International Journal of GEOMATE, March, 2017, Vol.12, Issue 31, pp. 88-94
Geotec., Const. Mat. & Env., ISSN:2186-2990, Japan, DOI: http://dx.doi.org/10.21660/2017.31.6558

CONSTITUTIVE MODELING OF COAL ASH USING MODIFIED CAM CLAY MODEL

* Erica Elice Saloma Uy [1] and Jonathan R. Dungca [2]

[1]Graduate Student, De La Salle University, Philippines; [2] De La Salle University, Philippines

*Corresponding Author, Received: 15 June 2016, Revised: 18 August 2016, Accepted: 30 Nov. 2016

ABSTRACT: Coal ash is a by-product from coal-fired power plants that generates electricity. These waste materials most of the time is kept in storage facilities. Due to the growing demand in electricity generation, storage facilities can no longer accommodate the waste materials. Instead of disposing the waste materials, it can be used as a construction material. A promising civil engineering structure that can use coal ash as a construction material is land reclamation. The structure needs huge volume of materials and this can maximize the usage of coal ash. In the Philippines, most land reclamation projects are conducted at the sea. From this, distilled water was replaced with sea water to have a better evaluation of the strength properties of coal ash. Consolidated drained test was performed having three conditions with respect to sea water exposure. First condition is no exposure, second condition is immediate exposure and third condition is prolonged exposure. Results show that coal ash exposed to seawater, immediate and prolonged, has smaller shear strength. On the other hand, it still has reasonable strength suitable for land reclamation projects. Constitutive modeling using Modified Cam Clay model is incorporated in the study to be able to predict its behavior and failure in terms of mean effective stress, deviator stress and specific volume.

Keywords: Coal Ash, Critical-State, Modified Cam Clay

1. INTRODUCTION

The Philippine government relies on coal-fired power plant to provide electricity. The country already has 19 power plants, 11 in Luzon, 6 in Visayas and 2 in Mindanao [1]. The Department of Energy recently announced that 23 new power plants will be opened by 2020 [2]. This is to address the increasing demand of electricity of the country. These power plants produce by-products such as fly ash and bottom ash. They are normally stored at impoundments or landfills. There are cases that the capacity of the storage facility is not enough and this leads to problems in proper disposal of the waste materials. This can have a negative impact to the environment and community close to the storage facility. In the Philippines, this incident is possible since coal-fired power plant is one of the main sources of electricity. It provides approximately 40% of the total power generation needed by the country [2]. Furthermore, most power plants operate for 24 hours such as the coal-fired power plant in Calaca, Batangas. The power plant is estimated to discharge at about 62.62 tons of ash per hour [4]. Instead of disposing or storing the by-products it is better to find an alternative use such as a construction material. There are already existing studies that these by-products have a potential in substituting some construction materials for civil engineering structures. A study on its applicability as a sub base material for highway embankments was conducted. Based on the results, it meets the strength requirements for highway embankments [5]. Another study showed its applicability for lightweight concrete production [6]. A promising civil engineering structure that can use the by-product as construction material is land reclamation. This civil engineering structure is normally constructed in areas where there is a shortage in space. This type of structure is usually constructed in the Philippines especially in highly urbanized areas.

It is the objective of this study to determine the performance of the by-product as a construction material. To be specific, bottom ash was tested under Consolidated Drained Triaxial Test. The effect of seawater is considered so distilled water was changed to seawater. Three conditions were simulated in the test, first condition is no exposure, second condition is immediate exposure and third condition is prolonged exposure. Modified Cam Clay model is incorporated to study its behavior with respect to the mean effective stress (p'), deviator stress (q) and specific volume (v).

