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ASSESSMENT OF CRITICAL-STATE SHEAR STRENGTH PROPERTIES OF COPPER TAILINGS

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ABSTRACT: Philippines, with a total of 7,107 islands, have one of the largest mineral resources in the world. The copper and gold deposits are considered to be among the largest in the world (Bureau of East Asian and Pacific Affairs, 2010). Mining minerals generate waste material called mine tailings. Impoundment of mine tailings is normally done to store these waste materials. One of the most common types used in impounding tailings is raised embankments because of its low economic cost. This impoundment uses natural soil, tailings, and waste rocks as the construction material. There are cases that raise embankments experience stability failure which can affect the environment and well-being of the community where it is situated.

It is the interest of this study to assess the possibility of using mine tailings, specifically copper tailings, as a construction material. Index properties were first established following ASTM standards. From this, it was established that the copper tailings has plasticity. Unconsolidated undrained, consolidated undrained and consolidated drained test were conducted to determine the critical shear strength of the copper tailing. The copper tailings were tested having two relative densities namely, 60% and 90%. The effective critical angle of friction was found to have a range of 21°-28°. Since critical-state parameters are considered in the study, Cam clay model can be implemented so that to its behavior and failure mechanism can be predicted.

Keywords: Mine Tailings, Critical-State, Cam Clay

1. INTRODUCTION

Philippines, with a total of 7,107 islands, has one of the largest mineral resources in the world. According to National Economic Development Authority (NEDA), the country has an estimated USD 840 billion (Php 47 trillion) worth of unexplored gold, copper, nickel, chromite, manganese, silver and iron [1]. The copper and gold deposits of the Philippines are also among the largest in the world. Mining generates waste material called mine tailings. The waste materials are commonly stored by impoundment of the mine tailings. A raised embankment is widely adopted in impounding tailings due to its low economic cost [2]. This storage facility uses natural soil, tailings, and waste rocks as the construction material. There are cases that raise embankments experience stability failure which can affect the environment and well-being of the community where it is situated. One of the well-known disasters in the Philippine mining industry was the Marcopper incident which happened in 1996 [3]. Mine tailing spill occurred because of the leak at the drainage of the storage facility the Tapian Pit. This caused a fracture in the drainage tunnel which resulted to the spill that consists of four million metric tons of waste. Although Philippines is gifted with vast amount of minerals, not all companies follow the framework of responsible mining. One of which is in accordance with the international best practice such as ensuring environmentally responsible mining. Up to this date, there have been 21 tailing dam failures in the Philippines from 1982 up to 2007. Six out of 21 events were classified as major dam failure [3]. These events harmed the communities living near the mining facility. It also polluted the bodies of water destroying the livelihood of the locals. Since mine tailings are valueless and are produced in large volumes, it is normally stored at impoundment of mine tailings. Instead of just storing the waste materials, this study aims to investigate its potential as a construction material. Even though there are already several studies performed in other countries, there is a lack of research in the Philippines regarding the geotechnical characteristics of mine tailings [2].

It is the objective of this study to establish the index properties and critical shear strength of copper mine tailings. Index properties were established following American Society for Testing and Materials (ASTM) standards. Critical state condition is considered to have a better understanding of the mechanical behavior of the copper mine tailings. Unconsolidated undrained (UU), consolidated undrained (CU) and consolidated drained (CD) test were performed using a triaxial apparatus to determine its critical shear strength. Cam clay model is incorporated in the study since critical state condition is applied.

