Pertanika J. Sci. & Technol. 28 (S2): 149 - 160 (2020)

SCIENCE & TECHNOLOGY

Journal homepage: http://www.pertanika.upm.edu.my/

Physical and Mechanical Study of Palm Oil Fuel Ash (POFA) based Geopolymer as a Stabilizer for Soft Soil

Isam Adnan Khasib[1] and Nik Norsyahariati Nik Daud[1,2]*

[1]*Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia*
[2]*Housing Research Center (HRC), Faculty of Engineering, Universiti Putra Malaysia, 43400, Serdang, Selangor, Malaysia*

ABSTRACT

Construction of structures on soft soil is a challenging task and considered as one of the biggest concerns in geotechnical engineering. Binders that are environmentally friendly such as fly ash based geopolymer have been explored widely. In this study, the agro-waste material, Palm Oil Fuel Ash (POFA) was used to produce an environmentally friendly geopolymer binder to be used in soft soil stabilization. POFA was used in three ratios; 10%, 20% and 30% of dry weight of soil to produce geopolymer. Sodium hydroxide (NaOH) was used as an alkali activator at 12 molarity along with sodium silicate (Na_2SiO_3). Physical properties of soil (Atterberg Limits, Plasticity Index, and Linear Shrinkage Limit) and compaction assessment; before and after mixing with the geopolymer binder were investigated. The studied soil was classified as an inorganic high plasticity silt (MH), according to the Unified Soil Classification System (USCS). From compaction results; optimum moisture content (OMC) values showed a decreased pattern from 24.7% to 17.5%; and maximum dry density (MDD) increased from 1.37 Mg/m^3 to 1.73 Mg/m^3 for geopolymer with POFA ranging from 0% to 30% of the dry weight of soil, respectively. The optimum dosage of POFA based geopolymer was found to be 30% according to all tests mentioned. These properties suggest the potential use of the agro-waste based geopolymer binder to stabilize the soft soil.

Keywords: Agro-waste, geopolymer, geotechnical properties, palm oil fuel ash, soft soil, stabilization

ARTICLE INFO

Article history:
Received: 10 February 2020
Accepted: 13 November 2020
Published: 31 December 2020

DOI: https://doi.org/10.47836/pjst.28.S2.12

E-mail addresses:
essamkasseeb@gmail.com (Isam Adnan Khasib)
niknor@upm.edu.my (Nik Norsyahariati Nik Daud)
* Corresponding author

INTRODUCTION

Population growth and space limitations make soil improvement necessary to provide a strong underground layer to assist in

ISSN: 0128-7680
e-ISSN: 2231-8526

infrastructure construction. Expansive and plastic soils are considered a destruction that damages the foundations, roads and water networks, so this is considered a huge challenge to geotechnical engineers.

Stabilization of soil has been widely investigated by many studies using traditional binders such as lime, cement or a combination of both (Asgari et al., 2015; Wang et al., 2018). Although they have shown their effectiveness in soil stabilization, they have some deficiencies. Too much consumption of energy and natural resources for the production process make these binders unsuitable for stabilization as well as their financial and environmental issues. Cement manufacture produces a lot of CO_2 emissions, and CO_2 has been proven to be one of the main causes of global warming and high temperature associated (Gartner, 2004; Matthews et al., 2009). It was indicated that for producing 1 ton of cement, nearly 1 ton of CO_2 was emitted (Du et al., 2016). Moreover, CO_2 emitted due to cement production forms around 7% of the total greenhouse gases in the atmosphere (Criado et al., 2007).

Other cementitious materials used in stabilization include aluminosilicate materials such as fly ash. The intent of using fly ash in soil stabilization is for industrial wastes disposal and the good strength associated when applied to the soil. Kolias et al. (2005) studied the effectiveness of using high calcium fly ash along with cement in high and low plastic clay soils stabilization and the results showed that tensile, compressive and flexural strength, modulus of elasticity was enhanced. The main types of fly ash are class C and class F fly ash. Nalbantoğlu (2004) used class C fly ash to stabilize expansive soil and after laboratory testing, the results indicated that class C fly ash reduced clay size particles, plasticity index and the swell potential which led to texture and plasticity improvement of soil. In addition to that, class F fly ash has been investigated to stabilize sandy soil to be used as base layers in highways when combined with cement since it cannot be used alone due to low reactivity with soil (Arora & Aydilek, 2005). By-products agricultural wastes such as palm oil fuel ash (POFA) has shown its capability as good binder in soil stabilization. POFA has proven it's possibility to replace the use of cement in stabilization of peat soil based on unconfined compression tests since it has shown high strength comparing to cement stabilized soil (Ahmad et al., 2011). Moreover, Nik Daud et al. (2018) investigated both agricultural wastes, palm oil fuel ash and rice husk ash and they had shown their effectiveness in stabilization in terms of physical properties and optimum conditions of soil.

