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ESTIMATING HYDROCOMPRESSION SETTLEMENT OF MINE TAILINGS

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ABSTRACT

The disposal of the enormous amounts of tailings regularly produced from mining operations is the most common environmental issue associated with mining activities. 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 hazardous chemical substances as backfill or as embankment materials in the construction of tailing dams. To evaluate its applicability as construction materials, geotechnical characteristics of tailings need to be established. This study was conducted to determine the geotechnical characteristics of mine tailings from concrete aggregate quarry in Cavite and gold mine sites in Davao and Masbate. Standard ASTM procedures are performed to obtain the physical characteristics such as grain size distribution, Atterberg Limits, specific gravity, minimum and maximum index densities and compaction behavior. Results indicate that the tailing samples are non-plastic and considered as fine-grained consisting of fine sands and silts. Compaction tests show that the moisture versus unit weight relationship is characterized by a concave downward curve with the optimum water content ranging between 13% to 17%, with a maximum dry density ranging from 15.6 kN/m^3 to 17.7 kN/m^3. Microfabric analyses performed using electron microscopy show a microstructure that is granular with some flaky particles. Oedometer tests were conducted to obtain the consolidation parameters and stress-strain behavior of tailings under vertical loads. 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, 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. Tests results revealed that tailings are only slightly susceptible to hydrocompression. Based on the experimental data obtained, polynomial relationships were developed to estimate the hydrocompression settlement as a function of vertical stress.

Keywords: *mine tailings, geotechnical characteristics, microfabric structure, consolidation parameters, hydrocompression settlement*

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1. INTRODUCTION

The mining industry contributes substantially to overall economic growth of the Philippines. 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).The disposal of the enormous amounts of tailings regularly produced from mining operations is the most common environmental issue associated with mining activities. 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. Dams, embankments and other types of surface impoundments are by far the most common storage methods used today and remain of primary importance in tailing disposal planning (Vick, 1990). These storage facilities are constructed with the steepest possible slopes to reduce cost, and are often constructed using the coarse fraction of the tailings.

In tailing dams, the mine tailings are generally deposited in slurry form. As the tailings settle and solidify, water rises to the surface from where it can be decanted. 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. The chronology of tailings dam failures in the Philippines from 1982 to 2007 compiled by Philippine Indigenous People Links showed a total of 21 dam failures (Phil. Indigenous Peoples Links, 2010). One of the reported failures was the collapsed of tailing dams and spillways in San Marcelino, Zambales on Sept. 11, 2002 due to heavy rains which resulted in the flooding of low-lying villages with mine waste and other chemicals. Another incident of dam failure happened on Dec. 6, 1993 at Marinduque Island during which the Maguila-Guila siltation dam collapsed due to pressure from heavy siltation on the dam wall. This resulted in the flooding of the Mogpog River and town that killed 2 children and numerous livestock and contaminated agricultural lands.

It is 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 hazardous chemical substances as backfill or as embankment materials in the construction of tailing dams. To evaluate its applicability as construction materials, geotechnical characteristics of tailings have to be established. However, proper tests should be undertaken prior to its application as mandated by Republic Act 6969 known as "*Toxic Substances and Hazardous and Nuclear Wastes Control Act of 1990*" to determine if these waste materials are free from chemical substances that can pose risk or injury to health and the environment.

The cost of impoundment can also be reduced with the re-use of these waste materials. Studies about mine tailings and its possible reuse have been undertaken in other countries. In the Philippines, most studies on mine tailings have focused on its effect to the environment; no study about its geotechnical characteristics has been conducted. For this reason, literature on the geotechnical behavior and parameters of mine tailings in the Philippines is not available.

Considering the large volume of tailings generated and currently in storage facilities together with the increasing pressure on the mining industry to sustain stringent safety and environmental standards, this research study aims to contribute knowledge, data and insights on the geotechnical characteristics of mine tailings in order to determine its possible re-use as fill or embankment materials.

The objective of this study is to determine the geotechnical characteristics of mine tailings from selected mining sites in the Philippines through series of laboratory experiments, such as: physical properties including grain-size distribution, Atterberg limits, specific gravity, maximum and minimum index densities and soil classification; compaction behavior which is describe in terms of optimum moisture content and maximum dry unit weight; microfabric structure through scanning electron microscopy; and consolidation properties. This study also aims to evaluate the hydrocompression settlement behavior of tailings.

Geotechnical characterization is an essential step towards determining the suitability of mine tailings as fill or embankment materials. The use of mine tailings as fill or embankment materials would alleviate disposal problems and reduce impoundment cost. The geotechnical parameters obtained from this study provide baseline geotechnical data on mine tailings in the Philippines that are needed to design the storage facility.