2. COPPER MINE TAILINGS

Copper mine tailings are obtained from Barrio Maglinao, Municipality of Basay Negros Oriental, Central Visayas. The mining site was operated by Construction and Development Corporation in the Philippines (CDCP) in 1979 and it was closed down in 1983 [4]. The site left negative environmental impacts to the Municipality of Basay especially to the Pagatban River. The mineralization for the Basay Copper Project is copper porphyry. Extensive open mining and limited underground mining was conducted between 1979 and 1983. In order to extract copper, the ore was first crushed and grinded. Forth floatation was performed to remove unwanted rock, gangue, from the copper ore. From this process, a 25% copper concentrate was achieved. Further refinement of the mineral was performed by smelting. The impurities were removed in a form of a slag. The mineral would now be in copper iron sulphide solution or matte. This is followed by conversion from matte to blister copper or partly purified copper having a blistered surface. In preparation for the last stage of extraction, the blister is casted into anodes. Lastly, electrolytic refining is executed by purifying the copper up to 99.99% through electrolysis [4]. The waste generated from extraction, copper mine tailings, were stored in tailing dams. The copper tailings obtained were in a somewhat dry condition and it formed a rock like formation.

3. EXPERIMENTAL PROGRAM

3.1 Preliminary Phase

The index properties of the copper mine tailings were obtained in accordance to ASTM standards. The following are the tests performed: Mechanical Sieve Analysis (ASTM D422), Hydrometer Test (ASTM D422), Atterberg limits [Plastic, Liquid (ASTM D4813) and Shrinkage limit (ASTM D427)], Specific Gravity (ASTM D854), Compaction Test (ASTM D698), Relative Density Test and Unit Weight Determination which includes the Maximum Index Density (ASTM D4253) test and Minimum Index Density Test (ASTM D4254).

3.2 Triaxial Compression Phase

3.2.1 Sample Preparation

The reconstituted samples were prepared by moist tamping. The method was applied since it minimizes particle segregation and it is applicable for most types of sands in compacting under a wide range of relative densities. The samples were initially dried to accurately achieve the desired relative density (D_r) of 27%, 60%, and 90% [5]. The mentioned relative densities are used to simulate a loose, medium dense and highly dense reconstituted sample, respectively. The amount of water mixed with the sample was less than its optimum moisture content. This allows the sample to be molded without crumbling. The sample was soaked for 16 hours as per ASTM standards. A cylindrical mold with a diameter of 38 mm and a height of 76 mm was used. This mold was used to ensure that the diameter of the sample was at least 30 mm. The largest particle which was contained within the sample was also maintained to be 1/6 smaller of its diameter. A ratio of the height to diameter between 2 to 2.5 is followed [6].

3.2.2 Unconsolidated Undrained

The unconsolidated undrained (UU) test or Quick Test (Q-Test) was performed based on ASTM D 2850. For this set-up, drainage was not permitted all throughout the experiment. Consolidation was not necessary but confining pressures are still applied at a fast rate. The rate of loading used for applying the axial load is dependent on the type of soil tested. For this study, a rate of approximately 1%/min is used since the soil is has plasticity. It was stopped when the sample experiences failure or it reached critical state. For the experiment proper, samples were prepared having an initial relative density of 27%, 60%, and 90%. The confining pressures (σ_3) used are 25 kPa, 50 kPa and 100 kPa [6]. A total of 9 samples were tested for the UU-condition.

3.2.3 Consolidated Undrained

The consolidated undrained (CU) test or R-Test (Rapid Test) was performed based on ASTM D 4767 – 02. For this condition, the specimen was allowed to consolidate prior to the shearing phase. There are three phases in this condition namely, saturation, consolidation and shearing phase. For the saturation phase, to ensure that the sample is fully saturated a B-value is computed. It is the ratio of the pore water pressure and confining pressure at the time when the volume change is constant. The B-value must be greater than 0.95 to ensure that the sample is fully saturated. For the consolidation phase, the confining pressure (σ_3) was applied. The drainage was left open until zero pore water pressure is achieved [8]. For the shearing phase, the rate of loading of 1%/min was applied to simulate rapid loading. It was stopped when failure or critical state condition was experience. For the experiment proper, samples were prepared having an initial relative density 60%, and 90%. The confining pressures used in this condition are 50 kPa, 100 kPa and 200 kPa [9].

The 25 kPa confining pressure was not applied in this condition because the range of back pressures used is larger. The sample will not consolidated instead it will saturate. A total of 6 samples were tested for the CU-condition.