However; in recent years, researchers started looking for binders that could provide better strength, replacing the disadvantages of traditional binders and be environmental friendly at the same time. They came up with the idea of what was called geopolymer to be considered as the next generation. Geopolymer can be defined as an inorganic polymer mainly from Al and Si with 3D cross-linked polysialate chains structure with an empirical formula of M_n [-(SiO_2) z-AlO_2] H_2O, where M is an alkali cation, z is the Si/Al molar ratio, n is the polymerization degree (Duxson et al., 2007).

Alkali activation process happens when adding an alkali activator such as NaOH, KOH, Na_2SiO_3, K_2SiO_3 or a combination of them to the fly ash and the result is called alkali activated material or geopolymer. The need of a liquid alkali activator is to dissolve the aluminum (Al) and silicon (Si) found in fly ash to help in the geopolymerization process by forming aluminosilicate gels (Pourakbar et al., 2016). Factors affecting geopolymer characteristics and strength include type and chemical composition of aluminosilicate material used, type and molarity of alkali activator, alkali activator to aluminosilicate material ratio, curing time and curing temperature. Preparation and physical structure of different types of fly ash based geopolymer corresponding to their expected compressive strength as well as their applications have been reported (Zhuang et al., 2016). In recent years, many researches started investigating the feasibility of using aluminosilicate materials in producing geopolymer to be used to stabilize the soft soil (Phetchuay et al., 2016; Phummiphan et al., 2016). Rivera et al. (2020) studied clay soil stabilization using alkali activated fly ash (two types of fly ash) mixed with granulated blast-furnace slag (GBFS) and lime; and tested for unconfined compressive strength (UCS), flexural strength (FS) and durability where NaOH and Na_2SiO_3 were used as alkaline activator. Moreover, Teing et al. (2019) investigated the efficiency of using alkali activated fly ash at high percentages in stabilization of residual soil using unconfined compressive strength, scanning electron microscope (SEM) and energy dispersive X-ray spectroscopy (EDX) tests. Furthermore, fly ash along with coir fibers in an alkaline environment have been used to stabilize soft soil for subgrade applications (Tan et al., 2019). A comparative study made using fly ash in stabilizing soil with and without alkali activator found that strength of alkali activated fly ash was increased from 0.3 to 2.8 MPa at 28 days (Rios et al., 2016).

In very limited trials, agricultural wastes based geopolymer such as Palm oil fuel ash (POFA) based geopolymer have been employed in stabilization of clayey soil. Pourakbar et al. (2015) used alkali activated palm oil fuel ash to stabilize high plasticity clay and it was concluded that alkali activated agricultural waste was an efficient binder that could extinguish the use of cement and be environmentally friendly at the same time. Also, Sukmak et al. (2017) studied strength and microstructural properties of soil stabilized with POFA based geopolymer to find the optimum ratios of alkali activator and POFA. However, most research efforts focused on the microstructural properties of POFA based geopolymer stabilized soil such as scanning electron microscope (SEM), fourier transform infrared (FTIR) and X-ray diffraction tests; and mechanical properties such as unconfined compressive strength. For a better understanding of stabilization with POFA based geopolymer, identification of physical properties (liquid limit, plastic limit and shrinkage limit); and pH of soft soil stabilized with POFA based geopolymer is required. Plasticity is known to have a huge influence on soil stabilized performance (Little & Nair, 2009). Therefore, such agricultural waste geopolymer binder should be clearly studied to understand its impact on the properties of soft soil.

