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RESEARCH ARTICLE

Geotechnical improvement of soft clay using cockleshell ash and rice husk as stabilising agents

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Abstract - This study investigates the effectiveness of Rice Husk Ash (RHA) and Cockle Shell Ash (CSA) as sustainable stabilizing agents for improving the engineering properties of soft kaolinite clay. A series of laboratory tests were conducted to evaluate the physical and mechanical behaviour of the treated soil, including particle size distribution, specific gravity, Atterberg limits, Standard Proctor compaction, and undrained shear strength (USS). Kaolin samples were initially stabilized with varying dosages of RHA (3%, 6%, and 9%) to determine the optimum content for maximum strength improvement. The optimum RHA content was then combined with CSA at different proportions (3%, 6%, and 9%), and the specimens were cured for 1, 7, and 14 days. The results indicate that the addition of CSA to RHA-stabilized soil significantly influences the engineering properties of the clay. The inclusion of CSA reduced the specific gravity and optimum moisture content (OMC), while increasing the plasticity index (PI), maximum dry density (MDD), and undrained shear strength (USS). The highest strength improvement was observed for the mixture containing 9% RHA and 6% CSA after 7 days of curing, where the USS increased by 616.77% compared with untreated kaolin clay. This significant strength enhancement demonstrates the synergistic interaction between RHA and CSA when used as stabilizing agents. Overall, the findings indicate that the incorporation of CSA into RHA-stabilized kaolinite clay can effectively improve the mechanical performance of soft clay soils. The use of these waste-derived pozzolanic materials provides a sustainable and environmentally friendly approach for soil stabilization in geotechnical and construction applications.

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1. Introduction

In the past few years, the main challenges geotechnical engineers have had to tackle have been construction-related. In recent decades, geotechnical engineers have increasingly encountered challenges in constructing infrastructure on problematic soils, particularly soft, highly compressible clay deposits [1]–[5]. These soils exhibit low shear strength and high compressibility, which may lead to excessive settlement and structural instability if not properly treated [6, 7]. Among various soil types, clay soils are especially problematic due to their tendency to undergo significant volumetric changes in response to variations in moisture content [3] – [4], [8] – [9]. Clay particles typically have diameters smaller than 2 µm, although some classification systems extend this limit to approximately 5 µm. Their extremely fine particle size and large surface area enable them to retain significant amounts of water, resulting in swelling during wetting and shrinkage during drying cycles [3], [10]. Consequently, the expansive nature of clay soils presents considerable challenges for construction activities and often requires appropriate ground improvement techniques prior to development [11]. Soil stabilisation is one of the most widely adopted ground improvement methods for enhancing the engineering properties of weak soils. This technique aims to improve soil strength, stiffness, and durability by incorporating stabilising agents or modifying the soil structure [5], [12]. Traditionally, chemical stabilisers such as cement, lime, and bituminous materials have been extensively used to enhance the mechanical properties of expansive and soft soils [5]. Among these materials, cement has been the most applied stabilising agent due to its effectiveness in improving soil strength and durability [13]. However, the large-scale production of cement poses significant environmental concerns, particularly due to its high carbon dioxide (CO_2) emissions and associated greenhouse gas impacts [14]–[16]. It has been reported that cement manufacturing can emit between 600 and 1200 kg of CO_2 per metric ton of cement produced [8], [14], [17]. In fact, nearly one ton of CO_2 may be emitted into the atmosphere during the production of one ton of cement, contributing substantially to global greenhouse gas emissions [20].

In response to these environmental concerns, researchers have increasingly explored the use of alternative sustainable materials as partial replacements for conventional cementitious stabilisers. Various industrial and agricultural waste materials, such as fly ash, bagasse ash, eggshell ash, silica fume, and rice husk ash (RHA), have been investigated for their potential applications in soil stabilisation [21]–[25]. The utilisation of waste-derived materials not only reduces environmental pollution from waste disposal but also promotes sustainable resource management and circular economy practices [26]– [27]. Furthermore, many of these waste materials contain pozzolanic compounds that can react with calcium-based materials to form cementitious products, thereby enhancing soil strength and stability. The incorporation of such materials in geotechnical applications has gained increasing attention due to their environmental benefits, cost-effectiveness, and favourable engineering properties [4]–[5]. Among the various agricultural wastes, rice husk ash has

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attracted considerable attention as a potential soil-stabilising agent. Rice husk is a by-product of the rice milling process, and global rice production generates approximately 770 million metric tons annually, with more than 10% of this being rice husk [28]–[29]. When properly burned, rice husk produces rice husk ash, which contains a high proportion of amorphous silica, typically 85%-90%, contributing to its strong pozzolanic characteristics [34]. Due to its high silica content, RHA can react with calcium hydroxide to form cementitious compounds that enhance soil strength and durability [30]. Previous studies have demonstrated that incorporating RHA can improve soil mechanical properties, making it suitable for applications such as subgrade stabilisation and backfilling [31]. In addition, RHA has been shown to reduce soil swelling by filling voids between particles, thereby limiting water penetration and enhancing soil structural integrity [35]– [36]. However, excessive RHA content may diminish performance gains and pose environmental concerns due to the accumulation of mineral residues [37].

Another promising waste material for soil stabilisation is cockle shell ash (CSA), derived from discarded cockle shells produced by the seafood industry. The disposal of cockle shell waste presents significant environmental challenges due to the large volume of shells often discarded in landfills [40]. At the same time, the cement industry is responsible for approximately 7–8% of global CO_2 emissions, with roughly 900 kg of CO_2 released per ton of cement produced. Consequently, the reuse of cockle shell waste as a construction material has been proposed as a sustainable alternative that can simultaneously reduce environmental waste and decrease dependence on cement-based stabilisers [41]. Cockle shells are primarily composed of calcium carbonate ($CaCO_3$), which can be converted into calcium oxide (CaO) through calcination, providing cementitious properties that contribute to soil stabilisation [44]–[45]. Several studies have reported that the incorporation of cockle shell ash can significantly improve the engineering properties of problematic soils. For example, the addition of CSA to expansive clay has been shown to reduce the plasticity index and enhance both compressive and shear strength due to the formation of cementitious bonding between soil particles [46]. Similarly, mixtures containing 2.5%–10% cockle shell powder have been reported to increase specific gravity and reduce soil plasticity in marine clay deposits [47]. Furthermore, research on calcined cockle and scallop shells has revealed the formation of calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which contribute to improved soil strength and stability through pozzolanic reactions [48]. These findings suggest that CSA can serve as a sustainable, environmentally friendly stabilising material to improve soil performance. Although both rice husk ash and cockle shell ash have demonstrated promising results in soil stabilisation individually, studies investigating their combined application remain limited, particularly for soft kaolin clay. Most existing research focuses on single additives or on conventional cement-based stabilisation, leaving the synergistic interaction between silica-rich RHA and calcium-rich CSA insufficiently explored. In addition, the effects of combined RHA–CSA mixtures on key geotechnical properties, such as compaction behaviour, strength development, and plasticity characteristics, have not been systematically examined. Furthermore, limited information is available regarding the effects of short-term curing periods on the early-stage strength development of soils stabilised using these waste-derived materials.

Therefore, a clear research gap exists in understanding the combined stabilisation mechanism of RHA and CSA and their potential to enhance the engineering properties of soft kaolin clay. Considering the complementary chemical composition of RHA (rich in amorphous silica) and CSA (rich in calcium compounds), their combined use is expected to promote the formation of cementitious compounds such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H), which can improve soil strength and structural stability [49]–[50]. In response to this research gap, the present study investigates the geotechnical performance of kaolin clay stabilised with different proportions of rice husk ash and cockle shell ash. Laboratory tests were conducted to evaluate changes in index properties, compaction characteristics, and unconfined compressive strength under curing periods of 1, 7, and 14 days. In addition, empirical correlation models were developed to support practical design applications. The findings of this study provide new insights into the synergistic behaviour of RHA–CSA stabilised soils and demonstrate the potential of waste-derived materials as sustainable alternatives for soft clay stabilisation.

2. Materials and Methods

2.1 Materials Preparation and Properties

Kaolinite is widely used in numerous applications. It is classified as a 1:1 dioctahedral type of clay mineral [50]. The term kaolinite is derived from "kaolin," which originates from the Chinese "Kao-ling" (Pinyin: Jailing), meaning "high ridge." [51]. Kaolin is a natural white soil mineral formed by the decay of some granitic and rhyolitic rocks and chemical decomposition [52]. Kaolinite clay is a mineral whose chemical composition is $Al_2Si_2O_5(OH)_4$ [53]. Kaolinite clay, commonly known as kaolin, is a type of clay available in natural deposits or can be artificially produced in laboratories [11] and is a finely textured clay that exists in nature [54]. Kaolin clay, composed of platy particles held together by hydrogen bonding and weak electrostatic interactions, has a water-attracting property that enables it to form a uniform clay matrix when moistened [11]. The engineering characteristics of the kaolinite soil are listed in Table 1. Kaolin S300, which has been used in this study, is a commercially processed kaolinite clay commonly used as a standard reference material in geotechnical laboratory studies due to its uniform mineralogical composition and consistent particle size distribution.

