

STRENGTH DEVELOPMENT OF KAOLIN CLAY STABILISED WITH PALM OIL FUEL ASH (POFA) AND CALCINED EGGSHELL (CES) BINDER

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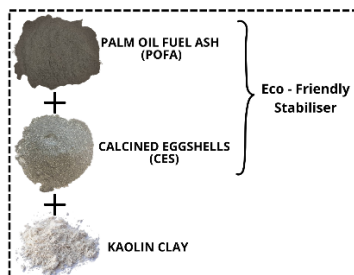
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Graphical abstract



Abstract

In geotechnical engineering, the structures built over soft soil pose significant challenges owing to their low strength, high compressibility, and tendency to undergo excessive settlement and structural failure. Therefore, soil stabilisation is required to improve the poor properties of the soil. Using by-products in soil stabilisation has been extensively studied as an alternative and sustainable soil binder to replace cement due to its efficiency in enhancing soil performance. This research takes the opportunity to investigate the potential of various locally available by-products, which are Palm Oil Fuel Ash (POFA) and Calcined Eggshell (CES), as a sustainable binder for kaolin clay stabilisation. The influence of different proportions and dosages of POFA:CES mixtures over curing times on the Unconfined Compressive Strength (UCS) was evaluated for the above purpose. The changes in chemical composition and microstructure of unstabilised and stabilised kaolin clay were also investigated to determine the underlying stabilisation mechanisms through X-ray Fluorescence (XRF) and Scanning Electron Microscopy with Energy-Dispersive X-ray Spectroscopy (SEM-EDX). The findings revealed that the maximum strength development within 7 days was achieved with 50:50 proportion of POFA:CES at 25% dosage. Furthermore, the kaolin clay strength increased significantly with higher POFA:CES dosages and longer curing durations. This research highlights the potential of POFA:CES binders to enhance kaolin clay performance and promote sustainable construction practices, aligning with Sustainable Development Goal 9 by promoting innovative and resilient infrastructure development.

Keywords: Soft soil, kaolin clay, soil binder, soil stabilisation, Palm Oil Fuel Ash (POFA), Calcined Eggshell (CES), microstructure analysis, Unconfined Compressive Strength (UCS)

Abstrak

Dalam kejuruteraan geoteknikal, struktur yang dibina di atas tanah lembut menimbulkan cabaran yang signifikan kerana kekuatan yang rendah, kebolehan mampatan yang tinggi, dan kecenderungan untuk mengalami penurunan berlebihan serta kegagalan struktur. Oleh itu, pengukuhan tanah diperlukan untuk memperbaiki sifat tanah yang lemah. Penggunaan produk sampingan dalam penstabilan tanah telah dikaji secara meluas sebagai pengikat tanah alternatif dan lestari untuk menggantikan simen kerana keberkesannya dalam meningkatkan prestasi tanah. Kajian ini mengambil peluang untuk menyiasat potensi pelbagai bahan sampingan yang terdapat secara tempatan, iaitu Abu Pembakaran Kelapa Sawit (POFA) dan Cengkerang Telur Dikalsinasi (CES), sebagai bahan pengikat mampan bagi penstabilan tanah liat kaolin. Pengaruh pelbagai nisbah dan dos campuran POFA:CES terhadap tempoh penyembuhan dan Kekuatan Mampatan Tidak Terkurung (UCS) telah dinilai bagi mencapai objektif tersebut. Perubahan dalam komposisi kimia dan mikrostruktur bagi tanah liat kaolin yang tidak distabilkan serta yang telah distabilkan turut disiasat bagi menentukan mekanisme penstabilan menggunakan Pendarfluor Sinar-X (XRF) dan Mikroskop Elektron Imbasan-Spektroskopi Sinar-X Serakan Tenaga (SEM-EDX). Penemuan kajian ini menunjukkan bahawa perkembangan kekuatan maksimum dalam masa 7 hari dicapai dengan nisbah 50:50 POFA:CES pada dos 25%. Ia memenuhi keperluan kekuatan minimum untuk subgrad jalan raya (400 kPa). Selain itu, kekuatan tanah liat kaolin didapati meningkat dengan ketara selari dengan peningkatan dos POFA:CES dan masa pengawetan. Kajian ini menekankan potensi pengikat POFA:CES untuk meningkatkan prestasi tanah liat kaolin dan mempromosikan amalan pembinaan lestari, selaras dengan Matlamat Pembangunan Lestari 9 yang memfokuskan kepada pembangunan infrastruktur yang inovatif dan berdaya tahan.

Kata kunci: Tanah lembut, pengikat tanah, abu pembakaran kelapa sawit (POFA), cengkerang telur dikalsinasi (CES), kekuatan mampatan tidak terkurung (UCS)

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1.0 INTRODUCTION

Soil is a crucial component in construction, as it serves as the base that supports the entire load of foundations and structures built over it. Unfortunately, the soil on the construction site does not always have sufficient strength to support the load from the structures, especially when faced with the poor properties of clay soil [1, 2, 3]. This may cause excessive settlement or structural failure. Moreover, clay soil swells when wet and shrinks when dry, causing significant volume changes and movement, potentially leading to structural damage [1]. With rapid urbanisation to fulfill society's demand and 'good' soil scarcity, construction over such soils is inevitable. Therefore, improving poor clay soil properties is essential to ensure the durability, stability, and safety of any structure constructed on it.

Chemical soil stabilisation methods using cementitious materials, such as lime and cement, through in-situ mixing or grouting, integrating them as slurry or powder with soft clays, which have long been applied in the construction industry. These techniques greatly improve clay soil performance through chemical reactions by altering the clay soil's physical and chemical properties [2]. In this case, cement is particularly effective in amplifying cohesion and durability, thereby making the clay soil more resistant to erosion and moisture-related issues. Meanwhile, lime effectively stabilises clay-rich soils by minimising

plasticity and enhancing compaction and load-bearing capacity. This stabiliser is effective in improving the clay soil's geotechnical properties, but it also has several disadvantages, namely cost [2, 3], environmental impacts during manufacture [2, 3], and concerns regarding long-term structural integrity [3]. CES is produced by calcining waste eggshells to CaO (hydrated to Ca(OH)₂), whereas POFA is the palm-oil mill boiler by-product, ash from burning shell/fibre rich in amorphous silica [4, 5, 6]. Recent studies show that eggshell-derived calcium sources (CES) provide highly reactive CaO/Ca(OH)₂ and can strengthen clay soils, especially when paired with a silica-bearing pozzolan such as ground glass. However, no prior work has tested POFA–CES blends in soils or established an optimal POFA:CES ratio. Motivated by the Ca–Si hydrate mechanism, this study determines suitable POFA:CES proportions for soft-soil stabilisation [7, 8, 9]. Specifically, eggshell-derived limes (CES) are highly calcium-rich (≈97% CaO in eggshell quicklime; ≈90% Ca(OH)₂ in eggshell hydrated lime) and, when used with a silica-bearing pozzolan, can improve soil strength and stiffness [9]. In soils, calcined eggshell powder (ESP) used alone typically achieves an optimum of about 6–8% by dry soil for UCS/CBR gains [8]. Separately, POFA is identified as a silica-rich material, and GPOFA–ESP combinations have been investigated in cementitious systems to exploit the SiO₂–CaO complementarity and determine optimum proportions, this supports the Ca–Si synergy concept

but does not yet establish a soil-specific POFA:CES ratio [10]. Consistently, lime–POFA blends have been shown to enhance the strength of kaolinitic clay [11], whereas POFA used alone in clayey soils yields only modest UCS gains up to 28 days [12]. Together, these findings underscore the need for a calcium source with POFA and motivate the POFA–CES ratio optimisation addressed in this study. Accordingly, a clear gap remains for clay soil stabilisation of prior geotechnical work in these sources uses CES alone or CES with non-POFA pozzolans, so the optimal POFA:CES ratio for soils and its microstructural basis are still unreported and will be addressed in this study [6]. Although calcining eggshells releases some CO₂, its impact is considerably lower than that of cement production, as CES is derived from waste eggshells calcined at approximately 900 °C, compared to cement clinkerisation above 1400 °C [2, 3, 5], thereby valorizing waste while reducing embodied energy.

