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THE EFFECT OF VOID RATIO, MOISTURE CONTENT AND VERTICAL PRESSURE ON THE HYDROCOMPRESSION SETTLEMENT OF COPPER MINE TAILING

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ABSTRACT: Copper mine tailing (CMT) has the potential to be used as embankment material but this waste material contains plasticity. Soils containing plasticity are highly reactive to any form of liquid and considered to have greater compressibility when exposed to water. As an embankment material, CMT is susceptible to different environmental condition which can cause significant settlement. One possible cause of volume loss is the compression due to wetting or hydrocompression. This study aims to determine the consolidation properties and hydrocompression settlement of waste materials with plasticity like copper mine tailing when used as embankment material. One-dimensional consolidation tests were performed on reconstituted specimens. The obtained consolidation properties indicate that CMT is very slightly compressible under over-consolidated condition to moderately compressible under normally consolidated condition. The hydrocompression settlement of CMT in relation to initial void ratio, moisture content and vertical pressure was investigated. The hydrocompression settlement increases with increasing pressure until the preconsolidation pressure is reached, then decreases with pressure beyond the preconsolidation pressure. Samples with lower density and initial water content less than its optimum exhibit greater hydrocompression settlement. The determined hydrocompression strain in every condition is less than 5% which means that CMT has a degree of collapsibility classified as low to negligible despite of having plasticity. CMT when used as embankment materials should be prepared with initial moisture content slightly more than its optimum, it should be in its very dense condition and preloaded with vertical stress more than its preconsolidation pressure to make hydrocompression strain negligible.

Keywords: Copper Mine Tailings, Embankment, Hydrocompression, Consolidation

1. INTRODUCTION

The disposal of the enormous amount of wastes regularly produced from mining processes is one of the most common environmental issues associated in the operation. One possible option to address disposal problem is to utilize these waste materials that do not contain deleterious components as embankment materials. To evaluate the suitability of solid wastes as embankment materials, its geotechnical characteristics have to be established. The determination of the consolidation properties that describe the compressibility and the one-dimensional settlement of mining wastes when subjected to vertical stresses had been covered in the study of some researchers [1]–[3]. However, compressibility and settlement of embankment materials are not only caused by vertical stresses imposed to the earth structure. During service life of embankment or fill materials, environmental changes can lead to an increase in its moisture content which can affect the compressibility and settlement behavior. Waste materials, when use as embankment materials, are susceptible to this kind of condition where significant settlement can rapidly occur. One possible cause of volume loss is the compression due to wetting or termed as "hydrocompression" or "hydrocollapse". Some soils can swell, collapse, shrink or experienced extreme settlement if exposed to water or any fluid. Investigation about the hydrocompression of gold mine tailings and wastes from aggregate quarry in the Philippines with non-plastic fines was discussed in previous study [1]. Findings of the study showed that these wastes materials which are non-plastic are less susceptible to hydrocompression.

Copper mine tailing has the potential to be used as embankment material [4] but this waste material contains plasticity, a property prevalent in clay minerals. Soils containing clay minerals are highly reactive to any form of liquid and considered to have greater compressibility when exposed to water. Several studies proved that compressibility and collapsibility of embankment materials are dependent on several factors like amount of moisture, clay mineralogy, density and applied pressure. Increasing the moisture content affects the compaction behavior and compressibility of municipal solid wastes used as embankment. Its compaction period shortens while compressibility increases when water was added [5]. Clay mineralogy affects the coefficient of consolidation (Cv). The increase or decrease of Cv which describes the compressibility in clays is governed by the mechanical and physicochemical factors [6]. The study of Langroudi and Jefferson [7] investigates the contribution of hydraulic and stress history in collapsibility of excavated calcareous clayey loess re-used as embankment materials. The findings showed that controlled stress-hydraulic paths can guarantee the long-term response of embankments made of excavated calcareous clayey loess.