2. BOTTOM ASH

The bottom ash samples were obtained from IloIlo Power Plant. From visual inspection, the material had three compositions. Particles with the size of small gravels, sand, and fines were present. For the fines, it is lightweight which makes it easily blown away by air. Its index properties are determined similar to [3] and the results are tabulated in Table 1. For the index properties, bottom ash is classified as silty sand (SM). It has no plasticity since liquid limit and plastic limit is zero. It is noticeable that the sample has sufficient amount of sand particles and followed by fines content. Compared to other studies, the result of the specific gravity is higher than the range of values suggested, 1.899 to 1.903 [7]. Their coal ash was from a different manufacturing plant. This might have contributed to the difference in index properties of the coal ashes.

Table 1. Index properties

Index Property	
Specific gravity(Gs)	2.25
Liquid limit(LL)	0.00%
Plastic limt (PL)	0.00%
Maximum void ratio (e_{max})	0.94
Minimum void ratio (e_{min})	0.85
Maximum dry unit weight(γ_{dmax})	13.94 kN/m^3
Optimum water content (ω_{opt})	15.85%
USCS	SM
%Gravel	0.86
%Sand	50.44
%Fines	48.70

Table 2. Chemical composition of sea water

Compound	Concentration,g/L
NaCl	24.53
MgCl	5.2
NaSO	4.09
CaCl	1.16
KCl	0.695
NaHCO	0.201
KBr	0.101
HBO	0.027
SrCl	0.025
NaF	0.003
Ba(NO	9.94E-05
Mn(NO	3.40E-05
Cu(NO	3.08E-05
Zn(NO	9.60E-06
Pb(NO	6.60E-06
AgNO	4.90E-07

3. EXPERIMENTAL PROGRAM

3.1 Triaxial Compression Phase

3.1.1 Sample Preparation

The sample was prepared by moist tamping. Relative compaction was the controlled parameter to achieve a target initial condition. This was used instead of relative density in order to simulate actual site conditions [8], [9]. The target value is 95% since it was the desired in situ condition. The maximum dry density served as the reference point to achieve the target relative compaction. The amount of distilled water or sea water was based on the value of optimum moisture content.

Three conditions were prepared to check the effect of seawater towards the strength of bottom ash. The first one is the sample with no exposure. For this case, only distilled water was mixed with the bottom ash. The second condition is the immediate exposure to sea water. For this case the sample was still prepared similar to the first condition. It is during the Consolidated Drained Test where the sample was exposed to sea water. For the third condition, prolonged exposure was simulated so sea water was already mixed with the bottom ash prior to the Consolidated Drained Test. The amount of sea water is computed based on the optimum moisture content. The samples for the three conditions were soaked for 16 hours as per ASTM provisions.

3.1.2 Sea water Preparation

Artificial sea water was used in the experiment. It was formulated following ASTM D 1141 – 98, also known as the “Standard Practice for the Preparation of Substitute Ocean Water”. A pH value of 8.2 and chlorinity of the sea water was maintained at 19.38. The chemical composition of the sea water is shown in Table 2.

3.1.3 Consolidated Drained

Consolidated Drained Test was performed to evaluate the strength of the sample against long-term loading. The test has three phases namely, saturation, consolidation and shearing phase. The saturation phase was first performed to ensure that the sample is fully saturated. The B-value or the ratio of the pore water pressure and confining pressure was constantly monitored. This parameter must have a value greater than 0.95 to ensure a fully saturated sample. The confining pressures (σ_3) used to consolidate the sample are 50 kPa, 100 kPa, and 200 kPa. They are applied incrementally to have a conservative simulation of the stresses. The sample was allowed to consolidate until there are no significant volume changes in the sample. For the shearing phase, a slow rate of 0.05 mm/min was used to ensure the dissipation of pore water pressure is attained. This phase usually lasts for a minimum of 4 hours to a maximum of 7 hours. For the first condition, 3 samples were tested for each confining pressure. For the second condition, 2 samples were tested for each confining pressure. Lastly for the third condition, 1 sample was tested for each confining pressure.

From this, a total of 18 samples were tested for this experiment.

