SEMARAK ILMU PUBLISHING

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

Koh Yee Fei[1], Akmal Daniel Nurhakim Azman Putera[1], Tuan Noor Hasanah Tuan Ismail[1,*], Yasmin Yuriz[1], Mohd Latiff Ahmad[2], Riffat Shaheed[3]

[1] Department of Civil Engineering Technology, Faculty of Engineering Technology, Universiti Tun Hussein Onn Malaysia, Kampus Pagoh 84600 Muar, Johor, Malaysia
[2] D'lariz Logik (M) Sdn. Bhd., Technology Park, Malaysia Corporation Sdn. Bhd., Bukit Jalil, Kuala Lumpur, Malaysia
[3] Civil Engineering and Building Construction, Unitec Institute of Technology Auckland, New Zealand

ARTICLE INFO

Article history:
Received 15 August 2025
Received in revise 10 September 2025
Accepted 25 September 2025
Available online 12 October 2025

Keywords:
Soil stabilisation; Kaolin Clay soil; Palm Oil Fuel Ash (POFA); Eggshell Powder (ESP); Calcined Eggshell (CES); Guar Gum (GG); Unconfined Compressive Strengh (UCS)

ABSTRACT

Clay soils with high plasticity and water content present significant challenges in construction due to low bearing capacity and instability. Conventional binders like cement and lime, while effective, raise environmental concerns and may underperform in certain soil types. This study investigates the use of sustainable soil binders derived from agricultural and industrial wastes, namely Palm Oil Fuel Ash (POFA), Eggshell Powder (ESP), Calcined Eggshell (CES), and Guar Gum (GG), to improve the geotechnical properties of problematic soils. The research aims to address the environmental drawbacks of traditional binders by evaluating the efficacy of three binder combinations: POFA with ESP, POFA with CES, and POFA with CES plus GG, in enhancing the strength of Kaolin Clay. Laboratory tests assessed unconfined compressive strength (UCS) across various dosages and curing periods. Results revealed that the POFA-CES combination significantly outperformed others, achieving the highest UCS values, while Guar Gum addition had minimal impact on strength but altered binder behaviour. Optimal results were obtained at a 30% binder dosage with a 14-day curing period. The findings suggest that POFA and CES mixtures offer a sustainable, effective alternative to conventional binders, reducing environmental impact and promoting the use of local waste materials. These binders are viable for improving soil stability in road subgrades and other geotechnical applications, supporting eco-friendly construction practices.

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, binders such as cement and lime have been widely

* *Corresponding author.*
E-mail address: hasanah@uthm.edu.my

https://doi.org/10.37934/sej.11.1.3953

used due to their effectiveness in enhancing soil strength, reducing plasticity, and improving soil durability. These binders operate primarily through pozzolanic reactions that form cementitious compounds, which bind soil particles together. Lindh and Polina [1] reported that lime plays a crucial role due to its chemical fixation capacity in weak soils such as clays, improving workability and strength through cementitious reactions during stabilisation (28 days curing). However, despite their widespread use, these traditional binders 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. In 2020, Yu *et al*., [2] reported that lime-treated soils with high sulphate content had lower unconfined compressive strength (UCS) due to the excessive formation of ettringite crystals, which can have a deleterious effect on the soil matrix. Then, Shivanshi *et al.,* [3] highlighted that sulphate attacks, driven by the formation of ettringite (E) and thaumasite due to reactions between lime, clay, and sulphate in the presence of moisture, lead to distress in lime-treated sulphatic soils. Then, Jain [4] reported that in sulphate-rich soils, lime may cause sulphate attacks that lead to volume expansion, heaving, and eventual strength loss. These reactions cause volume expansion and heaving, which contribute to a reduction in strength, stiffness, and durability. Meanwhile, cement-treated soils tend to be brittle and prone to shrinkage cracking, especially in highly plastic soils, which limit their long-term durability [5]. These drawbacks highlight the need for developing alternative, sustainable soil binders derived from industrial and agricultural by-products to reduce negative environmental impacts and promote sustainable construction practices. In 2025, Almuaythir *et al.,* [6] highlighted the environmental benefits of using agricultural waste ashes over traditional cement and lime, such as reducing carbon footprint and repurpose waste materials, thereby offering a more sustainable option for soil stabilisation.

Among the promising eco-friendly alternatives are palm oil fuel ash (POFA) and eggshell waste. 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 taken from previous studies [7-8]. 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 [9]. Then, eggshell waste can be calcined to produce reactive calcium oxide (CaO), which results in 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 [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, the identification of 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 [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, which results in enhanced soil strength and durability [11-13]. Nevertheless, the sustainability concerns surrounding traditional materials motivate research into non-traditional, waste-derived soil binders such as POFA and CES, which reduce environmental impacts and overcome performance limitations in some soil types.