This research study aims to determine the consolidation properties and hydrocompression settlement of waste materials with plasticity like copper mine tailings through one-dimensional consolidation test. This study verifies if the plasticity of the material is one factor that will lead to greater hydrocompression settlement. It is also the objective of this study to investigate the effect of initial moisture content, initial void ratio in terms of relative density and pre-loaded vertical pressures to the hydrocompression settlement of copper mine tailings. The determination of consolidation properties and hydrocompression settlement are essential steps to completely evaluate the suitability of copper mine tailings for geotechnical application.

2. EXPERIMENTAL PROGRAM

Preliminary investigation was done to determine the physical properties and compaction behavior of copper mine tailing (CMT). The main experimental program consisted of determination of consolidation properties and hydrocompression settlement of CMT. Reconstituted specimen, 50 mm in diameter and 17 mm in height was prepared by moist tamping method to achieve the desired density. An amount of the dry CMT sample that provided the desired density for the specimen was mixed with the small amount of water to produce water content closed to optimum water content. The sample was then stored overnight before being tamped into the consolidometer mold to obtain the desired density.

2.1 The Copper Mine Tailing

The waste material used in this study is copper mine tailing (CMT) obtained from Barrio Maglinao, Municipality of Basay, Negros Oriental, Central Visayas in the Philippines. Mine tailing is produced after separating the important ore, which is copper, in open pit mining where blasting and crushing are performed. The copper tailings obtained from tailing dam were somewhat dry. Through visual inspection, dry CMT is grayish brown in color and resemble that of fine sand. When moist, CMT has soft consistency.

2.2 Determination of Consolidation Properties

The consolidation properties of the tailing samples were determined through one-dimensional consolidation test using the procedure described in ASTM D2435. Reconstituted specimen was prepared with a target relative density slightly closed to 90% to simulate the very dense condition of the embankment. Load increments that applied stresses of 12.5, 25, 50, 100 and 200 kPa were used. The tests were conducted with specimen fully submerged in water for the entire duration of the tests. This is to simulate the condition where embankment materials are expected to be at its most compressible state. Consolidation properties such as compression index (C_c), recompression index (C_r) and preconsolidation pressure (σ'_p) were determined using the Modified Strain Energy method [8]. The coefficient of consolidation (C_v) was determined using Taylor's square root of time method [9].

2.3 Determination of Hydrocompression Settlement

Variations in initial relative density, initial moisture content, and predetermined vertical stress were incorporated in the experimentation to verify the effect of these factors on the hydrocompression settlement of CMT. Reconstituted specimens were prepared at initial relative density of 60%, 80% and 100% to simulate the medium dense, dense, and very dense conditions of embankment, respectively. Three variations in water content at start of test were used; the dry phase where water content is slightly less than the optimum moisture content (w_{opt}), the optimum phase where water content is equal to w_{opt} , and the wet phase where water content is slightly more than the w_{opt}. Four (4) preloaded vertical stresses (25, 50, 100 and 200 kPa) were used. The preloaded stress simulates the overburden pressure imposed to embankment. A total of thirty six (36) test runs was performed. To evaluate the hydrocompression settlement, the introduction of water to the specimen was delayed until the preloaded stress was reached. At the desired preloaded stress, the specimen was flooded by filling the consolidometer reservoir with distilled water. Hydrocompression strain was observed and recorded for 24 hours, after which, specimen was unloaded and reloaded to complete the consolidation process. Observation was being prolonged when the deformation was still significant. The values of vertical strain of each test samples were plotted in a strain vs. elapsed time graph. The amount of hydrocompression strain is graphically measured from the intersection of tangent lines to the curve where flatter slope is observed and to the curve at early stages of plot [1].

3. RESULTS AND DISCUSSION

3.1 Physical Properties

The values of soil constants of CMT determined from the tests are presented in Table 1. The value of specific gravity showed that CMT has heavier grains as compared to conventional soil. This is because the sample is waste material and found to contain some traces of chemical elements like copper and titanium which are not usually found in conventional soil. Copper mine tailing from this study is considered to have low plasticity based on qualitative manner of plasticity index [10].