The primary aim of this researh was to investigate the effectiveness of using POFA as an agro-waste based geopolymer binder to stabilize soft soil. Due to that matter, physical and chemical properties of soft soil before and after treatment with POFA based geopolymer had been investigated to identify the feasibility of using such binder in soil stabilization. Furthermore, optimum conditions of soil; optimum moisture content (OMC) and maximum dry density (MDD) of treated and untreated soil with POFA based geopolymer would be determined by compaction behavior.

MATERIALS AND METHODS

The materials used to produce POFA based geopolymer in this research were: Palm oil fuel ash (POFA) and alkali activators; sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). POFA was obtained from Tenaga Sulpom Sdn Bhd, Selangor, Malaysia; and it was a residue after the burning of palm oil fibers and bunches in furnace to generate electricity and the waste generated named as POFA. Alkali activators were provided by a chemical supplier in Kuala Lumpur, Malaysia; NaOH was provided in pellets while Na_2SiO_3 was in liquid phase.

Soil Sample

The soil sample used in this study was categorized as a residual soil. Residual soil is a soil in which parent material has decomposed in situ. The soil was naturally dried and an oven was used to remove any moisture content before the testing process was carried out. After drying, the soil was separated manually using a small hammer and mechanically with a soil grinder to be ready for physical properties, pH and compaction tests.

Palm Oil Fuel Ash (POFA)

POFA was dried in the oven at 110 ± 5°C inside the laboratory. After drying, POFA was sieved using 300 µm sieve to remove large and not fully combusted materials. Since particles size of POFA highly affects the strength of POFA based geopolymer, a smaller size of particles should be obtained (Sharma et al., 2019). Therefore, after sieving the dried POFA, it was pulverized using Los Angeles abrasion machine by rotating the drum 30,000 cycles as shown in Figure 1 (Ranjbar et al., 2014). The prepared POFA was kept sealed in order not to get any moisture content from the surrounding that may affect stabilization process.

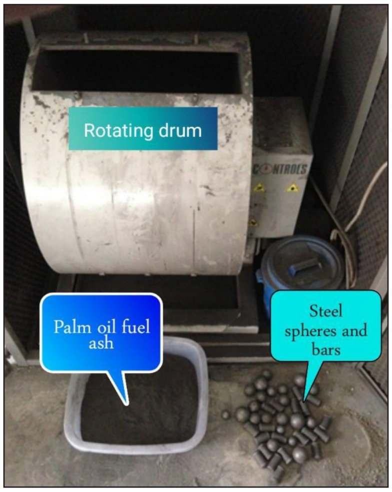

Figure 1. Los Angeles abrasion machine used in the study

Alkaline Activators

In this study, sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH) were used as alkali activators (L). Sodium hydroxide (NaOH) was dissolved in distilled water to prepare a 12-molarity sodium hydroxide (NaOH) solution. The solution was kept for 24 hours before it was mixed with sodium silicate (Na_2SiO_3). Since the molarity of the alkali solution was very high, the preparation was handled with gloves and mask.

POFA Based Geopolymer

Palm oil fuel ash was mixed with sodium silicate (Na_2SiO_3) and sodium hydroxide (NaOH). Ratio of sodium silicate to sodium hydroxide used was 2.5 and ratio of POFA to liquid alkali activator (L) which is combined between Na_2SiO_3 and NaOH was 1.32. These ratios were kept invariables during testing to investigate the feasibility of increasing geopolymer dosage and its effect on soil properties. After preparation of POFA and L in the proper weights, they were mixed inside a mixer for 10 minutes at a slow mode to produce a homogenous geopolymer. POFA based geopolymer before application to soil is shown in Figure 2.

Figure 2. POFA based geopolymer using 10% POFA material

Sample Preparation and Characterization Tests

Three POFA based geopolymer mixes were prepared and poured into soil. These mixes were prepared using POFA to be 10%, 20% and 30% of the dry weight of soil and then calculating the required quantities of NaOH and Na_2SiO_3 to produce the geopolymer before the application to soil. Table 1 illustrates the calculated weights of alkali activators (L); NaOH, Na_2SiO_3 and POFA used for 1 kilogram of dry soil. After geopolymer preparation, the soil was added to the geopolymer and mixed for another 10 minutes to ensure that the mixture is homogenous and then tested immediately. For testing methods, Physical properties of soil including Atterberg limits (liquid limit; LL and plastic limit; PL) and linear shrinkage limit were tested in accordance to British standard (British Standard Institution, 1990) before and after application of POFA based geopolymer to soil. Optimum moisture content (OMC) and maximum dry density (MDD) were investigated according to British Standard (British Standard Institution, 1990) by standard proctor compaction test. Moreover, pH of natural soil and treated samples had been studied using pH meter after curing for 8 hours to know the effect of alkali activator on soil's acidity and alkalinity before and after treatment.