To contextualise this gap within the current practice of concern for cement technical performance, it is prone to cracking over time as it undergoes natural shrinkage, compromising the durability and longevity of structures. Cement also requires a long curing time to achieve the desired strength, delaying construction processes and increasing labour and material costs. Malaysia Public Works Department reported that the soil stabilised with cement exhibits higher stiffness and strength; however, they are prone to shrinkage and cracking over time or under varying moisture conditions [13], compromising the long-term structural integrity of the pavement and leading to increased maintenance requirements. These obstacles highlight the need for more sustainable alternatives in construction materials to address environmental and performance-related challenges.

Recently, numerous researchers extensively studied alternative binders for soil stabilisation using local cementitious by-product resources to compensate for the shortcomings of traditional soil binders and, simultaneously, be environmentally friendly [14–25]. Snellings *et al.*, (2012) stated that the by-products indeed possess pozzolanic and cementitious characteristics, contributing to the soil-cement matrix's densification and strengthening, thereby enhancing the overall mechanical properties of the stabilised soil [26]. Utilising by-products for valuable construction materials is effective in elevating soil geotechnical properties and, concurrently, contributes to sustainable waste disposal and management practices.

Among by-products, utilising POFA as an alternative material for cement and lime demonstrates strong potential owing to its amorphous nature and high silica content, which promote pozzolanic reactions that effectively enhance the geotechnical and engineering properties of soft soils [1, 8, 27, 28, 29]. POFA is generated from palm-oil mills as a by-product of empty-fruit-bunch and shell combustion in boilers (≈800–1000 °C), reusing this ash as a supplementary binder valorises waste and can

partially displace clinker-based binders, with the potential to lower embodied CO₂ relative to cement-only stabilisation [35]. Aside from that, POFA has garnered much interest primarily because it is an extensively available waste material in Malaysia [1, 10] and has low profitable commercial value [1]. It demonstrates strong potential for sustainability and material availability to satisfy the needs in the construction industry. Without transforming POFA waste into beneficial materials, serious waste management problems will occur in the industry, forcing them to bear high costs for disposal, transportation, and environmental compliance. According to Pourakbar *et al.*, (2015), Malaysia produced about 3 million tonnes of POFA, which were then dumped in landfills, causing air pollution and groundwater quality issues due to various metals leached from the ash [2]. This is also supported by Toyeb *et al.*, (2023) [30]. Therefore, reusing these wastes for soil stabilisation is not only beneficial for construction purposes, but it can also help manage the waste sustainably.

Research on the effectiveness of POFA-stabilised soils, particularly clay soils, is limited, and often requires large amounts of binder to acquire adequate results. Furthermore, the POFA-stabilised soil failed to meet the JKR minimum standard for subgrade, which is 400 kPa required. Putra *et al.*, (2023) reported that POFA, which contains silica and alumina, is reactive when combined with lime and water, promoting a binding reaction in the clay soil matrix [31]. Despite the significance of this issue, not much effort has been made to assess the efficacy of POFA in combination with other calcium-based by-products for clay soil stabilisation to date. As a result, this research explored the potential of POFA along with calcined CES in stabilising Kaolin clay under appropriate conditions. CES is rich in calcium and is used as a sustainable alternative to lime in the mixture. CES is generated by heating chicken eggshells at high temperatures, typically between 800°C and 900°C. This heating process, known as calcination, removes organic matter and carbon dioxide, converting the calcium carbonate (CaCO₃) present in the eggshells into calcium oxide (CaO), also known as quicklime. The resulting calcium oxide is then used as a soil binder because it reacts with water and other soil components to form cementitious compounds, enhancing soil strength and stability [30, 31, 32]. Based on its chemical composition, POFA is generally classified as a Class F pozzolan, referring to its low calcium oxide content and high silica content [30, 33]. However, CES acts as a cementitious material rather than a pozzolan because of its high CaO content, making it similar to Class C in terms of its self-cementing properties [30, 34]. When mixed with POFA as the pozzolan, CES may enhance soil stabilisation by providing additional calcium ions for pozzolanic reactions. Toyeb *et al.*, (2023) asserted that combustion products, such as POFA and CES, can be categorised as either Class F or C, depending on their calcium content, where Class F has a maximum

calcium content of 18%, whereas Class C can contain more than 18% calcium [30].

For soil performance improvement, it is crucial to determine the ideal POFA and CES proportions and dosages in the mixture. The optimal combination ensures that the silica and calcium contained in POFA and CES react effectively with this kaolin clay, thus enhancing compaction, compressive strength, and kaolin clay stability. The kaolin clay was used as a material to be stabilised due to its poor engineering properties, including low plasticity, low shear strength, high compressibility, and poor bearing capacity under saturated conditions, making it unsuitable for direct application in foundations and subgrades without prior stabilisation [3, 29, 34]. Its consistent mineralogy and predictable behaviour make it a preferred baseline material in geotechnical studies for representing weak soils and assessing the performance of chemical and pozzolanic stabilisers [11, 29]. The right and accurate combination of by-products is the key to achieving consistent results and ensuring the binder's effectiveness across various soil types, resulting in enduring improvements in kaolin clay performance. Thus, this research investigated the influence of various POFA:CES proportions (100:0, 75:25, 50:50, 25:75, and 0:100) with binder dosages up to 25% based on dry weight of kaolin clay on the unconfined compressive strength (UCS) development, respectively. The effectiveness of kaolin clay stabilised with the optimal proportion and dosage of POFA:CES binder was further assessed at varying curing times of 1, 7, 14, and 28 days. Furthermore, the changes in the chemical composition and microstructure of unstabilised and stabilised kaolin clay were examined to ascertain the underlying stabilisation mechanisms through X-ray fluorescence (XRF), X-ray diffraction (XRD), and scanning electron microscopy (SEM). The success of this research will contribute to sustainable industrial practices and enhance the quality of infrastructure in a cost-effective and eco-friendly way.

