International Journal of GEOMATE, July 2019, Vol.17, Issue 59, pp.82 - 89
Geotec., Const. Mat. & Env., DOI: https://doi.org/10.21660/2019.59.8161
ISSN: 2186-2982 (Print), 2186-2990 (Online), Japan

EFFECTS OF ALKALI-ACTIVATED WASTE BINDER IN SOIL STABILIZATION

* Tan Teing Teing[1], Bujang B.K. Huat[2], Sanjay Kumar Shukla[3], Vivi Anggraini[4] and Haslinda Nahazanan[5]

[1,2,5]Faculty of Engineering, University of Putra Malaysia; [3]Edith Cowan University, Australia; [4]Monash University, Malaysia

*Corresponding Author, Received: 28 Nov 2018, Revised: 30 Dec. 2018, Accepted: 22 Jan. 2019

ABSTRACT: Generally, alkali-activated binders have received much attention in recent years due to their energy efficiency, environmentally friendly process, and excellent engineering properties. With respect to this fact, this study aims to investigate the effects of alkaline activation reactions on residual soil by using different percentages of fly ash as a precursor. Precisely, fly ash was incorporated with potassium hydroxide (10M) in order to stabilize the soil and enhance its expediency for various forms of construction. In particular, this experimental study was focused on determining the mechanical performance of stabilized soil. Evidently, the results showed that the different percentages of fly ash (40%, 50%, 60% and 70% by weight) used to stabilize the residual soil affected the unconfined compressive strength of the soil matrix. Also, it was observed that the compressive strength of soil increased progressively with the addition of fly ash. However, the longer the curing period of the stabilized soils, the higher the unconfined compressive strength of the soil. In fact, the microstructural analysis which employed scanning electron microscopy (SEM) revealed the material modifications that can be related to the strength behavior.

Keywords: Alkaline activation, Fly ash, Residual soil, Soil stabilization, Unconfined compressive strength

1. INTRODUCTION

Basically, stabilized soil is a composite material which is resulted from the combination and optimization of properties in individual constituent materials. Accordingly, well-established techniques of soil stabilization are often employed to obtain geotechnical materials. Subsequently, these materials are further improved through the addition of cementing agents such as Portland cement, lime, asphalt, etc. Currently, soil stabilization with cement and lime is a comprehensively researched treatment technique. Undeniably, these two major components have been widely used to improve the engineering properties of soils, thus allowing them to function as a better subgrade or subbase due to their strength and durability [1-2]. However, these traditional cementitious binders have several shortcomings, especially from the environmental and cost perspective.

Alkali-activated binders are introduced as good replacements for calcium-based binders (i.e., cement and lime) due to their distinctive mechanical properties as well as lower environmental ill effects and processing costs. Essentially, the synthesis of alkali-activated binders is formed by the reaction of any amorphous aluminosilicate materials with alkali (usually Na or K) or alkali-earth (Ca) metals. Typically, this synthesis involves the dissolution of mineral aluminosilicates, followed by the hydrolysis and condensation of the Al and Si components, resulting in the formation of a three-dimensional amorphous aluminosilicate gel [3-5]. To date, several waste materials which are rich in silica (SiO_2) and alumina (Al_2O_3) are used as precursors in alkali-activated binders such as Ground granulated blast-furnace slag (GGBS) [6], Metakaolin [7-8], Fly ash class F [9-11] and Palm oil fuel ash [12].

In view of the environmentally friendly process, namely the energy efficiency and excellent engineering properties, alkali-activated binders are fast emerging as materials of choice for high-demand civil engineering applications. Nevertheless, studies regarding the particular application on soil stabilization remain limited. For instance, a few published papers on alkaline activation [13-17] addressed the effectiveness of alkaline activation (AA) on soil stabilization. Based on the microstructural analysis, the researchers discovered that the binding gel (N-A-S-H) evolved inside the soil voids, leading to improved compressive strength and formation of more compact microstructures.

