sands and silts. TS#2 and TS#3 both have USCS classification of silty sand with symbol of SM. The soil constants of mine tailings determined from laboratory tests are presented in Table 1.

Table 1 Soil Constants of Tailing Samples

	TS#1	TS#2	TS#3
Specific gravity, *Gs*	2.57	2.72	2.71
Liquid Limit, LL %	27	24	23
Plasticity Index, PI %	0	0	0
Shrinkage Limit, %	21	20	20
Shrinkage Ratio	1.47	1.57	1.66
Min. Void Ratio, e_{min}	0.624	0.680	0.662
Max. Void Ratio, e_{max}	1.024	1.106	1.089
Max. dry unit weight, _$_{dmax}$ KN/m^3	15.56	17.12	17.72
Optimum moisture content, w_{opt} %	13.49	17.28	12.82

The study of tailing's micro fabric was undertaken through the use of scanning electron microscope (SEM). Figure 1 shows the micrographs of the 3 tailing samples. The micro fabric of TS#1 comprised of granular particle arrangement with clean contacts. The sample's structure consisted of a combination of rounded and sub-angular grains, with larger sizes and few silt-size grains thereby creating inter-granular voids. The micro fabric of TS#2 consisted mainly of well-rounded and elongated granular particle arrangement of smaller sizes with more silt grains. A combination of extremely large angular grains and abundant silt grains formed the micro fabric of TS#3. The micrograph clearly shows the irregular shapes and rough surface indicating a clothed silt grains contacts. Similar to TS#2, which is classified as silty sand, silt grains dominate the fabric of this sample.



TS#1 TS#2 TS#3

Figure 1. Micrographs of the 3 tailing samples

Consolidation Properties

The relationship between vertical effective stress and vertical strain for the tailing samples was obtained to determine the consolidation behavior and to measure the eventual magnitude of settlement that tailings will experience if they are used as fill or embankment materials. The vertical strain (_v) versus the log of vertical effective stress plot for the saturated tailings is shown in Figure 2. The three (3) tailing samples exhibited very little compression during the early stages of the consolidation test followed by great increase in deformation after the 40 KPa vertical stress as manifested by steep slope of stress-strain plot. The dominant compression mechanism which led to an increase in vertical strain is the slippage of soil particles as they rearrange themselves to a denser packing to accommodate higher stresses. Of the tailing samples, gold mine tailings from Davao showed great compression deformation. Rearrangement of soil skeleton for Davao gold tailings was easily achieved since the size of soil particles as seen in electron micrograph (Figure 1) was smaller as compared to the other tailing samples.

The preconsolidation stress ($_p$') is defined as the greatest vertical effective stress to which the soil has been subjected to in the past. To estimate the preconsolidation stress, the modified strain energy method developed by Zarco (2006) was adopted. The obtained values of $_p$' and consolidation parameters like compression index, Cc and the recompression index, Cr are presented in Table 2. The compression index, Cc, and recompression index, Cr, are index values required for primary consolidation settlement predictions. Comparing the values of Cc with the values derived from the study of other authors, the Cc of gold tailings (TS#2 and TS#3) are within the range of values reported by Aubertin, et.al (1996) (Cc = 0.046 to 0.130) for homogenized tailings, nearly close to the values obtained for gold tailings by Qiu & Sego (2001) (Cc= 0.083 to 0.156) and copper tailings by Germanov (2003) (Cc = 0.073). However, the measured value of Cc of TS#1 is lower than those found in literature for tailings. The compression ratio and recompression ratio, as shown in Table 2, were also computed to classify the compressibility of the tailing samples. Compressibility of tailing is classified based on soils' compressibility (Coduto, 1999). The 3 tailing samples, whether normally consolidated or over-consolidated, are classified as very slightly compressible.

The consolidation characteristics as described by coefficient of consolidation (Cv) was evaluated to predict the time rate of settlement. The graphical procedure adopted to evaluate Cv from oedometer test was the Taylor's square root of time fitting method. The plot of Cv against vertical stresses is presented in Figure 3. It is apparent from test results that values of Cv depend on whether the preconsolidation stress has been exceeded. For load increments less than the preconsolidation stress (< 50KPa), consolidation occurs rapidly and Cv values are relatively high. The typical trend exhibited by the tailing samples is that Cv values are higher in the early stages of overconsolidated range specifically at stress equivalent to 20 KPa and showed a relatively rapid decrease as the preconsolidation stress is approached. Lower values of Cv are observed at vertical stresses that exceed _p'.