4. RESULTS AND DISCUSSION

4.1 Stress-Strain Behavior and Mode of Failure

The stress-strain plots, Fig. 1, presented in this section were based on the sample's critical state or at failure condition. Based on the results, it was observed that all trials for each condition had a similar trend. Therefore, the results presented in this section are based on the last trial.

When no exposure to sea water was tested, it can be seen that at 200 kPa the sample experienced yield at less than 0.1% axial strain. At this point, the sample already exceeded its elastic limit. Following this behavior, the sample reached its plastic state as it is being axially compressed. Strain hardening is more pronounced after the yielding of the soil. This behavior is only visible in this condition. A common trend from all the condition is no defined peak can be seen in the stress-strain plot. Furthermore, the deviator stress and axial strain increases as the confining pressure was increased. The no exposure to sea water condition and prolonged exposure to sea water had almost the same results when it comes to the values the deviator stress experienced. The axial strain for no exposure to sea water had a larger value. For the immediate exposure condition, the deviator stresses are smaller. Based on the stress-strain behavior, prolonged exposure to sea water has minimal impact to the behavior of the bottom ash since it arrived at a similar trend with the first condition.

For its mode of failure, shear failure was observed for all tests as seen in Fig. 3. It is expected when the sample is a brittle sample. Only samples that are sandy can experience this type of failure. From this, the bottom ash used can be classified as a brittle sample. Furthermore, the presence of sufficient amount of sand in its composition contributed to this type of failure.

4.2 Critical-State Parameters

The critical state parameters were established based on the critical state model. The slope, M, of the critical state line (CSL) with respect to the deviator stress and mean normal effective stress was first established. This parameter can be obtained from Fig. 3. The area below CSL is the safe zone or the stresses where the sample is still in its elastic state. Based on the results, the second condition had the smallest slope, 1.3531. The third condition has the largest value of 1.4914. The slope has a relation to the effective critical angle of internal friction (φ'_{crit}) as shown [10]:

$$\sin\varphi'_{crit} = \frac{3M}{6+M} \quad (1)$$

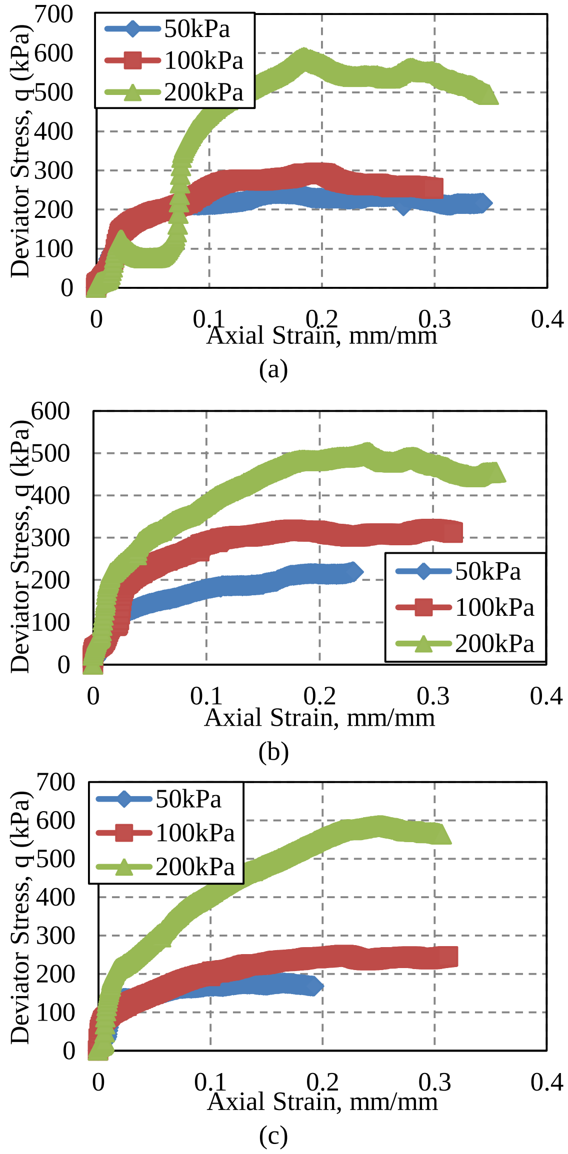


Fig. 1 Stress-strain plot of Bottom Ash a) no exposure b) immediate exposure and c) prolonged exposure.