3.2.4 Consolidated Drained

The consolidated drained (CD) triaxial test or S-Test (Slow Test) was based on the British Standard Methods of test for Soils for Civil Engineering Purposes. The test's purpose was to establish the drained shear strength parameters such as the critical state effective angle of internal friction (φ'_{crit}). For this condition, water was allowed to drain during the shearing phase. This was to simulate and determine the strength of the soil with respect to long-term loading. Similar to the CU test, CD test has three phases. The saturation and consolidation phase are similar with CU test. The rate of loading for the shearing phase must be slow enough to allow the dissipation of excess pore water pressure. A rate of loading of 0.5% axial strain per minute was used since it is applicable for sandy soil [15]. The confining pressure used for the consolidation phase are 50 kPa, 100 kPa and 200 kPa were used.

4. RESULTS AND DISCUSSION

4.1 Index Properties

The index properties of the copper tailings are presented in Table 1. The liquid limit falls under the category of a silty soil since it is in between 30-40%. The plastic limit, when computed, is characterized as a clayey soil based on the range of 25-50% [5]. The specific gravity is within 2.6 to 2.9 which is the range of values for a clayey and silty soil [7]. A grain size distribution curve (GSDC) was established as seen in Fig. 1.

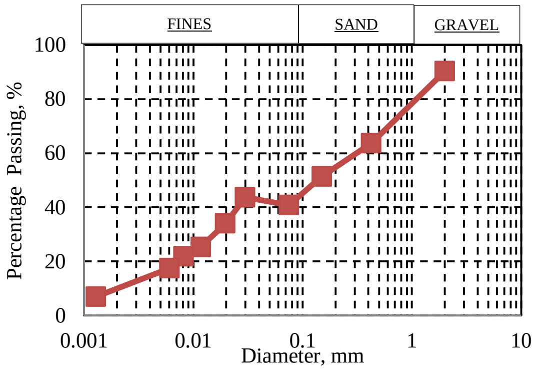

Fig. 1 Grain size distribution curve of copper tailings.

The plot is used to determine the soil gradation of the copper tailings. It contained a flat section at the fines section which is the indication that the sample is gap graded. A gap graded soil usually contains a large percentage of big and small particles with a limited amount of intermediate sizes [12]. When this type of gradation is compacted, it can result to larger voids compared to a well graded soil. The composition of the copper tailings was also determined through the sieving process that was performed in order to create the GSCD. The sample was sieved between #4 and #200 sieve. It resulted to the following composition, 0.15% gravel, 59.04% sand and 40.81% fines.

To properly define the soil classification of the copper tailings, the Unified Soil Classification System (USCS) was used since it can be applied in all types of soil [10]. Also, the system can further classify the soils into coarse-grained and fine-grained soils. From the system, the copper tailings can be classified as silty sand. Another classification system was used to check the suitability of copper tailings as support for roadways. The American Association of State Highway and Transportation Officials (AASHTO) was used since it can classify the material's general subgrade rating for roads. According to AASHTO soil classification system, the soil sample is classified as A-4 with a group index of 0. A group index close to zero indicates it is a good soil for highway subgrade. Its general subgrade rating is fair to poor. For this rating, the copper tailings can have fair to poor drainage and support when used as a subgrade material for embankments [10]. The results of the index properties were compared to some existing researches of copper tailings. The result of the specific gravity was compared to the research Characteristics of Copper Mine Tailings: A Case Study. Their sample was from the Sarcheshmeh Copper Complex Tailings Dam in Iran. Its specific gravity ranges from 2.6 to 2.8 [11]. The copper tailings tested have a larger value, 2.82, and its percentage error is 0.71%. The result of the shrinkage limit was also compared to the research Laboratory Properties of Mine Tailings. Their sample was from Kennecott Mining in Salt Lake County, Utah. Its shrinkage limit is 24.4% [9]. The shrinkage limit of the copper tailings is smaller, 21.58%, and its percentage error is 0.12%. The soil classification of the copper tailing from Kennecott Mining is also silty sand but the fines content is greater. The samples from Kennecott Mining only have 31.3%. Results from other researches may vary since the samples are taken from different areas. The origin of the sample may have an effect to the over-all composition of the sample.