2.0 METHODOLOGY

2.1 Materials

The kaolin clay used in this research was supplied by Kaolin (Malaysia) Sdn. Bhd., Perak, Malaysia. Kaolin clay is a white material composed mainly of hydrated aluminium silicate. In this study, commercial kaolin was used as a representative high-plasticity clay to emulate problematic subgrade conditions, rather than a field sample from the study site. It was selected for its uniformity to minimise natural variability while still reflecting poor clay behaviour. The clay exhibits poor geotechnical properties with high plasticity, low shear strength, and high compressibility that warrant stabilisation. Table 1 shows the index geotechnical properties of untreated kaolin clay. Most particles range from 25 to 35 μm , with a smaller fraction

between 0.4 and 0.75 μm . Based on the Unified Soil Classification System (USCS), kaolin clay is characterised as a high-plasticity clay (CH). According to Amran *et al.*, (2021), this type of soil is weak and not suitable for construction purposes. Using kaolin as a model clay provides a controlled baseline for evaluating the binder's efficacy before extending the approach to in-situ soils [34].

For this research, two primary by-products were used to formulate alternative and sustainable soil binders for stabilising the poor properties of kaolin clay with POFA and CES, as shown in Figure 1. POFA was employed as the primary material, while CES was used as the secondary material in the alternative binder mixture. POFA was chosen as an aluminosilicate source for the formulation due to its abundance of accessible waste material in Malaysia and its low profitable commercial value. While CES was selected as an alternative to lime in the formulation.

Table 1 Index properties of untreated kaolin clay with the standard used

Properties	Symbol	Standard	Value
Liquid limit	LL	BS1377:1990 - Part 2	70%
Plastic limit	PL	BS1377:1990 - Part 2	36%
Plasticity index	PI	BS1377:1990 - Part 2	34%
Specific gravity	G _s	BS1377:1990 - Part 2	2.64
Maximum dry density	MDD	BS1377:1990 - Part 4	1.385 g/cm ³
Optimum moisture content	OMC	BS1377:1990 - Part 4	27%

POFA employed in this research was acquired from Sedenak Palm Oil Mill, Johor, in wet conditions. POFA consists of high silica (SiO₂) content, which exhibits high potential to produce an efficient geopolymer. POFA was oven-dried at 105°C for 24h and later sieved through a 300 μm sieve for better pozzolanic activity and improved binding properties.

The eggshells used in this research were collected from a bakery shop located at Muar, Johor. For CES preparation, the collected eggshells were meticulously cleaned to remove impurities or residual substances. The process involved thoroughly washing and drying the eggshells. After drying, the eggshells were manually crushed into smaller pieces and further pulverised into fine particles using a mechanical grinder, producing eggshell powder (ESP). The resulting ESP was then sieved through a 200 μm mesh to obtain a fine powder. Subsequently, the powder was calcined in a furnace at 900°C for 2 hours. This heating process removed organic matter and carbon dioxide, transforming the calcium carbonate (CaCO₃) in the eggshells into calcium oxide (CaO),

also known as quicklime. In this study, POFA and CES were used as supplementary materials for soil stabilisation, serving as silica- and calcium-rich binders, respectively. Abdulrahman *et al.*, (2022) stated that calcium oxide is used as a soil binder as it can react with water and other clay soil components to form cementitious compounds, enhancing soil strength and stability [4]. The chemical composition of soil, POFA, and CES was analysed via the X-ray Fluorescence (XRF) test.

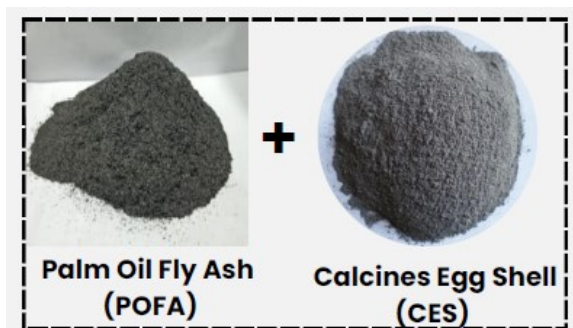


Figure 1 POFA and CES as an alternative soil binder

2.2 Experimental Work

The laboratory tests were undertaken to optimise and evaluate the efficacy of POFA:CES binder in stabilising kaolin clay, which attains optimum strength from the UCS test. The evaluation process was divided into three main stages, as summarised in Table 2. The first stage was to find the best POFA and CES proportion for the highest compressive strength. During stage 1, the POFA:CES dosage and curing time were kept constant at 15% and 7 days, respectively. The second stage was to evaluate the optimum dosage of POFA:CES mixture for achieving maximum compressive strength at the optimum POFA:CES proportion based on the findings from stage 1 and at 7 days of curing time. In stage 3, the strength development with POFA:CES binder was examined at various curing times (1, 7, 14, and 28 days). At this stage, the samples were prepared with optimum POFA:CES proportion (from stage 1) and dosage (from stage 2).

Table 2 Mix proportions and dosages of POFA:CES binder for UCS test

Context	POFA:CES (by mass)	Dosage (% of dry kaolin clay)	Curing time (d)
Baseline (control)	-	0	7
Stage 1 – proportion scan (fixed 25%, 7 d)	100:0	25	7
	50:50 (optimum)	25	7
	0:100	25	7
Stage 2 – dosage at 50:50 (7 d)	50:50	15	7
	50:50	20	7
	50:50 (optimum)	25	7
Stage 3 – curing at optimum (50:50–25%)	50:50	25	1
	50:50	25	7
	50:50	25	14
	50:50	25	28

2.3 Sample Preparation and Test Methods

2.3.1 Fourier Transform Infrared Spectroscopy (FTIR)

FTIR analysis was used to identify the functional groups of clay minerals based on the absorption bands of bonds that vibrate independently. Three by-product materials and a commercial binder were investigated for their chemical composition. The by-product materials included CES and POFA. Absorption bands in the hydrogen-bonding region are linked to cations connected to OH vibrations and appear at various frequencies. The FTIR method evaluates the short-range cation order by analysing the cation distribution surrounding hydroxyls [36]. The absorption spectra of most organic compounds are identified in the mid-infrared region (4000~ 500 cm⁻¹) [34].

2.3.2 Chemical Composition

The chemical composition of unstabilised and stabilised kaolin clay with POFA:CES binder was

analysed using a Rigaku Supermini 200 wavelength-dispersive X-ray fluorescence (WDXRF) analyser. For sample preparation, the kaolin clay was oven-dried at 105 °C for 24 hours to remove all moisture, as residual water may interfere with elemental detection. A similar procedure has been used by Al-hokabi *et al.*, (2021) and Amran *et al.*, (2021) [29, 34]. Kaolinite remains thermally stable at temperatures well above 105 °C, with dehydroxylation only starting around 450–600 °C, confirming that this drying temperature does not alter the mineral framework [29, 34]. Therefore, drying at 105 °C is important to ensure complete moisture removal while maintaining the integrity of the kaolin clay's chemical and microstructural characteristics.

After drying, the kaolin clay was finely ground into a homogeneous powder (<75 µm) to ensure consistent readings. The powdered sample was then pressed into pellet form using a hydraulic press with paraffin wax to maintain cohesion during testing. The pellet (approximately 32 mm diameter) was

compacted to a uniform density under controlled pressure, placed into the sample holder, and scanned using the WDXRF analyser. The emitted secondary X-rays were measured to determine the elemental composition of the sample.