Table 1
Geopolymer ingredients for each 1 kg of soil

# of geopolymer mixture	POFA (%)	POFA (g)	L (g)	NaOH (g)	Na_2SiO_3 (g)
1	10	100	76.9	22	54.9
2	20	200	153.8	44	109.8
3	30	300	230.8	66	164.8

Note. POFA – palm oil fuel ash; L – Liquid alkali activator, NaOH – sodium hydroxide, Na_2SiO_3 – sodium silicate

RESULTS AND DISSCUSION

Physical and Chemical Properties of POFA Based Geopolymer Stabilized Soil

The basic characteristics of soil before any treatment are illustrated in Table 2. According to Unified Soil Classification System (USCS), the soil was classified as inorganic high plasticity silt (MH) with liquid and plastic limits values are 50.8% and 31.5%, respectively. Figure 3 shows the particle size distribution of the soil examined with percent of passing sieve no. 200 is 52.2%. Although this type is not the most critical type of soil, it is still one of the challenges to geotechnical engineers. The chemical composition of POFA using XRF test is illustrated in Table 3**.** pH of untreated soil was 4.01 (as shown in Table 2) which indicates a strong acidic behavior, and this is due to the agricultural activities accompanying with the heavy use of fertilizers at the sample's location. According to the results shown in Table 4, liquid limit and plastic limit for the treated soil have shown a consistent behavior. Liquid limit and plastic limit increased almost steadily when increasing the dosage of POFA based geopolymer comparing to the untreated soil. This refers to the small particles' size of POFA mixed with the soil which results in high specific surface area of the particles. Therefore, increasing the surface area will increase the required water to cover the particles, resulting in liquid and plastic limit's increase (Taha, 2009).

Table 2
Physical properties of studied soil

Soil property	Unit	Standard	Value
pH	-	BS 1377: Part 3	4.01
Initial moisture content	%	BS 1377: Part 2	30.8
Specific gravity	-	BS 1377: Part 2	2.62
Plastic limit	%	BS 1377: Part 2	31.5
Liquid limit	%	BS 1377: Part 2	50.8
Shrinkage limit	%	BS 1377: Part 2	5.4
Optimum moisture content	%	BS 1377: Part 4	24.7
Maximum dry density	Mg/m^3	BS 1377: Part 4	1.37

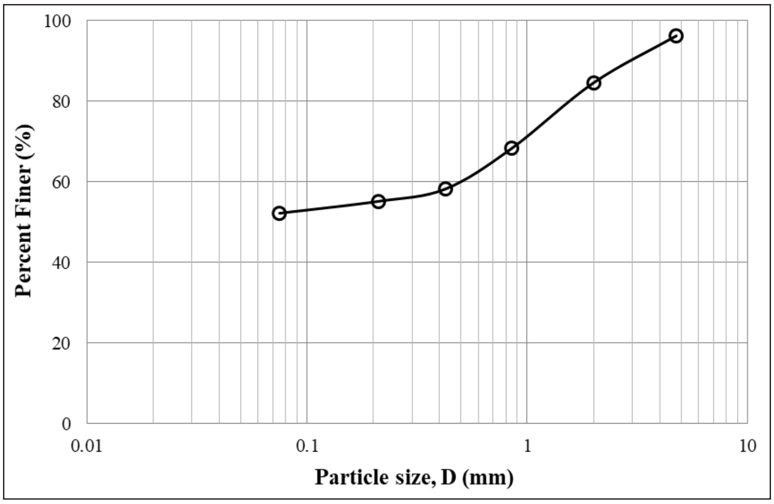

Figure 3. Particle size distribution curve of studied soil

Table 3
Chemical composition of POFA using XRF test

Component	%
Silicon dioxide (SiO_2)	42.23
Aluminum oxide (Al_2O_3)	16.88
Calcium oxide (CaO)	12.1
Potassium oxide (K_2O)	9.56
Sodium oxide (Na_2O)	5.83
Iron oxide (Fe_2O_3)	2.76
Magnesium oxide (MgO)	1.31