Table 1 Soil constants of CMT [4]

	Soil Constants
Specific Gravity, Gs	2.82
Liquid Limit, LL (%)	32
Plasticity Index, PI (%)	6
Minimum dry density, ρ_{dmin} (kg/m^3)	1,155.42
Maximum dry density, ρ_{dmax} (kg/m^3)	1,436.15
Maximum void ratio, e_{max}	1.441
Minimum void ratio, e_{min}	0.964
D_{10} (mm)	0.003
D_{50} (mm)	0.15
Maximum dry unit weight (kN/m^3)	15.70
Optimum moisture content, w_{opt} (%)	19.47

3.2 Compaction Behavior

The adequacy of embankment for an earth dam may depend on its compaction behavior. For a given compactive effort, there is a particular moisture content at which dry unit weight is greatest and compaction is best. The moisture content is known as the optimum moisture content (w_{opt}) and the associated dry unit weight is called the maximum dry unit weight. From Proctor test, the maximum dry unit weight of copper tailing is 15.70kN/m^3 corresponding to an optimum moisture content of 19.47%. Based on USCS criteria, the compaction characteristics of copper mine tailing is rated as good and its value as embankment material is reasonably stable when dense. AASHTO classification rated its anticipated embankment performance as poor to good.

3.3 Chemical Composition and Micro-fabric Structure

Energy Dispersive X-ray Spectroscopy (EDS) analysis was performed in order to know the chemical elements and its proportion present in the sample. Soils from different sources exhibit unique characteristics, hence it is useful to know its chemical composition as this will aid in understanding its behavior when it is expose to water and other environmental factors. Shown in Table 2 is the chemical composition of copper mine tailings in comparison with conventional soil. The chemical elements found in CMT are comparable to that of other geologic resources. CMT is comprised mostly of oxygen, aluminum, silicon, and iron with some magnesium, potassium, calcium, titanium, and copper. As presented, the abundance of oxygen, silicon, aluminum, and iron content is an indication of the pozzolanic or cementitious nature of the tailings [11].

Table 2 Chemical composition of copper mine tailing and conventional soil

Element	Copper Mine Tailing (%)	SOIL [12] (%)
Oxygen	49.72	46.6
Silicon	21.50	27.7
Aluminum	13.10	8.1
Magnesium	1.49	2.1
Iron	8.09	5.0
Potassium	1.68	2.6
Calcium	0.57	3.6
Copper	0.92	-
Titanium	0.90	-
Sodium	-	2.8

The micro fabric study of CMT was undertaken through the use of scanning electron microscopy (SEM) test. As illustrated, at magnification of 500X (Fig. 1a), the micro fabric of CMT comprised of an assemblages of clustered clay-size, platy particles. The sample's structure is somehow following the geometrical arrangement of edge-to-edge and face-to-face association. The micrograph of the sample at higher magnification (7500X) (Fig. 1b) shows dense flakes with 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.

3.4 Consolidation Properties

The relationship between vertical effective stress and vertical strain as expressed by the change in void ratio for the copper mine tailing samples was obtained to determine the consolidation behavior and to measure the eventual magnitude of settlement that sample will experience when they are subjected to one-dimensional compression.