Inevitably, low calcium fly ash is one of the most abundantly produced waste materials in tropical regions with a high content of silica and alumina. Specifically, fly ash is a byproduct produced from burning pulverized coal in electric power generating plants. It consists of inorganic and incombustible matter present in coal which transforms into a glassy amorphous structure during combustion. To note, some studies discovered that the appropriate dosage of activated fly ash for soft soil stabilization were 20, 30 and 40% [18]. Despite these positive developments, the state of several issues such as the curing condition, efficacy of high-percentage fly ash, the role of parent soil and type of alkaline solute in alkaline activation remain ambiguous. In this context, the present study explores the possible use of a higher percentage of fly ash in stabilizing residual soils under appropriate conditions.

Besides, the present work has aligned the development of an alternative alkali-activated binder for soil stabilization purposes with regards to different percentages of fly ash and concentration of 10M potassium-based activators. Then, the changes in the mechanical behavior of soil for various curing conditions were evaluated based on their unconfined compression strength (UCS). Also, the microstructural changes in the soil before and after the treatment were performed to determine the underlying stabilization mechanisms with the aid of scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDX) analyses.

2. MATERIALS AND METHODS

2.1 Materials

2.1.1 Natural soil

The residual soil used in the study was collected from a construction site (1-1.5 m under the natural ground surface) in Selangor, Malaysia. For reference, the physical characteristics of the soil are summarized in Table 1 according to the BS (1377-2) [19]. Additionally, the grain size distribution of soil is illustrated in Fig. 1. Based on the Unified Soil Classification System, the investigated soil was classified as high-plasticity clay (CH). In general, this type of soil is often too weak and soft, thus making it unsuitable for earthworks or foundation layers. Moreover, X-ray fluorescence analysis (XRF) and X-ray Diffraction (XRD) test were conducted to assess the chemical composition and mineralogy of residual soil, as shown in Table 2 and Fig. 2, respectively.

Table 1 The physical characteristics of natural soil.

Basic soil property	Value
Specific gravity (Gs)	2.6
Liquid limit (%)	61
Plastic limit (%)	30
Optimum water content (%)	23
Maximum dry density (Mg/m^3)	1.62
Organic content (%)	6.04

2.1.2 Fly ash

Particularly, the fly ash of class F (low calcium) used in this study was collected from coal combustion residuals of a thermal power station in Selangor, Malaysia. Then, the X-ray fluorescence (XRF) spectrometry was employed for elemental analysis of Al-Si minerals present in the Fly ash. Evidently, as observed from the chemical analyses of fly ash in Table 2, the residue contains a high amount of silica. Thus, this material can be a potential candidate as a precursor in the alkaline activation.

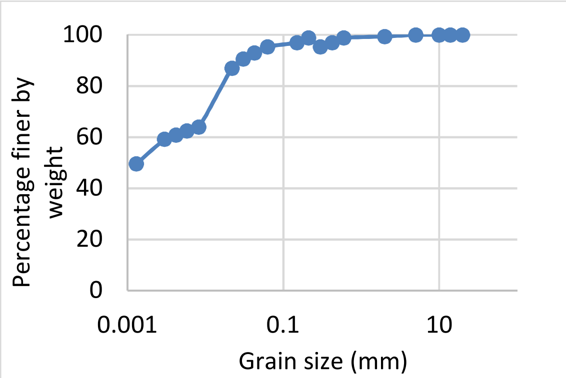


Fig. 1 Grain size distribution curve of soil.

Table 2 Chemical composition of soil and fly ash.

Constituent	Soil	Fly ash
Silica (SiO_2)	40.62	57.47
Alumina (Al_2O_3)	34.27	15.37
Iron oxide (Fe_2O_3)	10.49	4.71
Calcium oxide (CaO)	0.03	3.32
Potash (K_2O)	0.1	0.76
Magnesia (MgO)	0.09	1.23
Loss on ignition	13.37	0.7

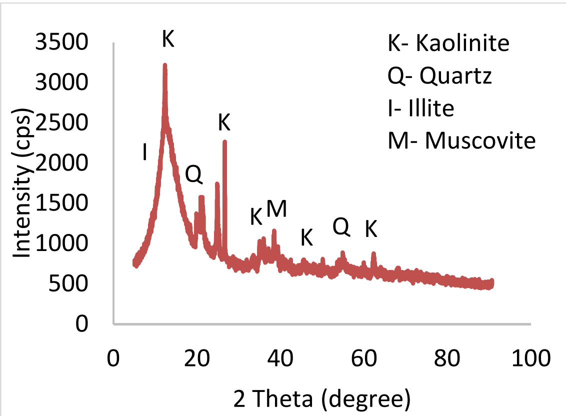


Fig. 2 XRD pattern of the original soil.