Table 4
Physical and chemical properties of soil treated with POFA – based geopolymer

Properties	Unit	Geopolymer in soil (%)			
		0	10	20	30
Plastic limit	%	31.5	34.6	38.3	40.1
Liquid limit	%	50.8	53.4	57.5	59.2
Shrinkage limit	%	5.4	5.2	4.7	4.5
Plasticity index	%	19.3	18.8	19.2	19.1
pH	-	4.01	12.8	13.92	14.0

However, some variations were exhibited regarding the plasticity index values. The highest value of plasticity index, which is the difference between, and liquid and plastic limits appeared in untreated soil and the lowest value was found to be at 10% POFA mixture.

The linear shrinkage limit decreased while increasing the percentage of geopolymer in the soil. The shrinkage value of untreated soil was 5.4% and then started to decrease by adding POFA based geopolymer. In particular, this reduction in shrinkage was mainly contributed by the strong bonding – geopolymer cementitious bonds combine soil particles together- and well arrangement of POFA within the soil particles in the existence of an alkali activator which works as a lubricant to facilitate the integration of geopolymer with soil resulting in low shrinkage limit.

Mixing soil with POFA based geopolymer produced a strong increase in pH, ranging from 12.8 until 14.0 for geopolymer-soil mixture with POFA ranging from 10% to 30% of soil dry weight. Clearly, this increase in pH reflects the ability of hydroxide ions (OH-) found in the alkali activator to generate the hydrolysis of alumina-silicate bonds in the geopolymer by increasing the value of pH to assist in the condensation reactions (Abdullah et al., 2020). The minimum pH value needed to sustain the geopolymerization process is 11 (Garcia-Lodeiro et al., 2015); in this study all values of pH were above 11, this indicates that geopolymerization process is effective and takes a place.

Liquid limit and plasticity index values for all samples tested were plotted on plasticity index chart as indicated in Figure 4. It shows that there was no considerable effect on the class of the original soil sample since all samples lie under A-line (soil was MH and remained MH before and after treatment). Also, it can be clearly observed that there was no noticeable change in plasticity index value.

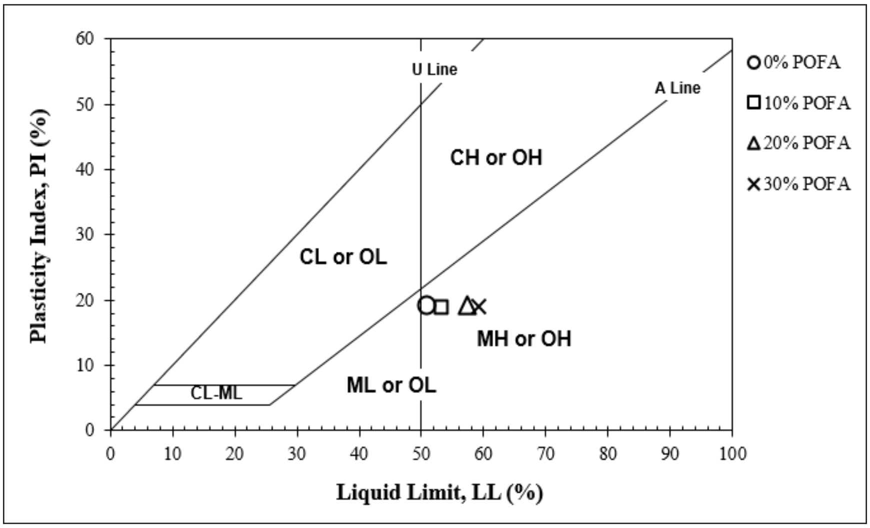

Figure 4. Plasticity index chart

Compaction Behavior

Figure 5 shows the moisture content and dry density relationship for untreated soil and treated samples. According to the curves, optimum moisture content (OMC) shows a decreasing pattern while maximum dry density (MDD) reveals an increment when increasing the geopolymer dosage. When POFA in the geopolymer mix increased from 0% to 30% of dry weight of soil, MDD increased from 1.37 Mg/m^3 to 1.73 Mg/m^3 and OMC decreased from 24.7% reaching to 17.5%. Undoubtedly, this is due to the effects of alkali activators used to produce the geopolymer mix since they performed as a lubricant that reduced the friction and repulsion forces; and improved sliding between soil particles which increased the dry density. Also, lubrication effect reduced the amount of free water required to obtain the optimum conditions, resulting in lower optimum moisture content.

