



Semarak Engineering Journal

Journal homepage:
<https://semarakilmu.my/index.php/sej/index>
ISSN: 3036-0145



Improvement of Geotechnical Properties of Kaolin Clay using a combination of Palm Oil Fuel Ash (POFA), Eggshell Waste, Guar Gum: A Preliminary Study

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ARTICLE INFO

Article history:

Received 15 August 2025

Received in revise 16 September 2025

Accepted 25 September 2025

Available online 3 October 2025

Keywords:

Clay soil, Palm Oil Fuel Ash (POFA); Eggshell Powder (ESP); Calcined Eggshell (CES); Guar Gum (GG); soil stabiliser; Unconfined Compressive Strength (UCS)

ABSTRACT

Clay soils with high plasticity and water content pose significant challenges in construction due to their low bearing capacity, settlement issues, and instability. Traditional soil stabilisers such as cement and lime improve these properties but involve challenges due to environmental concerns, resource depletion, and their performance limitations in some soil types. This study explores the potential of using sustainable and alternative soil stabilisers derived from agricultural and industrial wastes, specifically Palm Oil Fuel Ash (POFA), Eggshell Powder (ESP), Calcined Eggshell (CES), and the natural additive Guar Gum, to enhance the geotechnical properties of problematic soils. The research investigates the effects by formulating three binder combinations: POFA with ESP, POFA with CES, and POFA with CES plus Guar Gum, on the strength development, curing time, and dosage efficiency in stabilising Kaolin Clay. These formulations were tested on Kaolin Clay to evaluate their impact on unconfined compressive strength (UCS) across various dosages and curing periods. Results indicate that the combination of POFA and CES achieved superior strength enhancement compared to the other formulations, with UCS values significantly higher than untreated soils. The addition of Guar Gum did not improve the strength but influenced the binder's behaviour. Optimal performance was observed at a binder dosage of 30% with a curing period of 7 days. This study concludes that POFA and CES can serve as effective, eco-friendly soil stabilisers that reduce dependency on conventional cement and lime. Their use supports sustainable construction practices by utilising local waste materials and improving soil stability for infrastructure development. The findings recommend the practical application of POFA and CES mixtures as viable alternatives for road subgrades and other geotechnical works.

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<https://doi.org/10.37934/sej.10.1.2234>

1. Introduction

Soil stabilisation is a critical process in geotechnical engineering, aimed at improving the physical, mechanical, and chemical properties of problematic soils to ensure their suitability for construction and infrastructure development. Traditionally, stabilisers such as cement and lime have been widely used due to their effectiveness in enhancing soil strength, reducing plasticity, and improving soil durability. These stabilisers operate primarily through pozzolanic reactions that form cementitious compounds, which bind soil particles together, as reported by Lindh and Polina [1] and Almuaythir *et al.*, [2]. However, despite their widespread use, these traditional stabilisers face significant challenges related to environmental concerns, resource depletion, and performance limitations in certain soil types.

For instance, lime stabilisation can lead to deleterious effects such as carbonation, where weak calcium carbonate forms, and sulphate attacks in sulphate-rich soils, causing volume expansion, heaving, and eventual strength loss, as supported by several authors [3-5]. Meanwhile, cement-treated soils tend to be brittle and prone to shrinkage cracking, especially in highly plastic soils, which limits their long-term durability, as noted by Rehman *et al.*, [6]. These drawbacks highlight the need for developing alternative, sustainable soil stabilisers derived from industrial and agricultural by-products to reduce negative environmental impacts and promote sustainable construction practices.

Among the promising eco-friendly alternatives are Palm Oil Fuel Ash (POFA) and Calcined Eggshell (CES). POFA, a by-product of the palm oil industry, is abundantly generated and poses disposal challenges. It is rich in silica and alumina, which react with calcium hydroxide to form calcium silicate hydrate (C-S-H), thereby improving soil strength through pozzolanic activity, as discussed by Khalid *et al.*, [7] and Razali *et al.*, [8]. On the other hand, derived from discarded eggshells which is produced simply by cleaning drying, and grinding, eggshell powder (ESP) primarily comprises calcium carbonate (CaCO_3), making it an attractive alternative to traditional lime or cement in improving soil properties, according to Ngayakamo, Blasius, and Azikiwe [9]. Then, eggshell waste can be calcined to produce reactive calcium oxide (CaO), which results calcined eggshell (CES) that acts as a lime like binder. CES improves soil compressive strength and reduces plasticity by forming calcium silicate and aluminate hydrates when mixed with soil, according to Ngayakamo, Blasius, and Azikiwe [9].

Studying both ESP and CES in the context of soil stabilisation is essential for several reasons. First, these forms of eggshell possess different chemical and physical characteristics, leading to variations in their mechanisms of soil improvement. By analysing both, identification on which form delivers optimal performance for specific soil types and environmental conditions. Then, understanding both conditions ensures that soil stabilisation projects can be tailored according to available local resources, operational constraints, and sustainability goals. The combined use of POFA with ESP and CES leverages the pozzolanic and calcium-rich characteristics of these waste materials, offering an efficient and environmentally friendly method of soil stabilisation. This combination also avoids the excessive alkalinity associated with conventional lime treatments, presenting less risk of deleterious chemical reactions, as reported by Alhokabi *et al.*, [10].