The resulting values are as follows, 33.51°, 35.26°and 36.67° for the first, second and third condition, respectively. These values are the typical result of silty sand [11].

The equations for isotropic normal compression line (NCL) are also established to determine the critical state line of the bottom ash, Table 3. The equations resemble the equation of the line. From this, the critical state parameters such as slope of NCL (λ), y-intercept of NCL (N_p) and y-intercept of CSL (Γ) can also be established from the equations and are presented in Table 4. These parameters are used to plot create CSL with respect to the deviator stress and the mean normal effective stress. A sample plot is shown in Fig. 4. The points of NCL are from the consolidation phase while the points along CSL are from the shearing phase. The area beyond NCL is the impossible state. The area below NCL is where over-consolidation is encountered. On the other hand, the area below CSL is where expansion happens.

Fig. 2 Mode of failure for bottom ash.

The NCL and CSL for condition 1 and 2 were combined as seen in Fig. 5 and 6. Different behaviors can be observed from the 2 conditions. It is expected that as the confining pressure is increasing the specific volume is also increasing. For the first condition, the specific volume for 50 kPa and 200 kPa are almost similar. On the other hand, for 100 kPa, its specific volume decreased dramatically. The particle rearrangement for this confining pressure is larger compared to 50 kPa and 200 kPa. For the CSL, same observations can be seen for the specific volume. For the mean normal effective stress, 200 kPa had the largest values. For the second condition as seen in Fig. 6, the values of specific volume of NCL for 50 kPa and 100 kPa are almost the same. It can be observed that 50 kPa had slightly higher values. This is also evident for the CSL plot. The exposure to sea water may have affected the results of NCL and CSL of the second condition. The sample were 100 kPa was applied seemed weaker than the other samples for second condition.

Table 3. Isotropic normal compression line equations

σ_3	No Exposure	Immidiate Exposure
50kPa	2.2149 - 0.0954lnp'	1.9657 - 0.0602 lnp'
100kPa	2.8058- 0.2736 lnp'	1.9548 - 0.0684 lnp'
200kPa	2.1871- 0.0845 lnp'	2.4674 - 0.0922lnp'

Table 4. Critical state parameters

	σ_3	λ	N_p	Γ
No Exposure	50kPa	0.0954	2.2149	2.1195
	100kPa	0.2736	2.8058	2.5322
	200kPa	0.0845	2.1871	2.1026
Immediate Exposure	50kPa	0.0602	1.9657	1.9055
	100kPa	0.0684	1.9548	1.8864
	200kPa	0.0922	2.4674	2.3752