2. THE TAILING SAMPLES

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 waste from concrete aggregate quarry in Sapang I, Ternate, Cavite. Wastes materials are residues of crushed mountain rocks and are formed from washing these crushed rocks in the siltation pond through the natural process of sedimentation. Moist tailing samples from this source have grayish black color with soft consistency resembling that of fine sand when dry. The second sample designated asTS#2 is tailing from a gold processing plant located at Barangay Magdum, Tagum City, Davao del Norte. Gold content is separated from mined ore by carbon-in-leached process. Wastes coming out of the plant flow to an impounding pond where tailings are stored. The tailings coming from this source are almost dry when transported to the laboratory and is grayish brown. The third sample (TS#3) is tailing from gold mine site in Aroroy, Masbate which undergoes the same chemical process as TS#2. Tailings from the processing plant are discharged into a large tailings dam. Water decanted from the tailings dam is returned to the processing plant for possible re-use. Only solid wastes are left in the tailing dam. Through visual inspection, the grain texture of moist and dry sample show similarities with TS#1 but like TS#2 are grayish brown in color when dry.

3. EXPERIMENTAL PROGRAM

Series of laboratory tests based on ASTM standard procedures were carried out to determine the geotechnical characteristics 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, 50mm in diameter and 17 mm in height, 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. It was then placed in the oedometer apparatus and subjected to load increments. Load increments that applied stresses of 5, 10, 20, 40, 80, and 160 kPa were used. This low range in stresses is appropriate because it is operative in the majority of tailings management facilities (Qui & Sego, 2001). After the 160-kPa load, reloading was conducted in order to plot the rebound curve reversing the increments. Change in thickness of the sample was obtained after every 0.1, 0.25, 0.5, 1, 2, 4, 8, 15, and 30 min, 1, 2, 4, 8, and 24 hours from the time of each incremental pressure application with the use of electronic data acquisition system. The apparatus measures the vertical settlement of the sample using vertical transducers with data logger attached to the computer to process and record the data for the entire duration of test run. Tests runs were performed with sample in submerged condition to determine the consolidation parameters. The assembly was immersed in water to keep the sample saturated throughout the test. At the end of the test, the water content of the sample was determined and the final void ratio was calculated.

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 (εh) was measured from the plot of vertical strain versus time.

4. TEST RESULTS

4.1 Physical Properties

Grain-size Distribution

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. Figure1 illustrates the grain size distribution of tailing samples.

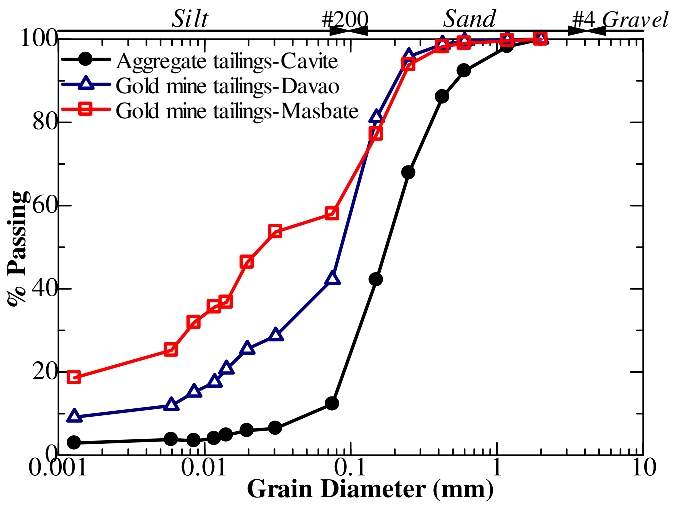

Figure 1 Grain-size distribution curve of mine tailings

Tailings from concrete aggregate quarry (TS#1) primarily consisted of fine sands with very few silts. TS#1 comprised on the average of 8% coarse sand, 17% medium sand, 63% fine sands and 12% silts, with grading curve described as uniformly graded. Gold mine tailings from Masbate and Davao both exhibited an almost equal distribution of fine sands and silts. Gold mine tailing from Davao (TS#2) has an average of 8% medium sands, 50% fine sands and 42% silts with grading characteristics of silty sand. Gold mine tailing from Masbate (TS#3) has an average of 2% medium sands, 40% fine sands and 58% silts. TS#3 has grading characteristics classified as silty sand similar to TS#2. The grading curve is somewhat gap graded.

Soil Constants

The soil constants of mine tailings determined from laboratory tests together with results from other studies are presented in Table 1.

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Table 1 Soil Constants of Tailing Samples

Type of Tailings Location/Source	Gs	LL %	PI %	SL %	SR	Min. Void Ratio, e_{min}	Max. Void Ratio, e_{max}	Max. Dry Unit Wt. KN/m^3	Min. Dry Unit Wt. KN/m^3
Concrete Aggregate (TS#1) Cavite/ this study	2.57	27	0	21	1.47	0.624	1.024	15.50	12.44
Gold (TS#2) Davao/this study	2.72	24	0	20	1.57	0.680	1.106	15.87	12.65
Gold (TS#3) Masbate/ this study	2.71	23	0	20	1.66	0.662	1.089	15.98	12.71
Copper Sarcheshmeh, Iran / Shamsai (2007)	2.79	26 to 39	4 to 12	-	-	0.40	1.0	17.42	-
Copper Bulgaria/ Germanov (2003)	2.68 to 2.78	-	-	-	-	0.525	1.12	12.92 to 17.42	-
Waste rock Australia / Sivakugan (2004)	2.8 to 4.4	-	-	-	-	-	-	-	-
Hard rock Quebec, Canada/ Aubertin (1996)	-	17.5	0	-	-	0.50	-	-	-

The results showed that the fine contents of tailing samples are non-plastic. Specific gravity tests carried out according to ASTM D854 showed that gold mine tailings appear to have heavier grains than concrete aggregate tailings. Tailings' specific gravity, *Gs* fall within the range of sand and silty sand (Bowles, 1978). The values of specific gravity were within the range of values of copper tailings from Bulgaria and nearly close to the value of copper tailings from Iran.