Soil stabilisation comprises both mechanical and chemical approaches, with chemical stabilisation focused on mixing soil with additives like cement, lime, and industrial wastes to induce chemical reactions that cement soil particles together through hydration and pozzolanic processes. This results in enhanced soil strength and durability, as supported by several authors [11-13]. Nevertheless, the sustainability concerns surrounding traditional materials motivate research into non-traditional, waste-derived stabilisers such as POFA and CES, which reduce environmental impacts and overcome performance limitations in some soil types.

Research has demonstrated that POFA enhances the unconfined compressive strength (UCS) of soils, particularly clayey and expansive types, by forming cementitious gels that improve soil structure and decrease permeability, as indicated by Halim *et al.*, [14] and Putera *et al.*, [15]. Similarly, calcined eggshell powder exhibits lime-like behaviour that stabilises clay and silty soils by producing calcium silicate and aluminate hydrates, resulting in increased strength and reduced swelling potential, according to Harikaran *et al.*, [16]. The synergistic application of POFA and CES has been shown to significantly improve soil strength, often outperforming single stabiliser systems and meeting relevant construction standards such as those for road subgrades and embankments, reported by Alhokabi *et al.*, [10].

The primary aim of this research is to determine whether the two sources of Palm Oil Fuel Ash (POFA), namely Sedenak and Bukit Pasir, exhibit equivalent performance when used as soil stabilisers. This comparison will help establish if the performance is consistent regardless of the POFA origin. Next, the paper also investigates the effects of using different formulation, namely eggshell powder (ESP) and calcined eggshell (CES), in combination with POFA, in enhancing soil stability. Then, the research explores whether guar gum (GG) can contribute to improving soil strength. Guar Gum, a natural polysaccharide, have been explored for their benefits in enhancing soil cohesion, moisture retention, and workability. These improvements contribute to the overall effectiveness of alternative binder systems, as described by Anusha *et al.*, [17] and Kumar *et al.*, [18]. These findings inform the development of three specific formulations: POFA:ESP, POFA:CES, and POFA:CES:GG. Lastly, the paper evaluates the effect of dosage and curing time on alternative soil stabiliser by optimum formulation by assessing their strength development over time, particularly focusing on how the strength evolves with curing and the influence of varying dosages of this combination on the strength performance, determining the ideal proportion for optimal soil stabilisation.

In summary, this study comprehensively compares POFA from different origins, analyses the efficacy of ESP versus CES as stabilisers with POFA, investigates the role of guar gum in soil strength enhancement, and evaluates the performance and dosage effect of the optimal combination over varying curing time and dosages to identify the best stabilising formulation.

2. Methodology

2.1 Research Design and Framework

The study is divided into three phases. In Phase 1, the focus is on identifying the best binder material among POFA A (Sedenak), POFA B (Bukit Pasir), Eggshell Powder (ESP), and Calcined Eggshell (CES) at a 25% dosage by weight, with curing conducted for 7 days using Kaolin Clay. Following this, Phase 2 investigates the effect of adding Guar Gum (GG) at 10% of the binder mixture on the overall strength of the binder at the same 25% dosage and 7-day curing period, again employing Kaolin Clay. Building on the results, Phase 3 evaluates the optimized binder formulation from Phase 1, which is a combination of POFA B and CES, by varying dosages (20%, 30%, 35%, and 40%) and curing durations (1, 3, 14, and 28 days) on Kaolin Clay to determine the optimal conditions.

2.2 Soil Collection and Preparation



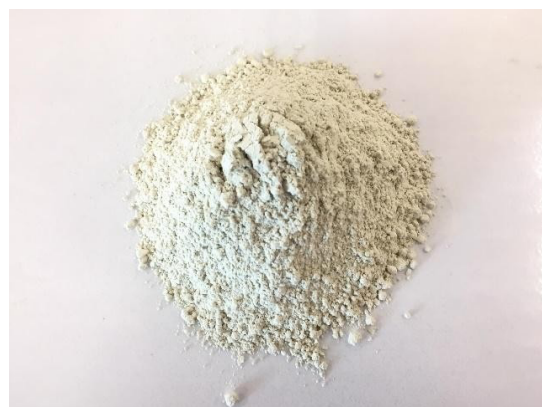
Fig. 1. Kaolin Clay

Kaolin Clay, as shown in Figure 1 was procured from Kaolin Malaysia Sdn. Bhd., then sieved through a 75 μm (No. 200) sieve and oven-dried at 105°C for 24 hours.