RHA is the residue left after the combustion of rice husks, the outer shells separated from paddy rice during dehusking. For every tonne of paddy rice processed, approximately 200 kilograms of husk are generated, and when burned, this husk produces approximately 40 kilograms of ash [55]. At temperatures above approximately 700 °C, the ash crystallises from amorphous SiO_2 to cristobalite or tridymite [56]–[57]. This ash is produced by burning rice husks in an incinerator at controlled temperatures of 500-800°C for 1-4 hours. As temperatures exceed 800 °C and after prolonged burning, the

RHA begins to crystallise into various modifications of quartz, for example, cristobalite [58]. The controlled combustion process ensures that the resulting ash exhibits high pozzolanic activity, the ability to react with calcium hydroxide to form compounds with cementitious properties. This reactive ash can effectively stabilise various soils, either alone or alongside lime or cement, and has been shown to significantly enhance strength, durability, and stability while offering a sustainable method of managing agricultural waste [59].

Table 1. Engineering properties of kaolinite soil

Properties	Unit	Result
Basic Engineering Properties		
Size range	mm	0.0008 - 0.063
USCS classification		ML
AASHTO classification		A-5
Specific gravity		2.64
Liquid Limit,LL	%	40.50
Plastic Limit, PL	%	31.40
Plasticity Index, PI	%	9.10
Compaction Properties		
Maximum dry density, MDD	g/mc^3	1.60
Optimum moisture content, OMC	%	19.20
Unconfined compressive strength, q_u	kN/m^2	38.90

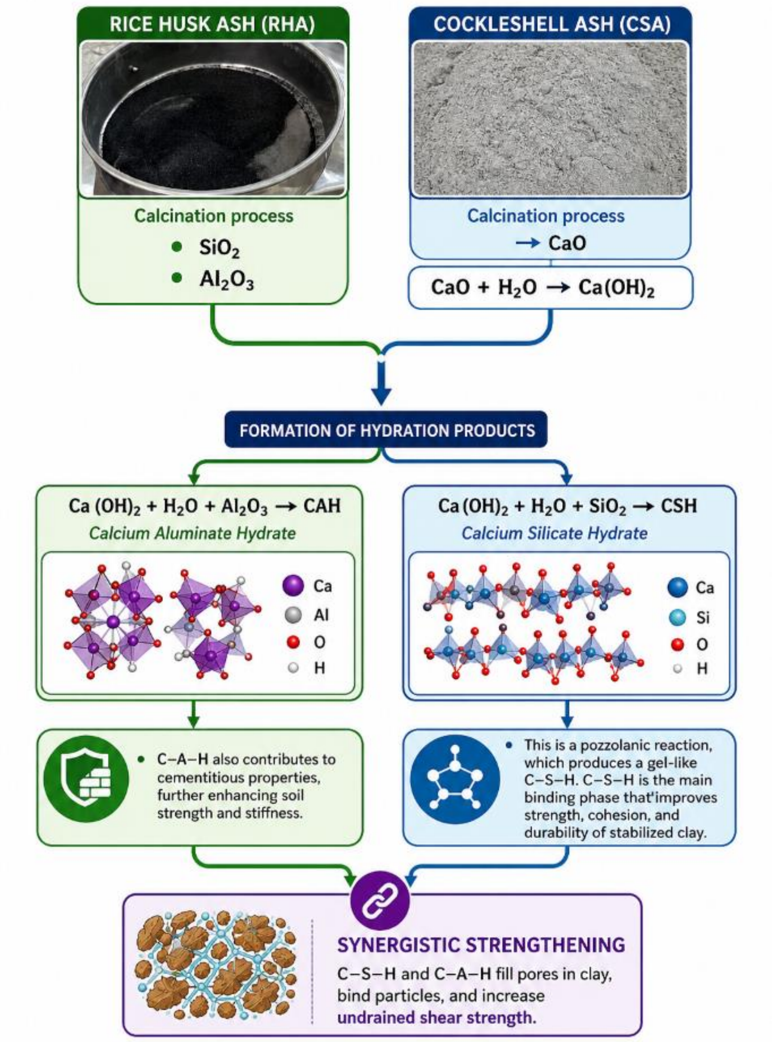

Figure 1. Mechanism of Kaolin stabilized with RHA and CSA

Cockle shells, largely consisting of calcium carbonate ($CaCO_3$), were sourced from eateries in Kuantan, Pahang, and along the eastern coastal regions of Malaysia. After being air-dried, the shells were crushed using a jaw crusher to achieve finer particles. The crushed material was then calcined at 800 °C for one hour, initiating the thermal decomposition of $CaCO_3$ into calcium oxide (CaO). The resulting cockle shell ash exhibited a distinct white hue, signifying successful calcination. To avoid any interaction with atmospheric moisture, the CSA was stored in a desiccator for 24 hours, ensuring complete cooling and preventing early hydration reactions. [60] stated that shell-like cockleshell ash is also more affordable than other typical soil stabilisers, such as lime and cement. The primary component, ($CaCO_3$), which is made up of the cockle shell, can be changed into calcium oxide (CaO) through the calcination process. These materials underwent a series of tests to determine their physical and compaction properties before the strength of the kaolin stabilised with RHA and CSA was evaluated. When RHA and CSA are incorporated into kaolin soil, a series of pozzolanic reactions occur. The CaO from CSA hydrates to form $Ca(OH)_2$, which then reacts with the amorphous silica (SiO_2) and alumina (Al_2O_3) in RHA to generate calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A–H) gels. These cementitious gels gradually fill pore spaces, bind soil particles, and densify the soil matrix, significantly enhancing the strength, stiffness, and cohesion of the stabilised kaolin [46], [61]. This chemical mechanism provides the scientific basis for the observed improvements in the unconfined compressive strength (UCS) and other engineering properties. All materials were tested for physical and compaction characteristics prior to strength assessments of the RHA–CSA–stabilised kaolin. The mechanism between RHA and CSA is displayed in Figure 1 below, while the procedure for this research is shown in Figure 2.