Soil Classification

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. According to AASHTO soil classification system, the TS#1 sample is under A-3(0) which indicates as fine sand with group index of zero. The general rating as subgrade material is excellent to good. TS#2 and TS#3 both have USCS classification of silty sand with symbol of SM. Under the AASHTO soil classification system, both samples belong to group A-4(0) described as silty soil with group index of zero. The general rating as subgrade material is fair to good.

The tailing samples in this study exhibited similarities in their physical properties because they come from the same parent material which is crushed mountain rocks. Their grading characteristics fall within the range of fine sands and silts because they are obtained from storage facility where tailings are deposited in slurry form. TS#2 and TS#3 are both from gold mined ore subjected to the same chemical process to extract the useful product, thus they have almost the same physical properties.

4.2 Compaction Behavior

When soil is used as material in embankment construction, either as backfill for a retaining wall or simply as engineered fill, it is generally compacted in place. The geo-mechanical properties of compacted fill are directly influenced by the in-place density. The compaction behavior of the tailing samples was determined using the procedure described in ASTM D 698. For a given compactive effort, there is a corresponding moisture content at which the dry unit weight is greatest and compaction is optimum. The moisture content is known as the optimum moisture content and the associated dry unit weight is called the maximum dry unit weight. The moisture versus unit weight relationship is characterized by a concave downward curve with the optimum water content ranging between 13% to 17%, with a maximum dry density ranging from 15.56 kN/m^3 to 17.72kN/m^3.According to USCS standards, the compaction characteristic of tailings is rated as good.Table 2 summarizes the compaction characteristics according to USCS and AASHTO standards.

Table 2 Compaction Characteristics of Tailing Samples

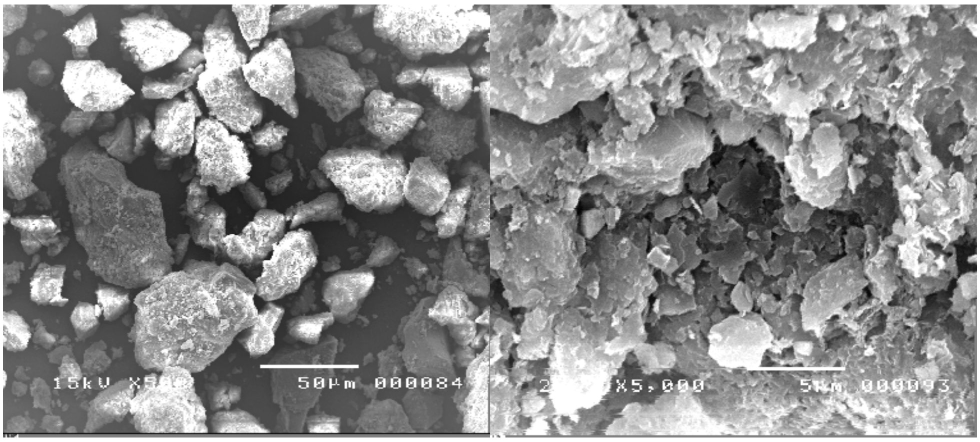
	TS#1 Concrete Aggregate Tailing from Cavite	TS#2 Gold Tailing from Davao	TS#3 Gold Tailing from Masbate
Max. dry unit weight, γ_{dmax} (KN/m^3)	15.56	17.12	17.72
Optimum moisture content, w_{opt} (%)	13.49	17.28	12.82
Compaction Characteristics and Ratings of USCS Classes for Soil Construction (US Army Corp of Engineers, 1953)			
Compaction Characteristics	Good	Good	Good
Compressibility and Expansion	Almost none to slight	Slight	Slight
Value as Embankment Material	Reasonably stable when dense	Reasonably stable when dense	Reasonably stable when dense
Value as Subgrade Material	Good to fair	Good to fair	Good to fair
Value as Base Course	Poor	Poor	Poor
General Guide to Selection of Soils on Basis of Anticipated Embankment Performance as per AASHTO Classification (Krebs, et.al. 1971)			
Anticipated embankment performance	Fair to good	Poor to good	Poor to good

4.3 Microfabric Assessment

Most soil's properties and characteristics like strength, permeability and compressibility are attributed to its micro fabric or sometimes termed as microstructure. The study of tailing's micro fabric was undertaken through the use of scanning electron microscope (SEM). Figure 2 shows the micrographs of the 3 tailing samples. As illustrated, at magnification of 500X, 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. With larger magnification, at 5000X, the grain consisted of flaky particles. The overall alignment of flakes was in some random direction with large inter-assemblage pore spaces depicting a loose packing.

