Thermal curing effects on alkali-activated treated soils with palm oil fuel ash

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A B S T R A C T

Regarding the significance of binder quantity, alkali activator molarities, and thermal curing, this work was utilized to geopolymerize with a potassium-based alkaline activator to strengthen soils. Five different molarities of palm oil fuel ash (POFA) in four different amounts were utilized to activate the clayey soil. POFA admixtures have been used to test soils. The results showed that for mixtures with 10 and 12.5 molarities, the unconfined compressive strength (UCS) with 15 % and 20 % of POFA was stronger. Comparing the strengths of the blends with various POFA amounts and concentration molarities allowed for this determination. To increase the strength, it is crucial to consider how the geopolymerization method's temperature and curing time affect the UCS of the soil-POFA mixture with and without fibers. The UCS of the treated soil mixtures was changed by heating at 30, 50, 70, and 90 °C. The outcomes demonstrate that increasing the curing temperature will hasten the alkaline activation process. After seven days of heating, the treated soil specimens with and without fibers exhibit the best mechanical properties at a healing temperature of about 70 °C, with compressive strengths of 16.7 and 11.4 MPa. The interaction between the geo-polymeric matrix and the fiber surface, the molarities of the alkaline solution, and the heating temperature were the most important aspects, according to an investigation of the microstructures, in improving the behavior of the reinforced mixes. By offering an efficient approach for increasing the qualities of soil treated by the alkali activation of POFA through the inclusion of glass fibers with adequate molarities of reagent and cure heating temperature, the current work offers new insights into soil stabilization operations. This has advantages over conventional

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calcium-based binders due to their emission of carbon dioxide during manufacture, which is one of the major causes of global warming.

1. Introduction

One of the advantageous ways to treat the engineering features of soils with various additions is soil stabilization. This approach has financial benefits, particularly when there are unsuitable soils on the construction site. In addition, there are no expenses associated with providing and delivering appropriate soil, nor is it necessary to remove inappropriate in situ untreated soil [4,18,19,29,30]. The use of calcium-based precursors (such as lime and cement) in this process has grown in popularity due to their durability, ease of customization, and cost-effectiveness. Even though these common chemical binders can provide a variety of soil engineering properties, they have several limitations, especially when examined from a sustainability perspective. For instance, cement contributes around 7 % of the world's artificial carbon dioxide emissions due to carbonate breakdown. Carbon dioxide, a significant greenhouse gas linked to global warming, is thought to be produced by one ton of cement, or roughly 1 t [21,23,27]. Therefore, it appears that there is a lot of interest in developing new soil precursors that have performance on par with or better than that of cement and other conventional binders but with lower processing and environmental costs [20,30]. Alkali-activated binders have so far been the subject of research that suggests these materials may represent the next generation of binders [10–12,16,20,34]. The process of 'geopolymerisation' refers to the dissolution of alumina (Al_2O_3) and silica (SiO_2) from some materials in an alkaline atmosphere and then polymerizing to create a new material known as geopolymerization. Davidovits [13,14] was the first to use it when he used the term "geopolymers" to refer to the results of the geopolymerisation of kaolin. A geopolymer is essentially a multiphase, amorphous to semicrystalline, aluminosilicate mineral polymer. These alkali-activated aluminosilicate binders are created by reacting unprocessed particles rich in silica and aluminum with an alkali solution to create a mixture of gels and crystalline materials that finally form an entirely novel, reliable matrix. It takes place in a very alkaline environment that reorganizes during the polycondensation reaction. Aluminum and silica are reorganized into a more stable Si-O-Al type structure during the polycondensation reaction in a highly alkaline environment, making materials that are chemically stable and have high mechanical strength [9,12,25,33]. The gel cannot turn into a well-crystallized structure, as is the case during zeolite formation, because the hardening process starts as soon as the aluminosilicate material is combined with the alkaline solution [34]. They compared the X-ray diffraction (XRD) analysis patterns of various minerals prior to and following activation and came to the conclusion that, despite a slight intensity decrease after geopolymerization, all of the main characteristic peaks of Al-Si persisted, indicating that there was not a complete dissolution into the gel phase. Furthermore, the absence of new peaks implied that no new significant crystalline phases occurred.

Most aluminosilicates are naturally crystalline, making them extremely stable in all but the most extreme situations. The aluminosilicate raw materials should first undergo thermal treatment in order to improve the conditions for the reaction of alkaline activation and to increase the amount of polymerization that occurs [35]. As a result, the constituent water will be lost and the aluminum and oxygen ions will re-coordinate, causing the formerly crystalline substance to become amorphous. These structural alterations encourage a climate where chemical fusions can happen more readily. Because of this, calcined raw materials like clay or feldspars are less appropriate for alkaline activation than non-calcined materials like ground blast furnace slag, palm oil fuel ash, fly ash, Portland cement, metakaolin, or pozzolanic wastes. Palm oil fuel ash (POFA) was utilized in this experiment for this reason as well as the environmental advantages of using a waste by-product [1–3,12,17].

A review of the aforementioned source precursors reveals that the utilization of (potential) waste by-products from various industries, such as industrial and agricultural wastes and wastes from rural and urban society, has been a major driving force behind the development of this promising method, principally to address the growing financial and environmental defies associated with handling these by-products. In a political environment where governments all over the world are taxing CO_2 emissions and sponsoring maintainable and eco-friendly materials, the use of these waste by-products through geopolymerized precursors can thus develop as important precursors in civil and structural engineering use (i.e. geotechnical projects).

