Geotechnical Properties of Cement-Stabilized Mine Tailings from Brgy. Gango, Libona, Bukidnon, Philippines

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ABSTRACT: Improving the geotechnical engineering properties of mine tailings using cement stabilization process can be adopted to reduce the volume of tailings and consequently the risk of toxicity it poses to people and the environment. Geotechnical properties of cement-stabilized mine tailings from Brgy Gango, Libona, Bukidnon, Philippines were investigated to assess its applicability for reuse as a construction material. Mine tailings were stabilized using ordinary Portland cement in four different formulations—0%, 6%, 8% and 10% by weight of soil and were subjected to compaction test, California bearing ratio (CBR) test, permeability test, unconfined compressive strength (UCS) test and direct shear test in accordance with ASTM standards. Based on the AASHTO Soil Classification System, the soil was classified as clay of low plasticity. The maximum dry density and optimum moisture content showed a decreasing trend from the varied mixture which resulted that adding cement did not improve the compaction characteristics of the stabilized mine tailings. Addition of OPC up to 6% and 8% had a significant effect on the increase of CBR and UCS values, respectively. In permeability test, it was observed that the rate of flow of water increases as the percent of OPC increases. The increase of the coefficient of permeability was influenced by the cementitious bond which forms new solid material within the treated sample. The soil particle becomes bigger in size and the rate of flow of water increases. Up to 6% addition of OPC is the optimum cement percentage to stabilized the mine tailings based on direct shear testing. In overall, the cement-stabilized mine tailings from Brgy. Gango, Libona, Bukidnon, Philippines can be safely used in sub-base road construction and as typically stabilized wastes for land disposal.

Keywords: geotechnical engineering, mine tailing, cement-stabilized soil, road construction.

1. INTRODUCTION

Mining industry is one of the most prominent and productive economic sector in the Philippines. Specifically, artisanal small-scale gold mining (ASGM) is the most common operation activity which contributes to about 70-80% of the total gold production gold production in the country (Israel and Asirot, 2002). The extraction of gold extraction is via the amalgamation process which relies on heavy use of mercury. This result to production of contaminated mine tailings that have been proven to contain up to 250 grams per ton of mercury (Appel, et al., 2011).

Despite its economic benefits, mining operations often face strong opposition from affected communities because of its adverse environmental and social effects (Adajar and Zarco, 2013). These wastes carry toxic material which may harm the people and the environment if not properly managed. The disposal of the enormous amounts of ASGM tailings regularly produced from mining operations is the main environmental issue associated with mining activities. The mine wastes might have sufficient amounts of mercury to cause danger to all living organisms as it pollutes the soil and water.

One of the sites in Mindanao, Philippines where the problem of ASGM tailings disposal is a great environmental concern is in Libona, Bukidnon. Libona is a first class municipality and known to have abundant gold deposits. Small-scale mining operations began to operate in Sitio Manlahuyan, in Barangay Gango in 1986. Large amount of ASGM tailings are still present in the site that need to be managed properly in order to minimize its negative effects to the community and to the environment (Canencia et al., 2015).

In order to address the disposal of ASGM tails in Libona, mine wastes will be stabilized using Ordinary Portland Cement (OPC) and will be assessed for its applicability for reuse as a construction material. Hence, the main objective of the study is to determine the geotechnical properties of cement-stabilized ASGM tailings in Sitio Manlauyan, Gango, Libona, Bukidnon. The cement-stabilized mine wastes were subjected to compaction, California bearing ratio (CBR), falling head permeability, unconfined compressive strength (UCS) and direct shear in accordance with American Standard and Testing Materials (ASTM) and its specific construction application was determined.

2. METHODOLOGY

2.1. Experimental Design

Three (3) soil samples at each of the replacement were prepared and mixed at 0%, 6%, 8%, and 10% of OPC using soil mixer with a water-cement ratio of 0.4 as the design mix of the study presented in Table 1. Digital weighing balance was used in weighing the soil samples based on the designed mixture.

Table 1. Design Mix of the Study.