2.1.3 Alkaline activator

In this study, potassium hydroxide (KOH), an inorganic compound which contains alkaline cations and anions was selected as an alkali activator due to its suitability for deep mixing and affordability. Specifically, the potassium hydroxide was supplied in the form of pellets from Evergreen Engineering and Resources, Malaysia. Firstly, the activator solution was diluted with distilled water which had a pre-designed concentration of 10 molars. Then, the solution was blended for 10 minutes in order to achieve full dissolution. After 24 hours, the solution was used.

2.2 Laboratory test

A series of laboratory tests consisting of Proctor compaction test and unconfined compression test (UCS) was conducted using different dosages of the fly ash. Besides, microstructural changes of soil before and after the treatment were performed to determine the underlying stabilization mechanisms with the aid of scanning electron microscopy (SEM) analyses.

Precisely, the quantities (or dosages) of selected binders used in this study were 40%, 50%, 60% and 70% by dry mass of the natural soil.

2.2.1 Sample preparation

Table 3 presents the composition of each mixture tested. There are two types of mixtures, based on the stabilization level, i.e., unstabilized soil (S) and activator-soil-binder (KSFA). Testing the original, unstabilized soil was included to provide an adequate reference regarding the analysis of the KSFA mixtures.

Potassium hydroxide (KOH) solutions with 10 molars were used to activate fly ash. The dry soil was initially mixed, by hand, with the fly ash. Then, the alkaline activator solution was then added to the solids and thoroughly mixed until a uniform blend was achieved. During this stage, additional water was added to the mixture to meet the optimum moisture content of the natural soil.

2.2.2 Standard Proctor compaction test

For the purpose of conducting standard Proctor compaction test, BS 1377–1990: Part 4 [20] was applied to determine the maximum dry density (MDD) and the optimum moisture content (OMC) of the soils. Ultimately, this test was performed to ascertain the moisture-density relationship of the untreated and treated soil. The first series of compaction tests were conducted to identify the compaction properties of the natural soils. This was followed by the second series in order to determine the Proctor compaction properties of the soil upon stabilization with varying amounts of fly ash.

For mixing purpose, the natural soil was thoroughly mixed with the fly ash by hand until a uniform color was achieved. Then, water was added to facilitate the mixing and compaction processes.

Group series	Test number	Samples	Curing (days)
S	S	Natural soil	7,28
KSFA group	KS40FA	10M KOH + Soil + 40% Fly ash	7,28
	KS50FA	10M KOH + Soil + 50% Fly ash	7,28
	KS60FA	10M KOH + Soil + 60% Fly ash	7,28
	KS70FA	10M KOH + Soil + 70% Fly ash	7,28

Table 3 Mixture proportions of various series of test specimens.

2.2.3 Unconfined compression test

In this study, the UCS tests were conducted in accordance with Part 7: Clause 7 of the BS1377 standard [21] to evaluate the efficacy of different fly ash percentages on the increase of shear strength with time after stabilization (Fig. 3). UCS values were measured in three different specimens, and the results were accepted only if they deviated less than 5% from the average. An Instron 3366 universal testing machine, fitted with a 100kN load cell, was used for these tests, which were carried out under monotonic displacement control at a rate of 0.2 mm/min.

First and foremost, the specimens used for the unconfined compressive tests were air dried for 24 hours to ensure that the soil has zero initial water content. Next, the required dosage rate for stabilizers of each specimen was attained by adding and mixing a calculated weight of additives by the dry mass of soil. Subsequently, the specimens then undergo manual compaction in a cylindrical mold which was 50mm in diameter and 100mm in height. Additionally, a 45-mm diameter steel rod was applied as a static load in their similar layers. Importantly, this measure was to eliminate the air pockets and to improve the homogeneity of the specimens. Later, the specimens were extruded and immediately wrapped in plastic sheets and polythene covers to prevent loss of moisture. In this study, the curing occurred at room temperature and humidity, and two different curing periods were considered (7 and 28 days). In order to achieve a state of approximate saturation before the unconfined compression strength test, the samples were unwrapped and submerged in water for the last 24 h of the respective curing period. The intention of this saturation is to remove the positive effects of suction on the specimens' compressive strength. The exception to this saturation procedure were the specimens of natural soil (S) because of the loss of structural integrity when submerged.