Despite the reality, that the locally available source binder (POFA) showed an effectiveness in the alkaline activation process, several issues are not well recognized, such as the binder quantity and alkali activator molarities with the host soil. Alkali-activated precursor in most alkali-activated treatment with and without elevated temperature occasions demonstrated considerable brittle high peak results of UCS [5,6]. This brittle high peak restriction is crucial in some geotechnical applications, such as when seismic loads, intense lateral earth pressure, or anticipated horizontal displacements are anticipated. The glass discrete fibers reinforcement was selected to create a stronger and more sustainable mechanical bond with the surrounding treated soil matrix [6]. The main constituents of glass discrete fibers reinforcement are roughly 60 % SiO_2, 13 % Al_2O_3, and 22 % CaO, along with other unique elements like potassium and other oxides. This work also concentrated on the value and period of temperature curing for treated soil with and without glass discrete fibers reinforcement as a source of discrete reinforcement added to the treated mixes.

The current study looks at how binder quantity affects the alkaline activation process by focusing on soil strength improvement with different alkali activator molarities. A further secondary aim is to investigate the effect of temperature on treated soil with and without glass fibers. The development of a substitute alkaline solution molarity with alkali-activated binder quantity for soil stabilization applications has been the first main emphasis. Then the thermal curing with and without glass discrete fibers reinforcement was carried out as an additional treatment to the alkali-activated matrix. Unconfined Compression Strength (UCS), which allows for the evaluation of the compressive strength to determine the influence of POFA percentage with different molarities of alkaline reagent and curing temperature on the various reinforced alkali-activated soils, was used to analyze the changes in the mechanical response.

Additionally, a detailed microstructural study was carried out.

2. Methodology

2.1. Materials used

The soil utilized for this investigation was found on the University Putra Malaysia campus, 1–1.5 m below the level of the surrounding terrain. The physical characteristics and chemical components of the two types of soil employed in this experiment, as determined by the Unified Soil Classification System [7], are shown in Tables 1 and 2.

For the geopolymerization reactions, POFA was obtained from a processing facility in Johor Bahru, Malaysia. To achieve the proper size, shape, and chemical composition, POFA initially underwent pretreatment that included calcination and grinding [4–6]. The resultant particles were pulverized for one day in a ball mill with an 80 cm diameter and then passed through a 300 m screen after POFA had been dried in an oven for one day at 105 °C. After that, any unburned carbon was removed from the ground POFA by heating it for roughly 60 min at 440 °C in an electric heater. Others who have demonstrated the effectiveness of this method to improve the specific surface and ash reactivity have documented a comparable pretreatment on a laboratory scale [29,4–6]. The method described by Tangchirapat et al. [32], in which unburned carbon is typically reduced or removed by a high-temperature burnout, is comparable to the one used in this procedure. Using a total carbon analyzer, the amount of unburned carbon in this treatment procedure was quantified. The carbon concentration in treated POFA decreased from 9.68 % to 1.5 %, as indicated in Table 3. More research is required before this technology may be introduced to the building sector. X-ray fluorescence (XRF) analysis was used to perform a spectrometry analysis following pretreatment (Table 3).

Potassium hydroxide (KOH) has been used as a source of K^+ cations to increase the alkalinity and serve as an alkali activator because of its proven efficacy. As previously given by R&M Chemical, the reagent was available in pellet form and could be diluted with enough distilled water to reach the desired concentration [4–6,28]. Before use, the alkaline solution was allowed to cool to room temperature because KOH interacts exothermically with water.

By dry weight, commercially available glass fibers have been introduced to selected soil 1 that has undergone 5 % thermal treatment [6]. The chemical characteristics of the fiber were freely accessible to the manufacturer and noted in Table 4.

2.2. Experimental study

Table 5 lists the ingredients of each tested combination. Unstable soils (first soil (S1) and second soil (S2)), activator-first soil (S1)-binder (K-S1-P), and activator-second soil (S2)-binder (K-S2-P) were the three types of combinations that were prepared. In order to offer an adequate reference for analyzing the combinations of K-S1-P and K-S2-P, unstable soils were included in the initial tests. Dry soils were first manually mixed with varying POFA dosages (10–25 %). Once a homogeneous mixture was attained, the needed quantity of air-dried soils and POFA were combined with the cooled alkaline solution.

Following the aforementioned blinding process, the samples were manually compacted in a cylindrical mold that was 50 mm in diameter and 100 mm high. A steel rod with a 45 mm diameter was used to deliver static stress in three equivalent layers. A dry density unit value of 1.58 Mg/m^3 has been set as the goal for all mixes. After extrusion, the samples were immediately covered with polythene plastic to prevent moisture loss. To acquire an approximate saturation level prior to the UCS testing, the specimens were unwrapped and immersed in water for the final 24 h before the experiments. With the exception of the unstable soil specimens of first soil 1 (S1) and second soil 2 (S2), which lose structural integrity when submerged, this saturation was applied to all specimens in order to remove the beneficial effects of suction on the specimens' compressive strengths.

After a treatment period interval of seven and twenty-eight days, the unconfined compressive strength (UCS) was measured according to part seven: clause seven of BS 1377 [8]. The results were only accepted if the anticipated UCS values were less than 5 % of the normal in three different samples. These trials were carried out at a speed of 0.2 mm per minute under monotonous displacement control on a universal Instron 3382 testing machine supplied with a 100 kN load cell. Each experiment yielded a complete stress-strain curve, and all samples were saved for later mineralogical analysis.

It should be emphasized that the goal of the study was to determine how healing temperature affects the strength of treated soil

Table 1
Physical characteristics of soils.