Treatment	Description
T_0	0% additional OPC
T_1	6% additional OPC
T_2	8% additional OPC
T_3	10% additional OPC

2.2. Sample Collection

Mine tailings were collected in the common mine tailing pond at Gango, Libona, Bukidnon with a latitude of 80 20’ 25” N and longitude 1240 43’58” E (Figure 1). Actual collection of soil samples were shown in Figure 2. The soil samples were air-dried at the laboratory. The dry disturbed soil samples were pulverized using rubber mallet and undergone sieve analysis through U.S sieve no. 40.

Figure 1. Location of the study (common mine tailings pond in Gango, Libona, Bukidnon).

Figure 2. Collection of Soil Sample in Gango, Libona, Bukidnon.

2.3. Determination of Grain Size Distribution

The Grain-size tests of the soil were performed in accordance with the ASTM D421 (Standard Method for Sieve Analysis of Fine and Coarse Aggregates). The soil was sieved through the nest of fine sieves, sieve numbers 3”, 1”, ¾”, ½”, 4, 10, 20, 40, 60, 100, and 200. A mechanical shaker was used having a minimum of 10 minutes shaking. The soil fraction retained on each sieve in a separate container was collected and masses were taken. The percentage retained, cumulative percentage retained, and the percentage finer was determined.

2.4. Determination of Atterberg Limits

The Atterberg Limits were determined in accordance with ASTM D4318 - Standard Test Method for Fall Cone Test. The soil sample is placed in a 55 mm diameter, 40 mm deep metal cup. The cone is released for 5 seconds so that it may penetrate the soil. Liquid limit is defined as the water content of the soil which allows the cone to penetrate exactly 20 mm during that period of time. The sample was allowed to dry on the glass plate until it become plastic enough to be shaped into a ball. The sample-ball was molded and rolled between the palms of the hands until cracks on the surface of the sample appeared. Then, sample was divided into small pieces and rolled to form thread having 3.2 mm diameter under enough pressure. The first crack appeared on the thread surface was determined as plastic limit. Plasticity index was calculated as the difference between the liquid limit and the plastic limit which measures the plasticity of the soil.

2.5. Soil Stabilization

An amount of water equivalent to 0.4 water to cement ratio was added to the four (4) treatments of pulverized soil sample. The sample was mixed for about 2 minutes until homogenous mixtures were attained and were stored and zipped.

2.6. Curing of Soil Samples

The stabilized samples were cured for 28 days to let the cement hydrate and react with the soil. The samples were zipped to prevent the moisture to evaporate during the curing period and stored away from direct sunlight. All the samples after 28 days curing were subjected to testing.

2.7. Compaction Test

The modified proctor test was conducted to all the samples based on ASTM 1557 and AASHTO T180 in order to determine experimentally the optimum moisture content at which the tailings became most dense and achieved its maximum dry density. The proctor compaction test consists of compacting soil samples at a given water content in a standard mould with standard compaction energy. It uses a 4-inch-diameter mould with the compaction of five separate layers of soil using 56 blows by a 4.5 kg hammer falling 18 inches.

Each of the soil samples were first air dried and then separated into 5 samples. The water content of each sample were adjusted by adding water (3% - 5% increments or more depending on the type of the soil). The soil samples were then placed and compacted in the Proctor compaction mould in five different layers where each layer received 56 blows of the standard hammer. Before placing each new layer, the surface of the previous layers were scratched in order to ensure a uniform distribution of the compaction effects. At the end of the test, after removing and drying of the sample, the dry density and the water content of the samples were determined for each Proctor compaction test.

2.8. California Bearing Ratio Test

The California Bearing Ratio was determined in accordance with ASTM D1883 (Standard Test Method for California Bearing Ratio of Laboratory –Compacted Soils). The soil specimens were compacted so that their compacted densities ranges from 95% to 100%. The samples were cured for about four days. Penetration pistons were applied to the samples. The optimum mixture of soil and cement was determined based on the maximum CBR observed from the several mixtures that was used.