Geopolymer with 30% POFA of the dry weight of soil showed the optimum conditions regarding maximum dry density and optimum moisture content between all treated samples with values 1.73 Mg/m^3 and 17.5%, respectively. This outcome was expected since the maximum quantity of alkaline activators were added in this mixture and could dissolve most of silicon and aluminum present in the POFA and soil compared to other dosages, leading to better OMC and MDD (Cristelo et al., 2011). Table 5 depicts the exact values of optimum moisture content and maximum dry density of the treated and untreated samples.

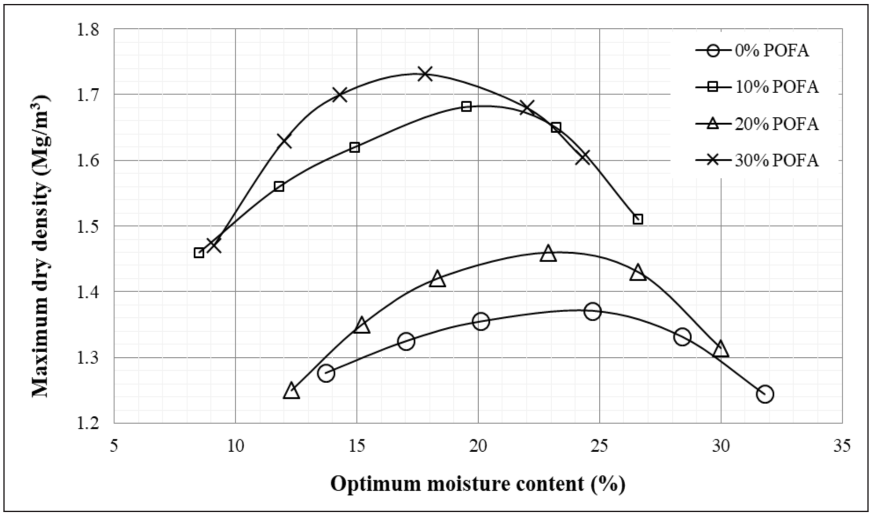

Figure 5. Maximum dry density and optimum moisture content curves of untreated and treated soil

Table 5
Compaction properties of treated and untreated soil

Parameter	Unit	Geopolymer (%)			
		0	10	20	30
OMC	%	24.7	23.0	20.3	17.5
MDD	Mg/m^3	1.37	1.48	1.68	1.73

Note: OMC – optimum moisture content, MDD – maximum dry density

CONCLUSION

This paper has described the effectiveness of using POFA as an agro-waste based geopolymer binder to stabilize soft soil. It can be concluded that POFA based geopolymer can be considered a potential binder to be used in soil stabilization. Treated soil has shown to have better plasticity behavior after mixed with geopolymer. Palm oil fuel ash based geopolymer has improved physical properties of soil including Atterberg limits, optimum moisture content and maximum dry density. It was realized that there were some changes in values of each property studied especially in the determination of optimum conditions of the treated soil. Finally, this study suggested the applicability of using agro-waste based geopolymer binder to stabilize the soft soil.

ACKNOWLEDGEMENT

The authors would like to express deep gratitude for the technical and financial support offered by the Civil Engineering Department, Engineering Faculty, Universiti Putra Malaysia.