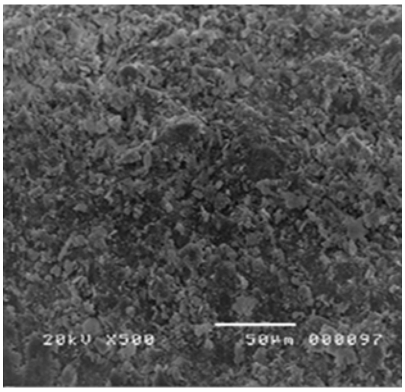


Fig. 1a Micrograph of CMT at 500X magnification

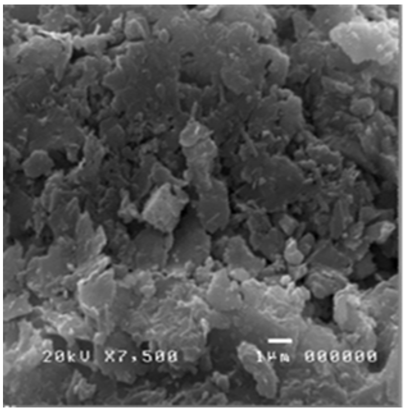


Fig.1b Micrograph of CMT at 7500X magnification

Soil exhibiting excessive settlement is not suitable as fill or embankment material because this can be detrimental to the integrity of the supported structure. Consolidation parameters which indicate the compressibility and the amount of settlement that copper mine tailing will experience are presented in Table 3. The preconsolidation stress (σ_p') of fine-grained materials is related to its stress history and significantly affects settlement calculations. The compression index, Cc, and recompression index, Cr, are index values required for primary consolidation settlement predictions. The compression index, Cc is used to classify the compressibility of soils which are normally consolidated. Likewise, the recompression index, Cr, is used to classify the compressibility of soils which are over-consolidated.

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, if overburden stresses are below σ_p', the soil is considered as over-consolidated and the irrecoverable deformation is considered to be negligible. If the overburden pressure is quite near of σ_p', it is classified as normally consolidated and the strain-deformation in this region is somehow tolerable while far beyond σ_p', the irrecoverable deformation is expected to be more significant. The compression ratio and recompression ratio were also computed to classify the compressibility of CMT. Copper mine tailing is classified as moderately compressible when it is normally consolidated and very slightly compressible when over-consolidated.

Table 3 Consolidation parameters of CMT

Compression Index, C_c	0.3416
Recompression Index, C_r	0.0263
Preconsolidation Pressure, σ_p' (kPa)	58.3

To predict the time rate of settlement, the consolidation characteristics as described by coefficient of consolidation (Cv) was evaluated. It is apparent from test results that values of Cv depend on whether the preconsolidation pressure (σ_p') has been exceeded or not. Values of Cv for each vertical stresses are summarized in Table 4. The typical trend exhibited by the sample is that Cv values are higher in the early stages of overconsolidated range specifically at stress near the preconsolidation pressure (σ_p') and showed a relatively rapid decrease for stresses beyond σ_p'. Lower values of Cv are observed at vertical stresses that exceed σ_p'.

Table 4 Values of Coefficient of consolidation, Cv

Vertical Effective Stress, σ (KPa)	C_v (cm^2/sec) x 10^{-3}
	Copper Mine Tailings (CMT)
5	3.9465
12.5	7.8671
25	12.4034
50	15.7816
100	11.2129
150	6.7777
200	5.7404

3.5 Hydrocompression Settlement

Copper mine tailings like soil have unique geotechnical characteristics including its behavior when saturated. Consolidation tests were performed on reconstituted specimens to determine the collapsibility of copper mine tailings due to intrusion of water or termed as hydrocompression settlement. This study presents the influence of relative density in terms of void ratio, moisture content and predetermined vertical stress on the hydrocompression settlement behavior of CMT. The influence of initial moisture content, w_i (dry phase: $w_i < w_{\text{opt}}$; optimum phase: $w_i \approx w_{\text{opt}}$; and wet phase: $w_i > w_{\text{opt}}$), and the degree of denseness in terms of relative density, Dr (medium dense, Dr ≈ 60%; dense, Dr ≈ 80%; and very dense, Dr ≈ 100%) together with the applied vertical stress (Low = 25 kPa, 50 kPa; and High = 100 kPa, 200 kPa) to vertical strain upon saturation were investigated by using varying amount of these factors in the experimentation. The collapsibility behavior of CMT was evaluated according to the amount of hydrocompression strain attained during inundation.

