Citation for published version:
Abdeldjouad, L, Asadi, A, Ball, R, Nahazanan, H & Huat, B 2019, 'Application of Alkali-Activated Palm Oil Fuel Ash Reinforced with Glass Fibers in Soil Stabilization', *Soils and Foundations*, vol. 59, no. 5, pp. 1552-1561. https://doi.org/10.1016/j.sandf.2019.07.008

DOI:
10.1016/j.sandf.2019.07.008

Publication date:
2019

Document Version
Peer reviewed version

Link to publication

University of Bath

Elsevier Editorial System(tm) for Soils and Foundations

Manuscript Draft

Manuscript Number: SANDF-D-18-00461R1

Title: Application of Alkali-Activated Palm Oil Fuel Ash Reinforced with Glass Fibers in Soil Stabilization

Article Type: Technical Paper

Keywords: Glass fibers; Alkaline activation; Ground improvement; Geopolymerisation.

Corresponding Author: Dr. Lokmane Abdeldjouad, Ph.D.

Corresponding Author's Institution: Universiti Putra Malaysia

First Author: Lokmane Abdeldjouad, Ph.D.

Order of Authors: Lokmane Abdeldjouad, Ph.D.; Afshin Asadi, PhD; Richard Ball, PhD; Haslinda Nahazanan, PhD; Bujang Huat, PhD

Abstract: The feasibility of using palm oil fuel ash (POFA) as a precursor for alkali activation reactions in combination with glass fibers as a discrete reinforcement has been investigated. Experimental work has focused on shear strength (using unconfined compression tests) and the tensile strength (using indirect tensile tests and flexural tests). According to the results, it was found that the peak stress increased and the post-peak behavior was modified from a brittle to a more ductile response depending on the amount of fiber reinforcement in the alkali-activated mixtures. Analysis of the microstructures revealed that the most significant factor contributing to the enhanced behavior of the reinforced mixtures was the interaction between the geo-polymeric matrix and fiber surface. This work brings new insights to the soil stabilization industry providing an effective method of enhancing the properties of soil treated by alkali activation of POFA (a low-value agro-waste by-product) through the inclusion of glass fiber additions. This brings advantages over the traditional calcium-based binders (i.e. lime and cement) as their production involves the emission of carbon dioxide, a contributing factor to the significant global warming.

Manuscript

Application of Alkali-Activated Palm Oil Fuel Ash Reinforced with Glass Fibers in Soil Stabilization

Lokmane Abdeldjouad[1], Afshin Asadi[2], Ball R. J.[3], Haslinda Nahazanan[1], Bujang B. K. Huat[1]

[1]Department of Civil Engineering, Faculty of Engineering, Universiti Putra Malaysia, Serdang, Selangor, Malaysia. Email: abdeldjouad.apply@gmail.com

[2]International College of Auckland, Auckland, New Zealand

[3]BRE Centre for Innovative Construction Materials, Department of Architecture and Civil Engineering, University of Bath, Bath, UK

Corresponding author: Lokmane Abdeldjouad (e-mail: abdeldjouad.apply@gmail.com), Haslinda Nahazanan (e-mail: n_haslinda@upm.edu.my)

ABSTRACT

The feasibility of using palm oil fuel ash (POFA) as a precursor for alkali activation reactions in combination with glass fibers as a discrete reinforcement has been investigated. Experimental work has focused on shear strength (using unconfined compression tests) and the tensile strength (using indirect tensile tests and flexural tests). According to the results, it was found that the peak stress increased and the post-peak behavior was modified from a brittle to a more ductile response depending on the amount of fiber reinforcement in the alkali-activated mixtures. Analysis of the microstructures revealed that the most significant factor contributing to the enhanced behavior of the reinforced mixtures was the interaction between the geo-polymeric matrix and fiber surface. This work brings new insights

to the soil stabilization industry providing an effective method of enhancing the properties of soil treated by alkali activation of POFA (a low-value agro-waste by-product) through the inclusion of glass fiber additions. This brings advantages over the traditional calcium-based binders (i.e. lime and cement) as their production involves the emission of carbon dioxide, a contributing factor to the significant global warming.

Key words: **Glass fibers, Alkaline activation, Ground improvement, Geopolymerisation**

INTRODUCTION

Soil stabilization is applied to soils in order to improve their engineering characteristics through the additions of various different additives (Mohammadinia et al. 2017; Tabarsa et al. 2018; Kamaruddin et al. 2019). Calcium-based binders such as cement and lime are widely used binders in soil stabilization (Kazemian et al., 2009; Pourakbar et al. 2015b; Anggraini et al. 2016; Bahmani et al. 2016). Although such traditional calcium-based binders can improve several engineering properties of soils, they have several shortcomings, especially when viewed from an environmental perspective. For instance, the cement industry is one of the primary producers of carbon dioxide. Cement generates around 7% of artificial carbon dioxide emissions due to carbonate decomposition (Gartner, 2004; Matthews et al., 2009). Therefore the development of new soil binders with lower environmental impact and equal or better performance compared to traditional alternatives is of great scientific and global importance.

Alkali-activated binders are known as high-performance inorganic materials. They have developed greatly in recent years on a global scale. Alkali-activated binders are synthesized by reacting amorphous alumino-silicate source materials such as fly ash, palm oil fuel ash, rice husk ash, metakaolin, calcium carbide residue, ground granulated blast furnace slag with an alkali (mostly sodium or potassium) or an alkali earth metal such as calcium (Davidovits 1988, 1991; Yunsheng et al. 2008). This process involves the dissolution of mineral alumino-silicates, followed by hydrolysis and condensation of the aluminum and silicon components (Davidovits 1988, 1991; Yunsheng et al. 2008). The result is a three-dimensional, essentially amorphous, alumino-silicate gel. According to previous studies, to have a positive effect on the mechanical properties of the alkali-activated binders and on the development rate of such properties, it is preferred to use calcium in the mixture to speed the development of calcium alumino-silicate hydrated gel (C.A.S.H.) along with sodium alumino-silicate hydrated gel (N.A.S.H.) (Cristelo et al. 2012a; Winnefeld et al. 2010). Due to the excellent engineering properties, alkali-activated binders have the potential to be considered as the material of choice for highly demanding geotechnical applications (Horpibulsuk et al. 2015; Pourakbar and Huat 2016). One particular application, focused on by some recent research papers is soil stabilization (Cristelo et al. 2011, 2012b, 2013, 2015b; Pourakbar et al. 2015b; Pourakbar et al. 2017; Arulrajah et al. 2016; Liu et al. 2016;; Alsafi et al. 2017; Mohammadinia et al. 2018; Muhammad et al. 2018; Latifi et al. 2018a, 2018b; Elkhebu et al. 2019; Abdeldjouad et al. 2019a, 2019b; Dehghan et al. 2018). The authors of these papers showed that the binding gel (either N.A.S.H. or C.A.S.H.) is developed inside the soil voids, helping to form more compact microstructures and, as a result, improved compressive strength.

One of the precursors that has been used is POFA because it is widely produced in large quantities in East Asian and West African countries by the oil palm industry owing to the burning of empty fruit bunches, fibre, and palm oil shells as fuel to generate electricity, where the waste, collected as ash, becomes POFA.

Despite the fact that alkali-activated binders have shown significant peak compressive strength in most cases, they also have a tendency to become brittle post-peak (Pourakbar et al. 2015b). This post-peak limitation is important in some geotechnical applications (Correia et al. 2015). For example, when seismic loads or high lateral earth pressures or horizontal displacements are expected (Pourakbar and Huat 2017; Nissa Mat Said et al. 2018). It is known that when fibers of relatively high tensile strength are embedded in a soil matrix, shear stresses are generated between the soil particles, which are then transferred to the fibers in form of tensile strength such as glass fibre, basalt fibre and polypropylene fibre, which increases the overall soil strength and rapids a brittle-to-ductile post-peak behaviors transition (Cristelo et al. 2015a). Due to the highly alkaline environment generated by the stabilizing agent used in the study, it was necessary to select a compatible fiber type. Through an extensive review of the literature, glass fibers were identified as possessing appropriate mechanical properties in terms of tensile, compressive and flexural strengths (Nematollahi et al. 2014). Glass fibers are composed of a number of different elements such as potassium and other oxides with the main components being approximately 60% of SiO_2, 13% of Al_2O_3 and 22% of CaO. In strong alkaline conditions, these fibers may undergo an alkali-silica reaction where silica and calcium are released. This may weaken the fibers but also provide a stronger mechanical bond with the surrounding soil matrix.