REFERENCES

Abdullah, H. H., Shahin, M. A., Walske, M. L., & Karrech, A. (2020). Systematic approach to assessing the applicability of fly-ash based geopolymer for clay stabilization. *Canadian Geotechnical Journal*, *57*(9), 1356-1368. doi:10.1139/cgj-2019-0215

Ahmad, J., Abdul Rahman, A. S., Mohd Ali, M. R., & Khif, K. F. (2011, December 5-6). Peat soil treatment using POFA. In *2011 IEEE Colloquium on Humanities, Science and Engineering Research* (pp. 66–70). Penang, Malaysia. doi:10.1109/CHUSER.2011.6163816

Arora, S., & Aydilek, A. H. (2005). Class F fly-ash-amended soils as highway base materials. *Journal of Materials in Civil Engineering*, *17*(6), 640–649. doi:10.1061/(asce)0899-1561(2005)17:6(640)

Asgari, M. R., Baghebanzadeh Dezfuli, A., & Bayat, M. (2015). Experimental study on stabilization of a low plasticity clayey soil with cement/lime. *Arabian Journal of Geosciences*, *8*(3), 1439–1452. doi:10.1007/s12517-013-1173-1

British Standard Institution (1990). *BS 1377: 1990. Method of test for soils for civil engineering purposes. Part 5: Compressibility, permeability and durability test*. London, United Kingdom: British Standards Institute.

Criado, M., Fernández-Jiménez, A., de la Torre, A. G., Aranda, M. A. G., & Palomo, A. (2007). An XRD study of the effect of the SiO2/Na2O ratio on the alkali activation of fly ash. *Cement and Concrete Research*, *37*(5), 671–679. doi:10.1016/j.cemconres.2007.01.013

Cristelo, N., Glendinning, S., & Teixeira Pinto, A. (2011). Deep soft soil improvement by alkaline activation. *Proceedings of the Institution of Civil Engineers: Ground Improvement*, *164*(2), 73–82. doi:10.1680/grim.900032

Du, Y. J., Bo, Y. L., Jin, F., & Liu, C. Y. (2016). Durability of reactive magnesia-activated slag-stabilized low plasticity clay subjected to drying-wetting cycle. *European Journal of Environmental and Civil Engineering*, *20*(2), 215–230. doi:10.1080/19648189.2015.1030088

Duxson, P., Fernández-Jiménez, A., Provis, J. L., Lukey, G. C., Palomo, A., & Van Deventer, J. S. J. (2007). Geopolymer technology: The current state of the art. *Journal of Materials Science*, *42*(9), 2917–2933. doi:10.1007/s10853-006-0637-z

Garcia-Lodeiro, I., Palomo, A., & Ernandez-Jimenez, A. F. (2015). Crucial insights on the mix design of alkali-activated cement-based binders. In Pacheco-Torgal, F., Labrincha, J., Leonelli, C., Paloma, A. and Chindaprasit, P. (Ed.), *Handbook of alkali-activated cements, mortars and concretes* (pp. 49-74). Cambridge, United Kingdom: Woodhead Publishing. doi:10.1533/9781782422884.1.49

Gartner, E. (2004). Industrially interesting approaches to "low-CO_2" cements. *Cement and Concrete Research*, *34*(9), 1489–1498. doi:10.1016/j.cemconres.2004.01.021

Kolias, S., Kasselouri-Rigopoulou, V., & Karahalios, A. (2005). Stabilisation of clayey soils with high calcium fly ash and cement. *Cement and Concrete Composites*, *27*(2), 301–313. doi:10.1016/j.cemconcomp.2004.02.019

Little, D., & Nair, S. (2009). *Recommended practice for stabilization of subgrade soils and base materials.* Texas, USA: National Cooperative Highway Research Program, Transportation Research Board of the National Academies. doi:10.17226/22999

Matthews, H. D., Gillett, N. P., Stott, P. A., & Zickfeld, K. (2009). The proportionality of global warming to cumulative carbon emissions. *Nature*, *459*(7248), 829–832. doi:10.1038/nature08047

Nalbantoğlu, Z. (2004). Effectiveness of class C fly ash as an expansive soil stabilizer. *Construction and Building Materials*, *18*(6), 377–381. doi:10.1016/j.conbuildmat.2004.03.011

Nik Daud, N. N., Sadan, N. A., Adesiji, R., & Anijiofor, S. C. (2018, November 7-9). Soil properties of residual soil mixed with agricultural waste ashes. In *Proceeding of 1st International Civil Engineering Conference* (pp. 165-169). Minna, Nigeria