4.2 Stress-Strain Behavior and Mode of Failure

The copper tailings were sheared until failure or once critical state is achieved. For the three triaxial tests a common trend was observed from the stress-strain plot. A sample result is presented in Fig. 2. Yield was constantly experienced during the early stages of the shearing phase. Based on the plots it normally happens at less than 5% strain. This behavior shows that the sample had already exceeded its elastic limit and immediately shifted to a purely plastic sample while it is being sheared. It is followed by strain softening for a small amount of time then it shifts to strain hardening all throughout. No peak was observed in the plots which can result to a plastic mode of failure. This was verified during the experiment that the sample had experienced a bulging mode of failure in all tests, Fig. 3. Based on the observed stress-strain behavior and the mode of failure, this indicated that the sample tested is ductile.

Table 1. Index properties

Index Property	Value
Specific gravity(Gs)	2.82
Liquid limit(LL)	32.05%
Plastic limt (PL)	25.81%
Plasticity index(PI)	6.24%
Shrinkage limit(SL)	21.58%
Shrinkage Ratio(R)	1.65
Maximum void ratio (e_{max})	1.441
Minimum void ratio (e_{min})	0.964
Maximum dry unit weight(γ_{dmax})	15.70 kN/m3
Optimum water content (ω_{opt})	19.47%

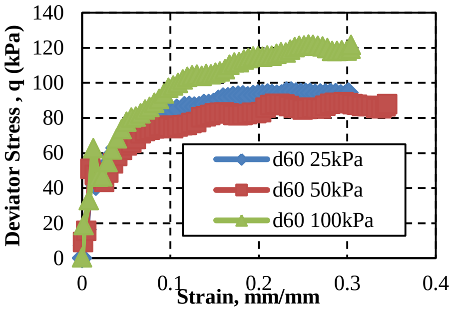

Fig. 2 Stress-strain plot of copper tailings for UU test Dr = 60%

Fig. 3 Stress-strain plot of Copper Tailings

4.3 Undrained Shear Strength

Average undrained shear strength (Su_{ave}) was computed from the three confining pressures applied in the UU test. The results are tabulated at Table 2. The average value was obtained since the deviator stress from the Mohr's Circle was not equal. Results of the average undrained shear strength of copper tailings were compared. The sample with 90% relative density had the smallest value of Su_{ave} while the largest has a 60% relative density. When the actual relative density was computed and compared with the target value, an error ranging from 0.66% to 17.7% was observed. Since the samples were reconstituted, difficulties in achieving the same target relative density and soil structure at minimal error can be encountered. It can also be observed that Su_{ave} at 90% relative density decreased. This result is due to the sufficient amount of fines present and a quick test was performed. Copper tailings are composed of 40.81% fines which made it a rather weak sample at this relative density and test [8].

The critical undrained shear strength (Su_{crit}) was obtained from the CU test. Results are tabulated at Table 3. It can be observed that a different trend occurred in this set-up. The samples prepared with a denser composition, D90, had a larger range of values. The void ratio after the consolidation was computed as seen in Table 4. The void ratio is relatively smaller after consolidation when compared to the initial void ratio. A smaller void ratio translates to a higher relative density. This explains the trend experienced in for the Su_{crit}.

The consistency of the sample can be classified based on its undrained shear strength [8]. The Copper tailings' Su_{ave} is classified as a sample with medium consistency. For the Su_{crit} it is classified as a sample with medium to very stiff consistency. A change in consistency can be observed because the consolidation phase of CU test improved the resistance of the sample to compression. A medium to very stiff consistency would have an undrained shear strength ranging from 25 kPa to 200 kPa [8].