This paper is focused on the development of an alternative alkaline activated binder for soil stabilization purposes, based on a previously POFA and potassium-based activators. In addition, the importance of glass fibers incorporated into the mixture as a source of discrete reinforcement was a focus of this work. The mechanical response has been evaluated through two tests allowing the characterization of compressive (uniaxial compression tests) and tensile (indirect tensile and flexural tests) strengths. Microstructural analysis of the soils before and after stabilization was investigated using SEM with EDS and FTIR.

EXPERIMENTAL INVESTIGATION

Materials

According to the Unified Soil Classification System (ASTM 2010), the soil used in this study is classified as medium plasticity sandy clay (CL). Table 1 shows the physical characteristics of the soil.

The POFA for the alkaline activation reactions was collected from a factory in Johor Bahru in Malaysia. To obtain a suitable size, shape, and chemical composition, POFA was initially subjected to a pretreatment including calcination and grinding (Pourakbar et al. 2015a). After POFA was dried for 24 hours in an oven, at 105°C, the resulted particles were ground in an 80 cm diameter ball-mill for 24 hours and then passed through a 300 μm sieve. Next, in order to remove any unburned carbon, the ground POFA was heated in an electric furnace at 440°C for approximately 1 hour. A similar lab scale pretreatment was reported by others (e.g. Pourakbar et al. 2015a) who demonstrated the effectiveness of this method for increasing the specific surface and reactivity of the ash. There is a need for further research in order to launch this technology into the construction market. Following the pretreatment, an elemental analysis was performed using X-ray fluorescence (XRF) spectrometry (Table 2).

Commercially available glass fibers were added at different levels of between 1 and 6% by dry weight to samples of the soil. The fiber's chemical characteristics were readily available from the manufacturer and reported in Table 2.

Due to its known efficiency, potassium hydroxide (KOH) was added as a source of K^+ cations to increase the alkalinity thus performing the role of an activator. As previously supplied by the company R&M Chemical, the reagent was available in pellet form which was diluted using sufficient distilled water to achieve a concentration of 10 molars (Pourakbar et al. 2016b; Abdeldjouad et al. 2019a, 2019b). Since KOH reacts exothermically with water, the solution formed was allowed to cool to ambient temperature before use.

Mixing Methodology

Table 3 presents the composition of each mixture tested. There are three types of mixtures, based on the stabilization/reinforcement level including un-stabilized soil (S), activator-soil-binder (KSP), and activator-soil-binder-fiber (KSPG). While testing of the original, un-stabilized soil was included to provide an adequate reference regarding the analysis of the KSP and KSPG mixtures.

The dry soil was initially mixed with POFA by hand, and also whenever required with glass fibers (1 to 6%). Then, the required dosage of air-dried soil and 15% of POFA was mixed by adding the cooled alkaline solution with the specified weights of glass fiber (percent by dry weight of mixture) until a uniform blend was reached.

Unconfined Compressive Strength Tests

The specimens were prepared right after the aforementioned mixing procedure by manual compaction in a cylindrical mold, 50 mm in diameter and 100 mm high, using a 45 mm diameter steel rod to apply a static load in three similar layers. A dry density value of 1.58 Mg/m^3 was targeted for all mixtures.

Moisture loss was prevented by immediately wrapping the specimens in polythene plastic covers after extrusion. To obtain a state of approximate saturation before the UCS tests, the specimens were unwrapped and submerged in water for the last 24 hours prior to the tests. This saturation was applied to all the specimens to eliminate the positive effects of suction on the specimens' compressive strength, except for the specimens of un-stabilized soil (S) because of the loss of structural integrity when submerged.

Unconfined compressive strength (UCS) measurement was conducted after a curing period of 7 and 28 days in accordance with Part 7: Clause 7 of BS 1377 (1990). 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 3382 universal testing machine, fitted with a 100 kN load cell, was used for these tests, which were carried out under monotonic displacement control at a rate of 0.2

mm/min. The entire stress-strain curve was obtained from each test and after shearing, all specimens were retained for mineralogical analysis.

Indirect Tensile Strength Tests

The indirect tensile strength (ITS) was determined using the method described in ASTM D3379 (1975). Cylindrical specimens were used, 100 mm in length and 50 mm in diameter. The tests were performed after a curing period of 28 days, applying a monotonic load speed of 0.6 mm/min on opposite sides of the specimen. The ITS was calculated based on the peak force applied using Eq. (1)

$$ITS = \propto \frac{2P}{\pi DL} \qquad (1)$$

where P = maximum load applied; D = diameter of the sample; L = length of the sample; and α = shape parameter, which can be estimated as α = 0.2621k + 1, in which k= length/diameter ratio of the specimen (Pourakbar et al. 2016a).

Flexural Strength Tests

Similar specimens to those described for the ITS test was used. Flexural strength was measured after 28 days curing using a three-point bending test according to ASTM D1635 (2012), under a monotonic speed of 0.1 mm/min. A support span of 60 mm was used. The flexural stress for the circular section of the outer layer of the specimen was calculated as follows:

$$First\ peak\ strength\ f = \frac{PL}{\pi r^3} \qquad (2)$$

where P = maximal applied load; r = radius of the specimen; and L = support span.

Microstructural Analysis

To understand the underlying mechanism of stabilization in this study, selected specimens were analyzed (after submitted to the respective UCS test) using a scanning electron microscope (SEM) and Fourier transform infrared spectroscopy (FTIR). For the SEM/Energy dispersive X-ray spectroscopy (EDS) analysis, the crushed treated soil specimens were attached to Al-stubs with double-sided carbon tabs and then coated with a thin layer of platinum in a sputter coater. The selected samples were eventually examined using SEM and EDS analyses. To conduct the FTIR test, the KBr pellet technique was used (3.5 mg of crushed specimens mixed with 800 mg of KBr) for the specified specimens.

RESULTS

Unconfined Compressive Strength

Figs. 1(a-b) show the results from the unconfined compressive strength tests. As it can be seen, alkaline activation treatment induced a brittle behavior and a large increase in strength after 28 days (KSP mixture). A sudden drop at failure strain of around 2% was observed when compared to the natural soil which was ductile with an unconfined compressive strength of 0.39 MPa at a failure strain of around 8.5%. An enhancement was achieved in KSPG group, which was indicated by the gradual drop in strength after a clear peak value was reached, based on the increment of fiber content and curing time. In this respect, the improvement of stress-strain behavior was more significant when the glass fibers dosage was greater than 2%.

Fig. 2 shows the difference between the compressive strength of the alkaline activation treated soil with and without fibers after curing times of 7 and 28 days. The inclusion of the fibers increased the compressive strength of the mixtures over the curing period. For the KSP mixture after 7 and 28 days of curing, values of 0.61 and 2.75 MPa were observed, respectively. When the glass fiber content used in alkaline activation, the compressive strength of the KSPG5 mixture reached values of 0.97 and 5.7 MPa at 7 and 28 days, respectively. These are 59 and 107% higher than those obtained with a similar mixture, only without fibers (KSP).