Research by Halim *et al.,* [14] has demonstrated that POFA enhances the unconfined compressive strength (UCS) of soils, particularly clay and expansive types, by forming cementitious gels that improve soil structure and decrease permeability. Putera *et al.,* [15] found that POFA contains a substantial amount of non-crystalline silica, which significantly contributes to the formation of C-S-H gel, the main binding agent that improves soil engineering qualities over time due to ongoing pozzolanic reactions. 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 [16]. The synergistic application of POFA and CES has been shown to significantly improve soil strength, often outperforming single binder systems and meeting relevant construction standards such as those for road subgrades and embankments [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 binders. 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 formulations, 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, has been explored for its benefits in enhancing soil cohesion, moisture retention, and workability. These improvements contribute to the overall effectiveness of alternative binder systems [17-18]. 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 the alternative soil binder 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, the increasing demand for sustainable soil stabilisation techniques has highlighted the limitations of traditional binders like cement and lime, which pose environmental concerns and performance issues in certain soil types. While Palm Oil Fuel Ash (POFA) and Calcined Eggshell (CES) have shown promise as eco-friendly alternatives, there is a significant research gap regarding the comparative performance of POFA from different sources, such as Sedenak and Bukit Pasir, and the synergistic effects of combining POFA with Eggshell Powder (ESP), CES, and Guar Gum (GG) in diverse soil conditions. This study aims to address this gap by evaluating the consistency of POFA performance across different origins, comparing the efficacy of ESP and CES in combination with POFA, assessing the contribution of GG to soil strength, and determining the optimal formulation and dosage for enhanced soil stabilisation over varying curing periods. The significance of this research lies in its potential to advance sustainable geotechnical practices by developing effective, waste-derived soil binder formulations, reducing environmental impacts, and providing practical guidelines for their application in construction, thereby contributing to more resilient and eco-conscious infrastructure development.

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

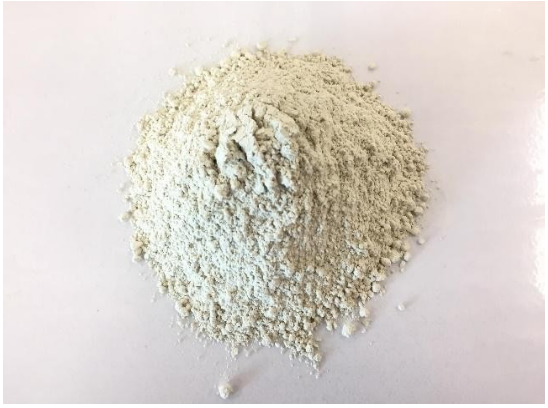
Kaolin Clay, as shown in Figure 1 was procured from Kaolin Malaysia Sdn. Bhd., then sieved through a 75 µm (No. 200) sieve and oven-dried at 105°C for 24 hours. The study by Alvarez-Coscojuela *et al.,* [19] uses kaolinite (kaolin) in its raw form (denoted as K) as a baseline or reference material to evaluate the effects of various chemical activation treatments.

Fig. 1. Kaolin Clay

2.3 By-Product Binder Collection and Preparation

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.
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 ($CaCO3$) present in the eggshells into reactive calcium oxide (CaO), thereby enabling pozzolanic activity.

(a) Palm Oil Fuel Ash (POFA)



(b) Guar Gum (GG)

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

(a) Eggshell Powder (ESP)

(b) Calcined Eggshell (CES)

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

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

The unconfined compressive strength (UCS) test is widely employed to evaluate improvements in soil strength following the addition of binders, 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 binders to interact effectively with the soil matrix.

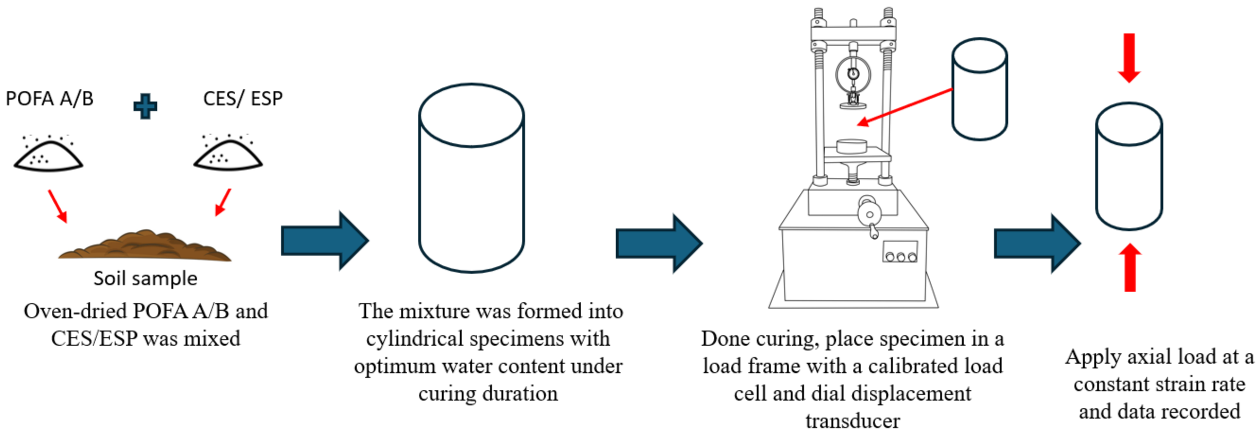


Fig. 4. The Unconfined Compressive Strength (UCS) test procedure

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 soil binder formulations enhance the mechanical properties and strength of the soil.