2.3.3 Standard Proctor Compaction Test

The standard Proctor compaction test was conducted to determine the optimum moisture content (OMC) and maximum dry density (MDD) of unstabilised kaolin clay in accordance with BS 1377: Part 4: 1990 (Clause 3). The material was oven-dried at 105 °C for 24 h and sieved through a 4.75 mm sieve. The kaolin clay sample was compacted into three equal layers, with each layer receiving 27 blows from a 2.5 kg rammer dropped from a height of 300 mm. This compaction procedure provided a total energy of approximately 600 kN·m/m³, equivalent to the standard Proctor compaction effort [29, 41].

The OMC and MDD of the unstabilised kaolin clay were used for preparing all stabilised specimens. Compaction tests were not repeated for each POFA:CES mix, as this study focused on assessing strength improvement under a consistent compaction condition. Pilot testing showed that the OMC and MDD values of kaolin clay stabilised with different POFA:CES dosages were very close to the unstabilised values, indicating no substantial changes in the optimum conditions. Therefore, the OMC and MDD of the unstabilised kaolin clay were taken as the reference for UCS sample preparation to represent the soil condition on site. Using a fixed OMC and compaction effort allows a direct comparison of stabiliser performance without the influence of varying density or moisture content, as also applied in previous studies [29, 34, 41].

2.3.4 Unconfined Compressive Strength (UCS) Test

UCS test was conducted in this research to evaluate the strength development of kaolin clay stabilised with POFA:CES binder at various proportions and dosages over time. The evaluation was performed in three (3) main stages, as presented in Table 2. To simulate the soil's conditions on site, unstabilised and stabilised kaolin clay samples with POFA:CES binder were prepared at regulated water content and dry density related to OMC and MDD obtained from the compaction test. In this research, kaolin clays were mixed with five proportions (100:0, 75:25, 50:50, 25:75, and 0:100) and dosages (0%, 5%, 10%, 15%, 20%, 25%) of POFA:CES binder to investigate their influence on UCS performance over times (1, 7, 14 and 28 days), as summarised in Table 2. Here, "proportion" refers to the POFA:CES mass ratio within the binder, while "dosage" refers to the total binder content (POFA+CES) expressed as a percentage of dry soil mass. Stage 1 varied proportion at 0–25% dosage and 7 days curing. Stage 2 kept the optimum proportion from Stage 1 and varied dosage (0–25%) at 7 days. Stage 3 used

the optimum proportion and dosage from Stages 1–2 to study curing time (1, 7, 14, 28 days).

Figure 2 depicts the overall sample preparation process for UCS test. Samples were prepared manually by mixing 0 to 25% POFA:CES binder (based on dry weight of soil) with the dry kaolin clay. Water was incorporated into the mixture up to the OMC level and mixed thoroughly until it achieved homogeneity. The kaolin clay sample was compressed in three (3) equal layers in the cylindrical mould (38 mm in diameter and 78 mm in height) using hydraulic press.

It was compacted to the OMC and MDD conditions recorded from the compaction test. Each layer's surface was scratched to enhance bonding between layers. After compaction, samples were trimmed to the required length, removed from the mould, labelled, and covered with thin plastic wrap. After that, samples were placed in the curing box and cured for 1, 7, 14, and 28 days at 27 °C (room temperature) and 90% humidity to prevent moisture loss during curing. The samples were subjected to the UCS test immediately after curing. This test was conducted according to BS 1924-Part 2: 1990 (Section 4) at a rate of 1 mm/min. Three samples for each mixture were prepared and tested to ensure consistency and accuracy of the results.

Although the stress path of the UCS test does not replicate the complex stress conditions that occur in the field, it is still widely adopted as a preliminary assessment method for soil stabilisation because of its simplicity, repeatability, and standardised procedure [11, 29, 34]. In this study, the UCS test was used to evaluate the relative strength improvement of kaolin clay stabilised with the POFA:CES binder at different proportions and curing periods. While the absolute UCS values may not directly represent in-situ performance, the test provides a reliable basis for comparing stabiliser effectiveness under controlled laboratory conditions [11, 34]. The outcomes obtained from the UCS test serve as an initial indicator for identifying promising mix formulations, which can later be validated using more representative field tests such as triaxial or plate load tests.

2.3.5 Microstructural Analysis

Scanning electron microscopy with energy dispersive X-ray (SEM-EDX) was employed to examine both unstabilised and stabilised soil samples with optimum POFA:CES formulation to assess the changes in micromorphology and chemical composition, adhering to ASTM E986-04 (2010). Small representative samples crushed in the UCS test were analysed by mounting them on the aluminium stubs with two carbon tabs on either side. A thin platinum coating (~10 nm) was applied using a sputter coater to enhance surface conductivity of the sample surface.