Properties	Standard	Soil 1	Soil 2
Liquid limit (LL) (%)	BS 1377-2	49	74
Plastic limit (PL) (%)	BS 1377-2	35	43
Plasticity index (PI) (%)	BS 1377-2	14	31
Specific gravity (G_S)	BS 1377-2	2.52	2.34
MDD (Mg/m^3)	BS 1377-4	1.58	1.32
OMC (%)	BS 1377-4	24	30
Sand (%)	USCS	32	-
Silt (%)	USCS	24	78
Clay (%)	USCS	44	22
UCS (kPa) - after compaction test	BS 1377-7	380–390	180–190

Table 2
Chemical analysis of soils.

Chemical properties	Soil 1 (%)	Soil 2 (%)
Silica (SiO_2)	31.2	55–60
Alumina (Al_2O_3)	21.9	23–29
Iron oxide (Fe_2O_3)	43.8	Below 6
Calcium oxide (CaO)	3.1	
Potash (K_2O)	-	Below 2.5
Magnesia (MgO)	-	Below 0.5
pH	5.3	3.8

Table 3
Chemical composition of POFA (before and after pre-treatment).

Constituent	Natural POFA	Treated POFA
Physical properties		
Specific gravity (GS)	2.42	2.51
Chemical properties		
Silica (SiO_2)	46.04 %	55.78 %
Alumina (Al_2O_3)	19.39 %	17.29 %
Iron oxide (Fe_2O_3)	6.10 %	4.17 %
Calcium oxide (CaO)	13.87 %	11.93 %
Potash (K_2O)	8.61 %	7.79 %
Magnesia (MgO)	-	-
Loss on ignition (LOI)	9.68 %	1.5 %

Table 4
Chemical composition of glass fiber.

Constituent	Glass fibers (%)
Silica (SiO_2)	59.9
Alumina (Al_2O_3)	13.09
Iron oxide (Fe_2O_3)	-
Calcium oxide (CaO)	22.5
Potash (K_2O)	2.77
Magnesia (MgO)	2.5
Loss on ignition (LOI)	-

Table 5
Mixture designation and composition.

Group	Mixture	Samples	Activator concentration (M)	Curing time (days)
S group	S1	Natural soil 1	0	-
	S2	Natural soil 2	0	-
K-S1-P group	K-S1-P10	KOH + Soil 1 + 10 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S1-P15	KOH + Soil 1 + 15 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S1-P20	KOH + Soil 1 + 20 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S1-P25	KOH + Soil 1 + 25 % POFA	5, 7.5, 10, 12.5, 15	7, 28
K-S2-P group	K-S2-P10	KOH + Soil 2 + 10 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S2-P15	KOH + Soil 2 + 15 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S2-P20	KOH + Soil 2 + 20 % POFA	5, 7.5, 10, 12.5, 15	7, 28
	K-S2-P25	KOH + Soil 2 + 25 % POFA	5, 7.5, 10, 12.5, 15	7, 28

both with and without fibers. At first, POFA and glass fibers (5 %) were combined side by side with the dry soil 1. Once a consistent mixture was achieved, the needed amount of air-dried soil and 15 % of POFA were combined by adding the cooled alkaline solution to the predetermined weight of glass discrete fiber reinforcement (percent by dry mixture weight).

Soon after the blinding phase, a few cylinder specimens from the treated soil 1 with and without discrete fibers reinforcement were heated in an electric heater at fifty, seventy, and ninety degrees Celsius for around one, three, seven, and twenty-eight days (Fig. 1). After being heated, these specimens were tested for UCS, and the outcomes were compared to those of samples that had been cured at 30 °C ambient temperature.

To further understand the impact of the precursor on the host soil, a few samples were analyzed using scanning electron microscopy (SEM) after being subjected to the particular UCS experiment. For the SEM evaluation, the crushed, treated ground samples were mounted on double-sided carbon tabs on Al-stubs and then coated with a thin layer of silver using a sputter coater. The chosen

Fig. 1. Heating and shearing procedures.

specimens were then subjected to SEM micrograph analysis.

3. Results and discussion

3.1. Impact of binder and alkaline solution molarity on mechanical behavior

The mean value of the compressive strengths of three tests is represented by each depicted compressive strength test data. Fig. 2 displays the UCS values for two distinct soils with 10 %, 15 %, 20 %, and 25 % POFA, potassium hydroxide solution, at molar concentrations of 5, 7.5, 10, and 12.5 molars. With time, the POFA addition boosted the dry soil's initial strength. It is possible that using 12.5 molar concentrations is ineffective in terms of cost/improvement ratio because the values for 12.5 and 10 molars were often relatively similar in the two soils. On the other hand, at 5 M alkaline activators, the dissolution of Si and Al present in POFA was low because of the relatively low base condition and, as expected, insufficient strength behavior achieved by the alkaline activators' poor reactivity. However, activator concentrations of 15 M and above were discovered to be unviable since they significantly enhanced parent soil plasticity and viscosity, resulting in a semi-plastic mixture with subpar UCS results. At twenty-eight days, the UCS of the first soil (S1) with 10 molars was 2.6 MPa, 2.7 MPa, 1.9 MPa, and 1.7 MPa for K-S1-P10, K-S1-P15, K-S1-P20, and K-S1-P25, respectively. Likewise, the UCS values of the second soil (S2) with 12.5 molars were 0.9 MPa, 1.2 MPa, 1.3 MPa, and 1.1 MPa, respectively. Although the 7.5 molar concentration mixture's strength was nearly equal to 10 molars after seven days. based on the POFA %. For K-S1-P10, K-S1-P15, K-S1-P20, and K-S1-P25, the UCS of the first soil (S1) with 7.5 molars was 0.5, 0.5, 0.4, and 0.4 MPa, respectively. Likewise, the UCS of the second soil (S2) with 7.5 molars was 0.2, 0.2, 0.3, and 0.3 MPa, for K-S2-P10, K-S2-P15, K-S2-P20, and K-S2-P25, respectively. In terms of strength development, Fig. 2 clearly shows that 15 % and 20 % of POFA are the optimal percentages in the first and second soils (S1 and S2), respectively. It should be noted that the blends investigated in this work have been compacted at the ideal point of the Modified Proctor curve for the treated soil blend with POFA (palm oil fuel ash) and water. The viscosity of the mixture increases when an alkaline solution is added in place of water, which might alter how they behave in general. Additionally, it should be highlighted that higher soil plasticity caused alkali-activated soil samples to lose strength when higher POFA levels (K-S1-P25 and K-S2-P25) were integrated.