Indirect Tensile Strength

Tensile load-deflection curves of the natural soil and stabilized mixtures, with and without fiber inclusion and after curing for 28 days, are shown in Fig. 3. It is noteworthy that the increase in fiber content caused a completely different post-peak behavior, along with an increase in peak stress and an increase in deflection at peak stress. For the natural soil, the peak stress value of 0.21 MPa was observed at a deflection of 0.75 mm. Compared with the potassium-based unreinforced alkaline activation treated specimens (KSP), an increase in the peak stress value of 0.71 MPa was observed, with lower deflection, at around 0.35 mm. The ITS of the KSPG3, KSPG4 and KSPG5 specimens achieved values of 3.59, 3.62 and 6.98 MPa, respectively with higher deflection, which are increased by 406, 410 and 883%, relative to the KSP specimen. Improvement in the post-peak behavior of the reinforced specimens, in which the fibers avoided the immediate structural collapse of the material by further prolonging the load-bearing capacity of every reinforced mixture was also noted.

Flexural Strength

Flexural load-deflection curves of natural soil and selected stabilized mixtures, after curing for 28 days and both with (KSPG) and without fiber inclusion (KSP), are shown in Fig. 4. The natural soil curve exhibited a flexural strength of 0.19 MPa at approximately 5 mm deflection. In contrast, the curves resulting from the stabilized mixtures showed a clear peak which is a direct measure of the flexural strength of the specimens, as well as a significant increase in the peak flexural load was observed with the addition of the reinforcement, together with an increase in the corresponding deflection. This effect was especially relevant regarding the 5% fiber content, i.e., the flexural strength of the KSPG5 mixture reached 1.82 MPa at 1.6 mm deflection, a value 182% higher than that obtained with the similar, unreinforced mixture (KSP) which achieved 0.64 MPa at only 0.55 mm deflection.

Microstructural Analysis

SEM micrographs of the un-stabilized soil (S), glass fibers, soil-binder mixtures (KSP) and soil-binder-fibers mixtures (KSPG5), after 28 days of curing, are presented in Figs. 5(a–d). The more open texture of the untreated soil is shown clearly in Fig. 5(a), whereas the discrete soil particles are shown more closely bound in the stabilized material, with the voids seemingly filled (Fig. 5d). This is consistent with the increase in strength registered by the soil-binder mixtures, relatively to the original soil (Figs. 1-4).

The SEM-EDS analysis of the reinforced alkaline activated specimen shown in Fig. 6 confirms the presence of the elements Si, Al, and Ca which is consistent with the chemical composition of both the POFA and the fibers. The Si and Al species dissolved from the POFA (and probably from the colloidal fraction of the soil) were the main sources of the Si─O─Al and Si─O─Si bonds in the alkaline activated matrix. But even so, some Si ions may be diffused from the soil surface of the glass fibers, and hence, contributing to the total aluminosilicate gel and increasing the density of the Si─O─Si bonds (because of the increase in Si/Al ratio). Also, the presence of Si on the surface of the fibers may have promoted the formation of the network-like bonds observed tightly wrapped around the fibers. This interaction would have restricted the relative movement between the fibers and the soil particles (Fig. 5e). The results from the SEM-EDS analysis demonstrates that the strengthening mechanism of the alkaline activation can be explained by a well-formed Si–O–Al and Si–O–Si three-dimensional structure, which agrees well with the high values recorded in the unconfined compressive strength, indirect tensile strength, and flexural strength tests.

The relationship between Al–O, Si–O, Si–O–Si or Si–O–Al asymmetric stretching peak positions and the extent of the alkaline activation process is complex but assists towards the study of the mechanism (Ahmari et al. 2012; Buchwald et al. 2007). FTIR was employed to identify the different types of bond within the short-range structure in the two treated mixtures, as shown in Fig. 7, by name KSP and KSPG5. For both KSP and KSPG5, the first peak was observed at wavelengths between 550 and 750 cm−1, centered at approximately 690.52 cm−1, which may indicate the symmetric extending vibrations of Si-O-Si and Al-O-Si. The second peak was located at wavelengths between 750 and 850 cm−1, centered at approximately 794.67 cm−1, which may indicate the ─CO3 vibrations in CaCO3. The third and the forth peaks are consistent with the asymmetric extending vibration band of Si–O–T (T = Al, Si), which can be observed in the region between 850 and 1,050 cm−1. Note that this peak represents strong evidence of successful soil treatment using the alkaline activation process and consequently high values recorded in tests for unconfined compressive strength, indirect tensile strength, and flexural strength. Another main peak within the range 1,400 to 1,430 cm−1 was attributed to the extended vibration of the Si-O link which may be an indication of silica polymerization in M─S─H gels. Due to the higher Si/Al ratio in reinforced alkali-activated samples, this peak is much clearer in KSPG5 compared to the peak of the same mixture without fibers (KSP). The broadband in the region 2,300–3,500 cm−1 characterizes the spectrum of expansion and deformation vibrations of OH and H–O–H groups from the weakly bound water molecules, which were adsorbed on the surface or trapped in the large cavities between the rings of the activated products.

DISCUSSION

Results indicate that the application of alkaline activation induced a significant increase in strength (Fig. 1). At 28 days, the UCS was higher for treated soil (KSP) compared to that of the original soil. Despite all, there was a tendency towards a more brittle behavior of the binder-soil mixtures registered, which was indicated by the sudden drop in strength after a clear peak value was reached. In order to improve this post-peak tendency, glass fibers were included, that resulted in an elevation in the peak strength of every mixture at every curing period. As shown in Fig. 1, the fibers were effective in reducing the post-peak strength loss. In addition, according to Figs. 1 and 2, it is possible to conclude that the improvement in the strength of the fiber-reinforced mixtures was a function of the curing time and the fiber content. This resulted in a noticeable improvement when the fiber dosage was greater than 3%. Indirect tensile strength and flexural strength tests revealed that the inclusion of fiber reinforcement in alkali-activated mixtures increased the peak tensile strength and improved the post-peak behavior from a brittle to a more ductile response.

The microstructural images (Figures 5 and 6) show that the presence of POFA during the alkaline activation process plays a significant role. Discrete soil particles in alkali-activated mixtures with POFA show a more closely bounded structure compared to untreated mixtures, where the seemingly filled voids result in the total strength increase shown in Fig. 1. Figure 5d shows an SEM micrograph of the POFA treated soil which indicates that the ultrafine particle size of the POFA led to an increasingly dense soil matrix. The gaps within the soil particles are filled with alkali-activated POFA. Moreover, the inclusion of glass fibers in alkaline solutes were highly effective reinforcing materials. The needle-like structure of the fibers acted in a similar manner to plant roots by distributing the stresses over a wider area and inhibiting cleavage propagation (Figure 5 and 6). This resulted in a total strength increase, as shown previously in Figs. 1-4. This is inconsistent with the study performed by Nematollahi et al. (2014), who concluded that the fracture strength of the glass fibers was of great effect when added to a geopolymer matrix.

The improved mechanical performance observed in unconfined compressive strength, indirect tensile strength, and flexural strength tests is related to the alkaline activation process and presence of glass fibre. The tensile strength and flexural strength basically increased with the presence of glass fibre. The improved performance was also largely related to the high calcium content of the fibers, which may dissolve and subsequently become incorporated into the alkaline activated matrix (Fig. 6). The additional nucleation sites, provided by the calcium ions, for precipitation of dissolved species (Yip et al. 2008) could contribute to the formation of C-A-S-H gel, in addition to the K-A-S-H gel formed from the activation of the main precursor (POFA). There were two mechanisms identifying the formation of the C-A-S-H gel (Yip et al. 2005). In the first case, both the A-S-H and C-S-H gels act as independent phases. This appears dominant in spectra 2 and 4 obtained from the fibers where the high Ca/Si ratio was observed which indicates partial activation of the fiber's surface and the presence of C-A-S-H gel within the matrix. The second mechanism indicates that the Ca ions act as a charge-balancing agent and are integrated into the C-A-S-H network. However, the second mechanism seems to have dominated in the areas with a low fiber presence, due to the low Ca/Si ratios at other points (Fig 6). The fibers' surface partial dissolution has mostly included Si ions which helped in formation of the microstructural network, hence sticking the fibers surface to the geo-polymeric matrix and improving the mechanical interlocking effect between the fibers and the matrix. This was a very interesting side-effect because the mechanical performance of a soil improved by fiber inclusion, as well-known, depends usually on the characteristics of the fibers, along with the adhesion of the soil-fiber interface (Cristelo et al. 2015a; Tan et al. 2019; Kamaruddin et al. 2019). With the previous considerations in mind, it can be concluded that the simultaneous formation of K-A-S-H gel (from the POFA and the solid surface of the fibers) and C-A-S-H gel (mainly from the calcium present on the solid surface of the fibers) was the main reason for bridging the particles forming the soil matrix and also for improving the internal stability and interfacial interactions between the fibers and the soil.