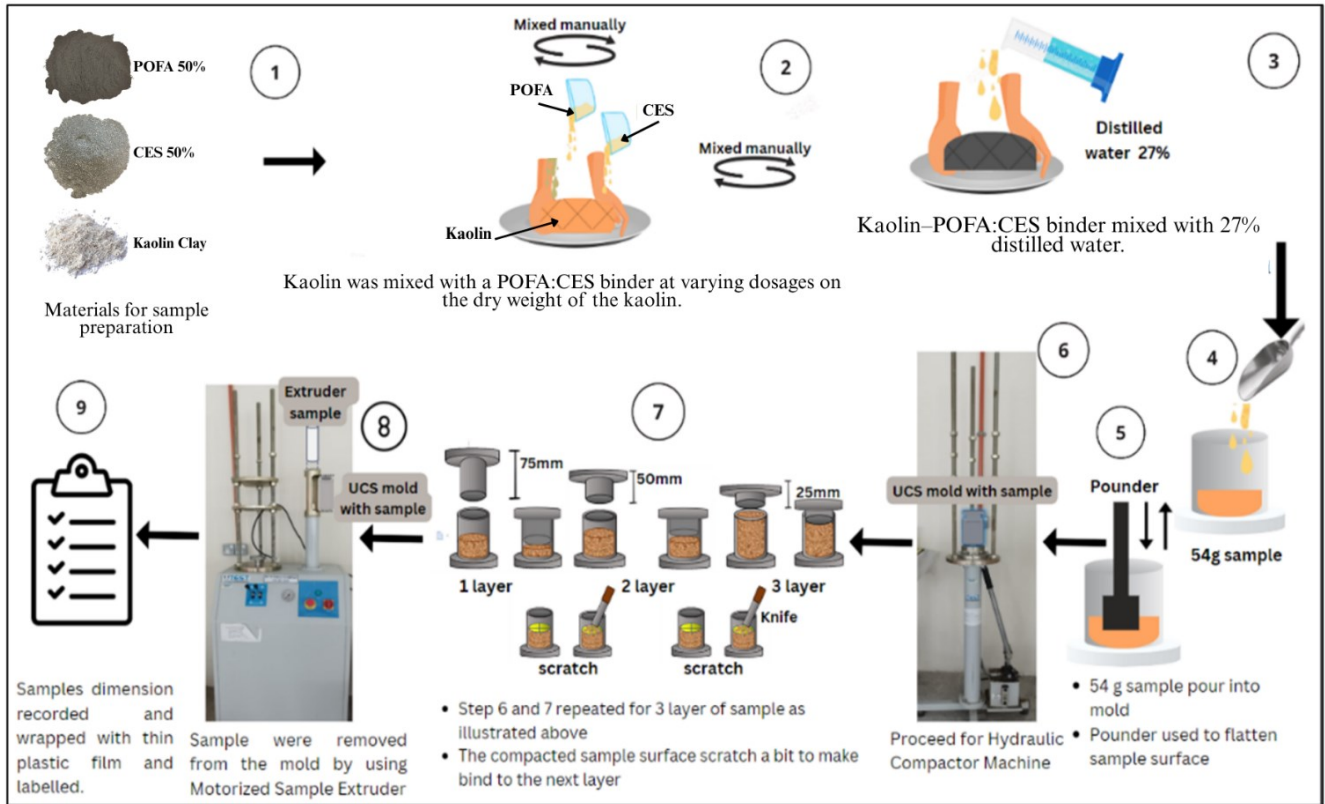


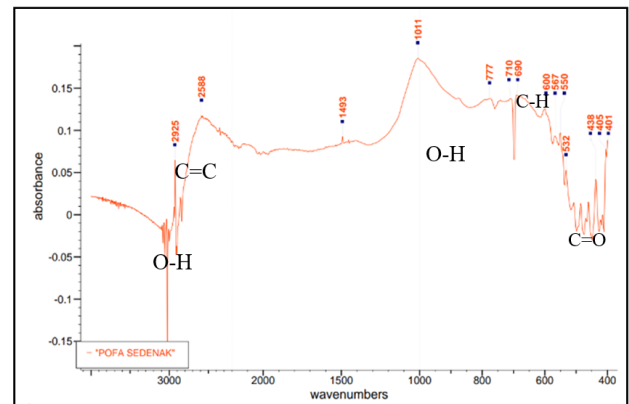
Figure 2 The whole process that is involved in the UCS

3.0 RESULTS AND DISCUSSION

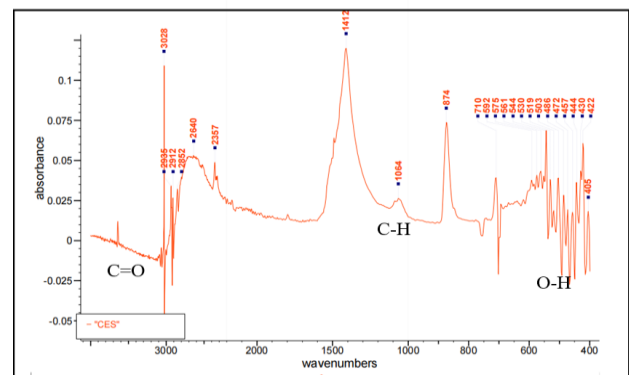
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Figure 3 (a) shows the infrared (IR) absorption frequencies observed for POFA. The recorded peaks inferred the presence of specific functional categories. The presence of esters, aldehydes, or carboxylic acids was indicated at 690.38 cm^{-1} , which corresponded to C=O stretching vibrations [32]. In addition, 2587.97 and 2925.44 cm^{-1} wavenumbers represented C=C and O-H stretching vibrations, respectively, indicating the existence of alkenes and carboxylic acids [7]. These functional groups may impact the characteristics of POFA and its efficiency in stabilising the soil [34].



(a)



(b)

Figure 3 FTIR spectra of (a) POFA and (b) CES

In contrast, Figure 3 (b) depicts the absorption peaks in the FTIR analysis of CES, indicating the presence of specific functional groups. It was found that the calcination process converted calcium carbonate (CaCO_3) in the eggshells to calcium oxide (CaO) and carbon dioxide (CO_2). The ideal calcination conditions for eggshells were 900 °C and 1 h, yielding calcium oxide with 99.06% w/w purity. This suggested the potential presence of CaCO_3 derivatives from the eggshell calcination process, offering binding properties for soil stabilisation [36]. Calcination process of eggshells may also contribute to the emergence of these specific functional groups [36].

3.2 Chemical Composition

The reactivity and ability of materials in improving kaolin clay performance are influenced by their chemical composition. Table 3 presents the weight percentage of the significant elements found in the materials tested by XRF. In kaolin clay, the basic elements were SiO_2 , CaO , Al_2O_3 , Fe_2O_3 , and K_2O .

POFA and CES have distinct chemical compositions, each containing elements that play their parts as soil binders. Rich in silicon dioxide (SiO_2 - 32.3%), POFA can be regarded a strong pozzolanic material, whereas calcium oxide (CaO - 14.6%) could enhance the cementitious reactions. Other elements were also present, such as iron oxide (Fe_2O_3 - 4.1%) and potassium oxide (K_2O - 12.4%), altering structural integrity and alkali behaviour. Conversely, CES was dominated by CaO (59.8%), marking its high effectiveness for stabilisation due to the binding nature. With minimum SiO_2 (0.36%), CES had less pozzolanic behaviour but provided sufficient calcium to promote hydration reactions in the soil.

Studies have indicated that POFA and CES are viable binders for improving weak soils. Zaini et al. [11] claimed that when POFA is mixed with cementitious materials, its silica content increases soil shear strength and decreases plasticity. Moreover, Adnan et al., (2024) highlighted that CES is an effective lime-based binder that improves soil workability and reduces swelling behaviour, comparable to traditional lime treatments [37]. When combined, POFA and CES create a pozzolanic-lime reaction, enhancing soil bonding, reducing permeability, and improving load-bearing capacity. Previous studies on industrial waste-derived stabilisers further validate their combined effectiveness [38].

POFA is classified as a pozzolanic material under Class F according to ASTM C618 due to its high SiO_2 content (>10%) and the likelihood that its $\text{CaO} + \text{Al}_2\text{O}_3 + \text{Fe}_2\text{O}_3$ composition does not reach 70%, making it suitable for self-cementing applications in construction and soil stabilisation. In contrast, CES does not meet the pozzolan criteria since its silica and alumina contents are extremely low. However, according to ASTM C51, it can be categorised as High Calcium Lime because its CaO content exceeds 50% after calcination, making it a viable substitute for lime in soil stabilisation. While the POFA:CES blend is

classified as a Class C. However, it features a Hybrid Pozzolanic-Cementitious Material, which combines the pozzolanic reactivity of POFA with the binding properties of CES, or as an alkali activator for geopolymers, offering a sustainable alternative for the construction industry.

Significant changes occurred in the chemical composition when POFA and CES were mixed at 50:50 ratio. The SiO_2 content decreased to 16.33%, which may slightly reduce pozzolanic activity but still allows secondary cementitious reactions. The CaO content increased substantially to 37.20%, enhancing stabilisation properties and improving hydration reactions, making the mixture more reactive in binding applications. Meanwhile, Fe_2O_3 remained at 2.05%, maintaining structural integrity, while K_2O decreased to 6.23%, supporting alkaline reactions beneficial for soil modification. This shift in composition enhances stabilisation effects, creating a well-balanced material that improves soil strength and durability while offering a sustainable alternative to conventional cementitious binders.