Inadequate activation time increases the quantity of unreacted precursor (POFA) in the mixture; this prevents it from acting as a binding product and instead causes it to function as a filler in the soil additive. Short healing times in the alkali-activated specimens lead to low to tiny strength as a result. By development, the amount of active aluminum and silicon in POFA that is converted into coupling products is directly impacted by the length of the curing period (Fig. 2). This figure shows that after 28 days, the alkali-activated samples (K-S1-P group and K-S2-P group) showed a substantial increase in strength.

The stress-strain curves from descriptive tests carried out on the selected blends of two distinct soils are shown in Fig. 3. These
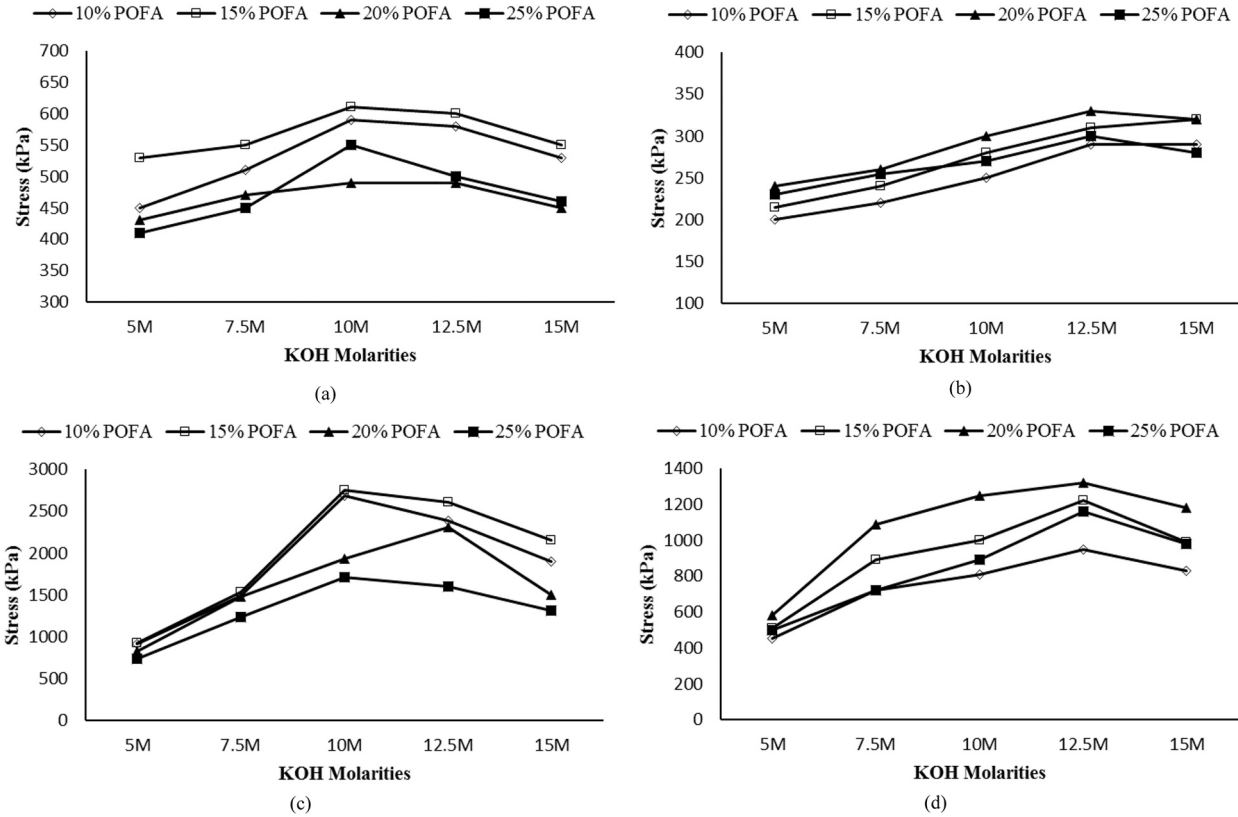
Fig. 2. UCS results at 7 and 28 days for the 8 mixtures (a) K-S1-P cured at 7 days, (b) K-S2-P cured at 7 days (c) K-S1-P cured at 28 days, (d) K-S2-P cured at 28 days.

curves clearly show two different patterns of performance: harder K-S2-P20 (12.5 molars) achieves lower peak strength at around 0.5 % of axial deformation, while more ductile K-S1-P15 (10 molars) achieves higher peak strength at around 2 %.

3.2. Impact of treatment condition on the mechanical behavior of treated soil

According to all accounts, thermal curing is another technique to boost the potency of such alkaline solution alternatives in addition to the ambient curing environment (30 °C) [5]. As shown in Figs. 4 and 5, samples that are cured and treated at elevated temperatures see a significant increase in the reaction rate, which results in specimens that have been alkali-activated having significantly higher strength UCS levels than those that have been restored at 30 °C.