CONCLUSIONS

Based on the laboratory tests and analyses presented in this paper, the following conclusions were reached;

- The compressive strength of the medium plasticity sandy clay was improved with a brittle behavior when POFA as a source binder and potassium hydroxide as an activator were used in the alkaline activation process.
- The peak tensile strength of the soil was improved when 3 to 5% of glass fibers were included into the alkali-activated treated soil with POFA.
- Inclusion of glass fibres into the alkali-activated treated soil with POFA improved the post-peak behavior of the soil matrix from a brittle to a more ductile response.
- From the microstructural analysis, it was concluded that the interaction between the glass fiber surface and the alkali-activated matrix, contributed to the enhanced behavior of the reinforced soil.

ACKNOWLEDGMENTS

The authors would like to express their gratitude to Universiti Putra Malaysia and Ministry of Science Technology Innovation (MOSTI) for providing financial support during the research under project no: 06-01-04-SF2387.

REFERENCES

Abdeldjouad L., Asadi A., Huat B.K., Jaafar S., Dheyab W., Elkhebu A. (2019a). Effect of Curing Temperature on the Development of Hard Structure of Alkali-Activated Soil. International Journal of GEOMATE, 17 (60), 117-123.

Abdeldjouad L., Asadi A., Nahazanan H., Huat B.K., Dheyab W., Elkhebu A. (2019b). Effect of Clay Content on Soil Stabilization with Alkaline Activation. International Journal of Geosynthetics and Ground Engineering, 5, doi.org/10.1007/s40891-019-0157-y.

Ahmari, S., Ren, X., Toufigh, V., & Zhang, L. (2012). Production of geopolymeric binder from blended waste concrete powder and fly ash. Construction and Building Materials, 35, 718–729.

Alsafi, S., Farzadnia, N., Asadi, A., & Huat, B. B. K. (2017). Collapsibility potential of gypseous soil stabilized with fly ash geopolymer; characterization and assessment. Construction and Building Materials, 137, 390–409.

Anggraini, V., Asadi, A., Farzadnia, N., Jahangirian, H., & Huat, B. B. K. (2016). Effects of coir fibres modified with $Ca(OH)_2$ and $Mg(OH)_2$ nanoparticles on mechanical properties of lime-treated marine clay. Geosynthetics International, 23(3), 206-218.

Arulrajah A., Mohammadinia A., Horpibulsuk S., Samingthong W. (2016). Influence of class F fly ash and curing temperature on strength development of fly ash-recycled concrete aggregate blends. Constr. Build. Mater., 127, 743–750.

ASTM. (1975). “Tensile strength and Young’s modulus for high-modulus single-filament materials.” ASTM D3379, West Conshohocken, PA.

ASTM. (2010). “Standard practice for classification of soils for engineering purposes (unified soil classification system).” ASTM D2487, West Conshohocken, PA.

ASTM. (2012). “Standard test method for flexural strength of soil cement using simple beam with three point loading.” ASTM D1635, West Conshohocken, PA.

Bahmani, S. H., Farzadnia, N., Asadi, A., & Huat, B. B. K. (2016). The effect of size and replacement content of nanosilica on strength development of cement treated residual soil. Construction and Building Materials, 118, 294-306.

British Standards Institution. (1990). “Methods of test for soils and civil engineering purposes.” BS1377, London.

Buchwald, A., Hilbig, H., & Kaps, C. (2007) Alkali-activated metakaolin-slag blends – performance and structure in dependence of their composition. Journal of Materials Science, 42(9), 3024–3032.

Correia, N. A., Oliveira, P. J. V., and Cust´odio, D. G. (2015). “Effect of polypropylene fibres on the compressive and tensile strength of a soft soil, artificially stabilised with binders.” Geotext. Geomembr., 43(2), 97–106.

Cristelo, N., Cunha, V. M., Dias, M., Gomes, A. T., Miranda, T., and Araújo, N. (2015a). “Influence of discrete fibre reinforcement on the uniaxial compression response and seismic wave velocity of a cementstabilised sandy-clay.” Geotext. Geomembr., 43(1), 1–13.

Cristelo, N., Glendinning, S., Fernandes, L., and Pinto, A. T. (2012a). “Effect of calcium content on soil stabilisation with alkaline activation.” Constr. Build. Mater., 29, 167–174.

Cristelo, N., Glendinning, S., Fernandes, L., and Pinto, A. T. (2013). "Effects of alkaline-activated fly ash and Portland cement on soft soil stabilisation." Acta Geotech., 8(4), 395–405.

Cristelo, N., Glendinning, S., Miranda, T., Oliveira, D., and Silva, R. (2012b). "Soil stabilisation using alkaline activation of fly ash for self compacting rammed earth construction." Constr. Build. Mater., 36, 727–735.

Cristelo, N., Glendinning, S., and Pinto, A. T. (2011). "Deep soft soil improvement by alkaline activation." Proc. ICE-Ground Improv., 164(2), 73–82.

Cristelo, N., Miranda, T., Oliveira, D. V., Rosa, I., Soares, E., Coelho, P., and Fernandes, L. (2015b). "Assessing the production of jet mix columns using alkali activated waste based on mechanical and financial performance and CO2 (eq) emissions." J. Clean. Prod., 102, 447–460.

Davidovits, J. (1988). "Geopolymer chemistry and properties." Proc., 1st European Conf. on Soft Mineralurgy (Geopolymere '88), J. Davidovits and E. J. Orlinsl, eds., The Geopolymer Institute, Compiegne, France, 25–48.

Davidovits, J. (1991). "Geopolymers." J. Therm. Anal. Calorim., 37(8), 1633–1656.

Dehghan, H., Tabarsa, A., Latifi, N., & Bagheri, Y. (2018). Use of xanthan and guar gums in soil strengthening. Clean Technologies and Environmental Policy, 21(1), 155–165.

Elkhebu A., Zainorabidin A., Bakar I., Huat B.K., Abdeldjouad L., Dheyab W. (2019). Alkaline activation of clayey soil using potassium hydroxide & fly ash. Int. J. Integr. Eng., 10(9), 99–104.

Gartner, E. (2004). Industrially interesting approaches to ‘low-CO2’ cements. Cement and Concrete Research, 34(9), 1489–1498.

Horpibulsuk, S., Suksiripattanapong, C., Samingthong, W., Rachan, R., and Arulrajah, A. (2015). “Durability against wetting–drying cycles of water treatment sludge–fly ash geopolymer and water treatment sludge–cement and silty clay–cement systems.” J. Mater. Civil Eng., 10.1061/(ASCE)MT.1943-5533.0001351, 04015078.

Kamaruddin F.A., Huat B.K., Nahazanan H., Anggraini V. (2019). Modified Natural Fiber on Soil Stabilization with Lime and Alkaline Activation Treated Marine Clay. International Journal of GEOMATE, 16 (58), 69-75.

Kazemian, S., Asadi, A., Huat, B. B. K. & Prasad, A. (2009). Settlement Problems in Peat Due to Their High Compressibility and Possible Solution Using Cement Columns. Fifth Forensic Engineering Congress, doi.org/10.1061/41082(362)26.