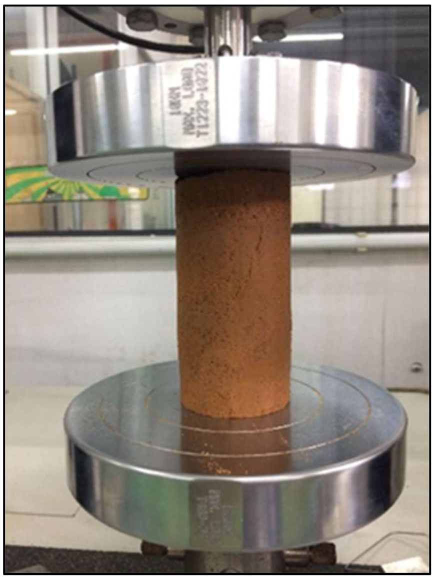


Fig. 3 UCS tests on soil samples.

2.2.4 Microstructure analysis

The scanning electron microscopy (SEM) and energy dispersive X-ray spectroscopy (EDS) analyses were taken into consideration to analyze the effect of the binder on the original soil. Once the specimens were submitted to the respective UCS tests, the crushed treated soil specimens were mounted on Al-stubs with double-sided carbon tapes and coated with a thin layer of platinum in a sputter coater. In this study, the SEM analysis provides the identification of pozzolanic reactivity, namely CSH and CAH. Whereas, EDS provides elemental analysis for selected areas of the SEM specimens to examine the occurrence of CSH and CAH gels.

3. RESULTS AND DISCUSSION

3.1 Effect on the compatibility

Figure 4 shows the compaction characteristics of soil-fly ash mixture. As depicted by this figure, the addition of 40, 50, 60 and 70% fly ash-soil mixtures exhibited a decrease in both the optimum moisture content (OMC) and maximum dry density (MDD). One probable reason for the reduction in optimum moisture content of the soil is because the addition of fly ash reduced the affinity of the soil for water [22].

Principally, the increase in maximum dry density is an indicator of improvement. Unfortunately, in this study, the addition of fly ash was revealed to reduce the maximum dry density. This unusual occurrence can be explained by the specific gravity and particles size of the soil and stabilizer. The specific gravity of fly ash is lower than that of residual soil. When more amounts of fly ash added to residual soil, the resulting mix will have a lower specific gravity leading to reduce the maximum dry density values. Indeed, the decreasing pattern exhibited by the maximum dry density revealed that a low compaction energy (CE) is required to attain its maximum dry density, thus incurring a lower cost for compaction [23].