3. Results
3.1 General Properties of Unstabilised Soil

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 [20,21].

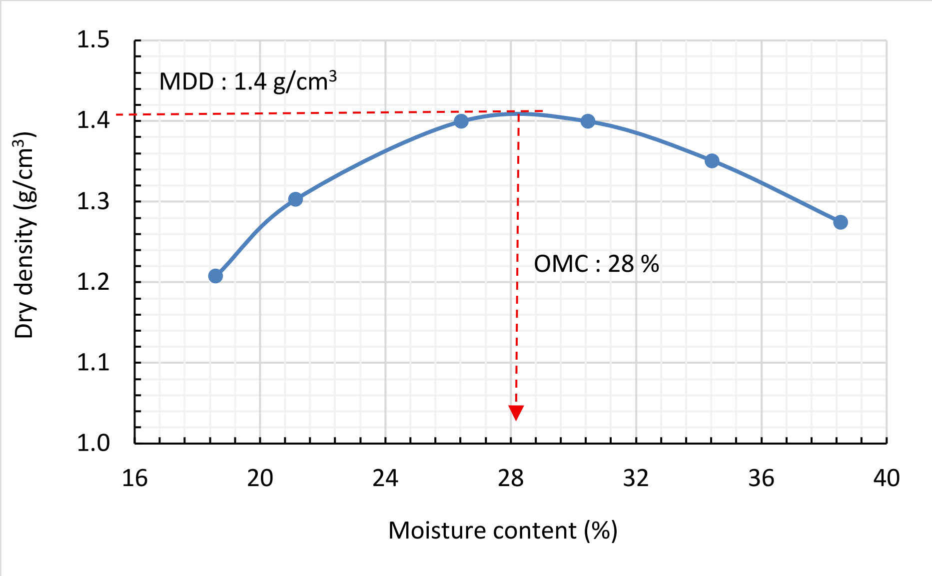


Fig. 5. Kaolin compaction characteristics (MDD and OMC)

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 (SiO_2), Calcium Oxide (CaO), and Potassium Oxide (K_2O) is essential for enhancing pozzolanic reactions and improving the mechanical properties of treated soils [22-23].

POFA A exhibits a higher concentration of SiO_2 (32.3%) and CaO (14.6%) compared to POFA B, which contains 18.37% SiO_2 and 12.05% CaO. POFA A, derived from Sedenak, exhibits a higher concentration of SiO_2 (32.3%) and CaO (14.6%) compared to POFA B from Bukit Pasir, which contains 18.37% SiO_2 and 12.05% CaO. Zhang *et al.,* [24] reported that these oxides are crucial for the formation of calcium silicate hydrate (C-S-H), which contributes to the development of long-term strength. Additionally, POFA A contains a significantly higher amount of Phosphorus Pentoxide (P_2O_5) at 5.93%, further supporting its chemical reactivity. In contrast, POFA B shows elevated levels of K_2O (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 [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 [26]. 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 (Na2O)	-	-	-	-	-
2	Aluminium Oxide (Al2O3)	2.21	-	-	-	-
3	Silicon Dioxide (SiO2)	32.3	18.37	-	0.36	14.4
4	Sulphur Trioxide (SO3)	1.06	2.80	-	0.09	7.14
5	Chlorine (Cl)	0.49	7.95	-	0.01	2.48
6	Potassium Oxide (K2O)	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 (TiO2)	-	-	-	-	-
9	Iron (Ill) Oxide (Fe2O3)	4.10	18.0	-	-	-
10	Gallium (Ill) Oxide (Ga2O3)	-	-	-	-	-
11	Arsenic Trioxide (As2O3)	-	-	-	-	-
12	Rubidium Oxide (Rb2O)	0.03	-	-	-	-
13	Yttrium (Ill) Oxide (Y2O3)	-	-	-	-	-
14	Zirconium Dioxide (ZrO2)	0.06	-	-	-	-
15	Niobium Pentoxide (Nb2O5)	-	-	-	-	-
16	Magnesium Oxide (MgO)	1.81	-	-	0.23	-
17	Zinc Oxide (ZnO)	0.07	0.22	-	-	-
18	Phosphorus Pentoxide (P2O5)	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 formulations. The UCS of mixtures containing POFA A or POFA B in combination with ESP or CES at 50:50 proportion were evaluated. The result shows a measurable difference in performance between the utilisation of POFA A and POFA B. The Result shows that POFA B provides 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.*, [30], LOI is indicative of unburnt carbon content, meaning POFA likely contains more residual carbon and organics, factors that can influence reactivity and water demand in cementitious systems. In soil stabilisation, cementitious systems play a critical role in enhancing soil strength by forming binding phases, improving compaction, reducing plasticity, and increasing load-bearing capacity [27].