Latifi, N., Vahedifard, F., Ghazanfari, E., & Rashid, A. S. A. (2018a). Sustainable Usage of Calcium Carbide Residue for Stabilization of Clays. Journal of Materials in Civil Engineering, 30(6).

Latifi, N., Vahedifard, F., Siddiqua, S., & Horpibulsuk, S. (2018b). Solidification-Stabilization of Heavy Metal-Contaminated Clays Using Gypsum: Multiscale Assessment. International Journal of Geomechanics, 18(11), 04018150.

Liu, Z., Cai, C., Liu, F., and Fan, F. (2016). “Feasibility study of loess stabilization with fly ash-based geopolymer.” J. Mater. Civ. Eng., 10.1061/ (ASCE)MT.1943-5533.0001490, 04016003.

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.

Mohammadinia A., Arulrajah A., Haghighi H., Horpibulsuk S. (2017). Effect of lime stabilization on the mechanical and micro-scale properties of recycled demolition materials. Sustainable Cities Soc., 30, 58–65.

Mohammadinia A., Arulrajah A., D'Amico A., Horpibulsuk S. (2018). Alkali-activation of fly ash and cement kiln dust mixtures for stabilization of demolition aggregates. Constr. Build. Mater., 186, 71–78.

Muhammad, N., Siddiqua, S., & Latifi, N. (2018). Solidification of subgrade materials using magnesium alkalinization: A sustainable additive for construction. Journal of Materials in Civil Engineering, 30(10), 04018260.

Nematollahi, B., Sanjayan, J., Chai, J. X. H., Lu, T. M. (2014). Properties of fresh and hardened glass fiber reinforced fly ash based geopolymer concrete. Key Engineering Materials 2014; Vols. 594-595: 629-633.

Nissa Mat Said, K., Safuan A Rashid, A., Osouli, A., Latifi, N., Zurairahetty Mohd Yunus, N., & Adekunle Ganiyu, A. (2018). Settlement Evaluation of Soft Soil Improved by Floating Soil Cement Column. International Journal of Geomechanics, 19(1), 04018183.

Pourakbar, S., Asadi, A., Huat, B. B., and Fasihnikoutalab, M. H. (2015a). Stabilization of Clayey Soil Using Ultrafine Palm Oil Fuel Ash (POFA) and Cement. Transp. Geotech., 3, 24–35.

Pourakbar, S. and Huat, B. K. (2016). A Review of Alternatives Traditional Cementitious Binders for Engineering Improvement of Soils. Int. J. Geotech. Eng., 11(2), 206–216.

Pourakbar, S., Asadi, A., Huat, B. B., and Fasihnikoutalab, M. H. (2015b). Soil Stabilization With Alkali-Activated Agro-Waste. Environ. Geotech., 2(6), 359–370.

Pourakbar, S., Asadi, A., Huat, B. B., Cristelo, N., and Fasihnikoutalab, M. H. (2016a). Application of Alkali-Activated Agro-Waste Reinforced With Wollastonite Fibers in Soil Stabilization. J. Mater. Civ. Eng., 04016206.

Pourakbar, S., Huat, B. B., Asadi, A., and Fasihnikoutalab, M. H. (2016b). Model Study of Alkali-Activated Waste Binder for Soil Stabilization. International Journal of Geosynthetics and Ground Engineering, 2, doi.org/10.1007/s40891-016-0075-1.

Pourakbar, S., and Huat, B. K. (2017). Laboratory-scale model of reinforced alkali-activated agro-waste for clayey soil stabilization. Advances in Civil Engineering Materials, 6 (1), 83–105.

Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvement using nanoclay-A sustainable material for construction. Construction and Building Materials, 158, 454-463.

Tan T., Huat B.K., Anggraini V., Shukla S.K. (2019). Improving the engineering behaviour of residual soil with fly ash and treated natural fibres in alkaline condition. International Journal of Geotechnical Engineering, doi.org/10.1080/19386362.2018.1564854.

Winnefeld, F., Leemann, A., Lucuk, M., Svoboda, P., and Neuroth, M. (2010). "Assessment of phase formation in alkali activated low and high calcium fly ashes in building materials." Constr. Build. Mater., 24(6), 1086–1093.

Yip, C. K., Lukey, G., and Van Deventer, J. (2005). "The coexistence of geopolymeric gel and calcium silicate hydrate at the early stage of alkaline activation." Cem. Concr. Res., 35(9), 1688–1697.

Yip, C. K., Lukey, G. C., Provis, J. L., and van Deventer, J. S. (2008). "Effect of calcium silicate sources on geopolymerisation." Cem. Concr. Res., 38(4), 554–564.

Yunsheng, Z., Wei, S., Zongjin, L., Xiangming, Z., and Chungkong, C. (2008). "Impact properties of geopolymer based extrudates incorporated with fly ash and PVA short fiber." Constr. Build. Mater., 22(3), 370–383.

List of Tables

Table 1. Physical characteristics of soil

Basic soil property	Standard	Value
Specific gravity (G_S)	BS 1377-2	2.52
Liquid limit (LL) (%)	BS 1377-2	48.7
Plasticity index (PI) (%)	BS 1377-2	34.5
OMC (%)	BS 1377-4	24
MDD (Mg/m^3)	BS 1377-4	1.58
UCS (kPa)	BS 1377-7	380-390

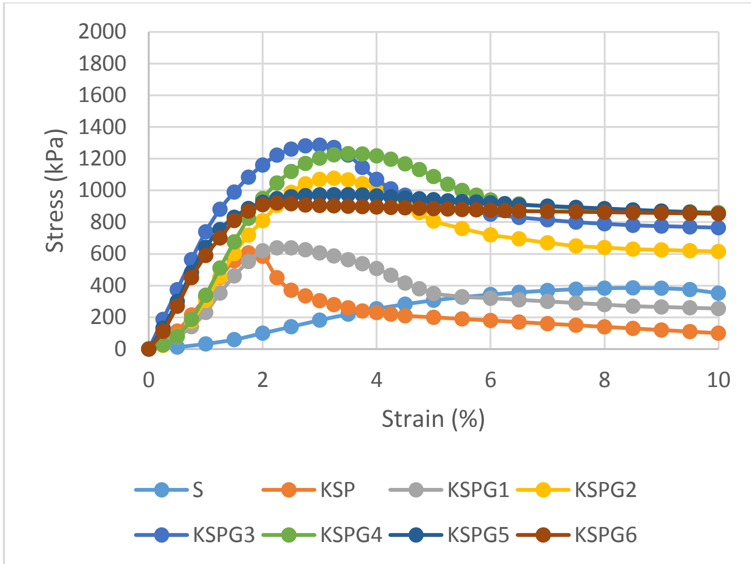
Table 2. Chemical analysis of soil, POFA and glass fiber analyzed by X-Ray Fluorescence (XRF)

Constituent	Natural soil (%)	POFA (%)	Glass fibers (%)
Silica (SiO_2)	41.26	46.04	59.9
Alumina (Al_2O_3)	36.96	19.39	13.09
Iron oxide (Fe_2O_3)	10.07	6.10	-
Calcium oxide (CaO)	-	13.87	22.5
Potash (K_2O)	11.71	8.61	2.77
Magnesia (MgO)	-	-	2.5
Loss on ignition (LOI)	-	9.68	-