2.3 By-Product Binder Collection and Preparation



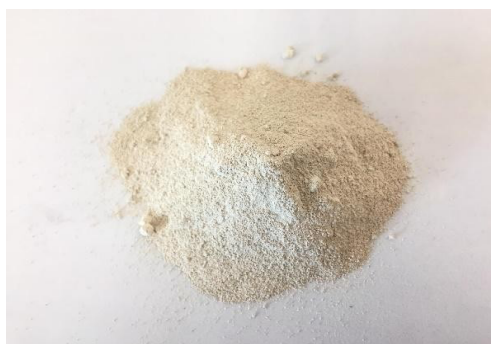
(a) Palm Oil Fuel Ash (POFA)



(b) Guar Gum (GG)

Fig. 2. (a) Palm Oil Fuel Ash (b) Guar Gum (GG)

Two types of Palm Oil Fuel Ash (POFA) in Figure 2(a) were collected from Sedenak (POFA A) and Bukit Pasir (POFA B). At the factories, both samples were calcined at 500°C to reduce moisture content and carbon dioxide. Once collected, it was oven-dried and followed by grinding and sieving to achieve a particle size smaller than 45 μm . Furthermore, Guar Gum (GG), as shown in Figure 2(b), a natural polysaccharide additive, was incorporated at a dosage of 10% in selected phases to investigate its influence on the strength and workability of the binder mixtures.



(a) Eggshell Powder (ESP)



(b) Calcined Eggshell (CES)

Fig. 3. (a) Eggshell Powder (ESP) (b) Calcined Eggshell (CES)

In addition to POFA and GG, Eggshell Powder (ESP), as illustrated in Figure 3(a) was prepared by washing eggshell waste, drying it at 105°C for 24 hours, then crushing, grinding, and sieving to 0.425 mm in size. To enhance its reactivity, the ESP underwent thermal treatment through calcination at 900°C for 2 hours to produce calcined eggshell, as shown in Figure 3(b). This process converted calcium carbonate (CaCO_3) present in the eggshells into reactive calcium oxide (CaO), thereby enabling pozzolanic activity.

2.4 Laboratory Testing Methods

2.4.1 Standard proctor compaction test

To obtain the Optimal Moisture Content (OMC) and Maximum Dry Density (MDD) of the Kaolin Clay, a standard Proctor compaction test is performed. The steps taken to identify the OMC and MDD data of kaolin, which is essential in determining the total mass of soil and volume of water used in preparing the sample for Unconfined Compressive Strength (UCS) test samples. Initially, 3 kg of Kaolin Clay is weighed, followed by the addition of water based on moisture content percentages: 18% water, equating to 540 ml for the first batch and 120 ml for the subsequent batch, is added and thoroughly mixed with the soil. The mixed soil is then placed into a cylindrical mould and compacted uniformly by applying 27 hammer blows dropped from a height of 300 mm, done in three layers. After compaction, the collar is removed from the mould, and any excess soil protruding above is trimmed off. The mould containing the compacted soil is then weighed. Subsequently, the base plate of the mould is removed, and soil samples for moisture content measurement are collected from both the top and bottom of the compacted specimen and placed into a pre-weighed empty can. The soil and can are weighed together and then dried in an oven at 105°C for 24 hours to determine the moisture content accurately.

2.4.2 Unconfined Compressive Strength (UCS) Test

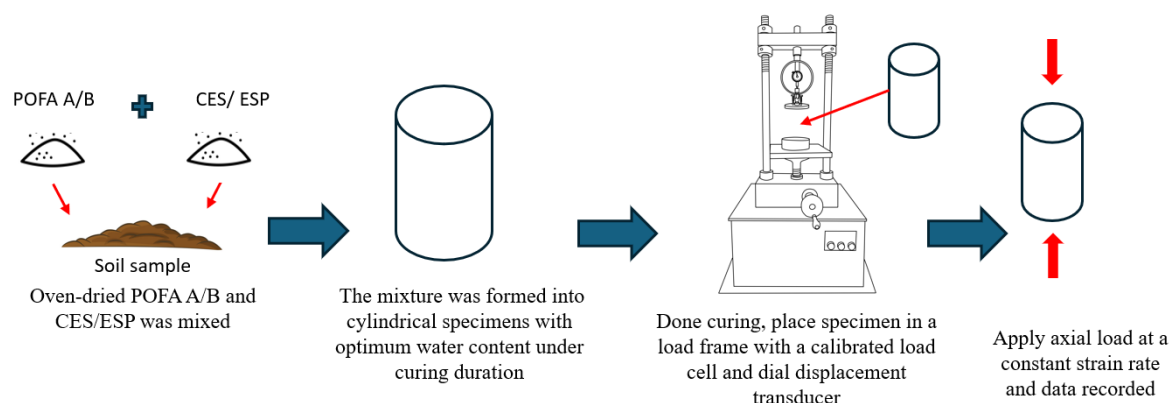


Fig. 4. The Unconfined Compressive Strength (UCS) test procedure

The unconfined compressive strength (UCS) test is widely employed to evaluate improvements in soil strength following the addition of stabilisers, specifically those formulated as POFA:ESP, POFA:CES, and POFA:CES:GG. As demonstrated in Figure 4, the testing procedure begins by attaching the mould to the plates. Next, 50 grams of Kaolin Clay is placed into the first layer of mould and compacted to a height of 76 cm using a compaction machine. This process is repeated for the second and third layers, each receiving 50 grams of clay and being individually compacted to ensure uniformity. After compaction, the soil sample is carefully extracted from the mould using a

mechanical device. The sample's dimensions, diameter, length, and weight are then measured accurately. The cylindrical soil specimens are subsequently cured for a predetermined duration to allow the stabilisers to interact effectively with the soil matrix.