Table 3 Chemical composition of materials

Element	Weight (%)			
	SOIL	POFA	CES	75%POFA + 25%CES
SiO_2	49.3	32.3	0.36	16.33
CaO	0.07	14.6	59.8	37.20
Al_2O_3	31.5	-	-	-
Fe_2O_3	2.46	4.1	-	2.05
K_2O	5.09	12.4	0.06	6.23
Other	11.58	36.6	39.78	38.19
Material classification	-	Class F	Class C	Class C

3.3 Compaction Characteristics of Unstabilised Kaolin Clay

Figure 4 illustrates the compaction curve of the unstabilised kaolin clay plotted between dry density and moisture content. The kaolin clay recorded an optimum moisture content (OMC) of 27% and a maximum dry density (MDD) of 1.385 g/cm^3 . These values represent the baseline compaction characteristics of the raw kaolin clay and were used to compare the subsequent strength development of the stabilised specimens. The compaction curve shows a typical behaviour of fine-grained clay, where the dry density decreases at moisture contents above and below the optimum [29,34].

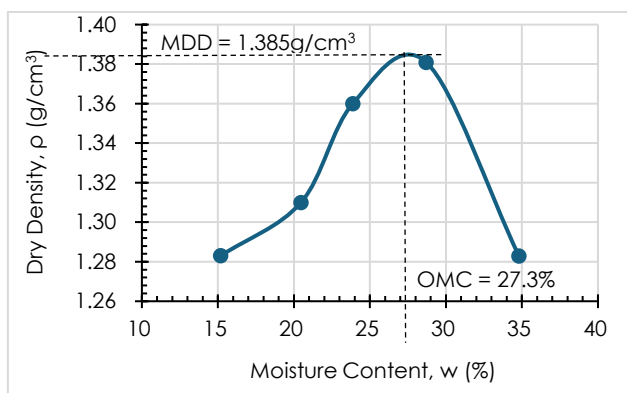


Figure 4 Compaction curve of unstabilised kaolin clay

3.4 Unconfined Compressive Strength (UCS)

The influence of varying proportions and dosages of POFA:CES binder (see Table 2) for soil stabilisation was assessed through the UCS test. The test began by evaluating its optimum proportion and was subsequently used to determine the effective dosage for kaolin clay stabilisation. The optimum POFA:CES proportion and dosage was then used to examine its strength development over time to ensure reliable long-term performance.

3.4.1 Effect of POFA:CES Proportion on Unconfined Compressive Strength of Stabilised Kaolin Clay

To examine the effect of POFA:CES proportions, kaolin clay mixtures with binder proportions of 100:0, 75:25, 50:50, 25:75, and 0:100 were tested following 7-day curing period with 25% binder dosage. Figure 5 depicts the strength performance of kaolin clay stabilised under these conditions. The findings show that the UCS value did not significantly differ as the POFA content increased from 0 to 50% or the CES content decreased from 100 to 50%. However, when the proportion exceeded 50:50, the UCS value slightly declined as the POFA content further increased from 50 to 100%. This was likely due to the insufficient calcium available to fully react with the excess silica and alumina from POFA, leading to incomplete pozzolanic reactions and reduced cementation. At 100:0 (pure POFA), the UCS value was the lowest, as no calcium source was available to activate the pozzolanic reaction, resulting in poor binding and reduced strength. The balanced POFA:CES mix proportion of 50:50 stood out as the optimum stabilisation formulation, achieving the peak UCS value of 485.12 kPa within 7 days. This was due to the optimal reaction between CaO from CES and reactive silica-alumina from POFA, forming C-S-H and C-A-H gels, which improved inter-particle bonding and soil structure [39]. This process reflects traditional stabilisers, which also rely on C-S-H formation for binding and strength enhancement [40]. Thus, the 50:50 proportion was the most effective proportion for pozzolanic activity, as both calcium and reactive silicates were equally available.

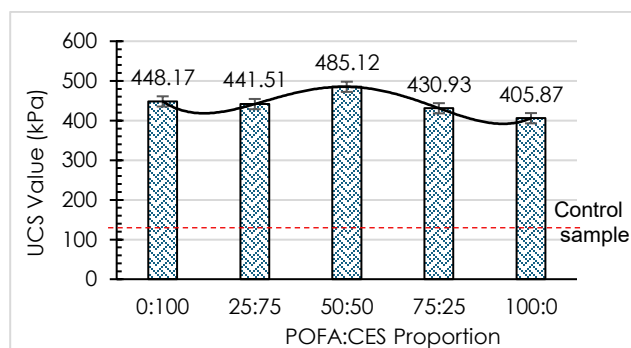


Figure 5 UCS strength of stabilised kaolin clay containing various POFA:CES proportions after 7-day curing

According to Kunther et al., (2017), calcium is essential for strengthening and stabilising C-S-H gel, the main binder in cementitious materials. Without calcium, silica alone is unable to form strong binding phases, proving that both elements are vital for effective cementation [41]. In a study conducted by Zaini et al., (2024) reported that the UCS value less than 20 kPa was achieved after curing for 7 days when the kaolin clay stabilised with 12% POFA alone [11]. In contrast, the UCS value of the POFA:CES (50:50) binder mix in this study was significantly higher at 485.12 kPa after 7 days, demonstrating that silica alone is insufficient to achieve optimum strength.

On the other hand, Mina et al., (2024) examined the compressive strength of clay soil stabilised with ESP after 7-day curing period [42]. The results showed that 12% ESP mix achieved the optimum compressive strength of 338.6 kPa. While this demonstrated some early strength improvement, the value remained lower compared to blended binders. The POFA:CES (50:50) mix proportion achieved a higher UCS value of 485.12 kPa at 7 days, highlighting the importance of balancing silica and calcium. ESP alone had poor pozzolanic reactions but performed better when paired with a calcium-rich stabiliser to enhance soil strength. This underscores the importance of binder formulation over sheer quantity, proving that efficient mix design of by-products can maximise strength while ensuring material sustainability. Variations in material type and dosage can alter the chemical composition of the stabiliser, thereby impacting the balance of reactive silica and calcium required for strength development.

3.4.2 Effect of POFA:CES Dosage on Unconfined Compressive Strength of Stabilised Kaolin Clay

Figure 6 demonstrates the effect of POFA:CES binder dosages on the UCS value of stabilised soil at 7 days curing time with POFA:CES proportion of 50:50. The graph shows that the UCS values of stabilised-kaolin clay increased progressively with increasing POFA:CES binder dosage up to 25%. The greatest gain was observed at the highest binder content of 25%, where the UCS value was triple that of the unstabilised kaolin

clay sample (from 131.34 to 485.12 kPa. However, POFA:CES dosage below 20% did not achieve the standard requirement of 400 kPa for low-traffic applications. Thus, the dosage of the stabiliser plays an important role in ensuring the soil achieves the required strength. This suggested a synergistic effect between POFA and CES at higher dosages. The increase in UCS value with binder dosage reflected the increasing cementitious compound formation in the soil matrix, which improved the binding between kaolin clay particles, reduced voids, and enhanced load-bearing capacity. In the presence of water, the silica and alumina in POFA react with calcium in CES. Therefore, when binder dosage is insufficient, the pozzolanic reaction is limited, resulting in poor cementitious gel formation, poorly bonded soil particles, and inadequate strength development, rendering the soil unsuitable for structural applications.