3.5.1 Effect of Applied Vertical Stress Prior to Inundation

The typical soil response when subjected to stresses lower than the preconsolidation pressure is to exhibit minimal deformation. Preloading the sample with lower stresses before inundation resulted to minimal deformation. However, after the preloading stage and when the sample was inundated with water, it resulted to greater vertical compressive strain. Rearrangement of particles was easily achieved with pressures lower than σ_p'. When the sample experienced sudden flow of water, the dry particles became very responsive due to its plasticity. The inter-assemblage pore spaces allow water to pass through easily that softens the bonds between particles, thus resulted to vertical compressive strain. The water serves as lubricant for the particles to easily rearrange into a denser configuration as manifested by greater hydrocompression strain. When the sample was preloaded with vertical stresses beyond the preconsolidation pressure, the hydrocompression strain decreased even for samples with relative density (Dr) near 60%. The sample has already achieved its denser and stable condition before the intrusion of water. When the sample was inundated with water, the collapsibility potential was reduced and the hydrocompression strain became negligible.

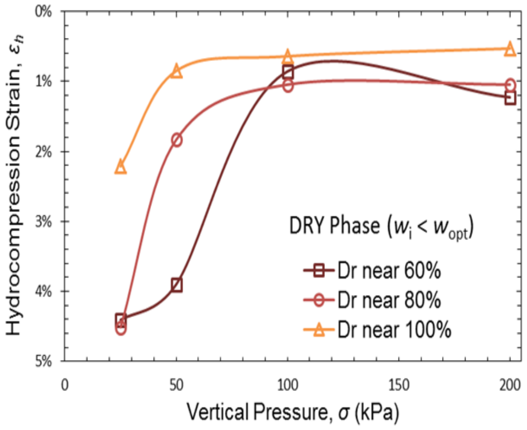
3.5.2 Effect of Initial Relative Density

The arrangement of the soil skeleton influenced the deformation of CMT due to sudden intrusion of water. During inundation, specimens with greater void ratio (Dr near 60%, medium dense condition) caused the water to easily penetrate the void spaces and increased the collapse potential. At lower relative density, the hydrocompression strain is more significant. As the void ratio decreases (Dr near 100%, very dense condition), the rate of flow of water into the sample also decreased, thus causing minimal disturbance on the particles and the hydrocompression strain became almost negligible.

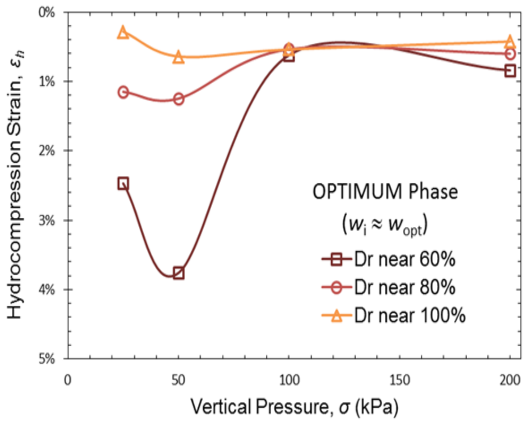
3.5.3 Effect of Initial Moisture Content

When specimen was prepared with initial moisture content slightly more than its optimum value, the collapse potential of the specimen was reduced to negligible value even when the predetermined vertical stresses were below the preconsolidation pressure and at medium dense condition. The hydrocompression strains at wet phase were less than the hydrocompression strains at optimum and dry phase. The presence of water in the void spaces in its initial condition reduces the sudden intrusion of water during inundation. Moreover, the pore water pressure aided in supporting the applied vertical load, thus the stress carried by the soil skeleton was reduced.