Following the curing period, an axial load is steadily applied to the specimen until failure occurs. During this loading phase, the stress-strain behaviour of the soil is continuously recorded. The entire testing procedure adheres to the standardized guidelines set forth in BS1377-7:1990, ensuring reliable and consistent data. This approach provides critical insights into how the different stabiliser formulations enhance the mechanical properties and strength of the soil.

3. Results

3.1 General Properties of Unstabilised Soil

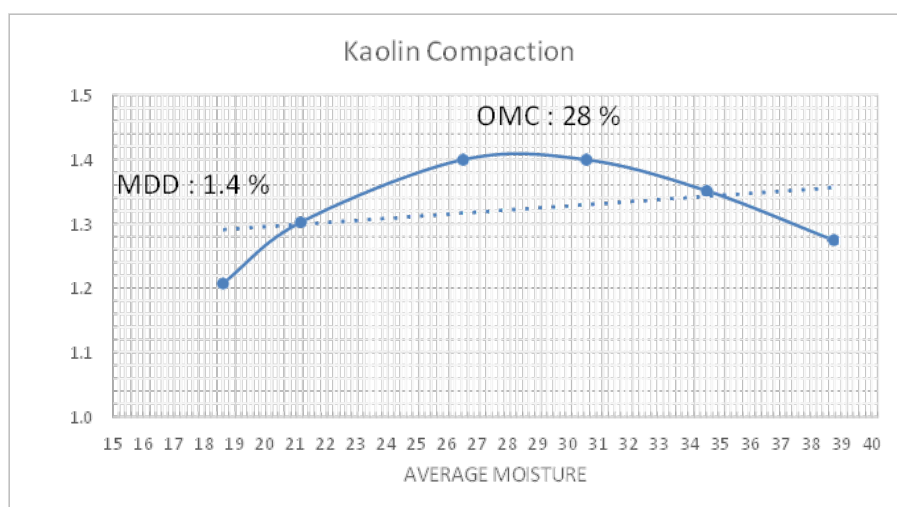


Fig. 5. Kaolin compaction graph for MDD and OMC

The Kaolin clay exhibits a maximum dry density (MDD) of approximately 1.41 g/cm³ and an optimum moisture content (OMC) of about 28%, as shown in Figure 5. A comparative study of kaolinite clay stabilisation shows the values for MDD typically range around 1.35 to 1.51 g/cm³ and OMC values tend to be in the range of approximately 28% to over 33%, depending on treatment and other factors, by several author [19,20].

3.2 Chemical Composition of POFA A, POFA B, ESP, CES and GG

Table 1 shows the chemical compositions of POFA A, POFA B, ESP, CES, and Guar Gum, highlighting their potential as sustainable binders in soil stabilisation. The presence of important oxides such as Silicon Dioxide (SiO₂), Calcium Oxide (CaO), and Potassium Oxide (K₂O) is essential for enhancing pozzolanic reactions and improving the mechanical properties of treated soils, as cited from several authors [21,22].

POFA A exhibits a higher concentration of SiO₂ (32.3%) and CaO (14.6%) compared to POFA B, which contains 18.37% SiO₂ and 12.05% CaO. POFA A, derived from Sedenak, exhibits a higher concentration of SiO₂ (32.3%) and CaO (14.6%) compared to POFA B from Bukit Pasir, which contains 18.37% SiO₂ and 12.05% CaO. These oxides are crucial for the formation of calcium silicate hydrate (C-S-H), which contributes to the development of long-term strength, as stated by Zhang *et al.*, [23]. Additionally, POFA A contains a significantly higher amount of Phosphorus Pentoxide (P₂O₅) at 5.93%, further supporting its chemical reactivity. In contrast, POFA B shows elevated levels of K₂O (39.45%)

and Iron (III) Oxide (Fe_2O_3) at 18.0%, which may accelerate early-stage reactions but could compromise long-term stability. Therefore, POFA A is considered more suitable as a stabilising agent due to its balanced composition of reactive oxides.

Guar Gum is a natural biopolymer. Its composition includes 44.4% K_2O and 14.4% SiO_2 , which may contribute to ionic bonding and gel formation. Moreover, its organic nature enhances water retention and improves the flexibility of the soil matrix, reducing micro-cracking during curing, as cited by Anshu *et al.*, [25].

Interestingly, although ESP contains an exceptionally high CaO content (99.92%), UCS test results revealed that CES outperformed ESP in terms of compressive strength. This finding suggests that thermal activation during calcination may have enhanced the reactivity and dispersion of CES particles, resulting in improved bonding within the soil structure, as reported by Wang, Kai and Xiaoxiong Zha [24]. The presence of additional oxides such as SiO_2 and P_2O_5 in CES, although in smaller quantities, may have contributed to synergistic effects with other binders. Furthermore, the high Loss on Ignition (LOI) value in CES (39.2%) indicates the presence of residual carbonates or organics that could influence the hydration process.