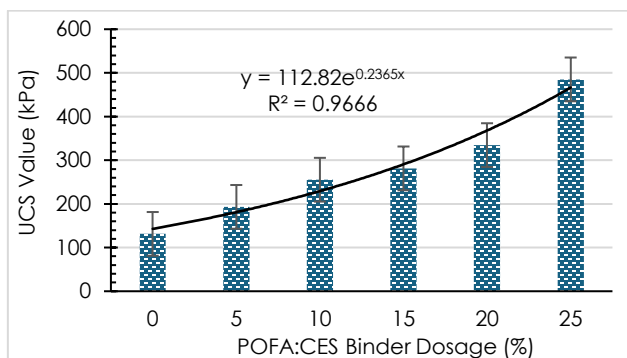


Figure 6 UCS strength of stabilised soil with varying POFA:CES dosages after 7 days of curing

Furthermore, an exponential trendline was fitted with the regression equation of $y = 112.82e^{0.2365x}$. This equation indicated R^2 value of 0.9666, highlighting a strong positive correlation between the POFA:CES binder dosage and UCS values. This high R^2 value suggested an excellent model fit, reinforcing the significant influence of POFA:CES binder dosage on soil stabilisation effectiveness.

According to Khasib *et al.*, (2021), the UCS values of soil increased consistently with higher dosages of POFA-based geopolymer [8]. In their study, high plasticity clay (CH) and low plasticity clay (CL) were treated with varying percentages of binder. The untreated CH and CL soils recorded low UCS values of 130 kPa and 260 kPa, respectively. When treated with 10% geopolymer, UCS values increased to approximately 550 kPa for CH and 780 kPa for CL, after 7 days of curing. Further increments in geopolymer dosage, up to 40%, resulted in higher strengths, reaching 1060 kPa and 1710 kPa for CH and CL, respectively. This proves that the binder dosage plays a crucial role in improving soil performance suitability for construction applications.

Toyeb *et al.*, (2023) explored the use of 20% POFA as an eco-friendly stabiliser for soft soils, revealing

remarkable improvements in soil strength [30]. Their findings showed that the unsoaked CBR increased from 3.25% in untreated soil to 8% after 7 days of curing, a significant 146% enhancement. SEM analysis demonstrated that POFA particles effectively filled soil pores, leading to a denser and more interlocked grain structure. Moreover, the soil's plasticity index dropped from 11.20% to 3.63%, reducing its swelling potential. The high silica content of POFA (55.36%) promoted pozzolanic reactions that reinforced the soil matrix, underscoring its viability as a sustainable soil stabiliser. The results align with those found in this study, where the optimum POFA:CES binder dosage of 25% led to significant strength gains after 7 days of curing. It confirms that increasing stabiliser dosage effectively enhances soil strength.

3.4.3 Stabilised Soil Strength Development with Optimum POFA:CES Formulation Over Time

In this stage, the development of the strength of soil stabilised with 25% POFA:CES dosage and optimum POFA:CES proportion (50:50) was observed at 1, 7, 14, and 28 days of curing time. Figure 7 illustrates that the UCS development of stabilised soil increased over time, likely due to ongoing pozzolanic reactions and continued hydration processes. The graph showed a consistently increasing trend, with an exponential best-fit line of $y = 179.01e^{0.4161x}$. This equation implied that UCS increased exponentially as curing time progressed, highlighting the binder's effectiveness in strengthening the soil over time. With R^2 value of 0.9978, the model exhibited a highly significant fit, suggesting that the exponential growth trend can explain approximately 97.12% of the observed variability in UCS values. This strong correlation underscored the critical role of curing duration in soil stabilisation, validating the POFA:CES effectiveness as a binder in improving UCS performance.

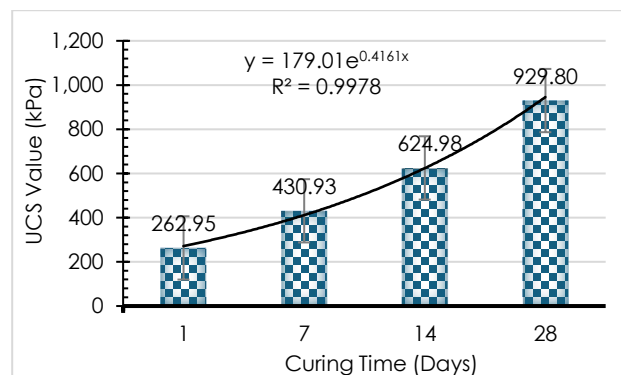


Figure 7 UCS of stabilised soil with optimum POFA:CES formulation at different curing times

The findings showed that the UCS improved significantly with longer curing time. The sharp rise of UCS value from curing time of 1 to 7 days indicated early strength development, while the continued increase in UCS value (929.80 kPa) up to 28 days

indicated the long-term strength improvement of the stabilised kaolin clay. The initial strength development was driven by the hydration of CaO in CES, forming calcium hydroxide ($\text{Ca}(\text{OH})_2$). It quickly reacts with reactive silica and alumina in POFA to initiate the formation of C–S–H and C–A–H gels [43]. As curing continues, more stable and dense cementitious gels are formed, filling voids and improving particle bonding. Consequently, the porosity is reduced, and strength further increases.

Khasib et al., (2021) reported that CL and CH soils treated with POFA-based geopolymers performed best at 30% binder dosage, achieving UCS values of 1710 kPa for CL and 130 kPa for CH at 7 days, which increased to 2860 kPa and 1060 kPa, respectively [8], after 28 days. While the absolute UCS values in this study were comparatively lower, it is important to consider the difference in soil type (kaolin, CH soil), lower binder content (25% versus 30–40%), and the use of blended POFA and CES, which is more sustainable and resource efficient. This study demonstrated that a lower binder dosage can still achieve significant strength gains. This highlighted the efficiency of the POFA:CES combination, offering sustainable and inexpensive alternative for soil stabilisation with robust early and long-term strength development.

Harikaran et al., (2023) investigated the expansive soil stabilisation using 9% lime and 12% ESP binder, achieving maximum UCS value of 306 kPa after 28 days [43]. Their results showed a moderate 12% UCS increase from 7 to 28 days (272 kPa to 306 kPa), attributed to the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) through pozzolanic reactions facilitated by calcium-rich additives.

In contrast, this study recorded a significantly higher UCS value of 929.80 kPa after 28 days, nearly three times greater than that reported by Harikaran et al., (2023)[43]. This notable improvement suggested greater binding efficiency and enhanced mechanical performance, likely due to geopolymerisation reactions, creating a stronger aluminosilicate matrix compared to traditional pozzolanic processes. Furthermore, the POFA:CES system exhibited a more dynamic strength gain of 92% over the same period (485.12 kPa to 929.80 kPa), reinforcing the role of accelerated geopolymerisation in improving UCS. Regarding binder dosage, Harikaran et al., (2023) used 21% (lime + ESP), while this study employed 25% of POFA and CES blend [43]. Despite the slightly higher dosage, the strength-to-binder efficiency of POFA:CES remained superior, likely due to its high reactive silica and alumina content, enhancing geopolymer formation. Chemically, the lime-eggshell system relied on pozzolanic reactions, forming CSH and CAH compounds, whereas POFA:CES underwent alkali-activated geopolymerisation, producing a three-dimensional aluminosilicate network known for greater mechanical strength and durability. The steady strength gain from 7 to 28 days reaffirmed that

curing time plays a crucial role in improving UCS due to ongoing pozzolanic reactions.