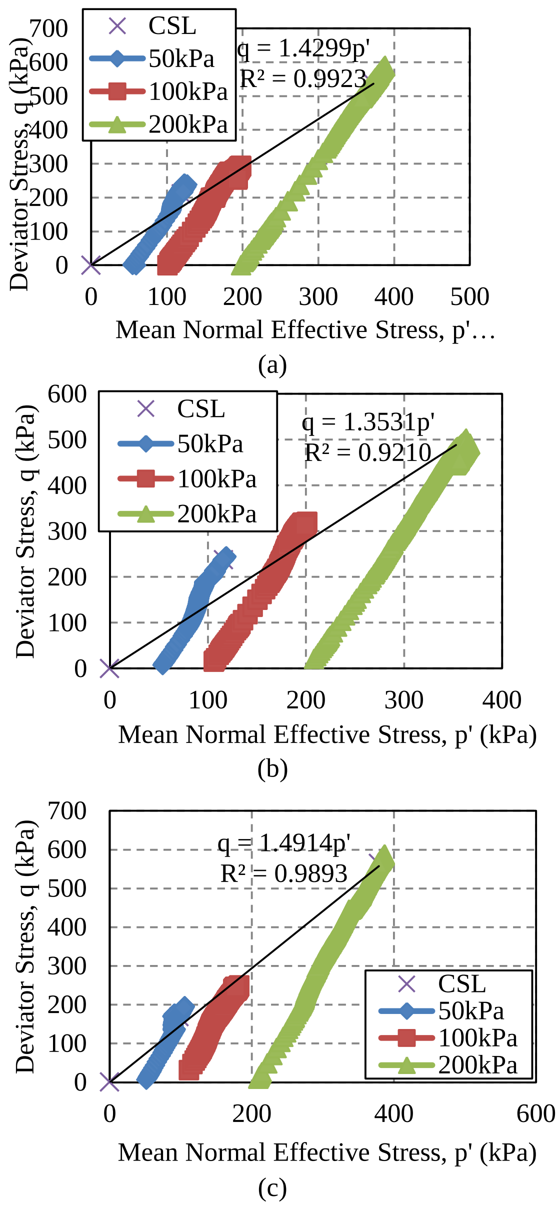


Fig. 3 Critical state line with respect to the deviator stress and mean normal effective stress a) no exposure b) immediate exposure and c) prolonged exposure.

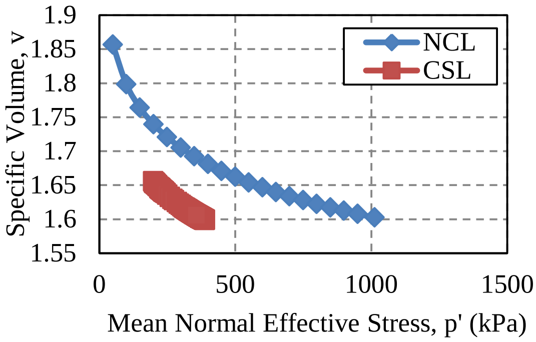
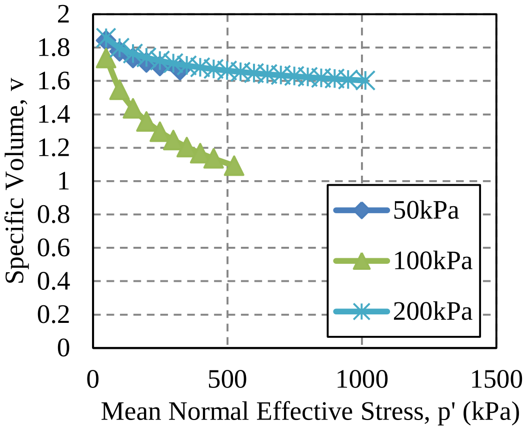
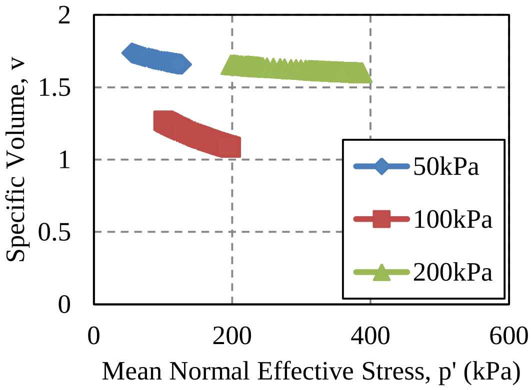


Fig. 4 Critical state line with respect to the deviator stress and mean normal effective stress a) no exposure b) immediate exposure and c) prolonged exposure.



(a)



(b)

Fig. 5 Specific volume versus mean normal effective stress plot for no exposure to sea water a) NCL and b) CSL.