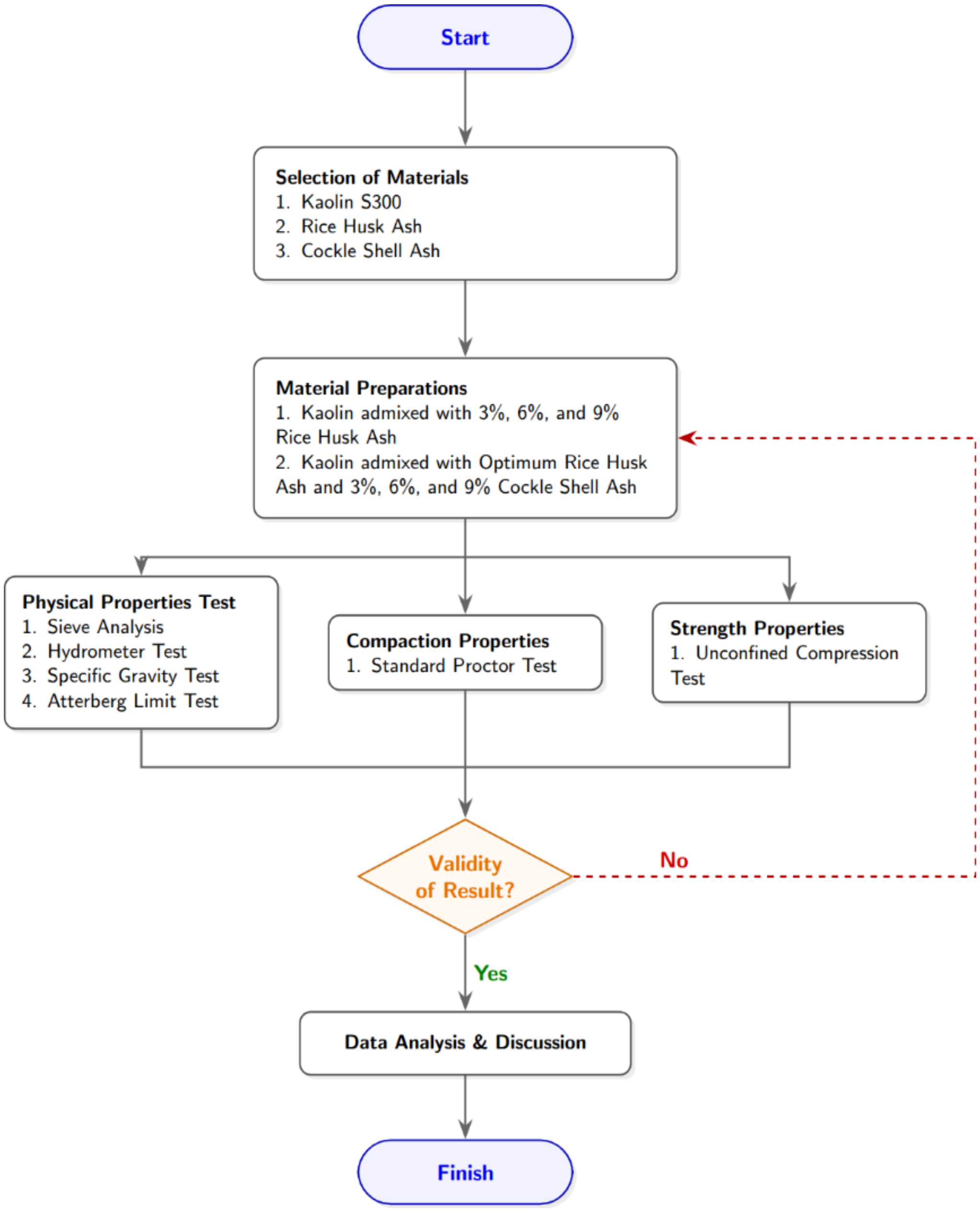

Figure 2. Procedure for research methodology

The percentages of RHA and CSA used in this study were selected based on findings from previous soil stabilisation research and preliminary laboratory investigations. RHA was incorporated at proportions of 3%, 6%, and 9% by dry weight of soil, as similar percentage ranges have been widely adopted in previous studies to evaluate the influence of RHA on the engineering properties of clay soils. For example, studies on expansive and clayey soils commonly investigate RHA contents within this range to determine the optimum stabiliser dosage that enhances strength and reduces plasticity.

The use of incremental proportions (3%, 6%, and 9%) enables evaluation of gradual changes in soil properties and facilitates identification of an optimum dosage that maximises strength improvement without excessive addition of stabilising material. Previous research has reported that the strength of stabilised soils generally improves with increasing RHA content up to approximately 3%–12%, beyond which strength may decline due to excessive ash content. After determining the optimum RHA content, CSA was introduced at 3%, 6%, and 9% to evaluate its additional stabilising effect when combined with RHA. CSA was selected due to its high calcium oxide (CaO) content, which can promote pozzolanic reactions when mixed with silica-rich materials such as RHA. The interaction between calcium-based and silica-based materials can form cementitious compounds that enhance inter-particle bonding and improve soil strength. Therefore, the selected percentage range was considered sufficient to examine the combined stabilisation effect while maintaining practical and economical proportions for soil stabilisation applications.

2.2 Experimental Methods

The basic engineering properties of the materials used in this study were determined through a series of laboratory tests conducted in accordance with established standards. Kaolin S300 was used as the base soil material to ensure uniformity and consistency in testing conditions, thereby improving the reliability and repeatability of the experimental results, as suggested by previous studies [54]. In the laboratory program, tests were performed on untreated kaolin, rice husk ash, cockle shell ash, kaolin–RHA mixtures, and kaolin–RHA–CSA mixtures. Prior to mixing, the kaolin soil was oven-dried at 105 °C for 24 hours to remove moisture and ensure consistent initial conditions. Similarly, both RHA and CSA were oven-dried at the same temperature for 24 hours before mixing to eliminate residual moisture. To determine the optimum RHA content, kaolin soil was initially mixed with 3%, 6%, and 9% RHA by dry weight of soil. These percentages were selected based on previous studies that commonly investigated RHA contents within this range for soil stabilisation applications [62, 63]. The mixtures were thoroughly homogenised using a mechanical soil mixer under dry mixing conditions to ensure uniform distribution of the stabilising agents within the soil matrix.

After identifying the RHA proportion that produced the highest undrained shear strength (USS), the optimum RHA content was incorporated into the kaolin soil and subsequently blended with 3%, 6%, and 9% CSA by dry weight of soil. These CSA proportions were selected based on previous research on seashell-derived ash materials used in soil stabilisation [53]. The untreated kaolin sample was used as the control specimen for comparison with the stabilised mixtures. Table 2 presents the sample coding system adopted throughout this study. Each code represents the composition of the soil mixture, including the percentage of RHA and CSA added to the kaolin soil. The selected mix proportions allowed systematic evaluation of the individual and combined effects of RHA and CSA on the engineering behaviour of the soil. The engineering properties of the soil mixtures were evaluated through laboratory tests conducted in accordance with established standards, as summarised in Table 3. These tests included particle size distribution analysis, specific gravity determination, Atterberg limits, Standard Proctor compaction, and unconfined compression testing.

Table 2. Samples coding

Sample	Coding	Content (%)		
		Kaolin	RHA	CSA
Kaolin (Control sample)	K	100	-	-
Kaolin with 3% of Rice Husk Ash	K3RHA	97	3	-
Kaolin with 6% of Rice Husk Ash	K6RHA	94	6	-
Kaolin with 9% of Rice Husk Ash	K9RHA	91	9	-
Kaolin with 9% of Rice Husk Ash and 3% of Cockleshell Ash	K9RHA3CSA	88	9	3
Kaolin with 9% of Rice Husk Ash and 6% of Cockleshell Ash	K9RHA6CSA	85	9	6
Kaolin with 9% of Rice Husk Ash and 9% of Cockleshell Ash	K9RHA9CSA	82	9	9

Table 3. Standard of laboratory testing

Test	Standard
Mechanical sieve analysis	BS 1377: Part 2: 1990
Hydrometer test	BS 1377: Part 2:1990
Specific gravity test	BS 1377: Part 2: 1990
Atterberg limit	BS 1377: Part 2: 1990
Standard proctor test	BS 1377: Part 4: 1990
Unconfined compression test	ASTM D2166

Unconfined compression tests (UCT) were carried out to evaluate the strength characteristics of the stabilised soils. For each test, approximately 150 g of soil mixture was prepared and compacted at its respective optimum moisture content (OMC) obtained from the Standard Proctor test. The compaction parameters for all mixtures are presented in Table 4. The specimens were prepared using cylindrical steel moulds with dimensions of 50 mm in diameter and 100 mm in height, as illustrated in Figure 3. Each specimen was compacted carefully to achieve a consistent density and uniform structure. After compaction, the specimens were carefully removed from the moulds and sealed in plastic bags to prevent moisture loss during curing. The prepared specimens were cured under controlled laboratory conditions at a temperature of approximately 25 ± 2 °C for curing periods of 1, 7, and 14 days prior to testing. During the curing process, the specimens were stored in a humidity-controlled environment to minimise moisture variation and ensure consistent curing conditions. The total number of specimens prepared for each mixture and curing period is summarised in Table 5. Multiple specimens were prepared for each condition to ensure consistency and reliability of the experimental results.

Table 4. Properties of kaolin, RHA, and CSA used in the UCT test

Type of Sample	Mass (g)	Volume (cm^3)	MDD (g/cm^3)	OMC (%)
K	310	196.35	1.60	20.34
K3RHA	310	196.35	1.65	19.80
K6RHA	310	196.35	1.52	20.60
K9RHA	310	196.35	1.86	20.00
K6RHA3CSA	310	196.35	1.70	19.80
K6RHA6CSA	310	196.35	1.52	20.60
K6RHA9CSA	310	196.35	1.46	20.90

Table 5. Number of samples of each curing day

Sample Code	1 Day	7 Days	14 Days	Total Samples
K	5	–	–	5
K3RHA	5	5	5	15
K6RHA	5	5	5	15
K9RHA	5	5	5	15
K6RHA3CSA	5	5	5	15
K6RHA6CSA	5	5	5	15
K6RHA9CSA	5	5	5	15
Total	35	30	30	95