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 [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 [28]. Generally, ESP contain calcium carbonate (CaCO3), while CES contain reactive CaO. Equation 1 shows the chemical equation of CaO after calcination at a higher temperature. CES displays high UCS because it triggers pozzolanic reactions like hydrated lime. Yamagoshi *et al*., [29] also found that 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 (SiO2) and Alumina oxide (AlO2).

$$CaCO_3 \longrightarrow CaO\,(s) + CO_2 \quad (1)$$

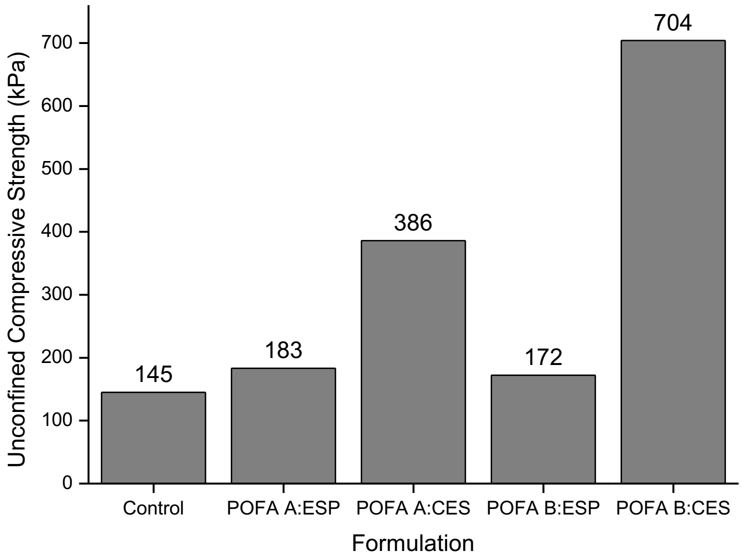


Fig. 6. UCS with different types of POFA with ESP and CES

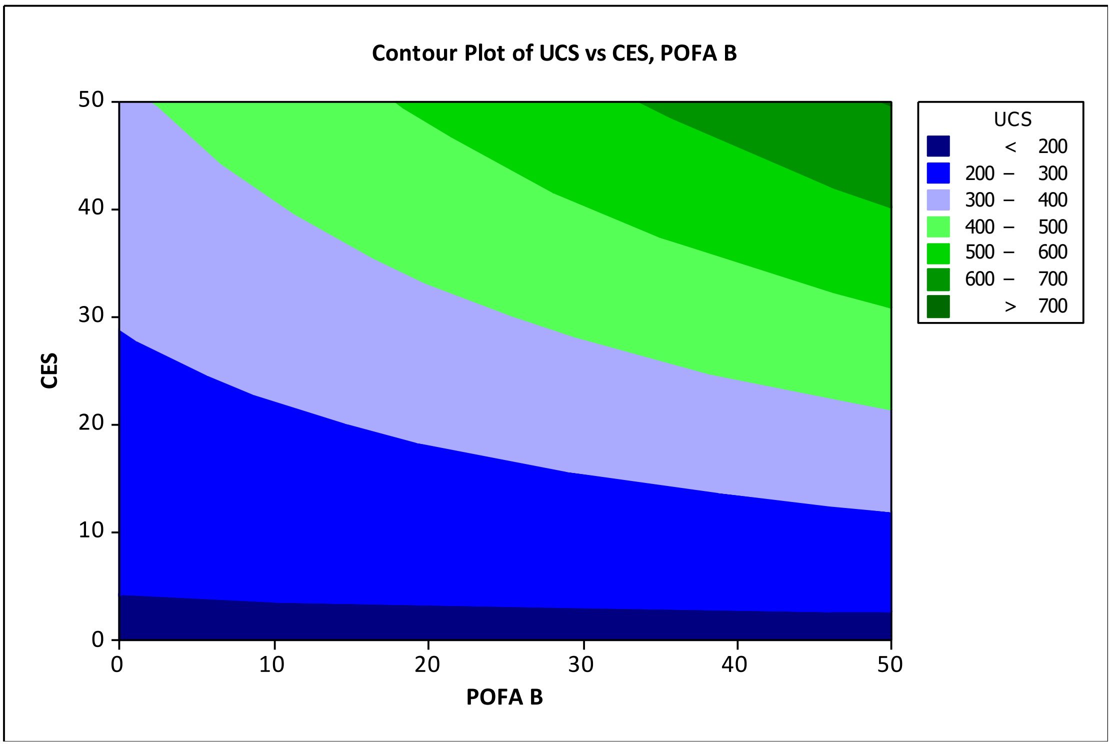


Fig. 7. The contour plot of different utilisation of POFA B

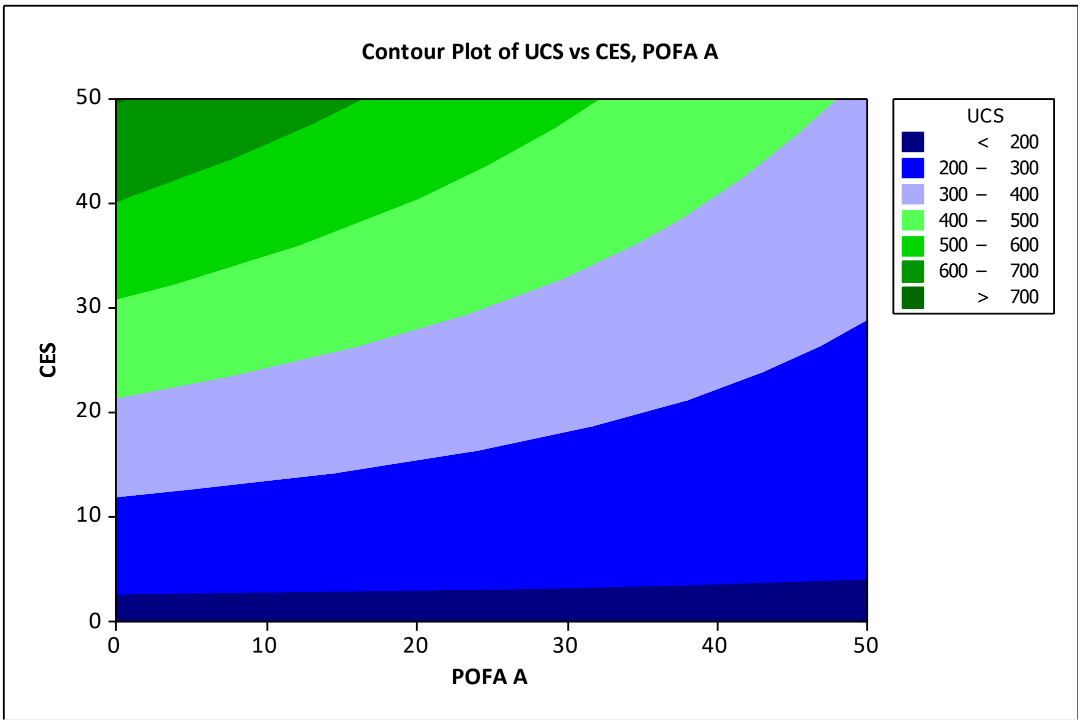


Fig. 8. The contour plot of different utilisation of POFA A

The contour plot identified a well-defined optimum region where UCS exceeds 700 kPa, point highest values for both POFA A and POFA B and CES. This suggests that the combination of POFA B with CES, as illustrated in Figure 7, improves the mechanical strength of soil. In contrast with a combination of POFA A and CES, as shown in Figure 8, 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