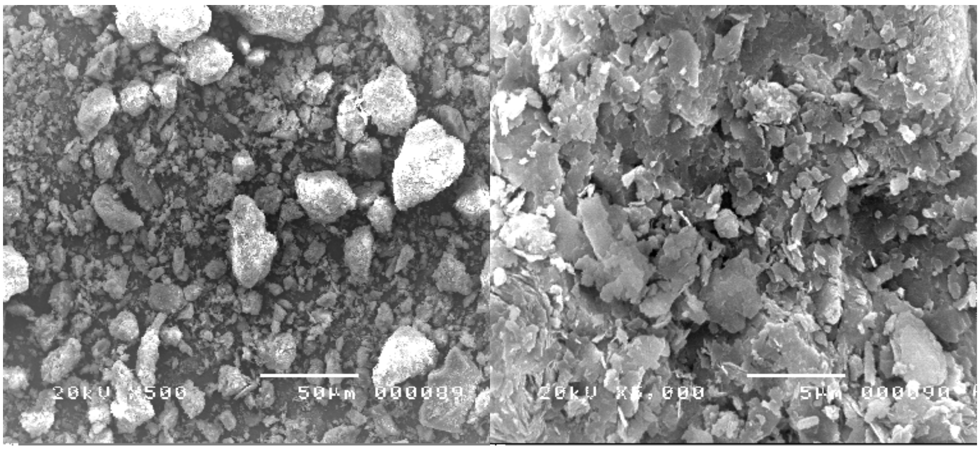
The micro fabric of TS#2, with 500X magnification, consisted mainly of well-rounded and elongated granular particle arrangement of smaller sizes with more silt grains. The micrograph of the sample at higher magnification (5000X) shows dense flakes with very small inter-assemblage pore spaces. The configuration of flakes was more or less closely packed with perturbed parallel face-to-face arrangement creating the impression of dense grain packing.

A combination of extremely large angular grains and abundant silt grains formed the micro fabric of TS#3 at magnification of 500X. 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. However, at higher magnification (5000X), an open type packing of flaky particles was observed. There were many inter-assemblage pore spaces and the overall alignments of flakes were in random direction.



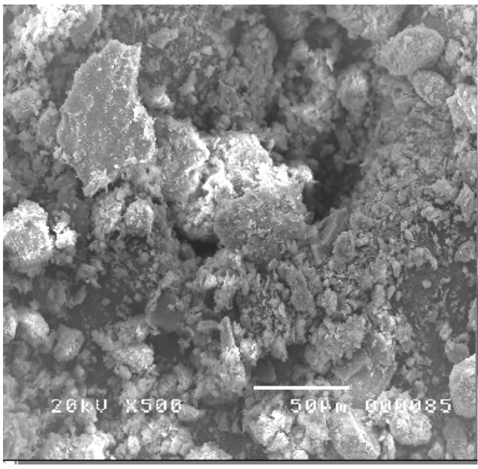
500X magnification 5000X magnification

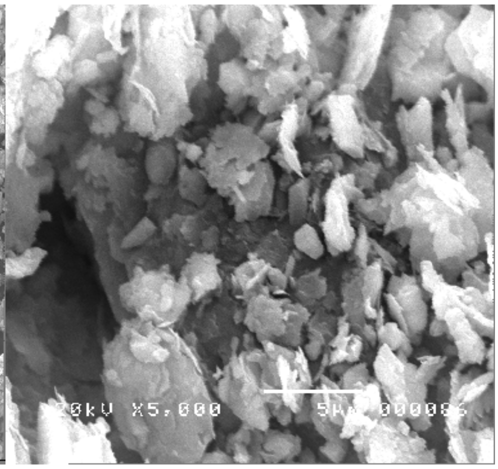
(a) Wastes from concrete aggregate quarry in Cavite (TS#1)



500X magnification 5000X magnification

(b) Gold mine tailings from Davao (TS#2)





500X magnification 5000X magnification

(c) Gold mine tailings from Masbate (TS#3)

Figure 2. Micrographs of the 3 tailing samples

4.4 Consolidation Properties

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 fill or embankment material.

Stress-Strain Behavior and Consolidation Parameters

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 tests were conducted with specimen fully submerged in water for the entire duration of the tests. This is to simulate the condition in the field where tailings is at its most compressible state.

The vertical strain (εv) versus the log of vertical effective stress plot for the saturated tailings is shown in Figure 3. 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 with vertical strain equal to 5.34%, while aggregate tailings has 3.17% vertical strain and gold tailings from Masbate has 3.73% vertical strain. Rearrangement of soil skeleton for Davao gold tailings was easily achieved since the size of soil particles as seen in electron micrograph (Figure 2) was smaller as compared to the other tailing samples.