3.5 Microstructural and Elemental Characterisation

Figure 8 shows the surface morphology and elemental composition of 28-day-cured unstabilised and POFA:CES-stabilised kaolin clay with the optimum proportion of 50% POFA and 50% CES, at a 25% dosage, coded as 50POFA:50CES_25% , as this achieved the highest UCS performance. Table 4 illustrates the elemental composition of unstabilised (control) and stabilised kaolin clay with 50POFA:50CES_25% as analysed by EDX.

Table 4 SEM- EDX results of (a)unstabilised, and (b) stabilised kaolin clay with optimum POFA:CES binder

(a) Unstabilised Kaolin Clay (control sample)			
Element	Weight %	Weight % Sigma	Atomic %
Silica	22.17	0.55	15.96
Oxygen	53.55	0.88	67.68
Aluminium	15.14	0.44	11.34
Potassium	6.54	0.29	3.38
Calcium	0.00	0.15	0.00
Magnesium	1.46	0.22	1.21
Iron	1.15	0.28	0.42
Total	100.00		100.00
(b) Stabilised Kaolin Clay (50POFA:50CES_25%)			
Element	Weight %	Weight % Sigma	Atomic %
Silica	21.16	1.24	19.44
Oxygen	19.21	0.31	24.28
Aluminium	10.94	0.72	8.74
Potassium	7.36	0.57	4.06
Calcium	22.16	1.59	11.90
Iron	1.98	0.62	0.76
Magnesium	2.51	0.49	2.22
Total	100.00		100.00

The microstructure of unstabilised kaolin clay (Figure 8(a)) exhibited large voids, discontinuous and open structures between kaolin clay particles, implying weak interparticle bonding. The EDX results for the unstabilised kaolin clay sample showed the absence of calcium and a high oxygen content of approximately 53.55% by weight, indicating an elevated number of voids between particles. This is supported by Alhokabi et al., (2022) [42].

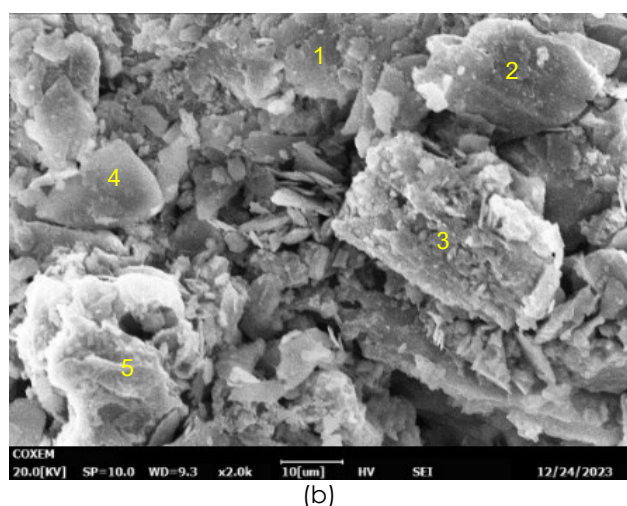
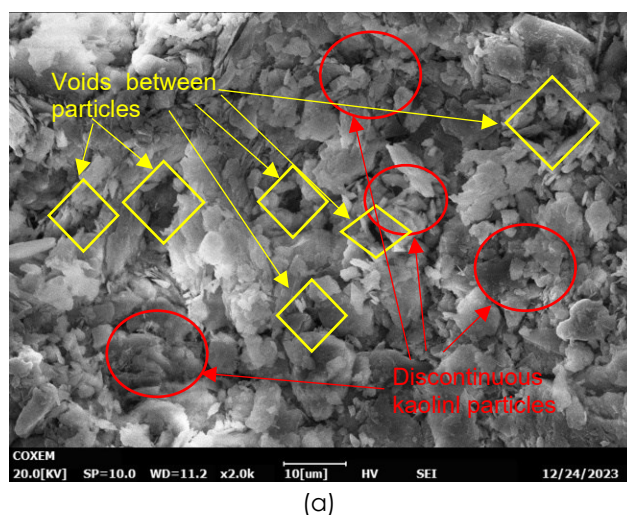


Figure 8 Surface morphology from SEM: (a) unstabilised kaolin clay, and (b) stabilised kaolin clay (50POFA:50CES_25%)

Figure 8(b) shows the reduction of voids and improvement in interconnection between particles on stabilised kaolin clay with 25% POFA:CES binder (50POFA:50CES_25%). The SEM-EDX showed that the microstructure and composition within stabilised kaolin clay particles changed and improved, unlike unstabilised kaolin clay. The identification of C–S–H and other reaction products in the SEM image was based on their typical morphology and supported by the SEM-EDX results. C–S–H generally appears as dense gel-like or fibrous formations filling the voids and coating the clay particles, which is consistent with observations reported in previous stabilisation studies [29, 34].

The EDX results for stabilised kaolin clay are presented in Table 4(b), manifesting that the oxygen weight reduced and the calcium weight was 22.16%. It was also found that silica, calcium, and aluminium had higher weight, as they were the major elements to produce cementitious gel (C–S–H) and hydration products. These findings confirm that the POFA:CES binder improves the microstructure and contributes to the strength development of kaolin clay.

4.0 CONCLUSION

This study examined the effect of POFA and CES as alternative binders for kaolin clay, addressing issues related to weak soil properties, promoting sustainable waste utilisation, and reducing environmental impact. This study's showed the significant influence of binder proportion and dosage in improving the engineering performance of stabilised kaolin clay. The UCS results confirmed that the balanced mix proportion of 50% POFA and 50% CES, coded as 50POFA:50CES, was the most effective for pozzolanic activity. It achieved the optimum UCS value of 485.12 kPa at 25% dosage after curing for 7 days. This supported the use of POFA as a sustainable soil binder when adequately paired with calcium-rich source such as CES. The results also showed that increasing the POFA:CES binder dosage significantly enhanced UCS values, with maximum performance at 25% binder content. This improvement in UCS with increasing binder dosage was attributed to the formation of calcium silicate hydrate (C–S–H), calcium aluminate hydrate (C–A–H), and calcium aluminosilicate hydrate (C–A–S–H), enhancing inter-particle bonding and clay structure. Furthermore, the UCS values increased with curing time, which illustrates that longer curing durations allowed more complete pozzolanic reactions and cementitious gel formation. This led to a denser, stronger, and more durable soil matrix. The results highlighted the significance of adequate curing time in optimising the performance of POFA:CES stabilised kaolin clay. From XRF analysis, high SiO_2 and Al_2O_3 contents were confirmed, reinforcing the pozzolanic activity of POFA. SEM observations revealed void reduction and enhanced interparticle bonding, which are directly associated with improvements in UCS. This research presents laboratory evidence of POFA:CES as a potential soil stabiliser for kaolin clay; however, further research will be conducted to evaluate its performance across various types of soil. At the same time, the field trials are recommended to validate its large-scale performance as well as under real environmental conditions.

This research contributes to the understanding of binder synergy in soil stabilisation, demonstrating that optimised mix proportions can accelerate early strength development compared to high binder dosage alone. These findings provide a viable alternative to using by-product materials in conventional cementitious methods, contributing to sustainable infrastructure solutions. This study aligns with Sustainable Development Goal 9 (SDG 9), promoting innovative and resilient infrastructure while optimising resource efficiency.

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Conflicts of Interest

The authors declare that there is no conflict of interest regarding the publication of this paper.

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