2.9. Falling Head Permeability Test

The falling head permeability test was conducted using Standard Test Methods for Measurement of Hydraulic Conductivity of Saturated Porous Materials Using a Flexible Wall Permeameter (ASTM D5084). The soil samples and the water required for mixing were first weighed according to its data on maximum dry density and optimum moisture content from the compaction test results. After the mixing process, it was compacted inside the cylinder with 3 layers and 25 blows per layer using a rubber mallet. The sample was then confined inside the cylindrical mould and the permeameter was attached to the syringe to the stand pipe. The valves were first locked to ensure that no water may pass through the cylinder. Water was poured above the stand pipe through a funnel. The safety valve was removed leaving a hole above the cylinder and the upper valve was turned on. Bubbles came gushing out on the hole at the safety valve as water flowed through the cylinder. The lock was then attached back to the safety valve. The upper valve was also turned off when there were no more bubbles which were signs of air voids. After it was turned off, a timer was set together when the upper and lower valve handle attached above and below the cylinder was turned on and was observed until it penetrates the soil. When it penetrated the soil, a drop of water was be noticed from the faucet attached below the cylinder. The timer was stopped and recorded and the upper faucet was turned off to record the initial height of water at the stand pipe. Another timer was set one (1) minute after the faucet was turned on again for three (3) trials to record initial and final heights. The coefficient of permeability was then determined by using the formula given below.

$$K = \frac{2.303\ aL}{At} \log_{10} \frac{h_1}{h_2} \qquad (1)$$

Where

K = coefficient of permeability in cm/s

a = inside cross-sectional area of stand pipe in cm2

L = length of specimen in cm

h1 = initial head in cm

A = cross-sectional area of specimen in cm3

t = time interval in seconds in which the head drops from h1 to h2

h2 = final head in cm

2.10. Unconfined Compressive Strength Test

The prepared specimens followed the procedures provided by ASTM D2166 -Standard Test Method for unconfined compressive strength of cohesive soil. The treated samples were added with water according to the attained optimum moisture content and maximum dry density. The compacted stabilized soil was extruded from the tube sampler and were cut to obtain the length to diameter ratio (L/d) to be approximately between 2 to 2.5, and were placed inside the cellophane. The diameter and length of each specimen were measured, and weighed. The specimen was placed in the compression device and was centered at the bottom plate. The device was adjusted so that the upper plate made contact with the specimen and the load and deformation dials were set to zero. The cylinder of soil without lateral support was tested to failure in simple compression, in a constant rate of strain.

2.11.Direct Shear Strength Test

The test was performed in the laboratory according to the standard test procedure ASTM D3080 – Direct Shear Test of Soils for Consolidated Drained Conditions. Treated soil samples was mixed with water according to the moisture content result from compaction test. It was compacted progressively by 1/3 of its total volume having 25 blows. The compacted soil was carefully removed from the sampler and placed inside a clean wrapper.

The dimension of each specimen was measured. Area and volumes were calculated. The specimen was placed in smooth layers. The upper grating on stone and loading block on top of soil were positioned. Desired normal load was applied before shear pin was removed. The dial gauge which measures the change of volume was then attached. Initial reading of the dial gauge and calibration values were recorded. As the motor was operated, the reading of the shear force was recorded as well as the volume change readings until failure.

3. RESULTS AND DISCUSSION

3.1. Grain Size Analysis

The percentages of gravel , sand and clay-silt were summarized in Table 2. There was an increase in clay and silt percentage from 97. 14% to 97.59% when 6% of OPC was added to the sample. However, the percent passing gradually decreases as 8% and 10% of cement were added to the soil sample giving the percent passing values of 97.48% and 95.88% respectively. This was probably due to the chemical reaction between cement and water that produces cementitious compound which has larger particle size compared to the tailing sample which resulted to the decrease of percentage passing (Das, 2015).