For one, three, seven, and twenty-eight days of heating, the compressive strengths of the first alkali-activated treated soil (K-S1-P) without fibers are shown in Figs. 4 and 5. In the long term (28 days), the reference alkali-activated treated soil (S1) with and without discrete fibers reinforcement achieved UCS values of 5.7 and 2.7 MPa, respectively. Due to the delayed specimen setting, the short-term mechanical strengths performance of geopolymeric treated soil (S1) with and without discrete fibers reinforcement cured at room temperature obtained 0.9 and 0.6 MPa, respectively, of UCS. According to estimates, a tough structure forms more quickly at high temperatures, especially in the early stages of an alkaline activation event. After seven days, the UCS values of the first alkali-activated treated soil (S1) with and without fibers were higher than those seen for specimens cured and treated at thirty degrees Celsius (laboratory ambient temperature), reaching higher values of 16.71 and 11.4 MPa, respectively. The UCS value for first soil (S1) with and without fibers at ninety degrees Celsius in twenty-eight days is, however, 1 and 1.3 MPa lower than that for first soil (S1) with and without fibers at ninety degrees Celsius in seven days, respectively, because the quick setting prevents the mixture from forming a more dense and hard structure. On the other hand, despite the fact that the late strengths of the alkali-activated treated mixture of first soil (S1) with and without discrete fibers reinforcement that was treated and cured at a laboratory ambient temperature improved, at 28 days old, it reached values of 5.7 and 2.75 MPa, respectively. The explanation for this performance is comparable to how temperature affects how strong metakaolin-based geopolymers become [24,26]. Early on, the strength's performance rises with elevated temperature because more alkaline activation occurs at higher temperatures, which increases the number of reaction products. On the other hand, it takes longer for specimens treated at 70 and 90 °C temperatures to reach strengths that are nearly identical to those seen after young age because the system loses water during curing, and the resulting deficiency in moisture makes it difficult for the glassy component of POFA (the first stage of cementitious gel formation) to dissolve completely in these circumstances [5,22].

Despite this, a tendency towards a more brittle behavior of the binder-soil combinations was observed, as shown by the sharp decline in strength following the achievement of a distinct peak value, as seen in Fig. 6. The effect of fibers at high temperatures was another important area of research in order to ameliorate this post-peak tendency. In comparison to the treated soil without fibers, the treated soil with fibers exhibited a higher UCS. The post-peak strength loss could be lessened by the fibers. Furthermore, it can be deduced that the curing temperature and the fiber concentration were related to the increase in strength of the fiber-reinforced mixes [5,6]. When the fiber dosage was 5 %, as indicated by Abdeldjouad et al. [6], there was a discernible improvement.

Alkali-activated soil combinations benefit from a faster increase in strength during the early stages of hardening when their curing time is extended. While the unconfined compressive strength of the first treated soil (S1) with and without fibers was only 1.8 and 1.3 MPa after curing for one day at 50 °C, the strength increased by approximately 6 times to 12 and 8 MPa when curing was prolonged to seven and twenty-eight days. The specimens treated at thirty, fifty, and seventy degrees Celsius had the strongest results after 7 days. Alkali-activated soils that are cured at ninety degrees Celsius have a curing time effect on strength improvement very similar to that of seventy degrees Celsius. The samples that were heated to ninety degrees Celsius reached their peak strengths at a young age (seven days), with UCS values for soil 1 with and without fibers of about 15.8 and 10.8 MPa, respectively. However, when the specimen was just exposed to ninety degrees Celsius for a single day, a trend of strength improvement was seen that was very comparable to that found with twenty-eight days of curing at thirty degrees Celsius. In this instance, treated soil with and without fibers has short-term
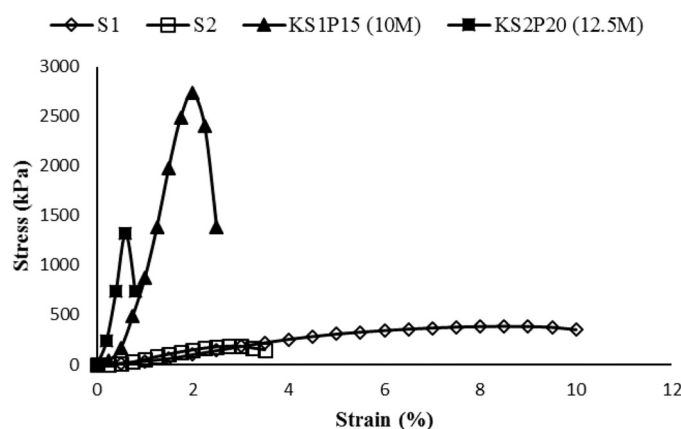