Figure 9 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 Section 3.3.1. 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 range of 20% to 40% and cured for 7 days, corresponding to the standard curing duration for cement.

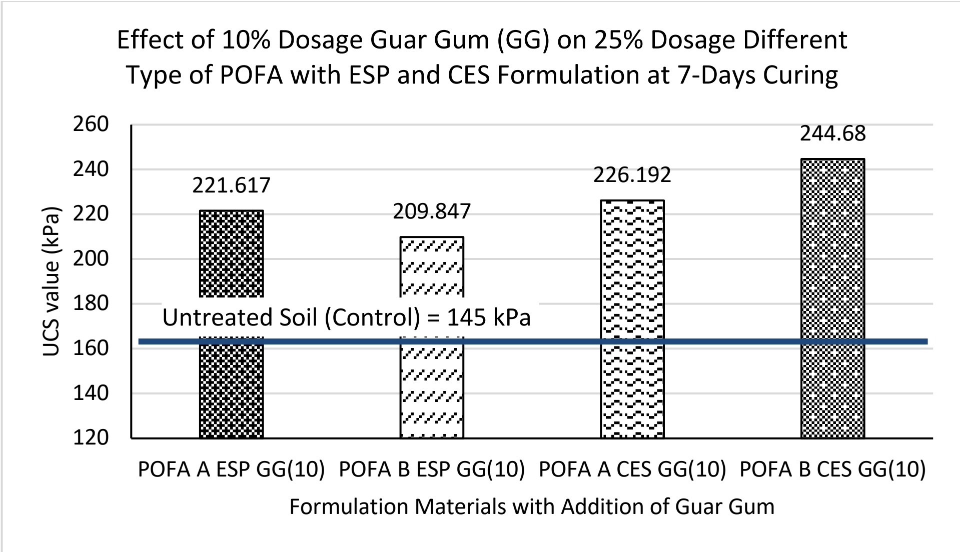


Fig. 9. Effect of Guar Gum (GG) on Different Types of POFA with ESP and CES

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

Based on the findings from Section 3.3.1, 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 10 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 decreases to 757.265 kPa and 730.849 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 145 kPa. This trend suggests that the optimal dosage for maximum soil strength enhancement lies at 30%, making it the best dosage concentration for formulation. R^2 of 0.9472 demonstrates a strong relation between UCS value and binder dosage. By referring to Equation 2, it helps predict the UCS value (e.g., strength or effect) and find the optimal dosage for the maximum effect. However, as the dosage (x) increases, the UCS value (y) rises, peaks at a certain dosage, and then starts to fall if the dosage keeps increasing. For example, too little or too much dosage might give lower UCS values, while a moderate dosage gives the highest UCS value.