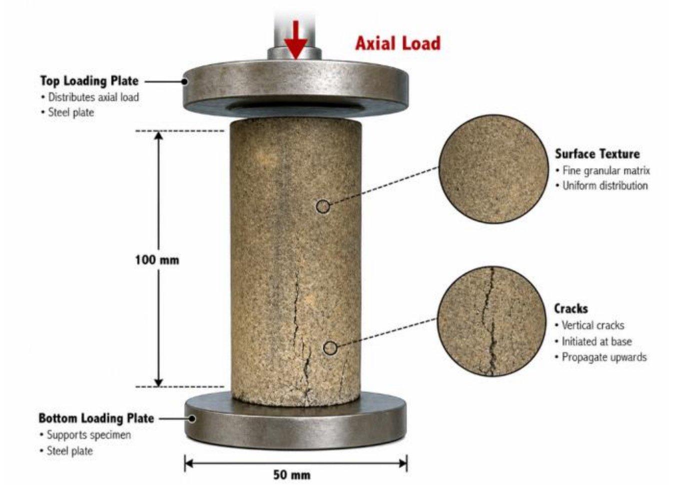

Figure 3. Dimensions of the cylindrical mould for each specimen

3. Results and Discussion

3.1 Specific Gravity

Kaolin S300 has a specific gravity of 2.65, which has been shown to be a true value, as confirmed by other researchers, who report that the specific gravity of kaolinite clay lies between 2.62 and 2.66 [6, 11]. However, after RHA was added to kaolin, the specific gravity decreased. Specific gravity decreased with the addition of rice husk ash. Kaolin's original specific gravity of 2.64 was reduced to 2.59, 2.45, and 2.60 when mixed with 3%, 6%, and 9% RHA, respectively. The biggest significant drop, 7.2%, occurred at the 6% RHA level. RHA has a lower density than soil minerals, which explains this pattern. According to [64], on controlled-burn RHA, the RHA particles act as a filler in soil pore spaces due to their lower specific gravity compared to soil. As the concentration of RHA in soil-ash mixes increases, the total specific gravity decreases. A fluctuating trend in specific gravity was noted for blends with 9% RHA mixed with 3%, 6%, and 9% CSA. The specific gravity fell from 2.43 (3% CSA) to 2.37 (6% CSA), probably because heavier kaolin particles were substituted with the lighter CSA. Nonetheless, with 9% CSA, the value rose to 2.51, suggesting a shift in the trend. This change can be linked to better packing efficiency and particle interlocking at increased CSA levels, which minimise void spaces and improve density. Moreover, the denser, calcium-rich structure of CSA becomes more prominent, counterbalancing the lighter component of RHA. This occurrence aligns with results from concrete research employing cockle shell ash. For instance, Sagala et al. [65], noted that at reduced replacement percentages, the ash particles engage with one another and occupy the voids in the concrete matrix, resulting in lowered porosity and absorption. Nonetheless, at higher replacement levels, voids form due to the aragonite structure of seashell ash.

3.2 Atterberg Limit

The Atterberg limits test results showed a clear trend: the addition of rice husk ash significantly influenced the consistency limits of the kaolin clay, as shown in Figure 4. The plasticity index (PI) decreased progressively from 11.22% in the untreated kaolin sample (K) to 1.93% with the inclusion of 9% RHA (K9RHA), indicating a substantial improvement in workability. When cockle shell ash was incorporated alongside 9% RHA at varying proportions (3%, 6%, and 9%), a slight rebound in PI values was observed, reaching 2.58%, 3.64%, and 3.44%, respectively. This trend suggests that while RHA alone reduces soil plasticity by altering the clay's physicochemical interactions, the addition of CSA may slightly counteract this effect due to its cementitious and calcareous nature. However, all treated mixtures still exhibited lower PI values than the untreated kaolin, reflecting an overall enhancement in soil behaviour. These results align with previous findings by Sujatha et al. [66], who reported that the inclusion of RHA in soft clay not only reduces the liquid limit (LL) and plasticity index but also improves the soil's workability and strength properties. Their study confirmed that the pozzolanic activity of RHA leads to the flocculation and agglomeration of clay particles, thereby reducing plasticity and improving compaction characteristics. Thus, the combined use of RHA and CSA in this study proves to be an effective strategy for stabilising soft kaolin clay by reducing its plasticity and enhancing engineering performance. In a similar vein, Nahar et al. [64] noted that incorporating ash significantly reduces the PI, thereby enhancing soil stability and reducing vulnerability to water-induced deformation. Consequently, the findings of this research validate that the combinations of RHA and CSA effectively enhance the plasticity properties of kaolin clay, rendering them appropriate for soil stabilisation purposes.

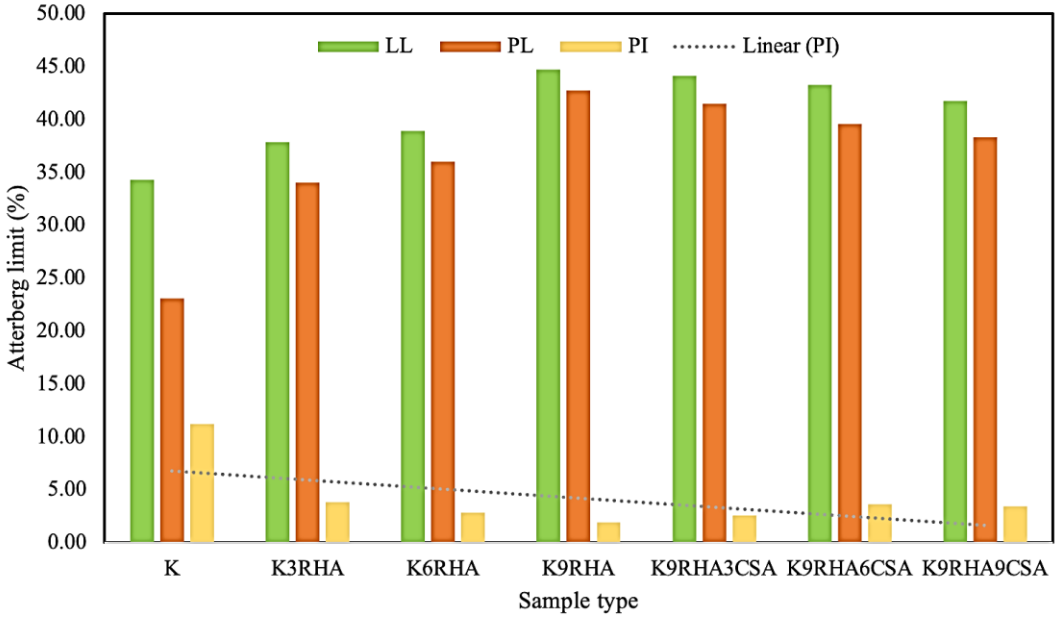

Figure 4. Relationship between types of samples and samples' Atterberg limits (%)

3.3 Standard Compaction Test

The standard compaction test has been used to determine the maximum dry density and OMC of untreated kaolin, RHA, CSA, and kaolin admixed with 3%, 6%, and 9% of RHA and the optimum stabiliser content of kaolin- RHA admixed with 3%, 6% and 9% of CSA. The compaction characteristics of untreated and stabilised kaolin are shown in Figure 5 and further discussed based on the trends of optimum moisture content and maximum dry density. The MDD of untreated kaolin (K) was 1.60 g/cm³, with an OMC of 20.34%, which falls within the typical range of 1.4 to 2.0 g/cm³ and 14% to 30%, respectively, as reported by previous studies on clayey soils [6, 11, 67]. The incorporation of RHA alone showed a variable effect on the MDD. At 3% RHA (K3RHA), the MDD increased slightly to 1.65 g/cm³, indicating an improvement in particle packing due to the filler effect of the ash and attributed to the lighter weight and higher moisture absorption capacity of the fibres [68]. However, increasing RHA to 6% (K6RHA) reduced MDD to 1.52 g/cm³, likely due to the lower specific gravity and porous nature of RHA, which replaced some of the denser kaolin particles. Interestingly, at 9% RHA (K9RHA), the MDD sharply increased to 1.86 g/cm³, possibly due to improved packing efficiency and particle rearrangement at higher RHA contents, which might have allowed denser compaction despite the ash's lightweight nature.

Following this, combinations of RHA with CSA were evaluated to further enhance compaction behaviour. The mix K9RHA3CSA, which includes 9% RHA and 3% CSA, achieved an MDD of 1.70 g/cm³, showing better compaction than the 6% RHA mix, but still lower than K9RHA. The highest CSA inclusion (K9RHA9CSA) led to a decrease in MDD to 1.46 g/cm³, likely because the excessive ash content increased the overall porosity and reduced particle interlocking. The OMC values across all mixtures fluctuated slightly within a narrow range of 19.8% to 20.9%, suggesting that the presence of RHA and CSA did not drastically alter the water demand of the mixtures. However, samples with higher CSA content

(K9RHA9CSA) required slightly more moisture (20.9%) to reach maximum compaction, possibly due to the high calcium oxide content in CSA, which may initiate early pozzolanic reactions and consume additional water during the process. The observed decrease in MDD with the increasing addition of CSA in the K9RHA-based mixtures can be attributed to the increased flocculation and agglomeration within the soil matrix, as reported by [69]. This behaviour facilitates compaction at early stages but increases the overall void volume, thereby reducing the achievable dry density. Furthermore, the combined presence of CSA and RHA, both characterised by high water retention and lower specific gravity, leads to a higher optimum moisture content and lower MDD, consistent with findings by [70], who noted that such organic-like fractions hinder water availability for effective hydration and compaction. [71], also supported this observation by stating that such lightweight additives reduce the compacted density of soil materials. In general, higher MDD values are desirable for construction purposes, as they indicate better load-bearing capacity and reduced settlement potential. However, in the case of expansive soils, such as kaolin, excessively high dry densities may correlate with higher swelling pressures, which can be detrimental. Therefore, a balanced combination of RHA and CSA, such as K9RHA3CSA, may offer a compromise between improved compaction and reduced expansion behaviour.