Fig. 3. Stress-strain curves of the selected mixtures: (a) S1; (b) S2; (c) K-S1-P15 (10 M); (d) K-S2-P20 (12.5 M).
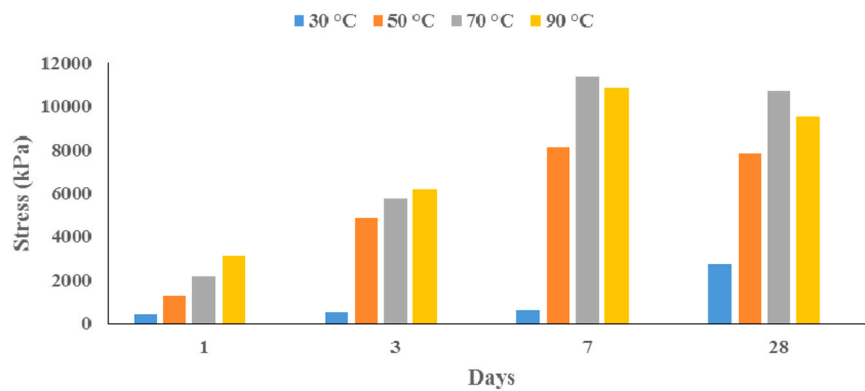
Fig. 4. Development of compressive strength of alkali-activated soil 1 without fibers cured at 30, 50, 70 and 90 °C over time (1, 3, 7 and 28 days).
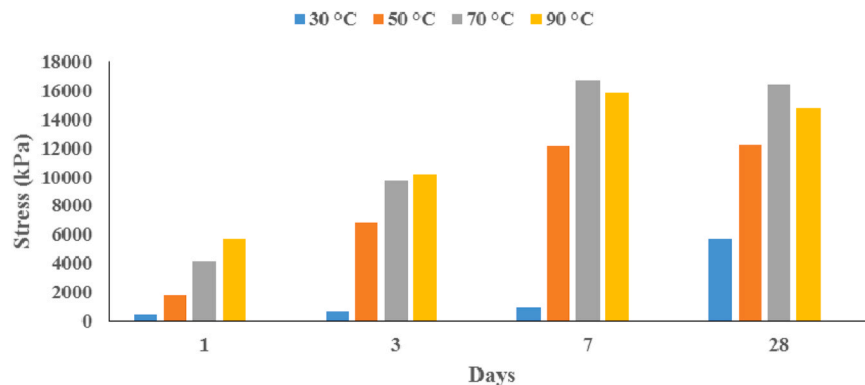

Fig. 5. Development of compressive strength of alkali-activated soil 1 with fibers cured at 30, 50, 70 and 90 °C over time (1, 3, 7 and 28 days).
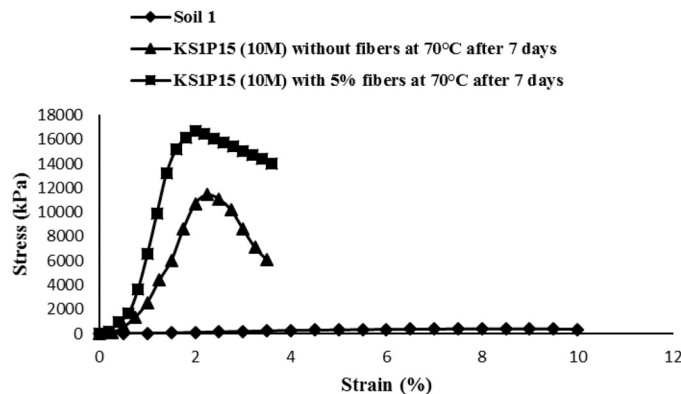

**Fig. 6.** Stress-strain curves of K-S1-P15 (10 M) with and without fibers at 70 °C after 7 days.

UCS values of about 5.7 and 3.1 MPa, respectively, while the long-term age (twenty-eight days) strength is not affected.

This study's goal of achieving cost sustainability and efficacy was defeated since it may not be practicable to apply such heating conditions on a construction site and may also be financially and environmentally expensive.

3.3. Microstructural analysis

The SEM micrographs analysis of the parent untreated soils are shown in Fig. 7(a)–(b), respectively, to better explain the stabilization procedures carried out by the geopolymerization method. The source binder (POFA) SEM micrograph in Fig. 7(c) following processing demonstrates how POFA's ultrafine particle size led to an increasingly thick microstructure. Regarding this, processed
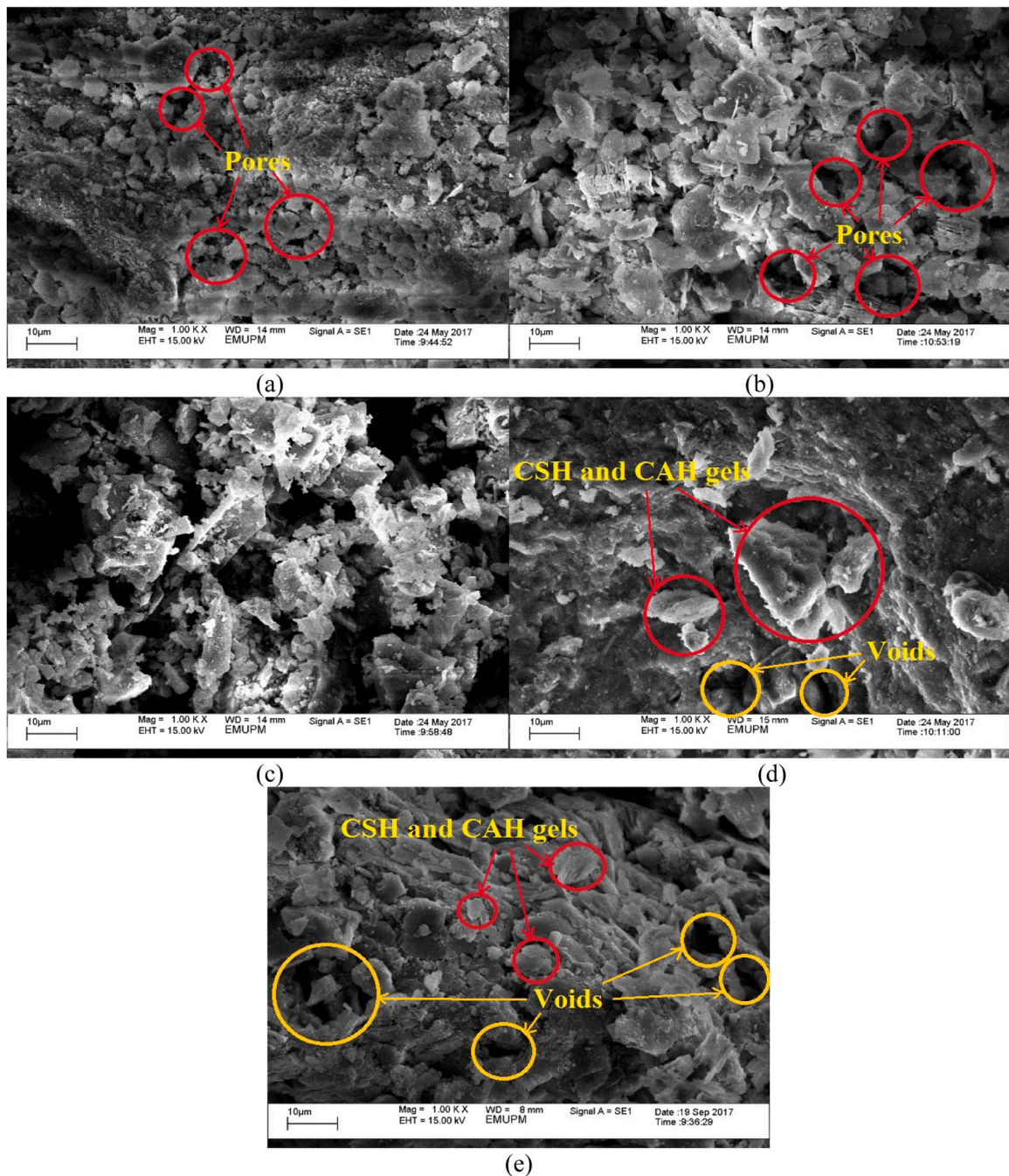
Fig. 7. SEM micrographs of (a) soil type 1, (b) soil type 2 (c) POFA after pre-treatment process, (d) KOH-soil type 1-POFA [K-S1-P15 (10 M)], (e) KOH-soil type 2-POFA [K-S2-P20 (12.5 M)].