Table 2. Soil Type Percentages

Treatment	Gravel	Sand	Clay and Silt
T_0	0	2.86	97.14
T_1	0.18	2.23	97.59
T_2	0.16	2.36	97.48
T_3	0.38	3.74	95.88

3.2. Soil Classification

Table 3 shows the soil classification of the samples based on American Association of State Highway and Transportation Official (AASHTO) and Unified Soil Classification System (USCS). T_0 and T_3 sample were both classified under the group A-7-6, while T_1 and T_2 sample were under group A-6. All samples belong to fine-grained soil category for having 50% or more percent passing through sieve no. 200, and were classified as CL or clay of low plasticity/lean clay based on USCS soil classification system.

Table 3. Soil Classification of the Samples

Treatment	AASHTO	USCS	Soil Plasticity
T_0	A-6(13)	CL	Medium Plasticity
T_1	A-7-6(19)	Cl	Medium Plasticity
T_2	A-7-6(19)	CL	Medium Plasticity
T_3	A-6(14)	CL	Medium Plasticity

3.3. Atterberg Limits

T_0 sample as shown from Figure 3 has the least value of liquid limit of 37.45%. Lean clays have correspondingly low liquid limit which indicate low compressibility and low in shrinks swell tendencies. Increasing trend in LL was observed as percent of OPC content increases. Liquid limit values vary from 37.45% to 41.01%, improvement of liquid limit attributed that more water is required for the cement treated soil to make it fluid. Figure 4 shows the plastic limit of all the samples which vary from 23.83% to 26.1%. Figure 5 indicates that as cement content of the sample increases, the plasticity index also increases up to 8%. All the samples were classified soil with medium plasticity. High plasticity soil exhibits low strength and low compressibility. This indicate that the controlled sample ($T_{0)}$ has the best plasticity characteristic among all the treatments..

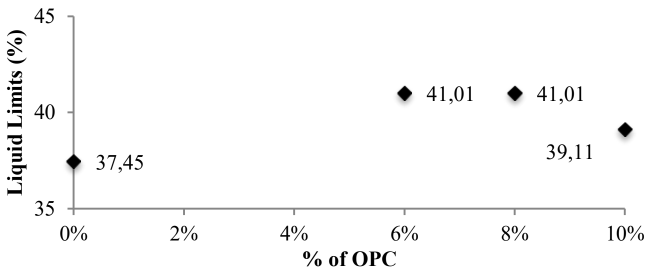

Figure 3. Liquid Limit of the Soil Samples.

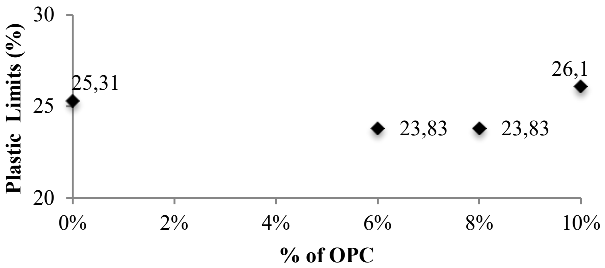

Figure 4. Plastic Limit of the Soil Samples.

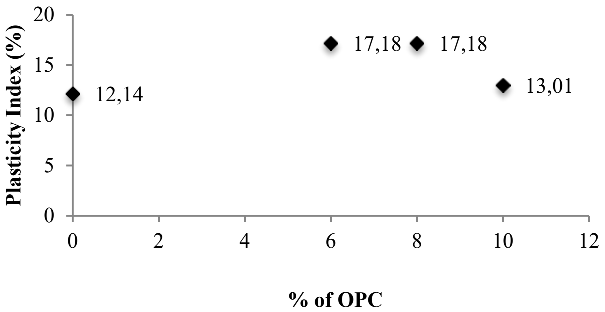

Figure 5. Plasticity Index of the Soil Samples.

3.4. Compaction

The cement-stabilized soil samples showed an increasing trend of OMC from 11.5% to 12.72%, smaller compared to controlled sample as shown in Table 4. These reduction of OMC and MDD valued is attributed to the addition of fines in the form of cement. The study of Manjunatha and Sunil (2013) showed similar effect of decreasing result of OMC and MDD using different stabilizing agent.