4.3 Modified Cam Clay Model

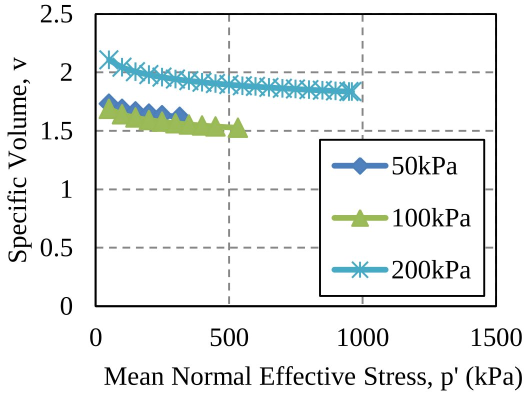
Modified cam clay model (MCC) is an elasto-plastic model that characterizes the soil in terms of the mean normal effective stress, deviator stress and specific volume [12]. The model is the result of the enhancements made in the Cam Clay Model.

The model has an elliptical yield locus having this equation [10]:

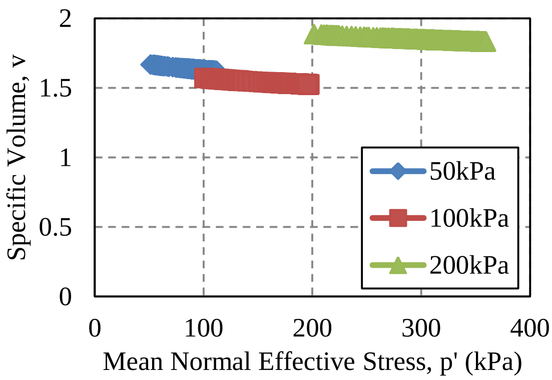
$$\frac{p'}{p'_c} = \frac{M^2}{M^2 + q/p'} \tag{3}$$

where:
p' = mean normal effective stress
q = deviator stress
p'_c = preconsolidation stress
M = slope of CSL from q vs p'

The preconsolidation stress is estimated by using Eq. 3. The q and p' at critical state was used [10]. The largest preconsolidation stress bottom ash can withstand is 1030.02 kPa. This value was obtained from the third condition. The equations presented were used to create the yield locus seen in Fig. 7 for a sample with a confining pressure of 200 kPa. Only the equations with 200 kPa are presented since it can cover all the stresses from 50 kPa and 100 kPa. It can be seen that Eq. 5 had the smallest preconsolidation stress and slope M.



(a)



(b)

Fig. 6 Specific volume versus mean normal effective stress plot for immediate exposure to sea water a) NCL and b) CSL.

$$\frac{p'}{1013.16} = \left(\frac{1.4299^2}{1.4299^2 + \left(q^2/p'^2\right)}\right)$$

(4)

$$\frac{p'}{960.27} = \left(\frac{1.3531^2}{1.3531^2 + \left(q^2/p'^2\right)}\right)$$

(5)

$$\frac{p'}{1030.02} = \left(\frac{1.4914^2}{1.4914^2 + \left(q^2/p'^2\right)}\right)$$

(6)

The yield locus presented in Fig. 7 serves as the boundary of the soil with respect to plastic and elastic state. A similar trend was observed for all samples for the plot of yield locus. Points within the yield locus are stresses at the elastic state while points beyond are at its plastic state or failure state.

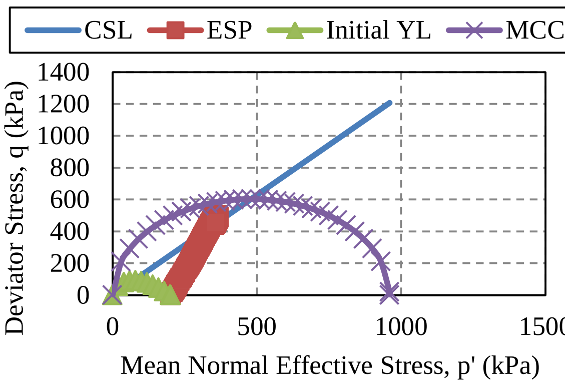


Fig. 7 Stress path with yield locus of bottom ash CD test with 200 kPa confining pressure.