POFA can, under the right conditions, fill the large pores seen in host soils [4,5].

Figs. 7(d) and 3(e), respectively, show selected SEM images of stabilized specimens [K-S1-P15 (10 molars) and K-S2-P20 (12.5 molars)] after twenty-eight days of cure that obtained the high UCS levels. The discrete particles of the POFA-treated samples (Fig. 7 (d)–(e)) are more tightly bound than those of the untreated soils (Fig. 7(a)–(b)), despite the fact that the microstructures of the chosen samples are still rough. Fig. 7(d)–(e) shows how alkali-activated POFA fills in the spaces left by the soil particles. This demonstrates that the Si-O-Al and Si-O-Si structure, which is well in line with the higher UCS observed outcomes, can explain the alkaline activation reinforcement process [4,6].

Raising the restoration temperature was known to increase the amount of binders dissolving (mostly Al and Si) from the amorphous

stages in POFA components and speed up the formation of hard structures, particularly in the initial stages of alkaline activation. After 28 days at thirty degrees Celsius, the holes were slightly larger (Fig. 8(b)), but gel continued to form after being kept for a while because the larger pores were regularly filled with reaction products as the alkaline activation progressed, forming longer chains and branches. Due to the presence of a suitable geopolymer gel linking the soil components during early alkaline activation, treated soil specimens maintained at high temperatures (seventy degrees Celsius) had better compressive strength than those stored at 30 °C (as shown in Fig. 8(c)).

The high calcium concentration of the discrete fibers reinforcement, which could dissolve and then be absorbed into the activated alkaline matrix, was largely responsible for the increased performance of treated soil with glass fibers (Fig. 8(d)). The Si ions that were mostly present in the partial dissolution of the fiber surface assisted to build the microstructural network, adhering the discrete fiber reinforcement surface to the geo-polymer matrix and improving the mechanical interlocking effect between the fibers and matrix. This was a highly intriguing byproduct, as it is well known that the mechanical effectiveness of soil improved by discrete fiber reinforcement incorporation often depends on the characteristics of the discrete fibers reinforcement as well as the soil-fiber interface adhesion [6].