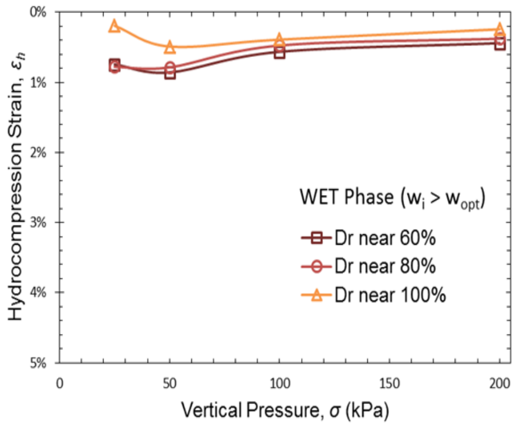
From test results, the amount of hydrocompression strain experienced by CMT is affected by the applied vertical stress prior to inundation, initial relative density and initial moisture content. Figure 2 shows the influence of these factors to hydrocompression strain. To reduce the magnitude of hydrocompression strain to a negligible value, CMT when used as embankment materials should be prepared with initial moisture content slightly more than its optimum value. If the initial moisture content is less than or equal to its optimum value, CMT should be in its very dense condition and it should be preloaded with vertical stress more than its preconsolidation pressure to make hydrocompression strain negligible. The degree of collapsibility of CMT at different conditions is summarized in Table 5 to 7. The determined hydrocompression strains in every condition is less than 5% which means that CMT has a degree of collapsibility classified as low to negligible despite of having plasticity. The amount of hydrocompression strain obtained is higher than the values obtained for non-plastic mine tailings [1] and within the range of values for mine spoils with low plasticity [13].



(a) Dry Phase



(b) Optimum Phase



(c) Wet Phase

Fig. 2 Effect of preloaded vertical pressure and relative density to hydrocompression strain when moisture content is in a.) Dry Phase b.) Optimum Phase and c) Wet Phase

Table 5 Degree of collapsibility of CMT at varying σ and *Dr* when initial moisture content is at dry phase condition ($w_i < w_{opt}$)

Pre-loaded Vert. Pressure (σ) KPa	Relative Density (*Dr*)	Hydro Com-pression Strain (ε_h)	Degree of Collap-sibility
25	59.23%	4.41%	LC
25	77.94%	4.51%	LC
25	96.29%	2.21%	LC
50	58.30%	3.90%	LC
50	78.70%	1.83%	LC
50	95.24%	0.85%	NC
100	59.86%	0.86%	NC
100	76.40%	1.05%	LC
100	92.23%	0.64%	NC
200	60.27%	1.23%	LC
200	76.02%	1.05%	LC
200	93.83%	0.53%	NC

LC – Low Collapsibility NC – No Collapsibility

Table 6 Degree of collapsibility of CMT at varying σ and *Dr* when initial moisture content is at optimum phase condition ($w_i \approx w_{opt}$)

Pre-loaded Vert. Pressure (σ) KPa	Relative Density (*Dr*)	Hydro Com-pression Strain (ε_h)	Degree of Collap-sibility
25	62.02%	2.47%	LC
25	77.27%	1.15%	LC
25	96.29%	0.28%	NC
50	57.25%	3.76%	LC
50	78.79%	1.25%	LC
50	96.90%	0.64%	NC
100	59.55%	0.62%	NC
100	80.78%	0.54%	NC
100	92.32%	0.54%	NC
200	60.79%	0.84%	NC
200	78.32%	0.60%	NC
200	93.83%	0.43%	NC

Table 7 Degree of collapsibility of CMT at varying σ and *Dr* when initial moisture content is at wet phase condition ($w_i > w_{opt}$)

Pre-loaded Vert. Pressure (σ) KPa	Relative Density (*Dr*)	Hydro Com-pression Strain (ε_h)	Degree of Collap-sibility
25	57.67%	0.74%	NC
25	76.50%	0.78%	NC
25	96.73%	0.19%	NC
50	58.09%	0.86%	NC
50	76.79%	0.78%	NC
50	92.23%	0.49%	NC
100	57.15%	0.56%	NC
100	75.64%	0.47%	NC
100	94.09%	0.39%	NC
200	58.19%	0.44%	NC
200	74.38%	0.38%	NC
200	93.47%	0.24%	NC