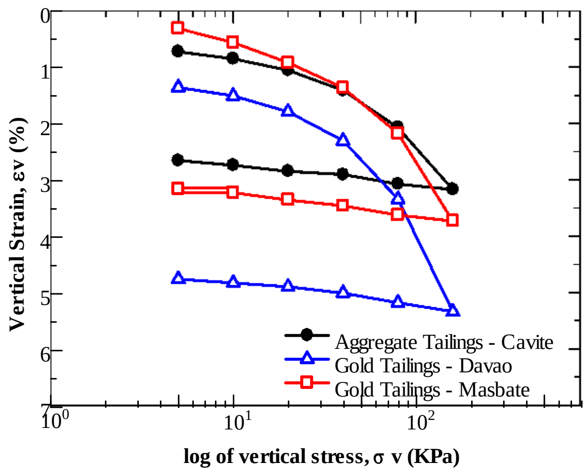


Figure 2. Stress-strain curve of tailings

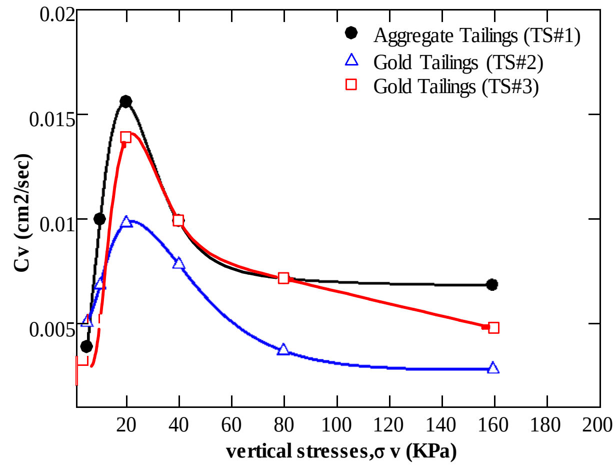


Figure 3. Time rate of settlement of tailings

Table 2. Consolidation parameters and classification of tailings' compressibility

Tailings Sample	_p' (KPa)	Cc	Cr	$\frac{C_c}{1+e_o}$	$\frac{C_r}{1+e_o}$	Classification
TS#1	51.37	0.0391	0.0039	0.0234	0.0023	Very slightly compressible
TS#2	56.00	0.0728	0.0055	0.0421	0.0032	Very slightly compressible
TS#3	55.17	0.0560	0.0044	0.0327	0.0026	Very slightly compressible

Hydrocompression Settlement

Consolidation tests were performed on reconstituted specimens to determine the susceptibility of mine tailings to compression due to wetting or termed as hydrocompression settlement. Studies had shown that even well compacted embankment fills could undergo some amount of compression due to wetting, especially if they were subjected to high pressures when wetted (Leonards and Narain 1963). During inundation, compressive vertical strain was observed in all specimens tested and the maximum vertical strain was noted when inundation was started after 40 KPa vertical stress. This vertical stress corresponds to an average embankment height of 2.4 m at maximum dry density in the field. A graphical procedure was used to determine the total hydrocompression strain where a best-fit line was determined from the strain versus time plot, and then the intersection of tangent lines to the curve where flatter slope was observed and to the curve at early stages of test is determined. The distance from the start of test to the point intersection of tangent lines is measured as the total compression due to wetting (hydrocompression strain). The procedure is appropriate for use even with samples that do not exhibit secondary compression.

Test results are summarized in Figure 4 showing the plot of hydrocompression strain (_h) as a function of vertical effective stress. It can be observed that, of the three tailing samples, gold tailings from Davao (TS#2) was the least responsive to wetting; the graph demonstrates that increasing the vertical stress caused a corresponding increase in hydrocompression strain. This is a typical hydrocompression behavior exhibited by samples with clay particles (Nwaboukei, 1986). The presence of more silt grains and elongated shape of TS#2 have caused the sample to behave like a clayey soil but the magnitude of hydrocompression strain was very minimal (maximum ε_h = 0.088%). However, after the sample became fully saturated and with increased vertical pressures, greater compression settlement was observed. Saturation caused the silt grains to soften while vertical pressures caused the grain particles to arrange in denser configuration. The graphs of TS#1 and TS#3 showed a different trend. There is a sudden increase in hydrocompression strain at 40 KPa vertical stress and, later on, gradually decreases as the vertical stress is increased. However, at higher stresses, the grain particles have already achieved its denser and more stable configuration, hence resulted to smaller compression. TS#3 was the most responsive to wetting (maximum ε_h = 0.98%) and this can be due to the presence of more silt grains with loose packing as can be seen from the micrograph. In summary, tailings exhibited very minimal values of hydrocompression strain as compared to the results found in literature. Kalinski (2010) reported volumetric strains associated with hydrocompression in the range of 5 to 11% for dry, uncompacted mine spoils and 1 to 4.5% for wet and compacted mine spoils. The minimal hydrocompression strain observed for tailings in this study can be attributed to its very dense condition and non-plastic fines in spite of having fine grains.