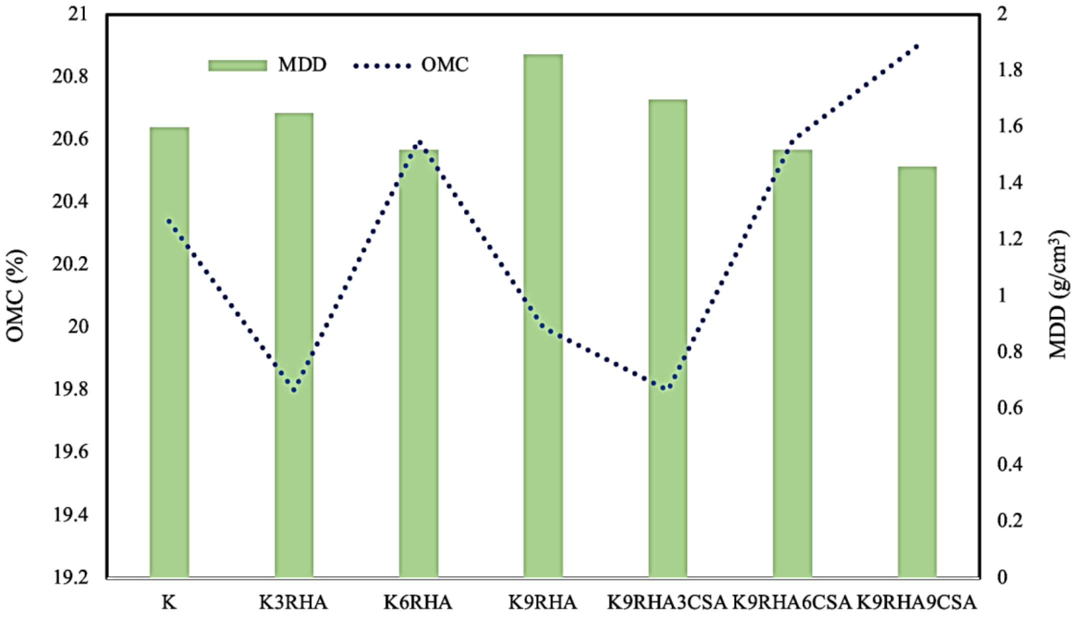

Figure 5. The correlation between MDD (g/cm^3) and OMC (%) for the kaolin sample admixed with 6% SF and various CSA contents (%)

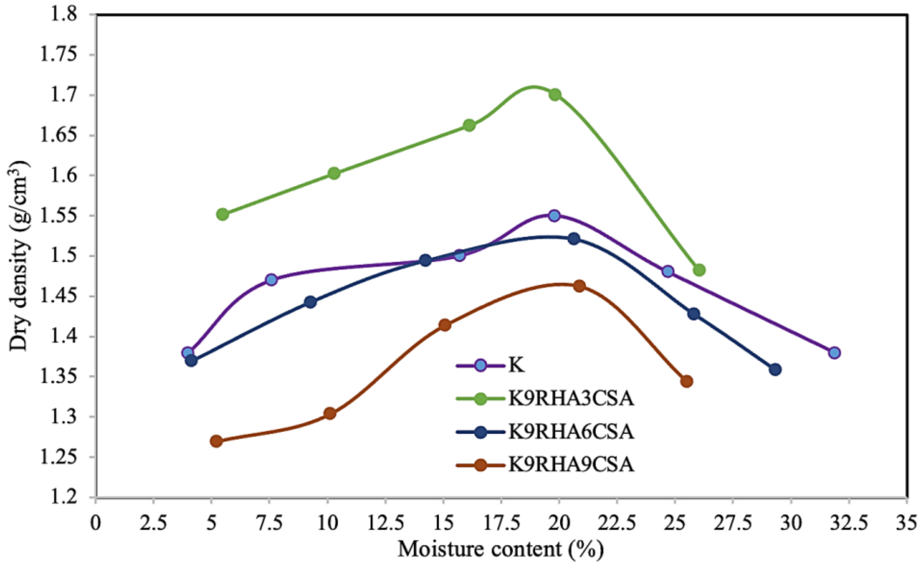

Figure 6. Compaction Curve on the mixture of kaolin with 9% of RHA and various percentages of CSA content (%)

The graph in Figure 6 above was plotted based on the results of the compaction curve for the kaolin-RHA mixture samples with 3%, 6%, and 9% CSA. It shows that the sample with 9% RHA and 3% CSA (K9RHA3CSA) had the highest maximum dry density of the blended mixes and the lowest optimum moisture content. This suggests that a tiny degree of CSA improves particle packing and compaction. However, as the CSA concentration grew to 6% or 9%, the MDD decreased. This is most likely due to the lighter, more porous structure of CSA, which replaced some of the heavier kaolin particles while increasing void space. Thus, excessive CSA reduced compaction efficiency, whereas a moderate level (3%) yielded optimal performance.

3.4 Particle Size Distribution Analysis

According to Table 5, untreated kaolin contains 51.03% particles that pass through a 0.075 mm screen, indicating that more than half of the sample consists of fine particles. These particles are often clay or silt, resulting in a soft, highly pliable soil. According to the Unified Soil Classification System, kaolin can be classified as a CH or MH type soil based on its plasticity characteristics, whereas American Association of State Highway and Transportation Officials (AASHTO) classification places it in A-7-5, which includes fine-grained soils with poor drainage and high plasticity**.** RHA has a substantially coarser particle distribution, with 96.01% of the material retained above a 0.075 mm screen. Only 3.99% of the sample passes through the 0.075 mm screen, indicating that RHA is primarily composed of sand-sized particles. RHA particles typically range in size from 0.063 mm to 0.3 mm, similar to the studies by [72] and [73]. Due to their low plasticity and dominance in the sand fraction, they are categorised as SP (poorly graded sand) in the USCS and as A-3 soil in the AASHTO, making them excellent for enhancing the granular behaviour of soft clays.

CSA has a similar coarse distribution, with just 5.05% of particles passing through the 0.075 mm screen and 94.95% retained. This implies that CSA is almost exclusively composed of sand-sized or larger particles, ranging from 0.15 mm to 4.75 mm. Because of its coarse and granular form, CSA corresponds with SW/SM (well-graded or silty sands) in USCS and A-1-b or A-3 in AASHTO, indicating its potential as a structural additive in soil stabilisation. For the stabilised sample K9RHA9CSA, the combination of RHA and CSA with kaolin resulted in a significant shift in the particle size distribution. Only 0.24% of particles passed the 0.075 mm sieve, meaning 99.76% of the material falls in the coarser fraction. This change indicates improved gradation and reduced plasticity, which enhances shear strength and reduces the swelling potential. Based on these characteristics, the K9RHA9CSA mixture may be classified as SM or SC in USCS, and A-2-4 or A-1-b in AASHTO, indicating good subgrade and structural properties with minimal fines.

Table 5. Comparative Gradation Analysis of Kaolin, RHA, CSA, and Mixtures Stabilised Sample (K9RHA9CSA)

Sample	Composition (%)			
	Kolin	RHA	CSA	Kaolin + 9% of RHA + 9% CSA
> 4.75 mm	0	0	0.22	0
0.075 – 4.75 mm	48.97	94.95	95.79	99.76
≤ 0.075 mm	51.03	5.05	3.99	0.24

The inclusion of RHA and CSA into soft kaolin caused a reshuffling of the soil particle matrix, resulting in a coarser kaolin-RHA-CSA (K-RHA-CSA) mixture. As shown in the particle size distribution curve in Figure 7, the curve for the treated sample (K9RHA9CSA) shifted slightly to the right, indicating a coarser gradation compared to untreated kaolin. The treated kaolin mixture comprises 0% gravel, 99.76% sand, and only 0.24% fines (silt and clay-sized particles), indicating that it is a sand-silt mixture under the Unified Soil Classification System. Similarly, the material belongs to the A-2-4 group in the AASHTO classification, which corresponds to sandy silt or sandy clay with limited plasticity.

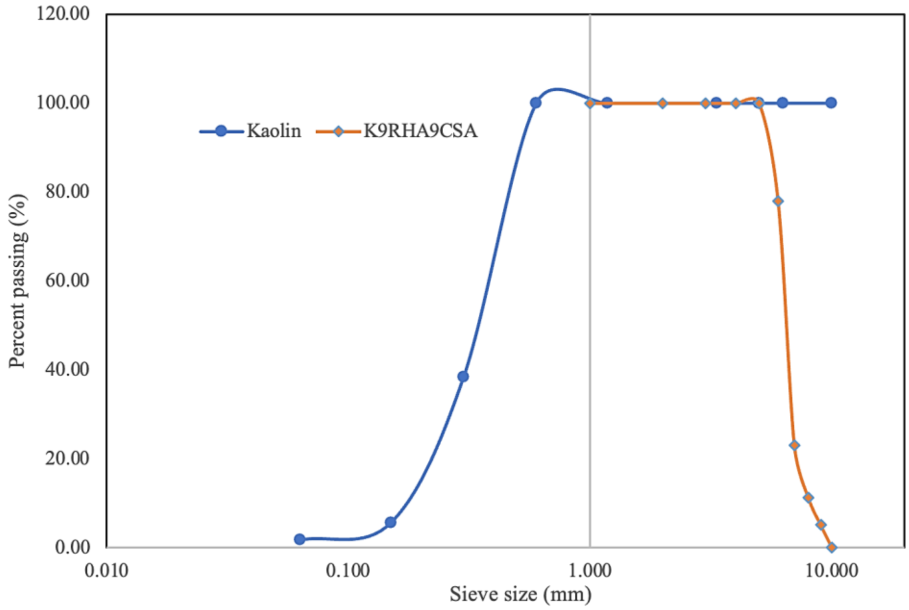

Figure 7. Comparison of PSD curves for untreated kaolin and stabilised sample (K9RHA9CSA)