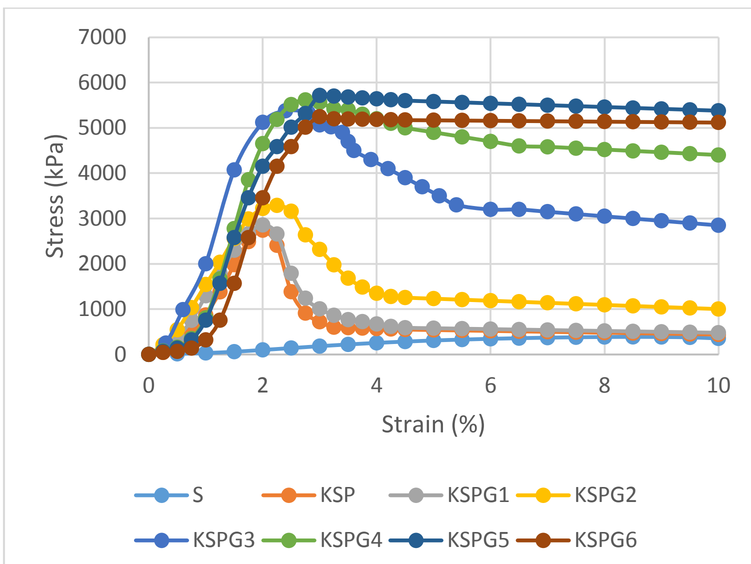
Table 3. Mixture Proportions of Various Series of Test Specimens

Group series	Test number	Samples	UCS test, curing (days)	Flexural strength test, indirect tensile strength test, curing (days)
S	S	Natural soil	-	-
KSP	KSP	10MKOH + Soil + 15% POFA	7, 28	28
KSPG group	KSPG1	10MKOH + Soil + 15% POFA + 1% glass fibers	7, 28	28
	KSPG2	10MKOH + Soil + 15% POFA + 2% glass fibers	7, 28	28
	KSPG3	10MKOH + Soil + 15% POFA + 3% glass fibers	7, 28	28
	KSPG4	10MKOH + Soil + 15% POFA + 4% glass fibers	7, 28	28
	KSPG5	10MKOH + Soil + 15% POFA + 5% glass fibers	7, 28	28
	KSPG6	10MKOH + Soil + 15% POFA + 6% glass fibers	7, 28	28

Figure



(a)



(b)

Fig. 1. Stress-strain behavior of treated soil samples after (a) 7 days and (b) 28 days curing

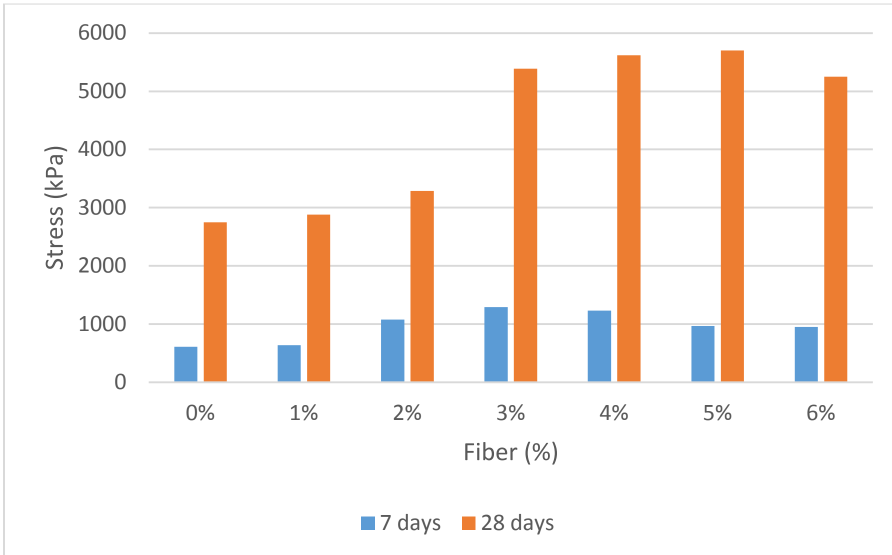


Fig. 2. Compressive strength of treated soil samples after (a) 7 days and (b) 28 days curing

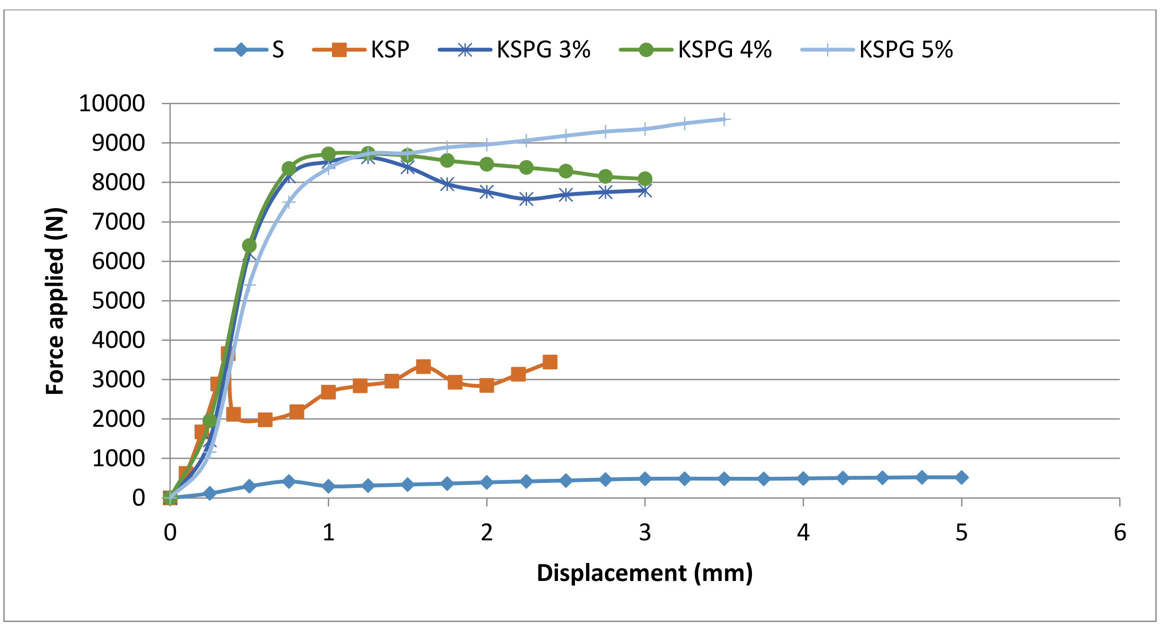


Fig. 3. Tensile load-deflection curves obtained after 28 days of curing

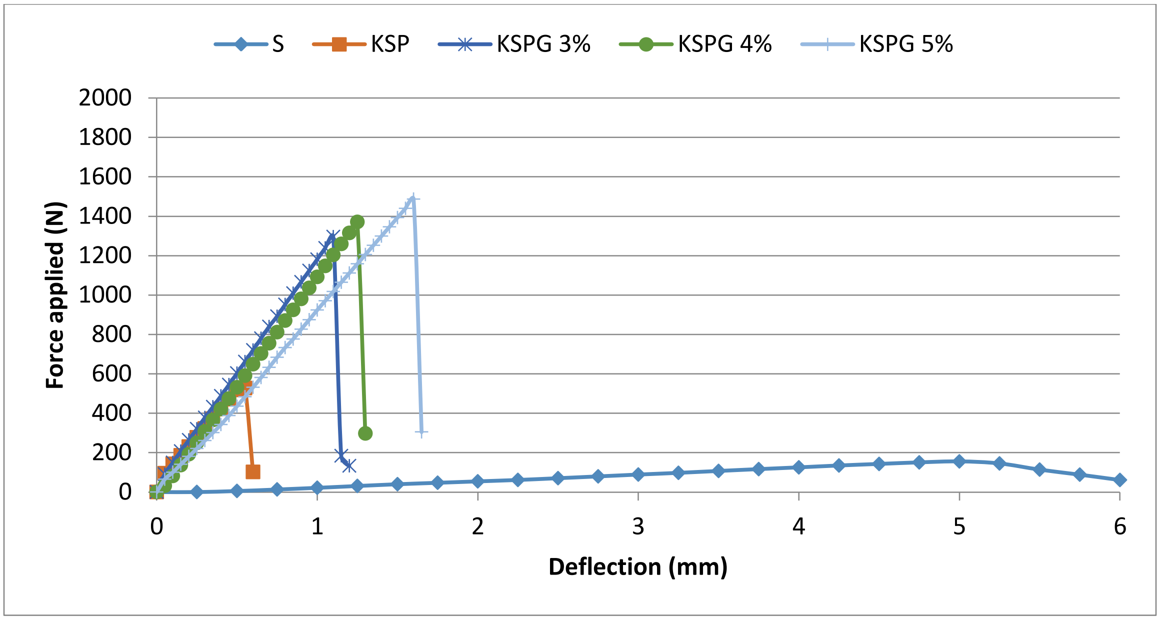


Fig. 4. Flexural load-deflection curves of treated test samples after 28 days of curing.