Table 1

The chemical compositions (weight percentages) of POFA A, POFA B, ESP, CES and Guar Gum from XRF analysis

No.	Composition	Weight Percent (%)				
		POFA A (Sedenak)	POFA B (Bukti Pasir)	ESP	CES	Guar Gum
1	Sodium Oxide (Na_2O)	-	-	-	-	-
2	Aluminium Oxide (Al_2O_3)	2.21	-	-	-	-
3	Silicon Dioxide (SiO_2)	32.3	18.37	-	0.36	14.4
4	Sulphur Trioxide (SO_3)	1.06	2.80	-	0.09	7.14
5	Chlorine (Cl)	0.49	7.95	-	0.01	2.48
6	Potassium Oxide (K_2O)	12.4	39.45	0.08	0.06	44.4
7	Calcium Oxide (CaO)	14.6	12.05	99.92	59.8	23.0
8	Titanium Dioxide (TiO_2)	-	-	-	-	-
9	Iron (III) Oxide (Fe_2O_3)	4.10	18.0	-	-	-
10	Gallium (III) Oxide (Ga_2O_3)	-	-	-	-	-
11	Arsenic Trioxide (As_2O_3)	-	-	-	-	-
12	Rubidium Oxide (Rb_2O)	0.03	-	-	-	-
13	Yttrium (III) Oxide (Y_2O_3)	-	-	-	-	-
14	Zirconium Dioxide (ZrO_2)	0.06	-	-	-	-
15	Niobium Pentoxide (Nb_2O_5)	-	-	-	-	-
16	Magnesium Oxide (MgO)	1.81	-	-	0.23	-
17	Zinc Oxide (ZnO)	0.07	0.22	-	-	-
18	Phosphorus Pentoxide (P_2O_5)	5.93	0.73	-	0.29	6.57
19	Strontium Oxide (SrO)	0.05	-	-	0.02	-
20	Manganese (II) Oxide (MnO)	-	0.30	-	-	-
21	Copper (II) Oxide (CuO)	0.09	0.12	-	-	-
22	Bromine (Br)	-	-	-	-	1.99
23	Loss On Ignition (LOI)	25.0	-	-	39.2	-

3.3 Unconfined Compressive Strength (UCS) Test Data

3.3.1 The effect of different types of POFA with ESP and CES

Figure 6 shows the unconfined compressive strength at different formulation. The UCS of mixtures containing POFA A or POFA B in combination with ESP or CES (50:50 proportion) were evaluated. The result shows a measurable difference in performance between the utilisation of POFA A and POFA B. Result shows that POFA B provide higher strength when combined with CES compared to POFA A. Based on XRF data, POFA A exhibited a significantly higher loss on ignition (25.0%) compared to POFA B (11.0%), indicating a greater proportion of unburnt carbon and organic residues. According to Hashim *et al.*, [29], LOI is indicative of unburnt carbon content, meaning POFA A likely contains more residual carbon and organics, factors that can influence reactivity and water demand in cementitious systems. In soil stabilization, cementitious systems play a critical role in enhancing soil strength by forming binding phases, improving compaction, reducing plasticity, and increasing load-bearing capacity, as reported by Almuaythir *et al.*, [26].

Then, the usage of ESP and CES displays a distinct unconfined compressive strength value. The CES yielded significantly higher UCS values than ESP, particularly in the POFA B blend (704 kPa), which was more than four times stronger than the control (145 kPa). In soil stabilisation, the UCS of clay soils increased markedly when treated with calcined eggshell, rising from about 80 kPa in untreated soil to approximately 420–500 kPa with 6–8% calcined eggshell, as cited from Dudekula *et al.*, [28]. In contrast, the use of uncalcined eggshell powder resulted in more modest gains, with UCS increasing from 80 kPa to around 150–200 kPa at 6–10% replacement, as reported by Dudekula *et al.*, [28]. Generally, ESP contain calcium carbonate (CaCO_3), while CES contains reactive CaO . Equation 1 shows the chemical equation of CaO after calcination at higher temperature. CES displays high UCS because it triggers pozzolanic reactions like hydrated lime. Yamagoshi *et al.*, [27], also found the presence of calcium in soil can improve its strength. They reported that the soil solidifies due to the hydration of calcium, Ca with silica oxide (SiO_2) and Alumina oxide (AlO_2).