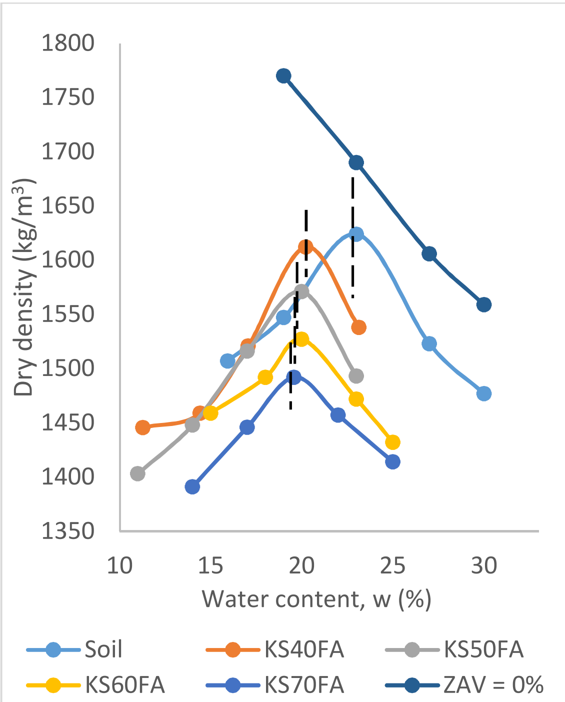


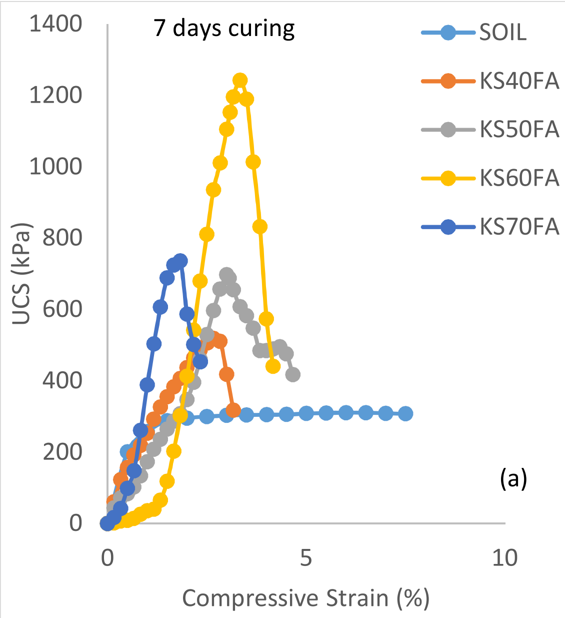
Fig. 4 Compaction curves for Soil-fly ash mixture.

3.2 Effect on the unconfined compression strength (UCS)

On top of that, Fig. 5 illustrates the plot between stress-strain behavior of soil and alkaline-activated soil with different percentages of fly ash (40%, 50%, 60%, and 70%) after curing times of 7 and 28 days.

Based on the illustration, it can be agreed that the alkaline activation stabilization which utilized potassium hydroxide as the base element of the activator was very effective in enhancing the strength of tested soils.

Initially, the strength of alkaline-activated soil increased until 60% of fly ash content (KS60FA) but started reducing when fly ash was further added. In particular, this reduction in strength was mainly contributed by the additional quantity of fly ash that became unbound silt particles which have neither appreciable friction nor cohesion [24-25].



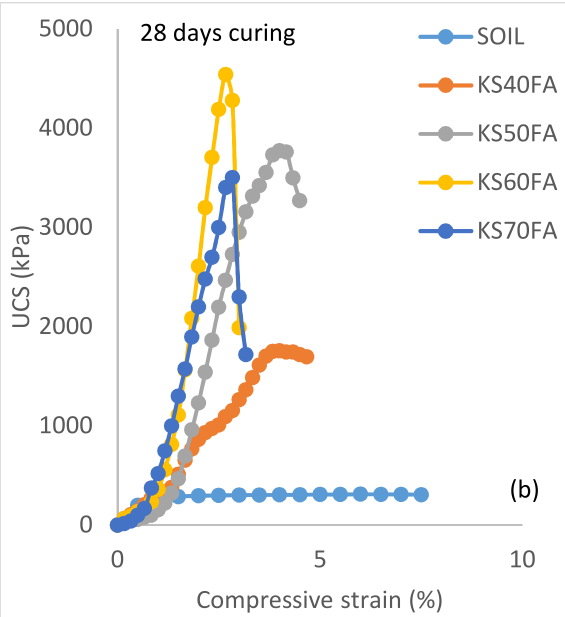


Fig. 5 Stress-strain behavior of treated soil samples after (a) 7 days; (b) 28 days.

Based on Fig. 6, it can be observed that the strength improvement of the treated soil was influenced by the addition of fly ash and the curing time. In this respect, KS60FA achieved the highest strength among all alkali-treated soil samples with readings of 1240 and 4760 kPa at 7 and 28 days, respectively. Undoubtedly, there is a significant improvement in strength after 28 days. Clearly, this outcome suggests that pozzolanic reactions are time-dependent. With respect to this finding, the bonding of particles with the fly ash progresses with time. Also, since fly ash contains a high content of silica, the reaction time will be delayed due to the low reactivity of silica and aluminum. Thus, it can be agreed that a short curing time results in low to moderate strength in the treated specimens.