5. CONCLUSION

Bottom ash was tested under Consolidated Drained Triaxial Test. The objective of the study was to investigate on the possibility of using the by-product as a material for reclamation. Exposure to sea water was considered since most reclamation projects are situated at the sea. Three conditions were considered, no exposure, immediate exposure and prolonged exposure. Results show that prolonged exposure to sea water has a minimal difference when compared to the no exposure condition. The values of effective critical angle of internal friction are as follows 33.51°, 35.26°and 36.67°. The value is comparable to a silty soil were its typical values ranges from 26° to 35°. For the Modified Cam Clay Model, the preconsolidation stress was computed and a similar trend was observed. The computed maximum value is 1030.02 kPa. The value is from the prolonged exposure condition. Furthermore, the material is still at its elastic state at a maximum deviator stress of 600 kPa and maximum mean normal effective stress of 500 kPa. From this, bottom ash is a promising material that can be used in a reclamation project.

6. ACKNOWLEDGEMENTS

First of all I would like to thank my adviser Dr. Jonathan Dungca for his encouragement, support, and guidance through the initial and final stages of completing this paper. Furthermore, I would like to thank Dr. Mary Ann Adajar, for his advice in further improving the research. I would also like to thank my friends and family, for motivating and inspiring us to give our best in making this paper. I would also like to thank the Civil Engineering Department of De La Salle University for their unending support. Lastly I would like to thank God for giving me the courage, wisdom and humility to finish this research.

7. REFERENCES

[1] Department of Energy. (2016). List of existing power plants as of December 2015. Retrieved from http://www.doe.gov.ph/power-and-electrification/list-of-existing-power-plants.

[2] Gonzales, I. C. (2015). 23 new power plants to go online by 2020. The Philippine Star. Retrieved from http://www.philstar.com/business/2015/06/15/1465896/23-new-power-plants-go-online-2020.

[3] Dungca, J. R. & Dychangco L. F. T. (2016). Strength properties of road base materials blended with waste limestones. International Journal of Geomate. 11(25). 2493-2498

[4] Antonio, O. (2006). Lime-fly ash stabilization of Calaca, Batangas bottom ash. [Graduate Thesis] University of the Philippines, Quezon City, Philippines.

[5] Jao, J. (2012). Strength and permeability characteristics of road base materials blended with fly ash and bottom ash. [Graduate Thesis]. De La Salle University, Manila, Philippines

[6] Ahmaruzzaman, M. (2010). A review on the utilization of fly ash. Progress in Energy and Combustion Science, 36(3), 327-363. Elsevier Ltd. doi:10.1016/j.pecs.2009.11.003

[7] Antonio, O. V. M., & Zarco, M. A. H. (2007). Engineering properties of Calaca Batangas bottom ash, 28(1), 37–56.

[8] Zabielska-Adamska, K. (2006). Shear strength parameters of compacted fly ash–HDPE geomembrane interfaces. Geotextiles

andnGeomembranes,n24(2),n91–102. doi:10.1016/j.geotexmem.2005.11.006.
[9] Kim, B., Prezzi, M., & Salgado, R. (2005). Geotechnical properties of fly and bottom ash mixtures for use in highway embankments, 914-924.
[10] Powrie, W. (2004). Soil Mechanics Concepts and Applications Second Edition. London: Spoon Press.
[11] Das, B. & Sobhan, K. (2014). Principles of Geotechnical Engineering Sixth Edition, United States: Chris Carson**.**
[12] Munda, J., Pradhan, P. K. & Nayak, A. K. (2014). A Review on the performance of Modified Cam Clay Model for fine grained soil. Journal of Civil Engineering and Environmental Technology. 1(5), 65-71.