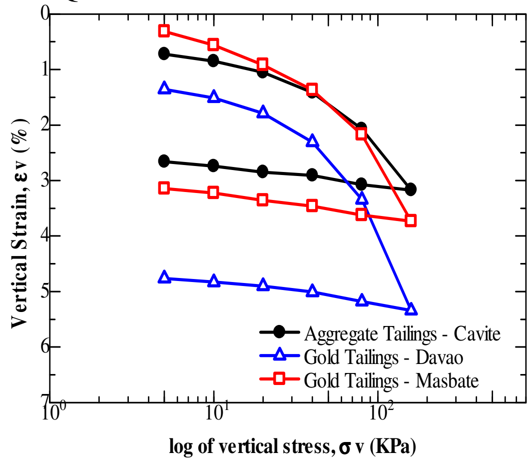


Figure 3. Stress-strain curve of tailings from oedometer test

The point in the stress-strain plot where the slope of the consolidation curve changes corresponds to the preconsolidation stress (σ_p'). The preconsolidation stress (σ_p') is defined as the greatest vertical effective stress to which the soil has been subjected to in the past. The preconsolidation stress of fine-grained materials is related to its stress history and significantly affects settlement calculations and the evaluation of undrained shear strength. Several methods have been developed to estimate the preconsolidationstress. In this study, the modified strain energy method developed by Zarco (2006) was adopted. The method uses the plot of total strain energy against the effective overburden pressure from the oedometer test. The true strain for each data point is calculated using the expression,

$$\varepsilon_v = \frac{e_o - e_i}{1 + e_i} \tag{1}$$

where : e_o = void ratio at the start of test
e_i = void ratio after each load increment

The incremental strain energy for each data point is calculated using the expression,

$$\Delta E = \left(\frac{\sigma_j + \sigma_{j-1}}{2} \right) \times \left(\varepsilon_{vj} - \varepsilon_{vj-1} \right), \text{ j = 1,2,3…n} \tag{2}$$

The total strain energy for each data point is the summation of the incremental strain energy. The parameter λ is the slope of best-fit line through the portion of laboratory curve coinciding with the virgin curve. The parameter κ is the slope of best-fit line through the rebound-recompression portion of the laboratory curve. After the parameters κ and λ are determined from the laboratory curve, and using the total strain energy (E_n) at the highest overburden pressure, P_n, the preconsolidation pressure is obtained using the expression:

$$\sigma'_p = \frac{\lambda P_n - E_n}{\lambda - \kappa} \tag{3}$$

The compression index (C_c) is numerically equal to 2.3 times λ and the recompression index (C_r) is numerically equal to 2.3 times κ. The obtained values of σ_p' and consolidation parameters like compression index, *Cc* and the recompression index, *Cr* are presented in Table 3. The compression index, *Cc*, and recompression index, *Cr*, are index values required for primary consolidation settlement predictions. From the test results, σ_p' of the 3 tailing samples is closed to 50 KPa. The stress at σ_p' delineates the region of semi-elastic behavior corresponding to over-consolidated states from the region of primarily plastic behavior which is associated with normal consolidation. Hence, at stresses up to σ_p', the irrecoverable deformation is considered to be negligible while beyond σ_p', the irrecoverable deformation is expected to be much more significant. This behavior is manifested in the stress-strain plot where steeper slope was observed beyond 50 KPa indicating that the sample underwent large deformation.

Table 3. Consolidation parameters of tailings from oedometer tests

Tailings Sample	σ_p' (KPa)	Cc	Cr
TS#1 Wastes from Aggregate Quarry	51.37	0.0391	0.0039
TS#2 Gold mine tailings – Davao	56.00	0.0728	0.0055
TS#3 Gold mine tailings – Masbate	55.17	0.0560	0.0044

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 aggregate quarry is lower than those found in literature for tailings.

The compression ratio and recompression ratio 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 classification of tailings' compressibility is shown in Table4.

Table 4. Classification of tailings' compressibility

Tailing Sample	$\frac{C_c}{1+e_o}$	$\frac{C_r}{1+e_o}$	Classification
S#1 Wastes from Aggregate Quarry	0.0234	0.0023	Very slightly compressible
TS#2 Gold mine tailings – Davao	0.0421	0.0032	Very slightly compressible
TS#3 Gold mine tailings - Masbate	0.0327	0.0026	Very slightly compressible

The consolidation characteristics as described by coefficient of consolidation (*Cv*) was evaluated to predict the time rate of settlement. Graphical procedures used to evaluate *Cv* from laboratory consolidation data include Casagrande's logarithm of time method and Taylor's square root of time fitting method. Cassagrande's logarithm of time method was not considered in this study because it requires that a substantial part of the consolidation curve be defined after 90 percent consolidation (t_{90}). Tailings samples subjected to compression test did not exhibit a substantial secondary compression; hence it is not possible to facilitate a good approximation of t_{90}. The graphical procedure adopted to evaluate *Cv* from oedometer test was the Taylor's square root of time fitting method because it does not need to be carried out beyond t_{90}. The square root of time method considers the early time response of the sample and uses the $t_{90.}$ The equation to compute for C_v is:

$$C_v = \frac{0..848H^2}{t_{90}} \tag{4}$$

where : H = thickness of specimen at 90% consolidation
Use half the thickness if the specimen is drained on both the top and bottom during the test.
t_{90} = time to reach 90% consolidation

The square root time method of determining *Cv* usually gives a larger value of *Cv* than does the log of time method, and this method is usually preferred since it gives a conservative factor of safety. The plot of *Cv* against vertical stresses is presented in Figure4. 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 over consolidated 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 σp'. Values of *Cv*for each vertical stresses together with reported data from literature are summarized in Table 5. The *Cv* values of tailing samples in this study compared fairly well with *Cv* of tailings from literature.