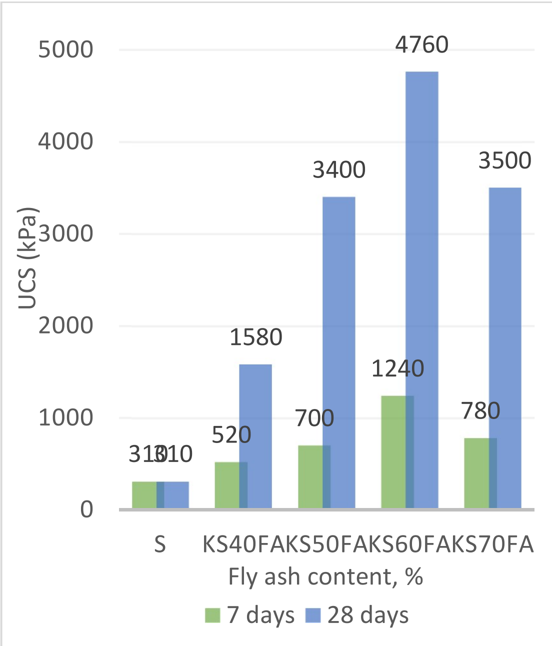


Fig. 6 UCS values of the test sample (S, KS40FA, KS50FA, KS60FA, and KS70FA) after 7- and 28-days curing.

3.3 Effect on microstructures

For a better understanding of the stabilization mechanisms, Fig. 7(a-c) shows the scanning electron microscopy (SEM) of natural residual soil, fly ash and treated soil after curing for 28 days. As a matter of fact, the treated sample (soil specimens treated with fly ash [60% by weight]) was subjected to SEM as shown in Fig. 7(c). Clearly, Fig. 7(a) shows the more open texture of the unstabilized soil while Fig. 7(b) shows the heterogeneous and non-uniform particle distribution of the raw fly ash. Based on the observation, the size of particles varied from small to large with smooth spherical shapes and rounded in nature. On the other hand, Fig. 7(c) shows the discrete soil particles appear more closely-bound and dense texture in the stabilized material with the void seemingly filled. No presence of borders was observed in the gel portion because of the ability of KOH to dissolve the fly ash and soil components.

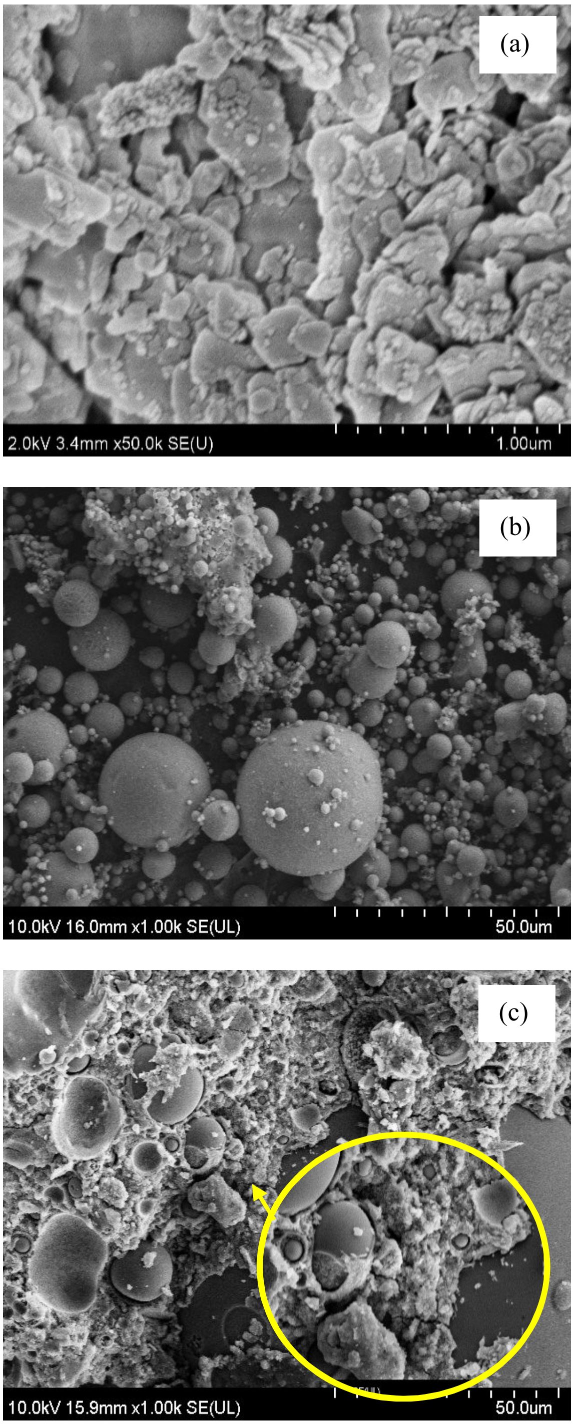


Fig. 7 SEM micrographs of (a) Natural soil; (b) Fly ash; (c) KS60FA.