Table 4. Compaction Test Result.

Treatment	Optimum Moisture Content (%)	Maximum Dry Density (kg/m^3)
T_0	13.57	1751.39
T_1	11.53	1587.51
T_2	11.56	1524.29
T_3	12.72	1475.77

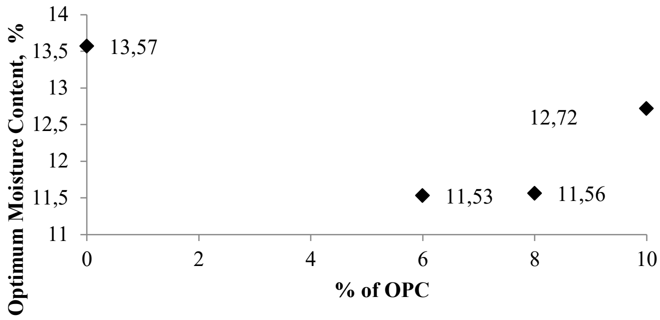

Figure 6. Variation of OMC with varying amount OPC

3.5. California Bearing Ratio

The addition of OPC in samples has increased the CBR values as observed Figure 7. Bowles (1992) stated that the subgrades having CBR value of 3-7% are poor to fair quality of subgrade and greater than 50% CBR value can be used as base material . T_0 is under poor to fair subgrade with the CBR value of 4.87%. T_1, T_2 and T_3 have 105.67%, 79.84% and 93.81% CBR values, respectively. All percent additives are excellent subgrade that can be used as base.

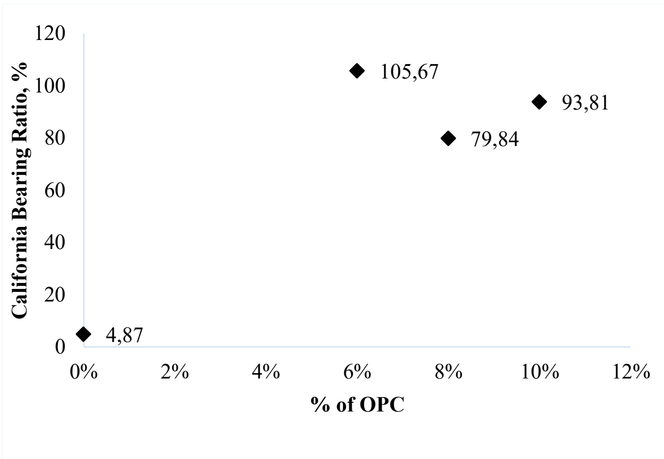

Figure 7. California bearing ratio of cement stabilized mine tailings.

3.6. Permeability Test Result

The coefficient of permeability (K) increased when added with OPC influenced by the time it was started to be tested and the percent of cement added. The K values of T_1 and T_3 were lower compared to T_0 and T_2. Setting aside the soil sample reduces its moisture content due to evaporation and causes the optimum moisture content to shrink.

The decrease or increase of K was influenced by the formation of cementitious bonds which creates new solid material within the treated mine tailings. These tailings are considered to have low to very low permeability typical of silty sand. This factor increases the average pore size to create a macro-pore structure which causes an increase in K (Tay & Goh 1991).

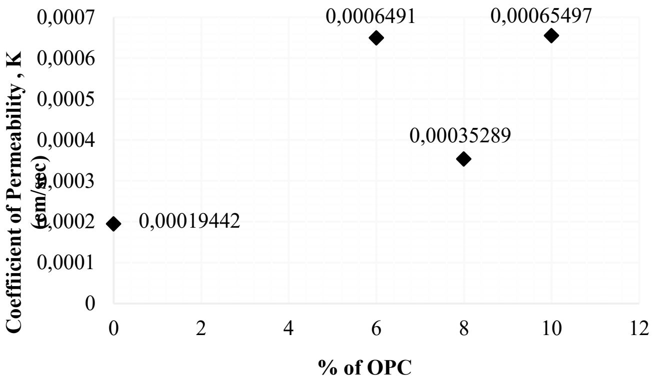

Figure 8. Coefficient of Permeability of Soil Samples.