$$\text{UCS Value}, y = -60.724\,(\text{binder dosage})^2 + 437.85\,(\text{binder dosage}) + 33.878 \tag{2}$$

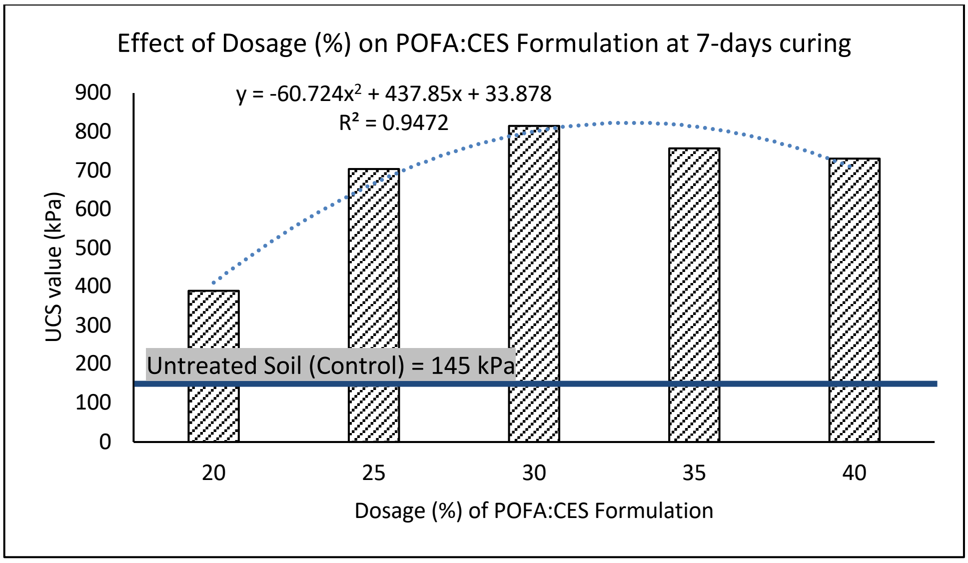


Fig. 10. Effect of Dosage on POFA:CES Formulation

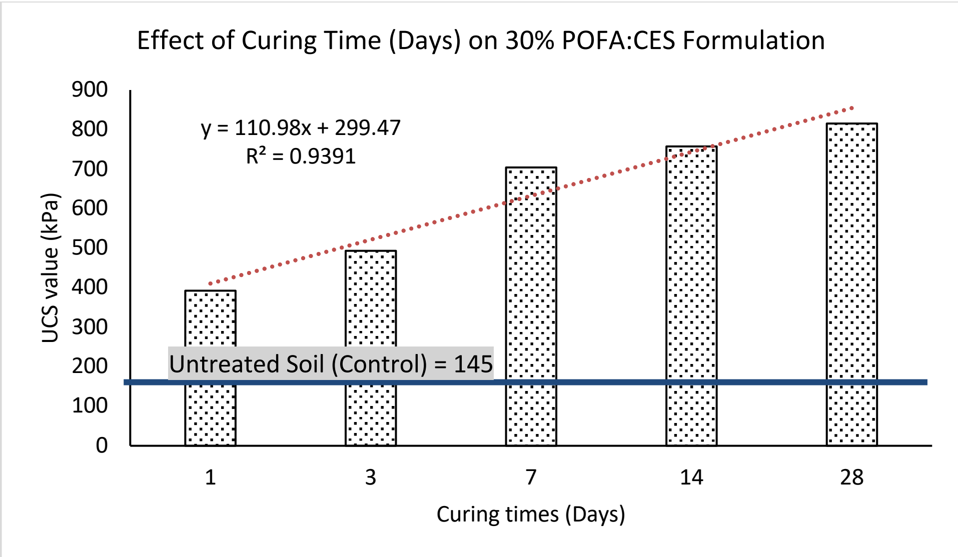


Fig. 10. Effect of curing time on POFA:CES formulation

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, as illustrated in Figure 10, indicates a steady increase in UCS values from 1 day to 28 days of curing, with the maximum strength at 28 days reaching 815.217 kPa. The lowest UCS recorded is at 1 day, reaching 392.333 kPa, though still well above the untreated control soil strength, which is 145 kPa. This pattern suggests that the soil's strength increases rapidly with longer curing times. Overall, the curing time graph confirms that 28 days is optimal for curing the soil treated with 30% POFA B: CES to achieve maximum strength. Based on the linear regression analysis, R^2 is nearest to 1, showing a strong relation between UCS value and curing time. The formula, as shown in Equation 3, predicts the unconfined compressive strength (y) of a material as a function of curing days (x), with a strength increase of 110.98 MPa per day and a theoretical starting strength of 299.47 MPa at zero days.

$$\text{UCS Value, } y = 110.98\,(\text{Curing days}) + 299.47 \tag{3}$$

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 the addition of Guar Gum (GG), as eco-friendly soil binders 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 28 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 while providing practical insights for their application in road subgrades and geotechnical infrastructure projects. This research contributes to reducing environmental impacts associated with conventional binders 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).