Phetchuay, C., Horpibulsuk, S., Arulrajah, A., Suksiripattanapong, C., & Udomchai, A. (2016). Strength development in soft marine clay stabilized by fly ash and calcium carbide residue based geopolymer. *Applied Clay Science, 127-128,* 134-142. doi:10.1016/j.clay.2016.04.005

Phummiphan, I., Horpibulsuk, S., Sukmak, P., Chinkulkijniwat, A., Arulrajah, A., & Shen, S. L. (2016). Stabilisation of marginal lateritic soil using high calcium fly ash-based geopolymer. *Road Materials and Pavement Design*, *17*(4), 877–891. doi:10.1080/14680629.2015.1132632

Pourakbar, S., Asadi, A., Huat, B. B. K., & Fasihnikoutalab, M. H. (2015). Soil stabilisation with alkali-activated agro-waste. *Environmental Geotechnics*, *2*(6), 359–370. doi:10.1680/envgeo.15.00009

Pourakbar, S., Huat, B. B. K., Asadi, A., & Fasihnikoutalab, M. H. (2016). Model study of alkali-activated waste binder for soil stabilization. *International Journal of Geosynthetics and Ground Engineering*, *2*(4), 1-12. doi:10.1007/s40891-016-0075-1

Ranjbar, N., Mehrali, M., Behnia, A., Alengaram, U. J., & Jumaat, M. Z. (2014). Compressive strength and microstructural analysis of fly ash/palm oil fuel ash based geopolymer mortar. *Materials and Design*, *59*, 532–539. doi:10.1016/j.matdes.2014.03.037

Rios, S., Cristelo, N., da Fonseca, A. V., & Ferreira, C. (2016). Structural performance of alkali-activated soil ash versus soil cement. *Journal of Materials in Civil Engineering*, *28*(2), 1–11. doi:10.1061/(asce)mt.1943-5533.0001398

Rivera, J. F., Orobio, A., Mejía de Gutiérrez, R., & Cristelo, N. (2020). Clayey soil stabilization using alkali-activated cementitious materials. *Materiales de Construcción*, *70*(337), 1-12. doi:10.3989/mc.2020.07519

Sharma, P. K., Singh, J. P., & Kumar, A. (2019). Effect of particle size on physical and mechanical properties of fly ash based geopolymers. *Transactions of the Indian Institute of Metals*, *72*(5), 1323–1337. doi:10.1007/s12666-019-01628-w

Sukmak, P., Sukmak, G., Horpibulsuk, S., Setkit, M., Kassawat, S., & Arulrajah, A. (2017). Palm oil fuel ash-soft soil geopolymer for subgrade applications: Strength and microstructural evaluation. *Road Materials and Pavement Design*, *20*(1), 110–131. doi:10.1080/14680629.2017.1375967

Taha, M. R. (2009). Geotechnical properties of soil-ball milled soil mixtures. In Bittnar, Z., Bartos, P. J. M., Nemecek, J., Smilauer, V., & Zeman, J. (Ed.), *Nanotechnology in Construction 3* (pp. 377-382). Berlin, Germany: Springer. doi:10.1007/978-3-642-00980-8_51

Tan, T., Huat, B. B. K., Anggraini, V., Shukla, S. K., Tan, T., Huat, B. B. K., ... & Nahazanan, H. (2019). Strength behavior of fly ash-stabilized soil reinforced with coir fibers in alkaline environment. *Journal of Natural Fibers*, 1–14. doi:10.1080/15440478.2019.1691701

Teing, T. T., Huat, B. B. K., Shukla, S. K., Anggraini, V., & Nahazanan, H. (2019). Effects of alkali-activated waste binder in soil. *International Journal of GEOMATE, 17*(59), 82–89. doi:10.21660/2019.59.8161

Wang, D., Zentar, R., & Abriak, N. E. (2018). Durability and swelling of solidified/stabilized dredged marine soils with class-F fly ash, cement, and lime. *Journal of Materials in Civil Engineering*, *30*(3), 1–12. doi:10.1061/(asce)mt.1943-5533.0002187

Zhuang, X. Y., Chen, L., Komarneni, S., Zhou, C. H., Tong, D. S., Yang, H. M., ... & Wang, H. (2016). Fly ash-based geopolymer: Clean production, properties and applications. *Journal of Cleaner Production*, *125,* 253–267. doi:10.1016/j.jclepro.2016.03.019