Table 2. Average undrained shear strength (Su_{ave})

	Su_{ave} (kPa)		
D_r	D27	D60	D90
CopperTailings	45.39	46.04	32.65

Table 3. Critical undrained shear strength (Su_{crit})

	Su_{crit} (kPa)	
D_r	D60	D90
Copper Tailings	42.42-74.12	78.49-117.75

4.4 Critical-Shear Strength

The critical shear strength is measured by determining the critical angle of internal friction from the CU and CD test. The typical values for angle of internal friction for silts range from 26° to 35° [8]. Based on the results as seen in Table 5, only the values at 60% relative density for both CU and CD test are in close agreement. The results are also compared to the shear strength of Copper Tailings from Kennecott Mining which is 34° [9]. Copper tailing's strength is considerably smaller since it has a greater amount of fines content, 40.81%. The samples from Kennecott Mining only have 31.3%. Based on the results of shear strength parameters, Copper tailings has sufficient strength but it is not close to the typical materials used for subgrade, embankment or structural fill. The typical materials used are well-graded sands with greater than 34° angle of internal friction [16].

Table 4. Summary of void ratio (e) for CU test.

D_r	σ_3	e_{target}	e actual		
(%)	(kPa)		Initial	After Saturation	After Consolidation
60	25	1.13	1.09	1.16	1.09
	50	1.13	1.22	1.37	0.94
	100	1.13	1.19	1.59	1.18
90	50	0.98	0.97	0.89	0.99
	100	0.98	0.99	0.78	0.97
	200	0.98	1.03	1.35	1.01

Table 5. Critical angle of interal friction (φ_{crit}).

		D_r (%)			
		60		90	
	Triaxial Test	φ_{crit}	φ'_{crit}	φ_{crit}	φ'_{crit}
Copper Tailings	CU	25°	27°	21°	22°
	CD	-	28°	-	24°

4.5 Critical-State Parameters

Critical state parameters are obtained from the CD test based on the concepts from the critical state model [13]. Results are tabulated at Table 6. The isotropic normal compression lines (NCL) of the copper tailings with 90% relative density are presented at Fig. 4. Void ratio (e) can be extracted from Fig. 4 since, specific volume (v) is [13]:

$$v = 1 - e \tag{1}$$

From the computations, the void ratio for 200 kPa NCL has values larger than e_{max}. Exceeding e_{max} can be an indication that the sample had already collapse at that confining pressure. This is also the reason of having a smaller φ_{crit} or φ'_{crit} at 90% relative density. The sample had already a weaker structure prior to the shearing phase. With this, the NCL for 100 kPa is considered as its maximum boundary while NCL for 50 kPa is the minimum boundary. Each data was linearized to determine the slope of NCL or compression index (λ) and y-intercept of the NCL line (Γ). The equations presented in Fig. 4 can be used to predict the specific volume for a certain mean normal effective stress or vice versa. The coefficient of determination for NCL at 100 kPa and 50 kPa is 0.8386 and 0.8631, respectively. Based on these values, the equation has the capability of predicting values at almost 85% accuracy. The slope can be used to compute for the settlement parameter such as compression index (C_c) using equation [14]:

$$\lambda = \frac{C_c}{\ln(10)} = \frac{C_c}{2.3} \tag{2}$$

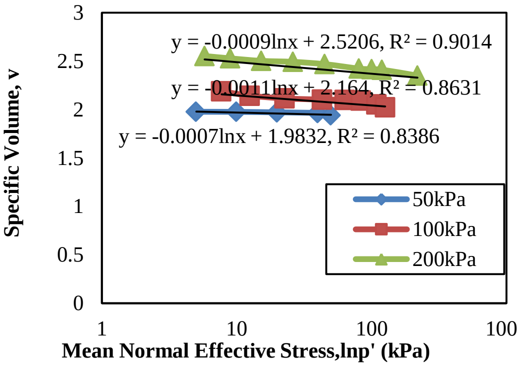

Fig. 4 NCL of copper tailings having D_r = 90% under CD test.

Values computed, using Eq. 2, were less than the typical values ranging from 0.1 to 0.8 [14]. From this result, Copper tailings can be considered as slightly compressible. The slope of the reloading or unloading line (κ) is zero since this step was not simulated in the experiment. The critical state line (CSL) of deviator stress (q) versus mean normal effective stress (p') has a slope M, Fig 6. It can be observed that sample with 60% relative density has a larger value. This is due to the collapse the sample experienced at 200 kPa for 90% relative density. After establishing the critical state parameters, the specific volume versus p' was redrawn using the formulas from the critical state model, Fig. 5. The area beyond NCL is the impossible state while the area below is where the over-consolidated soil is located. Points along NCL are normally consolidated soil. The area in between NCL and CSL is where compression occurs. The area under CSL is where expansion is encountered.