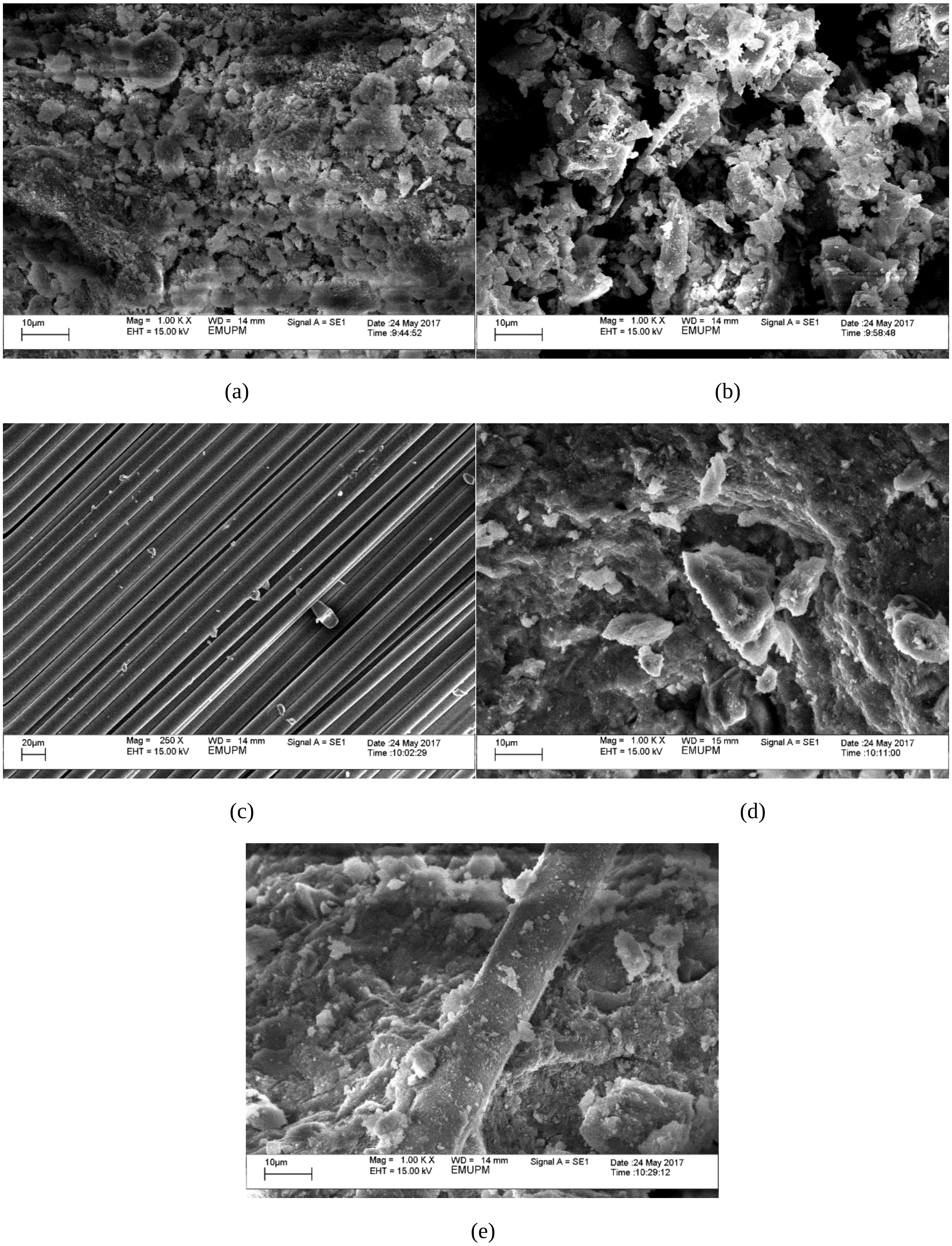
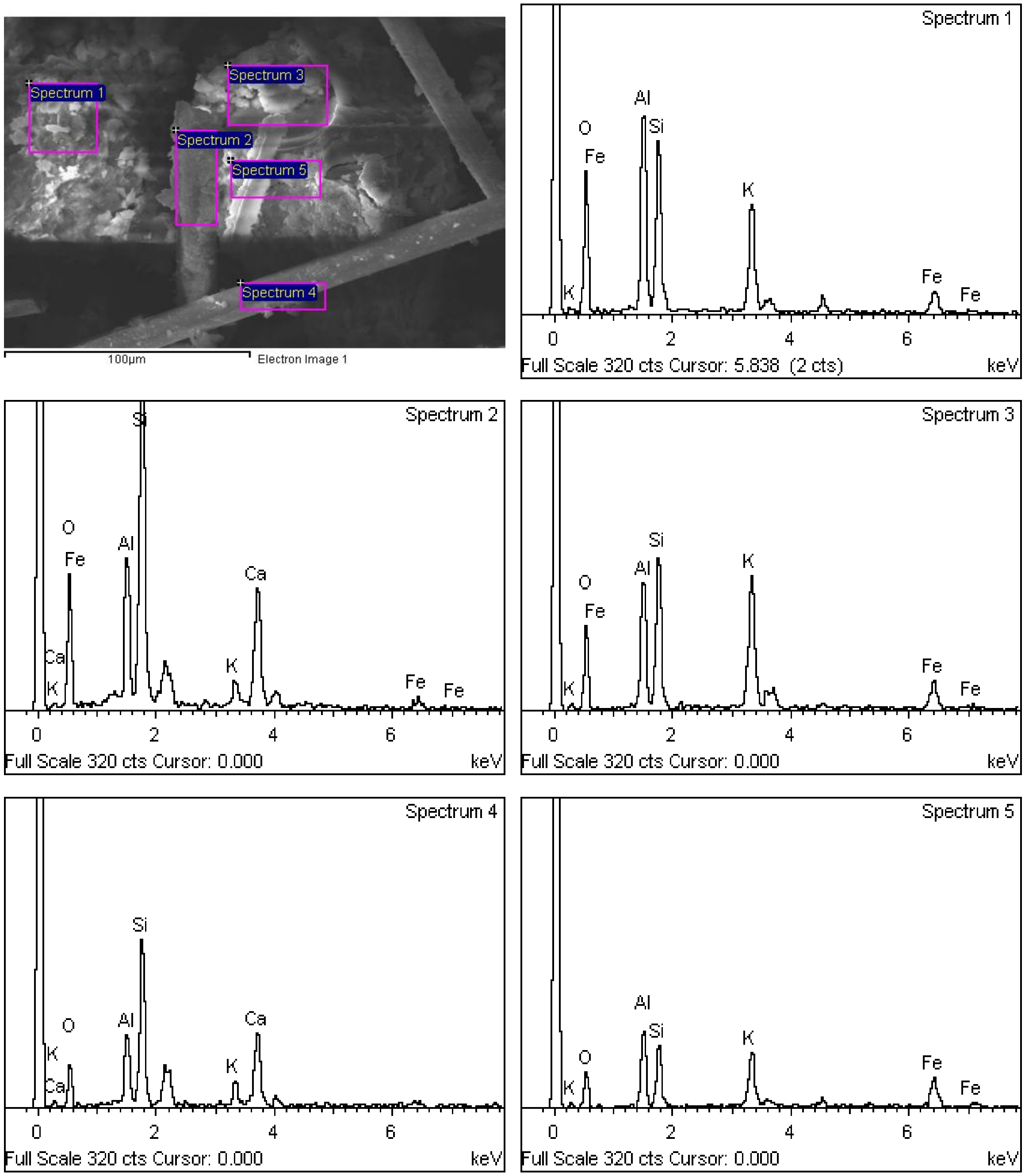


Fig. 5. SEM micrographs of (a) natural soil (S); (b) POFA; (c) glass fibers; (d) KOH-soil-POFA (KSP); (e) KOH-soil-POFA-fibers (KSPG5).