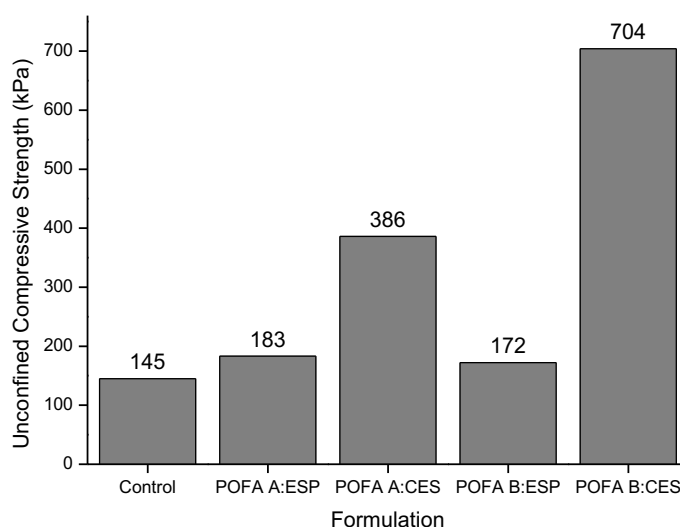
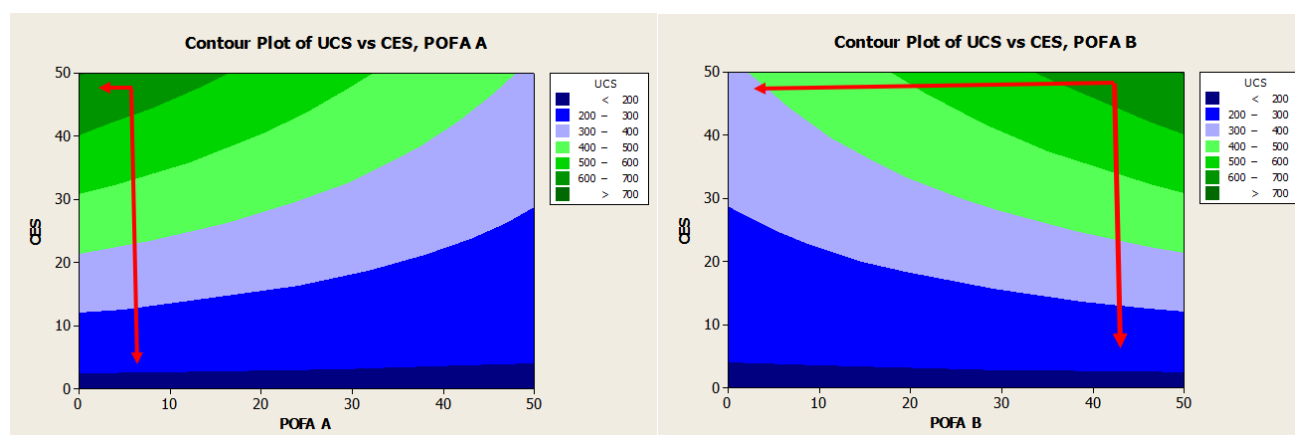


Fig. 6. UCS with different types of POFA with ESP and CES



(a) The contour plot of different utilisation of POFA A (b) The contour plot of different utilisation of POFA B.
Fig. 7. (a) The counter plot of different utilisation of POFA A (b) The contour plot of different utilisation of POFA B

The contour plot in Figure 7 identified a well-defined optimum region where UCS exceeds 700 kPa, point around highest values for both POFA A and POFA B and CES. This suggest that the combination of POFA B with CES as illustrated in Figure 6(b) improve the mechanical strength of soil. in contrast with a combination of POFA A and CES as shown in Figure 6(a), the optimum region was found at the combination of POFA A (less than 10 %) and CES (higher than 40 %).

3.3.2 The effect of Guar Gum (GG) on different types of POFA with ESP and CES

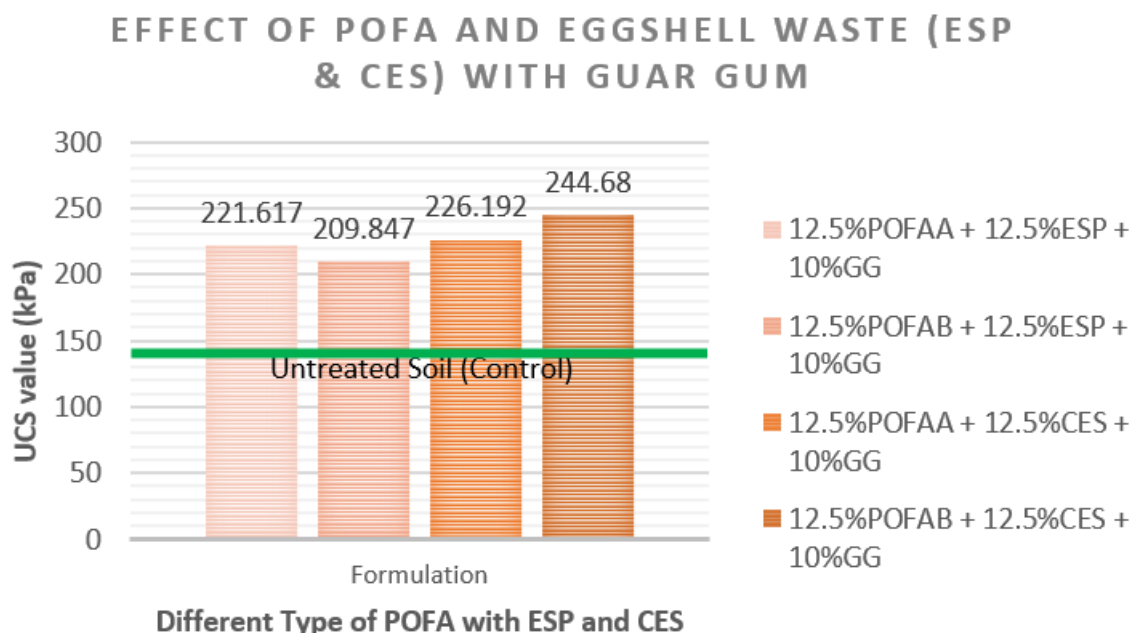


Fig. 8. Effect of Guar Gum (GG) on Different Type of POFA with ESP and CES

Figure 8 illustrates the reaction of a 10% dosage of GG on the binder mixture after 7 days of curing. The highest unconfined compressive strength (UCS) recorded was 244 kPa for the POFA B: CES mixture, representing an increase of 68.78% from the control UCS value of 145 kPa. However, when comparing these results, the performance of UCS with and without the additive material shows a contrasting trend. The highest UCS value without GG was 704 kPa, whereas with GG it decreased significantly to 244 kPa, indicating a reduction of 44.28%.