The compressive strength will be greatly reduced if the preservative temperature is raised above 70 °C for more than 7 days (see Figs. 4 and 5). The strength of 28 days was found to be slightly diminished when the temperature of restoration was raised to 50 °C. When treated for seven days with equal intensity at seventy and ninety degrees Celsius, the trend was discovered. At the start of polycondensation, when the preservation temperature reaches seventy and ninety degrees Celsius, the viscosity increases quickly. Free aluminum binders were caught, and the aluminosilicate source was immediately dissolved in response. As a result, the original and final setting periods for geopolymer slurries were both relatively short. The undissolved POFA elements were encased in geopolymer gel as a result of the geopolymer slurries' quick coagulation (see Fig. 8(c–d)), which prevented further amorphous phase dissolution and prevented the fluid slurries from condensing into a compact and hard structure. Additionally, at high sustaining temperatures, geopolymer gels' microcracks and contractions would cause severe shrinkage and dehydration. Therefore, the compressive strengths of the specimens that had been restored at seventy or ninety degrees Celsius for twenty-eight days were nearly identical to those that had been restored at fifty degrees Celsius for seven days. Unlike Portland cement mortars, this was different [15,31].
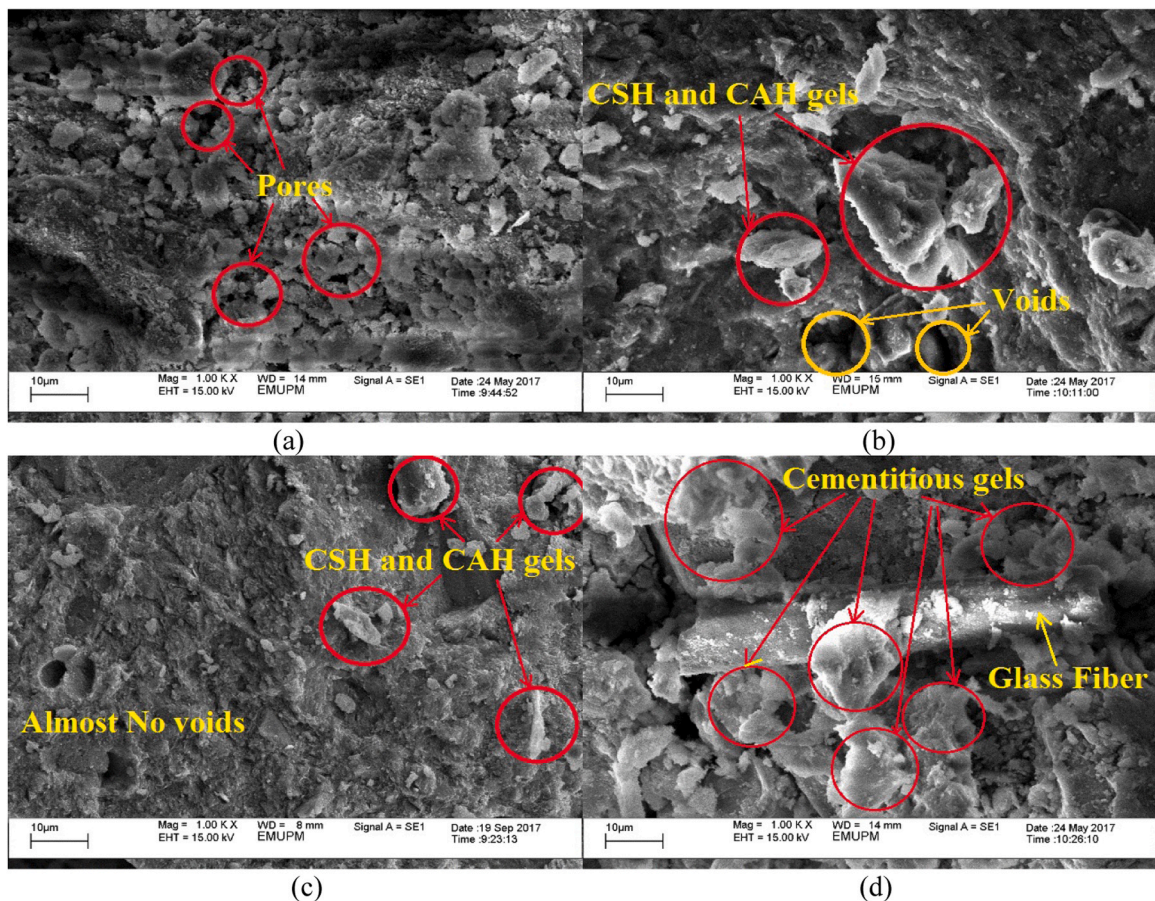
Fig. 8. SEM micrographs of (a) natural soil 1, (b) K-S1-P15 (10 M) without fibers at 30 °C after 28 days (c) K-S1-P15 (10 M) without fibers at 70 °C after 7 days (d) K-S1-P15 (10 M) with fibers at 70 °C after 7 days.

4. Conclusions

This work suggests that we can address two problems by using a new generation of soil binders called alkali-activated binders. First, environmental protection, efficient use of locally accessible by-products, and second, full omission of Portland cement and other conventional cementitious precursors from ground improvement applications.

According to the research, four variables—quantity of binder, alkali activator concentration, curing temperature, and reinforcement materials—have the greatest influence on the strength values of soil treated by the alkaline activation procedure.

1. A paste was created when palm oil fuel ash (POFA) was activated with potassium, mixed with soil, and allowed to dry. This new material had dramatically enhanced mechanical strength and deformation.
2. This waste by-product's alkaline activation is a straightforward method that doesn't require any elaborate or pricey processes, specialized equipment, or risky tactics.
3. The environment and hardening of treated soil are significantly impacted by temperature throughout the healing process. High temperatures hasten the breakdown of POFA components and the polymerization reaction process of precursors in the original alkaline activation process of the geopolymerization technology.
4. The discrete glass fiber reinforcement's surface and the alkali-activated treated matrix's interaction improved the power and conductivity of the repaired soils at high temperatures.
5. Increasing the curing period, especially during the first one, three, and seven days of the alkaline activation process, promotes the formation of a rigid structure. The hardening process is accelerated and the physical features of the samples of alkali-activated treated soils are developed with an appropriate temperature increase (below 70 °C).
6. Treatment and curing at excessively elevated temperatures (greater than 7 days at 70 and 90 °C) causes treated soil samples to become compact and difficult to compose, as a result of the geopolymer slurries' excessively quick setting velocity.

In addition to the positive findings of this study, the authors recommend that these engineering features be further researched in order to effectively advance the development of low-value by-products and their practical usage for applications such as ground improvement. It is strongly advised to use the alkaline activation technique to improve soft soils (organic and peat soils) through engineering. It is highly recommended to use an alkaline activation system to stabilize soil over a longer curing period. Model tests or full-scale field testing can be conducted in the hottest locations of the world (with varying high temperatures) to validate the laboratory results in order to imitate a sincere environment for the treated ground (by alkaline activation utilizing heat treatment). The potential weaknesses to the thermal practical application of this promising technology for soil development may exist in the coldest regions because of the treatment soil procedures by temperature.

CRediT authorship contribution statement

This piece of the submission is being sent via mail.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

No data was used for the research described in the article.

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