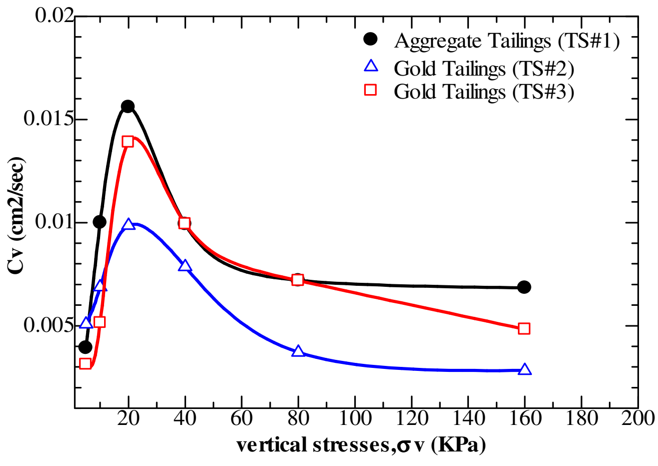


Figure 4. Time rate of consolidation of tailings against vertical stress

Table 5 Values of Coefficient of Consolidation (Cv)

Vertical Effective Stress, σ (KPa)	C_v (cm^2/sec) x 10^{-3} from this study		
	TS#1 Wastes from Aggregate Quarry - Cavite	TS#2 Gold Tailings - Davao	TS#3 Gold Tailings - Masbate
5	3.93	5.07	3.13
10	10.04	6.88	5.15
20	15.62	9.85	13.92
40	9.93	7.86	9.94
80	7.20	3.71	7.19
160	6.84	2.83	4.83
Type of Tailings	Source	C_v(cm^2/sec) x 10^{-3} from literature	
Hard rock mines	Aubertin et.al. (1996)	5.01 to 694	
Gold	Qiu& Sego (2001)	4.31 to 25.3	
Copper	Shamsai et.al. (2007)	5.0 to 20.0	
Copper	Germanov (2003)	9.6	

4.5 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; Nobari and Duncan 1972). 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 results of these tests are presented as strain versus stress diagrams in Figures5 to 7.

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 verticalstress. This vertical stress corresponds to an average embankment height of 2.4 m at maximum dry density in the field. The determined values of hydrocompression strain of the tailings samples were much less than vertical strain induced by the combination of vertical stresses and saturation. This is very noticeable at the curve after inundation where steeper slopes and greater amount of strain are observed.

The determined values of hydrocompression strain are presented in strain versus time plots. A graphical procedure similar to the Casagrande method for determining the end of primary compression in consolidation tests was suggested by Brandon, et.al. (1990) to determine the total hydrocompression strain. However, this procedure was not applied because the specimen did not exhibit a well-defined secondary compression. A new procedure was used where a best-fit line was determined from the strain versus time plot, 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 total compression due to wetting (hydrocompression strain) was then measured as shown in Figure 8.

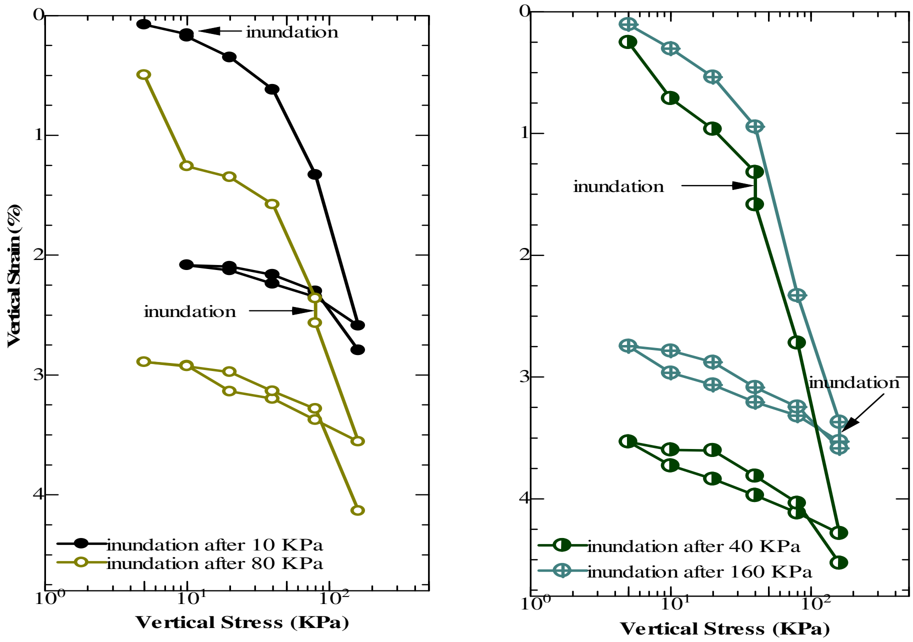
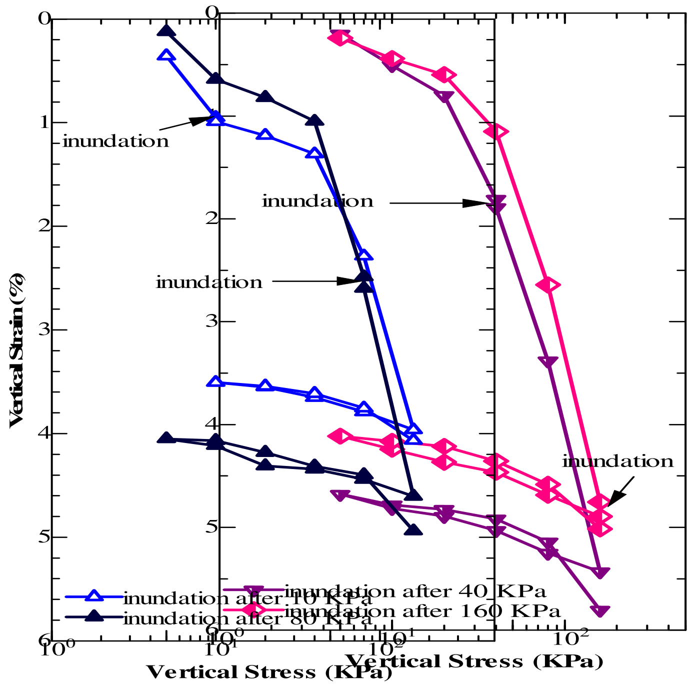