Concisely, the SEM micrograph and EDX data of Fig. 8 reveals the formation of CSH and ASH gels after 28 days of curing. This is caused by the hydration and pozzolanic reactions in the pore space, thus reducing the pore space.

Components (%)	K	Al	Si	Ca
Point 1	6.72	11.92	22.00	1.46
Point 2	26.68	7.47	35.03	3.72
Point 3	10.57	6.55	20.76	1.63

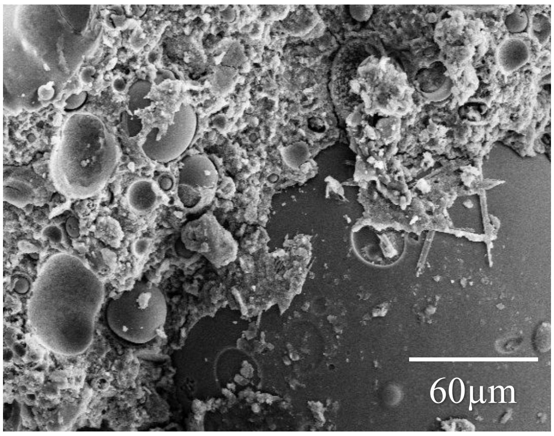


Fig. 8 Micrograph and EDX data of stabilized soil mixture after the curing of 28 days.

4. CONCLUSIONS

In this study, the use of alkali-activated binders for soil stabilization enabled the researchers to utilize locally available by-products in an efficient way in order to fully eliminate traditional cementitious binder (i.e. cement and lime), thus significantly reducing energy consumption while protecting the environment. Primarily, this study investigated the effectiveness of alkaline activation reaction on residual soil with different percentages of fly ash with a concentration of 10 molars of potassium hydroxide. Interestingly, it can be deduced from the results that an appropriate quantity of source binder (fly ash) will contribute to higher strength developments. Consequently, the curing time was also affected the strength development of the treated soil. The curing time was depending on the source binders and activator used.

Based on the microstructural analysis, it can be concluded that the simultaneous formation of ASH gel and CSH gel increased the interaction between soil and alkali-activated binders.

5. ACKNOWLEDGMENTS

First and foremost, the authors would like to express their gratefulness for the financial assistance provided by the Research Management Center (RMC) of University Putra Malaysia under FRGS. Also, the authors would like to extend their gratitude to Monash University Malaysia for their support during the FE-SEM and EDX analyses.