Based on these findings, the POFA B: CES formulation was selected for the subsequent experimental phases, as it demonstrated better performance compared to other formulations tested in phase 1. The main objective of the next phase was to evaluate the effectiveness of this binder formulation. In this phase, the binder formulation POFA B: CES was applied at a dosage of 30% and cured for 7 days, corresponding to the standard curing duration for cement.

3.3.3 The effect of dosage and curing time on alternative soil stabiliser by optimum formulation

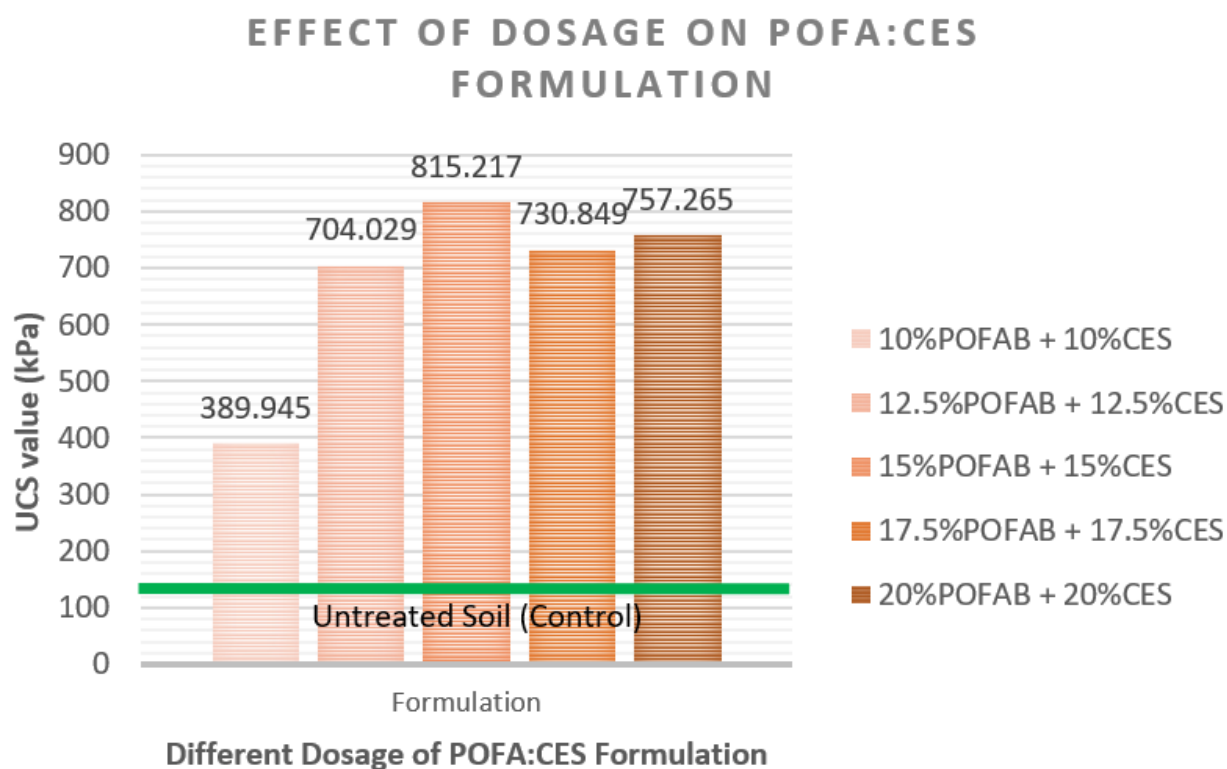


Fig. 9. Effect of Dosage on POFA:CES Formulation

Based on the finding from Section 3.3.2, the POFA B: CES formulation was selected for the subsequent experimental phases, as it demonstrated better performance compared to other formulations tested in phase 1. Figure 9 illustrates the effect of various concentrations of POFA B: CES on the Unconfined Compressive Strength (UCS) values of the formulation. As the dosage increases from 20% to 40%, there is a significant rise in the UCS value, indicating an improvement in soil strength. At 30% dosage, the UCS value reaches its peak at 815.217 kPa, which is the highest among all tested dosages. Beyond 30%, as the dosage increases to 35% and 40%, the UCS value slightly decrease to 730.849 kPa and 757.265 kPa respectively. Despite this slight reduction, the values remain substantially higher than the untreated soil control level, which is indicated by the

green line at about 140 kPa. This trend suggests that the optimal dosage for maximum soil strength enhancement lies at 30%, making it the best dosage concentration for formulation.

Following the identification of 30% as the optimal dosage, the curing time graph was conducted for final evaluation to assess how the strength develops over time at this dosage. The graph indicates a steady increase in UCS values from 1 day to 14 days of curing, with the maximum strength at 14 days reaching 815.217 kPa. For 7 days, there has been a slight decline in UCS values at 3 days reaching 392.333 kPa, though still well above the untreated control soil strength. This pattern suggests that the soil's strength increases rapidly during the first week of curing but then stabilises or slightly decreases with longer curing times. Overall, the curing time graph confirms that 14 days is optimal for curing the soil treated with 30% POFA B: CES to achieve maximum strength.