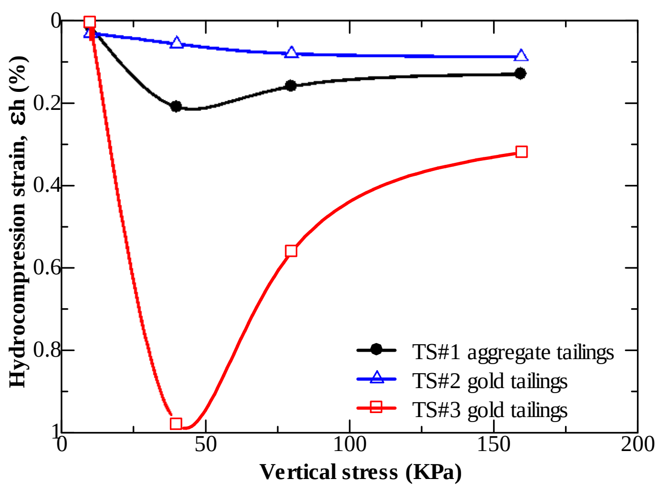


Figure 4 Plot of hydrocompression strain for each vertical stress

The plot of hydrocompression strain against vertical stress (Figure 4) is a useful tool to predict settlement due to wetting for various depths of embankment. Using the least square fit method, the relation of hydrocompression strain (ε_h) with vertical stress (σ') was formulated.

For TS#1, $\varepsilon_h = 8\times10^{-7}(\sigma') - 0.0002(\sigma') + 0.0156\sigma' - 0.1211$ (1)

For TS#2, $\varepsilon_h = -2\times10^{-9}(\sigma')^3 - 4\times10^{-6}(\sigma')^2 + 0.001\sigma' + 0.0199$ (2)

For TS#3, $\varepsilon_h = 5\times10^{-6}(\sigma')^3 - 0.0012(\sigma')^2 + 0.083\sigma' - 0.7101$ (3)

The above equations (1), (2), and (3) can be used to predict hydrocompression settlement for values of vertical stresses less than 160 KPa with initial relative density of 90%.

4. CONCLUSIONS

Series of laboratory tests were conducted to determine the physical properties and consolidation behavior of tailings found in the Philippines. Based on the experimental results, the following conclusions were drawn:

The three tailing samples are fine-grained consisting of fine sands and silts. Tailings from aggregate quarry (TS#1) is classified as poorly graded sand with silt having USCS symbol of SP-SM, gold tailings from Davao (TS#2) and Masbate (TS#3) are both classified as silty sand with USCS symbol of SM. The three tailing samples contain non-plastic fines. Tailings' microfabric features were evaluated through scanning electron microscope (SEM). TS#1 has granular particles with clean contacts comprising of rounded and sub-angular grains of larger sizes. The micro fabric of TS#2 consists mainly of well-rounded and elongated granular particle arrangement of smaller sizes with more silt grains. A combination of extremely large angular grains and abundant silt grains form the micro fabric of TS#3.

Stress-strain behavior of tailings from one-dimensional consolidation was evaluated. Gold mine tailings from Davao were shown to be 40% more compressible than aggregate tailings and gold tailings from Masbate. The measured values of consolidation parameters are within the typical ranges published for similar type of tailings. Based from the values of consolidation parameters, tailings are classified as slightly compressible.

The hydrocompression settlement of tailings was investigated and a new procedure for determining the hydrocompression strain was proposed. The procedure is appropriate for use even with samples that do not exhibit secondary compression. Tailings exhibited very minimal values of hydrocompression strain (_h) as compared to the results found in literature. Tests results revealed that tailings are only slightly susceptible to hydrocompression. The plot of hydrocompression strain (_h) as a function of vertical effective stress serves as a useful tool to predict settlement due to wetting for various depths of embankment. Based on the experimental data obtained, polynomial relationships were developed to estimate the hydrocompression settlement as a function of vertical stress.

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