6. REFERENCES

[1] Basha E.A., Hashim R., Mahmud H.B., and Muntohar A.S., Stabilization of residual soil with rice husk ash and cement, Construction and building materials, Vol. 19, Issue 6, 2005, pp. 448-453.
[2] Prusinski J. and Bhattacharja S., Effectiveness of Portland cement and lime in stabilizing clay soils, Transportation Research Record: Journal of the Transportation Research Board, Issue 1652, 1999, pp. 215-227.
[3] Davidovits J., Geopolymer chemistry and properties, In Geopolymer, Vol. 88, Issue 1, 1988, pp. 25-48.
[4] Weng L. and Sagoe-Crentsil K., Dissolution processes, hydrolysis and condensation reactions during geopolymer synthesis: Part I—Low Si/Al ratio systems, Journal of Materials Science, Vol. 42, Issue 9, 2007, pp. 2997-3006.
[5] Yunsheng Z., Wei S., Zongjin L., Xiangming Z., and Chungkong C., Impact properties of geopolymer based extrudates incorporated with fly ash and PVA short fiber, Construction and Building Materials, Vol. 22, Issue 3, 2008, pp. 370-383.
[6] Singhi B., Laskar A.I., and Ahmed M.A., Investigation on soil–geopolymer with slag, fly ash and their blending, Arabian Journal for Science and Engineering, Vol. 41, Issue 2, 2016, pp. 393-400.
[7] Zhang M., Guo H., El-Korchi T., Zhang G. and Tao M., Experimental feasibility study of geopolymer as the next-generation soil stabilizer, Construction and Building Materials, Vol. 47, 2013, pp. 1468-1478.
[8] Zhang M., Zhao M., Zhang G., Nowak P., Coen A. and Tao M., Calcium-free geopolymer as a stabilizer for sulfate-rich soils, Applied Clay Science, Vol. 108, 2015, pp. 199-207.
[9] Cristelo N., Glendinning S. and Teixeira Pinto A., Deep soft soil improvement by alkaline activation, Proceedings of the Institution of Civil Engineers-Ground Improvement, Vol. 164, Issue 2, 2011, pp. 73-82.
[10] Cristelo N., Glendinning S., Fernandes L. and Pinto A.T., Effects of alkaline-activated fly ash and Portland cement on soft soil stabilization, Acta Geotechnica, Vol. 8, Issue 4, 2013, pp. 395-405.
[11] Cristelo N., Miranda T., Oliveira D.V., Rosa I., Soares E., Coelho P. and Fernandes L., Assessing the production of jet mix columns using alkali activated waste based on mechanical and financial performance and CO2 (eq) emissions, Journal of Cleaner Production, Vol. 102, 2015, pp. 447-460.
[12] Pourakbar S., Asadi A., Huat B.B. and Fasihnikoutalab M.H., Stabilization of clayey soil using ultrafine palm oil fuel ash (POFA) and cement, Transportation Geotechnics, Vol. 3, 2015, pp. 24-35.
[13] Pourakbar S., Asadi A., Huat B.B. and Fasihnikoutalab M.H., Soil stabilization with alkali-activated agro-waste, Environmental Geotechnics, 2015.
[14] Cristelo N., Glendinning S., Fernandes L. and Pinto A.T., Effect of calcium content on soil stabilization with alkaline activation, Construction and Building Materials, Vol. 29, 2012, pp. 167-174.
[15] Zhuang X.Y., Chen L., Komarneni S., Zhou C.H., Tong D.S., Yang H.M., Yu W.H. and Wang H., Fly ash-based geopolymer: clean production, properties and applications, Journal of Cleaner Production, Vol. 125, 2016, pp. 253-267.
[16] van Deventer J.S., San Nicolas R., Ismail I., Bernal S.A., Brice D.G. and Provis J.L., Microstructure and durability of alkali-activated materials as key parameters for standardization, Journal of Sustainable Cement-Based Materials, Vol. 4, Issue 2, 2015, pp. 116-128.
[17] Sargent P., Hughes P.N., Rouainia M. and White M.L., The use of alkali-activated waste binders in enhancing the mechanical properties and durability of soft alluvial soils, Engineering Geology, Vol. 152, Issue 1, 2013, pp. 96-108.
[18] Dockter B.A., Eylands K.E. and Hamre L.L., Use of bottom ash and fly ash in rammed-earth construction, In International Ash Utilization Symposium, 1999.
[19] British Standards Institution, British Standard Methods of Test for Soils for Civil Engineering Purposes: Part 2: Classification tests. British Standards Institution, 1990.
[20] British Standards Institution, 1990. British Standard Methods of Test for Soils for Civil Engineering Purposes: Part 4: Compaction-related tests, British Standards Institution, 1990.
[21] British Standards Institution, 1990. British Standard Methods of Test for Soils for Civil Engineering Purposes: Part 7: Shear strength tests (total stress), British Standards Institution, 1990.
[22] Zha F., Liu S., Du Y. and Cui K., Behavior of expansive soils stabilized with fly ash, Natural Hazards, Vol. 47, Issue 3, 2008, pp. 509-523.

[23] Muntohar A.S. and Hantoro G., Influence of rice husk ash and lime on engineering properties of a clayey subgrade, Electronic Journal of Geotechnical Engineering, Vol. 5, 2000, pp. 1-9.
[24] Rios S. and da Fonseca A.V., Soil stabilization with alkaline activated fly ash, In VII Congresso Luso-Brasileiro de Geotecnia, Goiânia, Brasil, 2014.
[25] Cristelo N., Glendinning S., Miranda T., Oliveira D. and Silva R., Soil stabilization using alkaline activation of fly ash for self-compacting rammed earth construction, Construction and building materials, Vol. 36, 2012, pp. 727-735.