Figure 5 Stressvs strain plot indicating strain due to inundation of wastes from aggregate quarry from Cavite (TS#1)

Figure 6 Stress vs. strain plot indicating strain due to inundation of gold mine tailings from Davao (TS#2)



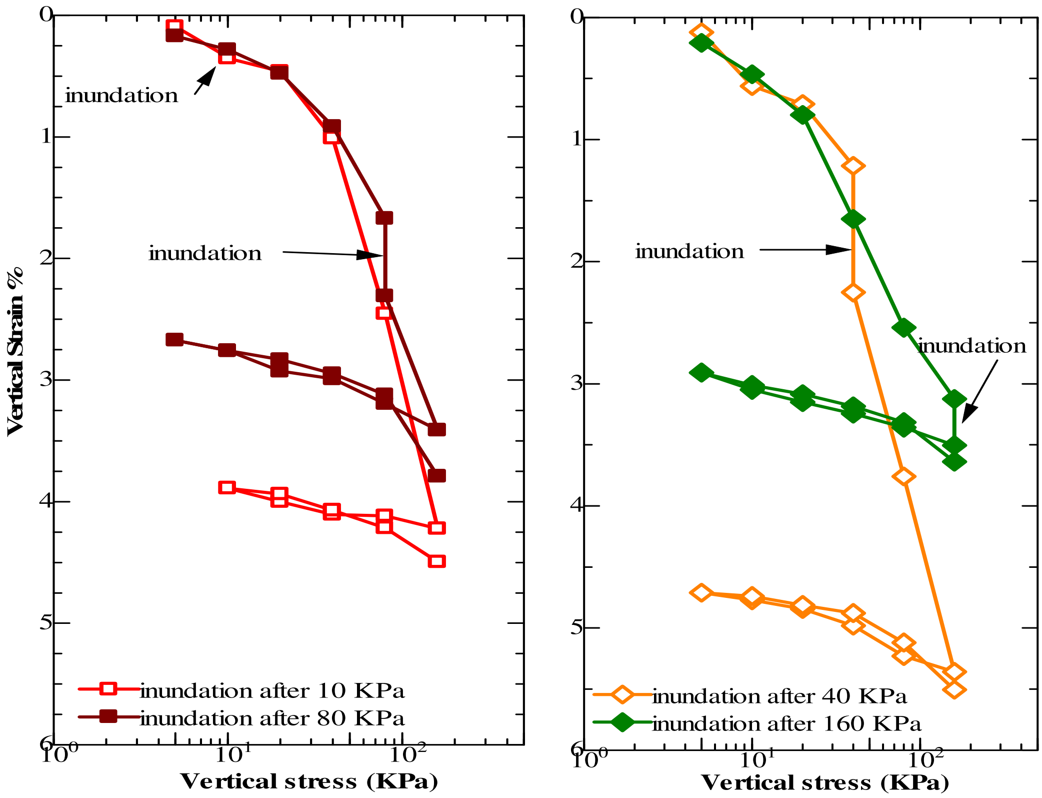


Figure 7 Stress vs. strain plot indicating strain due to inundation of gold mine tailings from Masbate (TS#3)