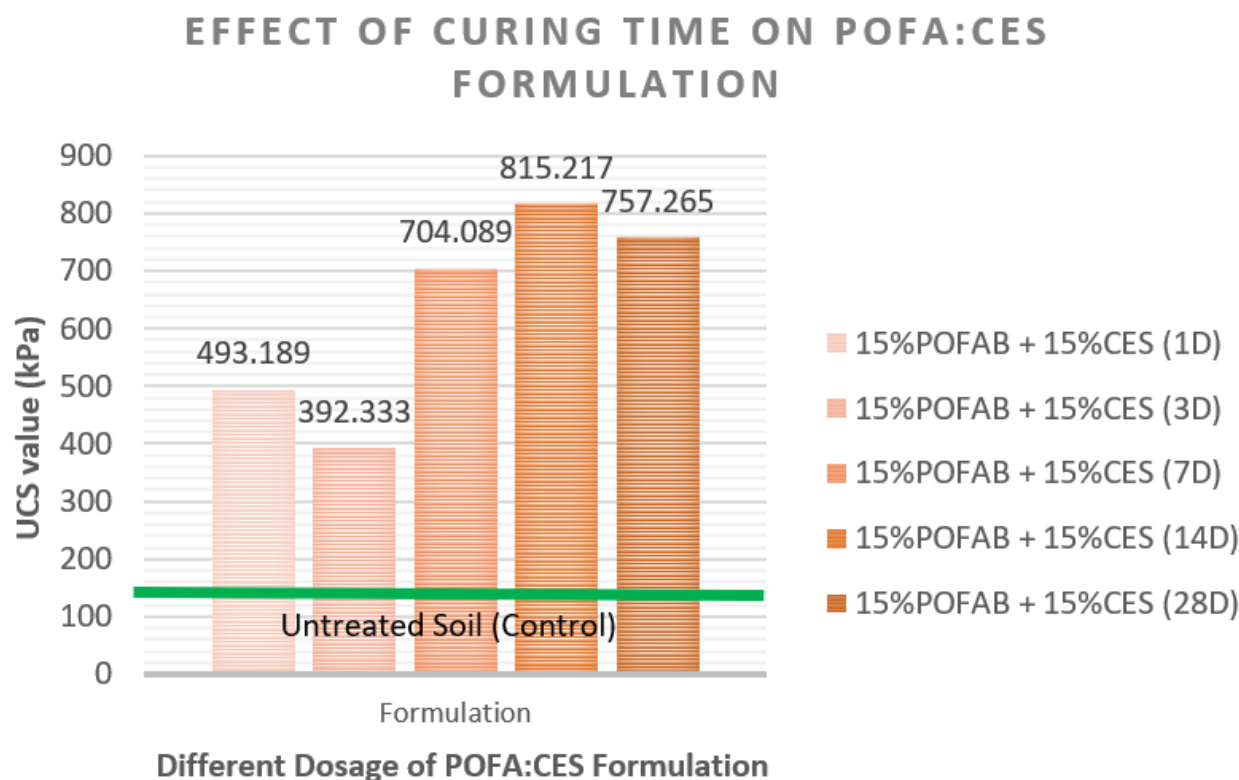


Fig. 10. Effect of Curing Time on POFA:CES Formulation

4. Conclusions

This study successfully explored the innovative use of sustainable waste-derived materials, Palm Oil Fuel Ash (POFA) combined with Eggshell Powder (EPS) and Calcined Eggshell (CES) along with addition of Guar Gum (GG), as eco-friendly soil stabilisers to improve the geotechnical properties of high plasticity clay soil. The originality of this research lies in the novel formulation and synergistic combination of POFA and CES as a blended binder, which, to the best of our knowledge, has not been extensively studied in the context of clay soil stabilisation. The incorporation of Guar Gum as a natural additive was also evaluated to understand its influence on binder behaviour.

Experimental results demonstrated that the POFA and CES combination significantly enhanced the unconfined compressive strength (UCS) of Kaolin Clay, outperforming the other tested mixtures and untreated soil. The optimal binder dosage was identified as 30% with a curing period of 14 days, achieving substantial strength gains while promoting sustainable construction practices by utilising abundantly available industrial and agricultural waste materials. Notably, the addition of Guar Gum

did not contribute to further strength improvement but altered the binder's interaction with the soil matrix.

The findings address the research objective of identifying effective, environmentally friendly alternatives to traditional cement and lime stabilisers while providing practical insights for their application in road subgrades and geotechnical infrastructure projects. This research contributes to reducing environmental impacts associated with conventional stabilisers and supports resource efficiency through waste valorisation.

Future work should focus on extending the scope of testing to different soil types, long-term durability assessments, and field trials to validate the laboratory findings and fully characterize the complex soil-binder interactions under varying environmental conditions.

Acknowledgement

This research was supported by Universiti Tun Hussein Onn Malaysia and D'Lariz Logik (M) Sdn. Bhd. through SEPADAN RE-SIP Grant (Vot. M114), and Universiti Tun Hussein Onn Malaysia through GPPS (Vot. Q600).

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