3.5 Shear Strength Analysis

The unconfined compression test was conducted to evaluate the strength improvement of kaolin clay stabilised with rice husk ash and cockle shell ash. As shown in Figure 8, untreated kaolin exhibited an initial unconfined compressive strength (qu) of 34.38 kN/m² and an undrained shear strength (su) of 17.19 kN/m², indicating the relatively weak nature of the untreated clay. The incorporation of RHA significantly improved the strength characteristics of the kaolin. When the RHA content increased from 3% to 9%, a progressive increase in both unconfined compressive strength and undrained shear strength was observed. The greatest improvement in the RHA-treated soil occurred at 9% RHA, where the compressive strength increased to 133.97 kN/m², representing approximately a 290% increase over the untreated kaolin. Similarly, the undrained shear strength increased to 66.98 kN/m². This improvement may be attributed to the presence of amorphous silica in RHA, which enhances particle packing and promotes cementitious bonding between soil particles.

To further enhance the mechanical performance of the stabilised soil, CSA was incorporated into the kaolin–RHA mixture at the optimum RHA content of 9%. The addition of CSAs at 3%, 6%, and 9% produced further variations in the soil's strength characteristics. The maximum compressive strength was recorded for the mixture containing 9% RHA and 6% CSA, achieving a UCS of 138.16 kN/m², representing an increase of approximately 301.8% over untreated kaolin. The corresponding undrained shear strength increased to 69.08 kN/m². The strength improvement observed with CSA addition can be associated with the calcium-rich composition of cockle shell ash, which contributes to improved particle bonding and soil matrix densification when combined with silica-rich materials such as RHA. However, when the CSA content was increased to 9%, a slight reduction in compressive strength was observed, with UCS decreasing to 136.24 kN/m². This reduction may be attributed to excessive ash content, which can lead to particle agglomeration or incomplete bonding within the soil matrix, thereby limiting further strength development. Overall, the results indicate that the combined use of 9% RHA and 6% CSA provide the most effective improvement in shear strength among the mixtures investigated. The interaction between silica-rich RHA and calcium-rich CSA appears to contribute to enhanced interparticle bonding, resulting in improved strength characteristics of the stabilized kaolin clay. These findings reveal that the optimal dosage for combining RHA and CSA is 9% RHA and 6% CSA, which produces the most effective pozzolanic reaction and increases particle bonding. The synergy between RHA and CSA promotes the gradual development of calcium silicate hydrate (CSH), which increases both compressive and shear strength. However, continued addition beyond this point appears to diminish efficiency due to overfilling or agglomeration.

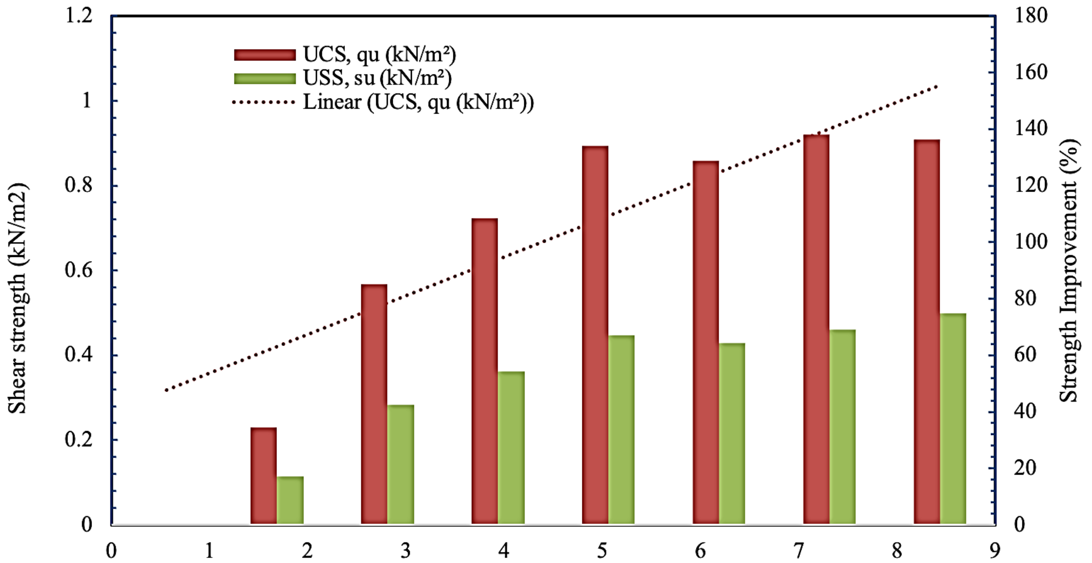

Figure 8. Variation of unconfined compressive strength and undrained shear strength of kaolin stabilised with different percentages of RHA and CSA

3.6 Correlation Analysis

This work demonstrated relationships among engineering parameters (specific gravity, Atterberg limits, Standard Proctor Compaction test, and Unconfined Compressive Strength Test) of soft kaolin with varying percentages of RHA and CSA. The correlation equations developed for these four (4) major factors are critical for forecasting the optimal model for determining the best use of RHA and CSA as stabilising agents. These equations are useful for implementing pozzolanic waste-based soil stabilisation techniques. As a result, the findings of this correlation analysis provide a solid foundation for future applications and evaluations of stabilised soft clay. Table 6 displays the correlation equations for the engineering parameters under investigation.

Table 6 shows that the inclusion of RHA and CSA as stabilising agents reliably predicts variations in the engineering properties of soft kaolin, as indicated by high coefficients of determination (R^2 values). The regression study shows a substantial association between stabiliser content and soil behaviour, with R^2 values above 0.7 for specific gravity, Atterberg limits, compaction characteristics, and unconfined shear strength. The unconfined compressive strength models for RHA and CSA across different curing days yielded R^2 values exceeding 0.95, with some reaching 1.0000, indicating an excellent fit to the experimental data. The Atterberg limits exhibited R^2 values ranging from 0.87 to 0.96, demonstrating that changes in plasticity can be well described by varied percentages of RHA and CSA. Similarly, compaction metrics such as maximum dry density ($\rho_{d(max)}$) and optimal moisture content (w_{opt}) indicated moderate to significant relationships for CSA, with R^2 values ranging from 0.6661 to 0.7531, whereas w_{opt} for RHA showed a smaller association ($R^2 = 0.0088$). Overall, these results confirm that more than 70% of the variation in most engineering parameters is attributable to the percentage inclusion of RHA and CSA. Hence, the developed correlation equations serve as useful predictive models for determining the optimum dosage of stabilisers, thereby providing valuable guidance for the soil stabilisation technique proposed in this study.

Table 6 Correlation equations and coefficient of determination (R^2) for engineering properties of soft kaolin stabilised with RHA and CSA

Test	Parameter	Correlation Equation	R^2
Specific Gravity Test	G_s (RHA)	$G_s = -0.0017RHA^2 + 0.0323RHA + 2.412$	0.4132
	G_s (CSA)	$G_s = 0.0025CSA^2 - 0.0115CSA + 2.3955$	0.6086
Atterberg Limit Test	LL (RHA)	$LL = 0.0627RHA^2 + 0.5075RHA + 34.699$	0.9532
	PL (RHA)	$PL = -0.1162RHA^2 + 3.0784RHA + 23.804$	0.9532
	PI (RHA)	$PI = 0.1789RHA^2 - 2.5709RHA + 10.895$	0.9614
	LL (CSA)	$LL = -0.3136CSA^2 + 3.5349CSA + 34.835$	0.9172
	PL (CSA)	$PL = -0.5478CSA^2 + 6.3852CSA + 24.167$	0.8979
	PI (CSA)	$PI = 0.2342CSA^2 - 2.8503CSA + 10.668$	0.8759
Standard Proctor Compaction Test	$\rho_{d(max)}$ (RHA)	$\rho_{d(max)} = 0.0081RHA^2 - 0.0508RHA + 1.6325$	0.6661
	w_{opt} (RHA)	$w_{op}t = -0.0017RHA^2 + 0.0077RHA + 20.203$	0.0088
	$\rho_{d(max)}$ (CSA)	$\rho_{d(max})= -0.0044CSA^2 + 0.02CSA + 1.62$	0.7531
	w_{opt} (CSA)	$w_{opt} = 0.0233CSA^2 - 0.1273CSA + 20.248$	0.7408
Unconfined Compression Test (UCT)	S_u (0 days) RHA	$Su = -0.3107RHA^2 + 4.7972RHA + 18.675$	0.9983
	S_u (0 days) CSA	$Su = -0.5099CSA^2 + 7.2063CSA + 19.151$	0.9813
	S_u (7 days) RHA	$Su = -0.2422RHA^2 + 11.599RHA + 13.715$	1
	S_u (7 days) CSA	$Su = -1.7605CSA^2 + 23.023CSA + 16.538$	0.9549
	S_u (14 days) RHA	$Su = -0.5005RHA^2 + 9.1814RHA + 21.43$	0.9211
	S_u (14 days) CSA	$Su = -1.7452CSA^2 + 21.656CSA + 21.421$	0.9661