3.6. Unconfined Compressive Strength

Unconfined compressive strength is a control parameter for road fill design. Achieving a compressive strength greater than 345kPa can help to significantly reduce the potential for settlement in deep fills (Ferguson and Levorson, 1999). Sample added with 8% of OPC has the highest value of UCS with 320.8 kPa, not reaching the desired value for deep fill purposes. However, the stabilized soil were classified as very stiff (200kPa- 400KPa) clay consistencies based on the classification of Das (2010). According to Amini et al. (2011), the effect of longer curing time (from 14 to 28 days) has greater effect to the mixture.Thus, the sudden decrease of strength may be also caused by the number of curing days. The UCS of soil significantly increases with the curing period and it is more consistently increasing up to the first 14 days according to Saha et al. (2013).

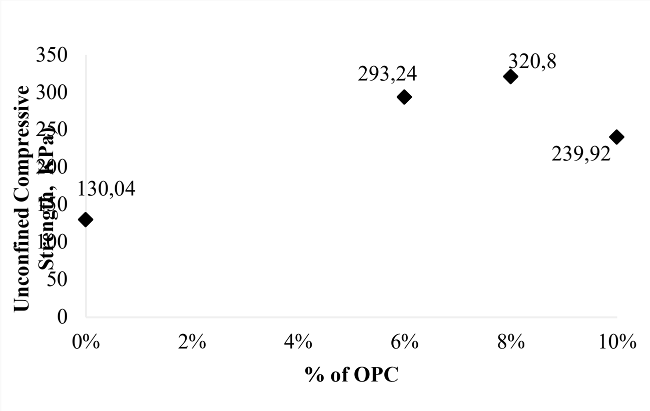

Figure 9. Variation of unconfined compressive strength with OPC.

3.7. Direct Shear Stress

It was observed in Figure 10 the relationship of shear stress with time increases until failure occurs which is at its peak. Compared to all other treatments, T_2 has the maximum shear stress which is 166.11 kPa that was observed at 30 seconds of the testing and ultimately settles at 59.52 kPa beginning at 40 seconds. This suggests that addition of 6% OPC gave the values of shear stress that can be mobilized within a soil mass without failure taking place.

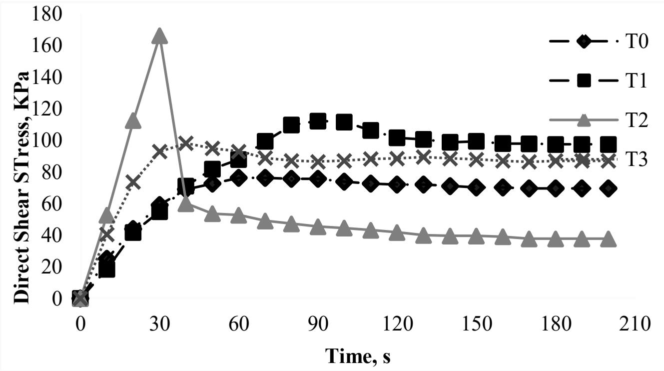

Figure 10. Time vs. Average direct shear stress graph of soil samples.

4. CONCLUSION

Based on the experimental results, the following conclusions were drawn:

i. The physical property of the artisanal gold mine tailings found in Gango, Libona, Bukidnon, Philippines were classified as olive brown and identified as silts with traces of sandy clays by the results in the grain size distribution. It has the value of 37.45%, 25.31% and 12.14% for liquid limit, plastic limit and plasticity, respectively. The soil was classified as A-6 (13) soil according to ASSHTO classification and CL soil based on USCS classification. The soil was low plasticity that implies low compressibility and lower tendency in swelling which was a good attribute for the acceptability of earthen materials in road construction applications;

ii. Cement causes the decrease in both MDD and OMC of the mine waste. Controlled (T_0) sample acquired the largest maximum dry density and optimum moisture content value of 1751.39 kg/m^3 and 13.57%, respectively. ;

iii. Stabilized soil samples have the CBR values of greater than 50% classified as excellent quality for sub-grade that can be used as base materials;

iv. As the percent of OPC increases, the coefficient of permeability also increases. Stabilization using OPC gave a great significance in the results yet it produced higher permeability results than that of the controlled treatment because OPC formed bonds between tailing particles that creates new solid material and caused faster discharge of water through the sample.