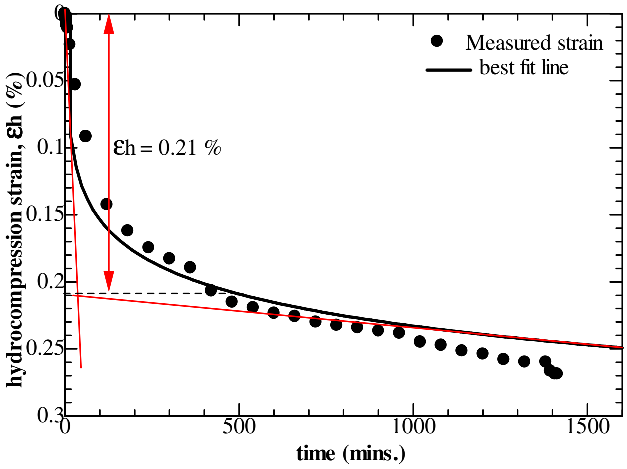


Figure 8 Typical test result in strain vs time plot used to measure hydrocompression strain

Test results are tabulated in Table 6 and are summarized in Figure 9 showing the plot of hydrocompression strain (εh) 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, 1976). 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 εh = 0.088%). This is because the microfabric structure of TS#2 as seen in Figure2 has dense packing with very small inter-assemblage pore spaces; hence, water intrusion caused minimal rearrangement of grain particles and therefore minimal compression settlement. 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. The inter-assemblage pore spaces present in the microfabric structure of TS#1 and TS#3 caused the water to easily penetrate the grains that resulted to greater hydrocompression strain as compared to TS#2. 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 εh = 0.98%) and this can be due to the presence of more silt grains with loose packing as can be seen from the micrograph (Figure 2) and its being gap-graded. 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 in spite of having fine grains.

Table 6 Results of consolidation tests to measure hydrocompression strain

Tailing Sample	Relative Density at start of test, Dr (%)	Water content at start of test, w_o (%) (near OMC)	Vertical stress at inundation, σ (Kpa)	Hydrocompression strain, εh (%)
TS#1 Aggregate tailings – Cavite	84.66	11.98	10	0.014
	84.74	11.59	40	0.210
	87.12	13.15	80	0.160
	89.16	10.40	160	0.130
TS#2 Gold tailings – Davao	85.29	13.24	10	0.030
	89.41	12.29	40	0.056
	89.18	14.45	80	0.080
	89.95	14.23	160	0.088
TS#3 Gold tailings – Masbate	88.76	11.15	10	0.005
	89.29	10.44	40	0.980
	89.52	10.38	80	0.560
	89.89	11.03	160	0.320

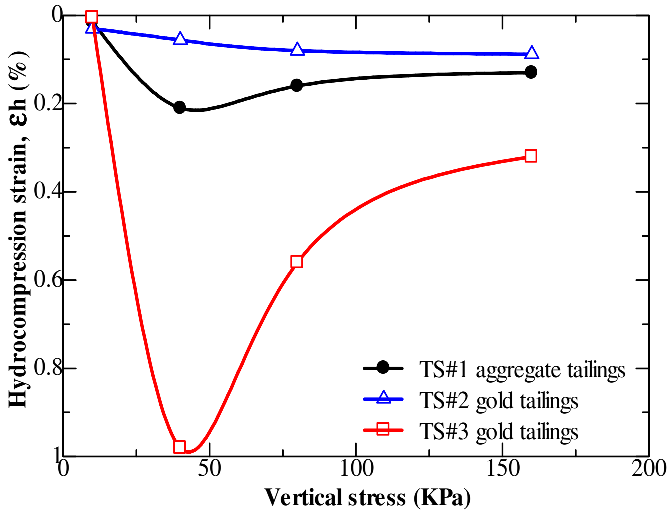


Figure 9 Plot of hydrocompression strain for each vertical stress

The plot of hydrocompression strain against vertical stress (Figure 9) 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 (εh) with vertical stress (σ') was formulated.

For TS#1, $$\varepsilon_h = 8\times10^{-7}(\sigma')^3 - 0.0002(\sigma')^2 + 0.0156\sigma' - 0.1211 \quad (5)$$

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

For TS#3, $$\varepsilon_h = 5\times10^{-6}(\sigma')^3 - 0.0012(\sigma')^2 + 0.083\sigma' - 0.7101 \quad (7)$$

The above Equations (5), (6), and (7) can be used to predict hydrocompression settlement for values of vertical stresses less than 160 KPa with initial relative density of 90%.

5. CONCLUSIONS

Series of laboratory tests were conducted to determine the geotechnical characteristics of tailings found in the Philippines namely, tailings from aggregate quarry in Cavite and tailings from gold mine sites in Davao and Masbate. Based on the obtained experimental results, the following conclusions were drawn:

Mine tailings, though coming from different sources, exhibited similarities in their physical properties. The three tailing samples are considered as fine-grained consisting of fine sands and silts. Wastes from aggregate quarry (TS#1) are 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 are non-plastic with a compressibility rating of almost none to slight. Their compaction characteristics are rated as good. If used as embankment materials, the three tailing samples have a rating of reasonably stable when dense.

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. The three tailing samples have flaky microfabric particles.

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 (εh) as compared to the results found in literature. Tests results revealed that tailings are only slightly susceptible to hydrocompression. The plot of hydrocompression strain (εh) 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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