4. Conclusions

This study investigated the effectiveness of rice husk ash and cockle shell ash as sustainable stabilising agents for improving the engineering properties of soft kaolin clay. Based on the experimental results obtained from laboratory testing, several conclusions can be drawn. The addition of RHA significantly improved the strength characteristics of the kaolin soil. The unconfined compressive strength increased from 34.38 kN/m² for untreated kaolin to 133.97 kN/m² at 9% RHA, representing an improvement of approximately 290%. This strength enhancement is attributed to the presence of reactive silica in RHA, which enhances particle bonding and soil matrix densification. Further improvement was observed when CSA was incorporated into the kaolin–RHA mixtures. The combination of 9% RHA and 6% CSA produced the highest compressive strength, 138.16 kN/m², representing an increase of approximately 300% over untreated kaolin. The presence of calcium compounds in CSA is believed to contribute to additional bonding within the soil structure, thereby enhancing the overall strength of the stabilised soil. However, increasing the CSA content beyond the optimum level did not result in further strength improvement. The mixture containing 9% CSA exhibited a slight reduction in compressive strength compared with the optimum mixture, suggesting that excessive ash content may reduce the efficiency of the stabilisation process. Overall, the results demonstrate that the combined use of RHA and CSA can effectively improve the mechanical performance of soft kaolin clay. The optimum mixture identified in this study was 9% RHA and 6% CSA, which provided the most significant strength improvement. These findings highlight the potential of utilising agricultural and marine waste materials as sustainable alternatives to conventional stabilisers in soil stabilisation applications. Future research is recommended to further investigate the long-term performance and microstructural characteristics of RHA–CSA-stabilised soils to better understand the underlying stabilisation mechanisms.

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Declaration of Competing Interests
The authors declare no conflicts of interest.

Credit Authorship Contribution Statement
Nik Noor Atyrah Nik Aziz (Conceptualisation; Methodology; Investigation; Data curation; Formal analysis; Visualisation; Writing - original draft)
Muzamir Hasan (Methodology; Validation; Formal analysis; Resources; Writing - review & editing; Supervision; Project administration)
Ng Jun Shen (Investigation; Data curation; Validation; Writing - review & editing)
Muhammad Zikhril Hafisz Zamri (Investigation; Resources; Data curation; Visualisation; Writing - review & editing)
Md Ikramul Haque (Formal analysis; Validation; Resources; Writing - review & editing)

Availability of Data and Materials
The data supporting this study's findings are available on request from the corresponding author.

Ethics Declarations
This study did not involve human participants or animals. Ethical approval was therefore not required.

Generative Artificial Intelligence Declarations
The authors claim that artificially intelligent-assisted technologies, such as generative AI, were not used to generate content, ideas, or theories. We have just utilised AI to enhance readability and refine the language. This was used with extreme human control and oversight. The authors take full responsibility for reviewing and approving the content.

References
[1] H. Afrin, "A review on different types soil stabilization techniques," *International Journal of Transportation Engineering and Technology*, vol. 3, no. 2, pp. 19-24, 2017, https://doi. 10.11648/j.ijtet.20170302.12.
[2] N. Latifi, A. Eisazadeh, A. Marto, and C. L. Meehan, "Tropical residual soil stabilization: A powder form material for increasing soil strength," *Construction and Building Materials*, vol. 147, pp. 827–836, 2017, https://doi.org/10.1016/j.conbuildmat.2017.04.115.
[3] Y. Liu, S. Wang, Y. Wang, and X. Jiang, "Stabilization of expansive soil using cementing material from rice husk ash and calcium carbide residue," *Construction and Building Materials*, vol. 221, pp. 1–11, 2019, https://doi.org/10.1016/j.conbuildmat.2019.05.157.
[4] R. Blayi, A. Sherwani, H. Ibrahim, R. Faraj, and A. Daraei, "Strength improvement of expansive soil by utilizing waste glass powder," *Case Studies in Construction Materials*, vol. 13, p. e00427, 2020, https://doi.org/10.1016/j.cscm.2020.e00427.
[5] S. Abbey, E. Eyo, C. Okeke, and S. Ngambi, "Experimental study on the use of RoadCem blended with by-product cementitious materials for stabilisation of clay soils," *Construction and Building Materials*, vol. 280, p. 122476, 2021, https://doi.org/10.1016/j.conbuildmat.2021.122476.
[6] Y. Li, "Effect of post-fire curing and silica fume on permeability of ultra-high-performance concrete," *Construction and Building Materials*, vol. 290, p. 123175, 2021, https://doi.org/10.1016/j.conbuildmat.2021.123175.
[7] I. Obianyo, A. Onwualu, and A. Soboyejo, "Mechanical behaviour of lateritic soil stabilized with bone ash and hydrated lime for sustainable building applications," *Case Studies in Construction Materials*, vol. 12, p. e00331, 2020, https://doi.org/10.1016/j.cscm.2020.e00331.
[8] P. Ghadir and N. Ranjbar, "Clayey soil stabilization using geopolymer and Portland cement," *Construction and Building Materials*, vol. 188, pp. 361–371, 2018, https://doi.org/10.1016/j.conbuildmat.2018.08.078.
[9] X. Bao, C. Li, Y. Zhang, and H. Wang, "Experimental investigation on mechanical properties of clay soil reinforced with carbon fiber," *Construction and Building Materials*, vol. 280, p. 122517, 2021, https://doi.org/10.1016/j.conbuildmat.2021.122517.
[10] B. Phanikumar and E. Ramanjaneya Raju, "Compaction and strength characteristics of an expansive clay stabilised with lime sludge and cement," *Soils and Foundations*, vol. 60, no. 1, pp. 129–138, 2020, https://doi.org/10.1016/j.sandf.2019.12.009.
[11] A. J. Alrubaye, M. Hasan, and M. Y. Fattah, "Stabilization of soft kaolin clay with silica fume and lime," *International Journal of Geotechnical Engineering*, vol. 11, no. 1, pp. 90–96, 2017, https://doi.org/10.1080/19386362.2016.1168720.
[12] L. Sharma, N. Sirdesai, K. Sharma, and T. Singh, "Experimental study to examine the independent roles of lime and cement on the stabilization of a mountain soil: A comparative study," *Applied Clay Science*, vol. 152, pp. 183–195, 2018, https://doi.org/10.1016/j.clay.2017.11.012.