References

[1] Lindh, Per, and Polina Lemenkova. "Laboratory experiments on soil stabilization to enhance strength parameters for road pavement." *Transport and Telecommunication Journal* 24, no. 1 (2023): 73-82. https://doi.org/10.2478/ttj-2023-0008

[2] Yu, Xinbao, Anand J. Puppala, Miladin Radovic, Sayantan Chakraborty, Jungyeon Jang, and Oscar Huang. *Eco-friendly stabilization of sulfate-rich expansive soils using geopolymers for transportation infrastructure*. No. 19GTUTA01. Transportation Consortium of South-Central States, 2020.

[3] Shivanshi, Arvind Kumar Jha, and Mohammad Parwez Akhtar. "Physicochemical and strength behavior in lime-treated soil submerged under gypsum and sodium sulfate contamination." *Journal of Hazardous, Toxic, and Radioactive Waste* 27, no. 2 (2023): 04023004. https://doi.org/10.1061/JHTRBP.HZENG-1185

[4] Jain, Pradeep Kumar. "Enhancing the properties of swelling soils with lime, fly ash, and expanded polystyrene-A review." *Heliyon* 10, no. 12 (2024). https://doi.org/10.1016/j.heliyon.2024.e32908

[5] Rehman, Zia Ur, Muhammad Rauf, Jiang Chaozhe, Fang Xu, Arshad Jamal, Ataur Rahman, and Jamil Iqbal. "Clayey soil stabilization with ordinary Portland cement using the stabilized soil as a mortar." *Discover Geoscience* 3, no. 1 (2025): 30. https://doi.org/10.1007/s44288-025-00135-4

[6] Almuaythir, Sultan, Muhammad Syamsul Imran Zaini, Muzamir Hasan, and Md Ikramul Hoque. "Stabilization of expansive clay soil using shells based agricultural waste ash." *Scientific Reports* 15, no. 1 (2025): 10186.https://doi.org/10.1038/s41598-025-94980-5

[7] Khalid, Nurul Ainul Hamizah Binti, and Alvin John Meng Siang Lim. "Case Study on Solving Soil Problem by Using Various Chemical Additives in Foundation." *Recent Trends in Civil Engineering and Built Environment* 3, no. 1 (2022): 703-712.

[8] Razali, N. O. R. A. I. D. A., NORAZZLINA M. Sa'don, and ABDUL RAZAK ABDUL Karim. "Stabilizing reinforced peat using calcium-based additive (SH85)." *J. Eng. Sci. Technol* 19 (2024): 186-206.

[9] Ngayakamo, Blasius, and Azikiwe Peter Onwualu. "Recent advances in green processing technologies for valorisation of eggshell waste for sustainable construction materials." *Heliyon* 8, no. 6 (2022). https://doi.org/10.1016/j.heliyon.2022.e09649

[10] Alhokabi, Abdulmajeed, Muzamir Hasan, Mugahed Amran, Roman Fediuk, Nikolai Ivanovich Vatin, and Honin Alshaeer. "The effect of POFA-gypsum binary mixture replacement on the performance of mechanical and microstructural properties enhancements of clays." *Materials* 15, no. 4 (2022): 1532. https://doi.org/10.3390/ma15041532

[11] Shojamoghadam, Soheila, Arash Rajaee, and Saeed Abrishami. "Impact of various additives and their combinations on the consolidation characteristics of clayey soil." *Scientific Reports* 14, no. 1 (2024): 31907.https://doi.org/10.1038/s41598-024-83385-5

[12] Verma, Harshal, Arunava Ray, Rajesh Rai, Tushar Gupta, and Neeraj Mehta. "Ground improvement using chemical methods: A review." *Heliyon* 7, no. 7 (2021). https://doi.org/10.1016/j.heliyon.2021.e07678

[13] Waciński, Witold, Ksawery Kuligowski, Małgorzata Olejarczyk, Marek Zając, Włodzimierz Urbaniak, Waldemar Cyske, Paweł Kazimierski, Robert Tylingo, Szymon Mania, and Adam Cenian. "Recycling of Industrial Waste as Soil Binding Additives—Effects on Soil Mechanical and Hydraulic Properties during Its Stabilisation before Road Construction." *Materials* 17, no. 9 (2024): 2000. https://doi.org/10.3390/ma17092000

[14] Halim, Nuradila Izzaty, Aidan Newman, Muhd Norhasri Muhd Sidek, Hamidah Mohd Saman, and Nurul Huda Suliman. "Effect of Utilisation of Nano POFA on Performance of Self-Consolidating High-Performance Concrete (SCHPC)." *Scientific Research Journal* 18, no. 2 (2021): 103-117. https://doi.org/10.24191/srj.v18i2.11396