v. Sample added with 8% of OPC has the highest value of UCS with 320.8 kPa, not reaching the desired value for deep fill purposes. However, the stabilized soil were classified as very stiff (200kPa-400kPa) clay consistencies;

vi. As the cement content for each treatment increases, there is an evident decrease in soil strength but values were still higher than of the controlled sample; and

vii. The study indicates that cement can be very effective in stabilizing the ASGM tailings up to 6% addition of cement that can be safely used in sub-base and base road construction and in typical stabilized wastes for land disposal.

5. REFERENCES

ASTM D421 – Standard Method for Sieve Analysis of Fine and Coarse Aggregates.

ASTM D3080 - Direct Shear Test of Soils for Consolidated Drained Conditions.

ASTM D4318 – Standard Test Method for Fall Cone Test.

ASTM C136. “Standard method for sieve analysis of fine and coarse aggregates”. ASTM International.

ASTM D1883. “Standard test method for California Bearing Ratio of laboratory – compacted soils”. ASTM International.

ASTM D6913 Standard test methods for particle-size distribution (gradiation) of soils using sieve analysis.

ASTM D2487-11 Standard practice for classification of soils for engineering purposes (Unified Soil Classification).

ASTM D2166 -Standard Test Method for unconfined compressive strength of cohesive soil.

ASTM D3080 – Direct Shear Test of Soils for Consolidated Drained Conditions

Adajar, M.A. and Zarco, M.A.. 2014. An empirical model for predicting hydraulic conductivity of mine tailings, Dec., 2014, Vol. 7, No. 2 (Sl. No. 14), pp. 1054-1061.

Appel, P., Na-Oy, L., Hatsukawa, Y., Osawa, T., Kystol, J., and Sorensen, L. (2011) “Cleaning mercury polluted mine tailings in the Philippines”.

Alhomiar, S. (2016). Thesis-Hydraulic Conductivity of Fly Ash-Amended Mine Tailings. Retrieved: https://dspace.library.colostate.edu/bitstream/handle/10217/176619/Alhomair_colostate_0053N_13648.pdf?sequence=1.

Bowles, J. (1992). Engineering properties of soil and their measurements, 4th Edition.

Canencia, O., Palmes, N., Ibonia, S., Talampas, W., Lammawin, V., Kawaling, G., Yañes, S., and Savaña, MJ. (2015) “Minin Industry in Northern Mindanao: Its Environmntal, Social and Health Impact Toward Responsible Mining. 2015”.

Das, B.M. 2010. “Principles of geotechnical engineering”. 7th Ed. Stamfold: Cengage Learning”.

Das, B. M. (2015). Fundamentals of Geotechnical Engineering, 4th Edition.

Ferguson G. and Levorson S.M. (1999). “Soil and Pavement Base Stabilization with Self-Cementing Coal Fly Ash. American Coal Fly Ash Association International, Alexandria, VA

Israel, C. and Asirot J., 2000. Mercury pollution due to small-scale gold mining in the philippines: an economic analysis, 2000-06, 1-62.

Sivakugan, N.,Rankine, R.M., Rankine, K.J., and Rankine, K.S., (2006). Geotechnical considerations in mine backfilling in Australia. Journal of Cleaner Production, 1168-1175.

Supriya Saha and Sujit Kumar Pal. (2013). “Influence of Fly Ash on Unconfined Compressive Strength of Soil and Fly Ash Layers Placed Successively”.

Tay, J. H., & Goh, A. T. (1991). "Engineering properties of incinerator residue. Journal of environmental engineering" 117(2), 224-235.

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