Components (%)	K	Al	Si	Ca	Ca/Si
Spectrum 1	10.18	13.35	12.12	0	0
Spectrum 2	1.81	8.22	20.08	9.71	0.48
Spectrum 3	14.37	10.64	13.78	0	0
Spectrum 4	4.24	7.68	19.58	13.23	0.68
Spectrum 5	12.30	13.57	11.82	0	0

Fig. 6. Micrograph and EDS data of glass fibers inclusion in stabilized soil mixture.

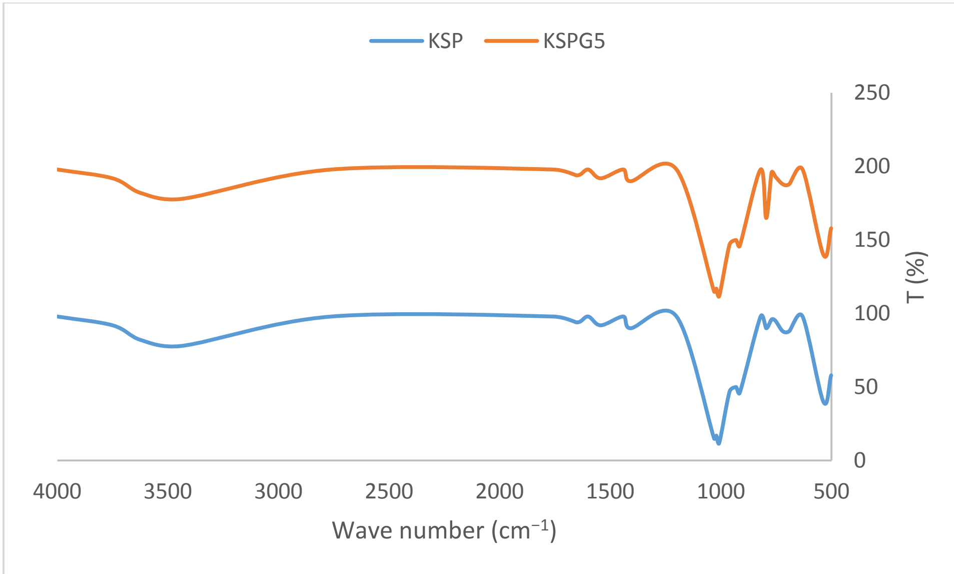


Fig. 7. FTIR of selected test samples.

1. GENERAL COMMENTS TO AUTHORS
   The manuscript discusses the feasibility of using palm oil fuel ash (POFA) as a precursor for alkali activation reactions in combination with glass fibers as a discrete reinforcement. Overall, the topic of the article is interesting. It will benefit readers in the field of soil stabilization techniques. This manuscript has been reviewed by experts in this field of study. The reviewers have recommended that the manuscript should be reassessed after extensive revisions. Some of the issues with the current version of the manuscript include grammatical errors throughout, English needs to be checked, literature review needs to be updated, quality of the images needs to be improved, technical items need to be addressed, results and analysis requires additional discussions.

Response: Thank you very much for your constructive comments. The manuscript was proofread by a native speaker, and all comments were responded to. We included several references, and we updated the literature review accordinglly. Also, results were further discussed. We highlighted all changes.

2. REVISIONS
- Technical items for which revisions are compulsory:
M1. Abstract: Novelty and significance of this study should be carefully addressed. What are the advantages of the used additive focused in this study relative to traditional additives (i.e., lime, cement and fly ash)? It is suggested that "Abstract" should be rewritten to highlight the key points of this study. It is too poor in its current form.

Response: The abstract was improved. Additionally the introduction was also improved to address the traditional soil binders and environmental issues associated with them and the need for development of new soil binders.

M2. Introduction: The literature covered was mainly from the stabilization in concrete application and since the nature of the stabilization in ground improvement is different from that of concrete applications, it is suggested to review the publication in the field of geotechnincs. Some of the suggested publications are: "Influence of class F fly ash and curing temperature on strength development of fly ash-recycled concrete aggregate blends" and "Alkali-activation of fly ash and cement kiln dust mixtures for stabilization of demolition aggregates" and "Effect of lime stabilization on the mechanical and micro-scale properties of recycled demolition materials".

Response: Thank you for your constructive comments and the suggestions. In addition to the following references, several references were added to address the geotechnical field.

M3. Introduction: This section can enhance with some more recent research on stabilization marginal soil with green additive in the concept of sustainable way:
a) Nissa Mat Said, K., Safuan A Rashid, A., Osouli, A., Latifi, N., Zurairahetty Mohd Yunus, N., & Adekunle Ganiyu, A. (2018). Settlement Evaluation of Soft Soil Improved by Floating Soil Cement Column. International Journal of Geomechanics, 19(1), 04018183.
b) Latifi, N., Vahedifard, F., Siddiqua, S., & Horpibulsuk, S. (2018). Solidification-Stabilization of Heavy Metal-Contaminated Clays Using Gypsum: Multiscale Assessment. International Journal of Geomechanics, 18(11), 04018150.
c) Muhammad, N., Siddiqua, S., & Latifi, N. (2018). Solidification of subgrade materials using magnesium alkalinization: A sustainable additive for construction. Journal of Materials in Civil Engineering, 30(10), 04018260.
d) Latifi, N., Vahedifard, F., Ghazanfari, E., & Rashid, A. S. A. (2018). Sustainable Usage of Calcium Carbide Residue for Stabilization of Clays. Journal of Materials in Civil Engineering, 30(6).

e) Tabarsa, A., Latifi, N., Meehan, C. L., & Manahiloh, K. N. (2018). Laboratory investigation and field evaluation of loess improvement using nanoclay-A sustainable material for construction. Construction and Building Materials, 158, 454-463.
f) Dehghan, H., Tabarsa, A., Latifi, N., & Bagheri, Y. (2018). Use of xanthan and guar gums in soil strengthening. Clean Technologies and Environmental Policy, 1-11.

Response: Thank you for your constructive comments and the suggestions. Several references were added to address the geotechnical field.

M4. line 96: is CL the correct terminology? Also, check the state the testing procedure for determination of soil classification.

Response: Yes, It was checked. The classification is correct.

M5. line 111: Considering all the treatment for the preparation of POFA, discuss the feasibility for large scale application.

Response: This study aimed at a lab scale investigation. A discussion has been added to address the need for further research in order to launch this technology into the construction market.

M6. line 124: Why 10 molar?

Response: the references were added.

M7. It would be better to add the FTIR result of pure soil, and soil treated with selected additive to the paper, so the FTIR discussion could be meaningful at that way. Generally, the quality of the figures is not good and those are presented too bleary. More discussion on the UCS test results is necessary, why the strength increased and what mechanism happened between the soil and additive? The latter is necessary to be added for the direct shear test results. The authors should provide a discussion and make a relation between strength tests and micro-structural results (Optical images). Needed more technical discussion and explanation on results.

Response: I appreciate your concern, however, the FTIR was employed to identify the significant role of the 'amorphous' bonds in the alkaline activated matrix as it was discussed, and that is why soil is not included. It should be noted that the SEM, EDS, and FTIR comprehensively supported the mechanism. The discussion on UCS, indirect tensile strength, and flexural tests were improved to address the relationship between strength tests and microstructural tests. The quality of the figures has been improved.

M8. Conclusion is generic; they need to clearly explain their findings in the conclusion not just providing the summary as it currently reads. Authors also need to edit the whole paper to avoid any typos.

The conclusion was improved, and the whole paper has been proofread.