[15] Putera, Akmal Daniel Nurhakim Azman, Mugilan Appoo, Tuan Noor Hasanah Tuan Ismail, Mohd Latiff Ahmad, Mudzaffar Syah Kamarudin, Nik Normunira Mat Hassan, Rahmat Muslim, and Riffat Shaheed. "Strength Development of Soil Stabilised with POFA-RCT Binder." *Journal of Advanced Research Design* 134, no. 1 (2025): 77-87. https://doi.org/10.37934/ard.134.1.7787

[16] Harikaran, M., P. Kulanthaivel, S. Gokulakannan, and S. Vinodhkumar. "Eco-friendly soil stabilization: a combined approach using lime and waste eggshell powder." *Global NEST Journal* 25, no. 7 (2023): 120-130.https://doi.org/10.30955/gnj.005077

[17] Anusha, S., and P. R. Harikrishna. "Guar gum, Gellan gum biopolymer soil stabilization." In *E3S web of conferences*, vol. 529, p. 01053. EDP Sciences, 2024. https://doi.org/10.1051/e3sconf/202452901053

[18] Kumar, Sumit, Brahm Deo Yadav, and Rohit Raj. "A review on the application of biopolymers (xanthan, agar and guar) for sustainable improvement of soil." *Discover Applied Sciences* 6, no. 8 (2024): 393. https://doi.org/10.1007/s42452-024-06087-7

[19] Alvarez-Coscojuela, Adrian, Jofre Manosa, Joan Formosa, and Josep Maria Chimenos. "Structural characterisation and reactivity measurement of chemically activated kaolinite." *Journal of Building Engineering* 87 (2024): 109051.https://doi.org/10.1016/j.jobe.2024.109051

[20] Bhoir, Swapnil, Dharmendra Dubey, and Manoj Dongare. "An overview of optimization techniques utilized in sheet metal blanking processes." *IJARSCT* 3 (2023): 2581-9429.

[21] Zaini, Muhammad Syamsul Imran, Muzamir Hasan, Sultan Almuaythir, and Masayuki Hyodo. "Experimental investigations on physico-mechanical properties of kaolinite clay soil stabilized at optimum silica fume content using clamshell ash and lime." *Scientific Reports* 14, no. 1 (2024): 10995. https://doi.org/10.1038/s41598-024-61854-1

[22] Tural, H. G., Bertug Ozarisoy, Shahram Derogar, and Ceren Ince. "Investigating the governing factors influencing the pozzolanic activity through a database approach for the development of sustainable cementitious materials." *Construction and Building Materials* 411 (2024): 134253. https://doi.org/10.30955/gnj.005077

[23] Cong, Ma, Chen Longzhu, and Chen Bing. "Analysis of strength development in soft clay stabilized with cement-based stabilizer." *Construction and Building Materials* 71 (2014): 354-362. https://doi.org/10.1016/j.conbuildmat.2014.08.087

[24] Zhang, Zhe, Yu Yan, Zhengyao Qu, and Guoqing Geng. "Endowing strength to calcium silicate hydrate (CSH) powder by high pressure mechanical compaction." *Cement and Concrete Research* 159 (2022): 106858.https://doi.org/10.1016/j.cemconres.2022.106858

[25] Anshu, Aditya Kumar, and Yamem Tamut. "Soil Stabilization with Guar Gum and Fly Ash." In *Indian Young Geotechnical Engineers Conference*, pp. 231-239. Singapore: Springer Nature Singapore, 2021. https://doi.org/10.1007/978-981-96-1373-1_21

[26] Wang, Kai, and Xiaoxiong Zha. "Optimizing Construction Spoil Reactivity for Cementitious Applications: Effects of Thermal Treatment and Alkaline Activation." Buildings 14, no. 9 (2024): 2954. https://doi.org/10.3390/buildings14092954

[27] Almuaythir, Sultan, Muhammad Syamsul Imran Zaini, Muzamir Hasan, and Md Ikramul Hoque. "Sustainable soil stabilisation using industrial waste ash: Enhancing expansive clay properties." Heliyon 10, no. 20 (2024). https://doi.org/10.1016/j.heliyon.2024.e39124

[28] Dudekula, Rehaman Basha, Ashwin Narendra Raut, and Sravan Kumar Chilukuri. "Using Palm Oil Fuel Ash as a Source Material for Alumina Silicate." Jordan Journal of Civil Engineering 18, no. 1 (2024).

[29] Yamagoshi, Yosuke, Y. Kitano, C. Kosugi, M. Nakagawa, Y. Akashi, E. Kiso, O. Miki, and K. Hata. "Basic characteristics of CaO-improved soil." Nippon Steel Sumitomo Metal Techn Rep 109 (2015): 51-58.

[30] Hashim, N. H., MN Muhd Sidek, N. Md Noor, S. R. Roselli, MA Mohd Yusoff, and MFS Saiful Bahari. "Utilisation of palm oil fuel ash (Pofa) as sand replacement for fresh and hardened concrete by using powder and liquidation method." In Journal of Physics: Conference Series, vol. 1349, no. 1, p. 012055. IOP Publishing, 2019. https://doi.org/10.1088/1742-6596/1349/1/012055