3.6 Formulation of Empirical Model to Predict Hydrocompression Strain

Using the response surface method (RSM), the relationship of the hydrocompression strain with initial void ratio, e_o, initial water content, w_i, and the preloaded vertical stress, σ¸ was formulated. The hydrocompression strain, εh can be expressed by the equation:

$$\varepsilon_h = \exp(4.8301e_0 - 11.4769w_i - 0.0047\sigma - 7.3814) \tag{1}$$

where:
e_o = initial void ratio
w_i = initial moisture content (e.g. w_i = 0.10 for 10% moisture content)
σ = vertical stress before inundation in KPa

To verify the predictive capability of the proposed model, the hydrocompression strain (ε_h) calculated using the proposed model was compared with the measured values from experimentation. Statistical analysis using T-test for paired samples was performed to determine if there is a significant difference between the measured values and the predicted values. The null hypothesis for the T-test states that there is no significant difference between the measured and predicted hydrocompression strain. The results for 36 number of observations with a level of significance equals to 0.05 (α = 0.05) showed a t_{stat} value (1.211) is less than $t_{critical}$ (1.689) and the *p*-value is greater than 0.05. This means that the null hypothesis should be accepted. It can be stated at 95% confidence level that that there is no significant difference between the measured ε_h and the predicted ε_h. The strength of association between measured ε_h and the predicted ε_h was verified using the Pearson's correlation coefficient and the data are presented in a scatter plot as shown in Fig. 3. The scatter of data points is nearer to a straight line which means that there is a linear positive correlation between the measured and predicted ε_h. The statistical analysis yielded a Pearson correlation value of 0.82 indicating a very strong association between the two variables (measured and predicted ε_h). It can be concluded that the proposed model (Eq. 1) can be used to predict the amount of hydrocompression strain as a function of initial void ratio, initial moisture content and the vertical stress prior to inundation.

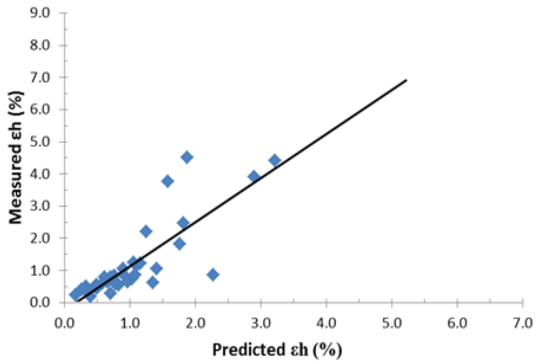


Fig. 3 Correlation of Measured ε_h with Predicted ε_h

4. CONCLUSION

The consolidation behavior and hydrocompression settlement of copper mine tailing were investigated to determine its suitability as embankment material. Based from laboratory test results, the following conclusions were drawn:

Copper mine tailing is considered to have low plasticity with chemical elements comparable to that of typical soil. The micro fabric comprised of an assemblages of clustered clay-size, platy particles.

Based on USCS criteria, the compaction characteristics of copper mine tailing is rated as good and its value as embankment material is reasonably stable when dense. AASHTO classification rated its anticipated embankment performance as poor to good.

Coefficient of consolidation (C_v) values are higher in the early stages of overconsolidated range specifically at stress near the preconsolidation pressure (σ_p') and showed a relatively rapid decrease for stresses beyond σ_p'.

The hydrocompression settlement of CMT increases with increasing pressure until the preconsolidation pressure is reached, and then decreases with pressure beyond the preconsolidation pressure. Samples with lower density and water content less than its optimum value exhibit greater hydrocompression settlement. The determined hydrocompression strains in every condition is less than 5% which means that CMT has a degree of collapsibility classified as low to negligible in spite of having plasticity.

To reduce the magnitude of hydrocompression strain to a negligible value, CMT when used as embankment materials should be prepared with initial moisture content slightly more than its optimum value. For cases where the initial moisture content is less than or equal to its optimum value, CMT should be in its very dense condition and it should be preloaded with vertical stress more than its preconsolidation pressure to make hydrocompression strain negligible.

Having good compaction behavior, reasonably stable when dense, with low compressibility and low collapsibility are indications that copper mine tailing despite of having plasticity has consolidation and hydrocompression characteristics suitable as embankment material.

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