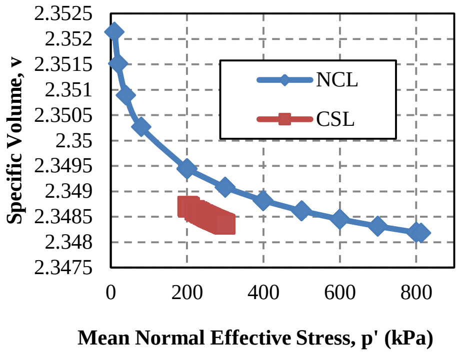

Fig. 5 Specific volume versus mean normal effective stress plot of copper tailings having D_r = 90% under CD test.

4.6 Cam Clay Model

The Cam Clay model was proposed by Roscoe and Schofield (1963). It considers the yield behavior of a soil through a yield locus as seen in Fig. 6. The yield locus is defined as the combination of the deviator stress, q, and the mean normal effective stress, p', that caused the yielding of a soil due to a preconsolidation stress, p'_o. The preconsolidation stress is estimated from the deviator stress and mean normal effective stress at critical state [13].

$$\frac{q}{Mp'}+\ln\left(\frac{p'}{p'_c}\right)=0 \qquad (3)$$

The yield locus serves as the boundary of elastic and plastic state [7]. Elastic state is within the locus while plastic state is beyond it. The model was applied since the sample experienced yield behavior. Furthermore, the model also integrates the critical state parameters together with NCL and CSL in its formulation. The model can be used to predict the possible deviator stress with a desired value of mean normal effective stress or vice versa to assess the behavior of the sample. The yield locus also shows the limiting values for deviator stress and mean normal effective stress.

Table 6. Summary of critical-state parameters

	Triaxial Test		D_r (%)	
			60	90
Copper Tailings	CD	λ	0.0002-0.0005	0.0007-0.0011
		Γ	1.7161-2.0176	1.9832-2.1640
		κ	0	0
		M	1.13	0.99

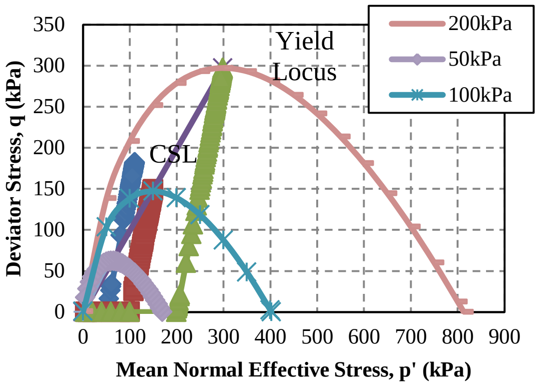

Fig. 6 Stress path with yield locus of copper tailings having D_r = 90% under CD test.

5. CONCLUSION

It is the interest of this study to assess the possibility of using mine tailings, specifically copper tailings, as a construction material. Index properties and critical shear strength parameters were first established following ASTM standards. From this, it was established that the copper tailings can be classified as silty soil with plasticity and a sufficient amount of fines content. Based on the AASHTO rating it can still be as an embankment material but with proper control. Based on the CU and CD test, the effective critical angle of friction has a range of 21°-28°. The material performs best at 60% relative density at critical state. When the critical state parameters are incorporated to the Cam Clay model, its maximum mean normal effective stress and deviator stress is 812.91 kPa and 297.15 kPa respectively.

The result presented in the research is not enough to completely assess Copper tailings' potential as a construction material. California Bearing Ratio test must be performed to further evaluate its subgrade strength [17]. Furthermore, the Copper tailings' performance as a fine aggregate should be tested [18], [19].

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