[13] S. Hsu, M. Chi, and R. Huang, “Effect of fineness and replacement ratio of ground fly ash on properties of blended cement mortar,” *Construction and Building Materials*, vol. 176, pp. 250–258, 2018, https://doi.org/10.1016/j.conbuildmat.2018.05.032.
[14] A. H. Ismail, A. Kusbiantoro, S. C. Chin, K. Muthusamy, M. Islam, and K. F. Tee, “Pozzolanic reactivity and strength activity index of mortar containing palm oil clinker pretreated with hydrochloric acid,” *Journal of Cleaner Production*, vol. 242, p. 118565, 2020, https://doi.org/10.1016/j.jclepro.2019.118565.
[15] R. M. Andrew, “Global CO_2 emissions from cement production,” *Earth System Science Data*, vol. 10, no. 1, pp. 195–217, 2018. https://doi.org/10.5194/essd-10-195-2018.
[16] W. Hu, Q. Nie, B. Huang, and X. Shu, “Investigation of the strength development of cast-in-place geopolymer piles with heating systems,” *Journal of Cleaner Production*, vol. 215, pp. 1481–1489, 2019, https://doi.org/10.1016/j.jclepro.2019.01.143.
[17] A. Hanif, P. Parthasarathy, H. Ma, T. Fan, and Z. Li, “Properties improvement of fly ash cenosphere modified cement pastes using nano silica,” *Cement and Concrete Composites*, vol. 81, pp. 35–48, 2017, https://doi.org/10.1016/j.cemconcomp.2017.04.008.
[18] A. Hanif, Y. Kim, Z. Lu, and C. Park, “Early-age behavior of recycled aggregate concrete under steam curing,” *Journal of Cleaner Production*, vol. 152, pp. 103–114, 2017, https://doi.org/10.1016/j.jclepro.2017.03.088.
[19] Y. Kim, A. Hanif, M. Usman, M. J. Munir, S. M. S. Kazmi, and S. Kim, “Slag waste incorporation in high early strength concrete as cement replacement: Environmental impact and influence on hydration and durability attributes,” *Journal of Cleaner Production*, vol. 172, pp. 3056–3065, 2018, https://doi.org/10.1016/j.jclepro.2017.11.105.
[20] P. Voottipruex, C. Teerawattanasuk, and I. Meepon, “Marginal lateritic soil treated using ceramic waste for rural road application,” *International Journal of GEOMATE*, vol. 16, no. 53, pp. 70–77, 2019, https://doi.org/10.21660/2019.53.47856.
[21] H. Jafer, W. Atherton, M. Sadique, F. Ruddock, and E. Loffill, “Stabilisation of soft soil using binary blending of high calcium fly ash and palm oil fuel ash,” *Applied Clay Science*, vol. 152, pp. 323–332, 2018, https://doi.org/10.1016/j.clay.2017.11.029.
[22] R. Kishor and V. P. Singh, “Evaluation of expansive soil amended with fly ash and liquid alkaline activator,” *Transportation Infrastructure Geotechnology*, vol. 10, pp. 685–706, 2023, https://doi.org/10.1007/s40515-023-00338-9.
[23] K. C. Onyelowe, D. Eidgahee, H. Jahangir, and M. Fakheran, “Forecasting shear parameters, and sensitivity and error analyses of treated subgrade soil,” *Transportation Infrastructure Geotechnology*, vol. 10, pp. 448–473, 2023. https://doi.org/10.1007/s40515-023-00331-2.
[24] R. Sukkarak, B. Thangjaroensuk, and P. Jongpradist, “Evaluation of fly ash and rice husk ash on the unconfined compressive strength of the compacted cement treated lateritic soil,” *Suranaree Journal of Science and Technology*, vol. 29, no. 5, p. 010165, 2022, https://doi.org/10.55766/sujst.v29i5.010165.
[25] T. Poltue, A. Suddeepong, S. Horpibulsuk, W. Samingthong, A. Arulrajah, and A. Aashid, “Strength development of recycled concrete aggregate stabilized with fly ash–rice husk ash based geopolymer as pavement base material,” *Road Materials and Pavement Design*, vol. 21, no. 8, pp. 2344–2355, 2019, https://doi.org/10.1080/14680629.2019.1593884.
[26] M. R. Karim, F. I. Chowdhury, H. Zabed, and M. R. Saidur, “Effect of elevated temperatures on compressive strength and microstructure of cement paste containing palm oil clinker powder,” *Construction and Building Materials*, vol. 183, pp. 376–383, 2018, https://doi.org/10.1016/j.conbuildmat.2018.06.147.
[27] S. Inazumi, S. Intui, A. Jotisankasa, S. Chaiprakaikeow, and T. Shinsaka, “Applicability of mixed solidification material based on inorganic waste as soil stabilizer,” *Case Studies in Construction Materials*, vol. 12, p. e00305, 2020. https://doi.org/10.1016/j.cscm.2020.e00305.
[28] L. Hu, Z. He, and S. Zhang, “Sustainable use of rice husk ash in cement-based materials: Environmental evaluation and performance improvement,” *Journal of Cleaner Production*, vol. 264, p. 121744, 2020, https://doi.org/10.1016/j.jclepro.2020.121744.
[29] B. J. S. Varaprasad, J. J. Reddy, and J. S. Reddy, “Exploratory study on agro-industrial wastes for improving geotechnical properties of expansive soil as sustainable material,” *Materials Today: Proceedings*, vol. 45, pp. 6665–6673, 2021, https://doi.org/10.1016/j.matpr.2020.12.078.
[30] N. T. Duong and N. T. Nu, “Effect of different types of rice husk ash on some geotechnical properties of cement-admixed soil,” *Iraqi Geological Journal*, vol. 53, no. 2C, pp. 1–12, 2020. https://doi.org/10.46717/igj.53.2c.1rs-2020-09-01.
[31] B. H. J. Pushpakumara and W. S. W. Mendis, “Suitability of rice husk ash (RHA) with lime as a soil stabilizer in geotechnical applications,” *International Journal of Geo-Engineering*, vol. 13, p. 4, 2022, https://doi.org/10.1186/s40703-021-00169-w.
[32] L. Behak, “Soil stabilization with rice husk ash,” in Rice – Technology and Production. *IntechOpen*, 2017, https://doi.org/10.5772/66311.
[33] S. Sathe, M. Z. Kangda, and S. Dandin, “An experimental study on rice husk ash concrete,” *Materials Today: Proceedings*, vol. 77, no. 3, pp. 724–728, 2023, https://doi.org/10.1016/j.matpr.2022.11.366.

[34] B. Kanddulna, N. Kisku, K. Murari, and J. P. Singh, “Experimental Study of Clayey Soil with Lime and Rice Husk Ash,” *International Journal of Engineering Trends and Technology*, vol. 38, no. 2, pp. 365–372, 2016, https://doi.org/10.14445/22315381/IJETT-V38P266.

[35] S. M. Abdulrahman, K. W. Abd Al-Kaream, and E. A. Ihsan, “Enhancing soil with low-cost pozzolanic materials: Rice husk ash and groundnut shell ash compared to cement,” *Mathematical Modelling of Engineering Problems*, vol. 11, no. 4, pp. 1115–1122, 2024, https://doi.org/10.18280/mmep.110430.

[36] H. A. Mboya, “Potential of Scoria, Pumice, and RHA as Supplementary Cementitious Materials for Reducing Setting Time and Improving Early Strength of Pozzolan Blended Composite Cement,” Ph.D. dissertation, Nelson Mandela African Institution of Science and Technology, Arusha, Tanzania, 2019, https://doi.org/10.58694/20.500.12479/955.

[37] P. Jongpradist, W. Homtragoon, R. Sukkarak, and W. Kongkitkul, “Efficiency of rice husk ash as cementitious material in high-strength cement-admixed clay,” *Advances in Civil Engineering*, vol. 2018, pp. 1–19, 2018, https://doi.org/10.1155/2018/8346319.

[38] S. A. Endale, W. Z. Taffese, D. H. Vo, and M. D. Yehualaw, “Rice husk ash in concrete,” *Sustainability*, vol. 15, no. 1, p. 137, 2023. https://doi.org/10.3390/su15010137.

[39] E. A. Basha, R. Hashim, and A. S. Muntohar, “Effect of the cement-rice husk ash on the plasticity and compaction of soil,” *Electronic Journal of Geotechnical Engineering*, vol. 8A, pp. 1–8, 2003.

[40] C. M. Yun, M. R. Rahman, K. K. Kuok, A. C. P. Sze, J. T. Kung-Jiek, and M. K. B. Bakri, “Uncrushed Cockleshell as Coarse Aggregate Filler Replacement in Concrete,” in *Waste Materials in Advanced Sustainable Concrete: Reuse, Recovery and Recycle*, M. R. Rahman, C. M. Yun, and M. K. B. Bakri, Eds. Cham, Switzerland: Springer Nature Switzerland AG, 2022, pp. 63–80, https://doi.org/10.1007/978-3-030-98812-8_4.

[41] A. L. da Silva, E. R. K. Rabbani, and M. Shakouri, “Seashell powder as a sustainable alternative in cement-based materials: A systematic literature review,” *Sustainability*, vol. 17, no. 2, p. 592, 2025, https://doi.org/10.3390/su17020592.

[42] M. Olivia, A. A. Mifshella, and L. Darmayanti, “Mechanical properties of seashell concrete,” *Procedia Engineering*, vol. 125, pp. 760–764, 2015, https://doi.org/10.1016/j.proeng.2015.11.127.

[43] K. Muthusamy, R. Embong, R. Jose, N. Mohamad, and N. S. H. Kamarul Bahrin, “Compressive strength of mortar containing cockle shell waste as mixing ingredient,” in *IOP Conference Series: Materials Science and Engineering*, vol. 1092, no. 1, p. 012001, 2021, https://doi.org/10.1088/1757-899X/1092/1/012001.

[44] M. M. Nujid, J. Idrus, N. A. Azam, D. A. Tholibon, and D. Jamaluddin, “Correlation between California Bearing Ratio (CBR) and plasticity index of marine soil stabilized with cockle shell powder,” *Journal of Physics: Conference Series*, vol. 1349, no. 1, p. 012036, 2019, https://doi.org/10.1088/1742-6596/1349/1/012036.

[45] M. H. K. Rahman, M. Md Nujid, J. Idrus, D. A. Tholibon, and N. F. Bawadi, “Unconfined compressive strength assessment of stabilized marine soil with cockle shell powder as sustainable material on subgrade pavement,” *IOP Conference Series: Earth and Environmental Science*, vol. 1205, no. 1, p. 012057, 2023, https://doi.org/10.1088/1755-1315/1205/1/012057S..

[46] S. Almuaythir, M. S. I. Zaini, M. Hasan, and M. I. Hoque, “Stabilization of expansive clay soil using shells based agricultural waste ash,” *Scientific Reports*, vol. 15, no. 1, p. 10186, 2025, https://doi.org/10.1038/s41598-025-94980-5.

[47] N. A. Azam, “Physical characteristics of marine clay stabilized with cockle shell powder,” B.Eng. (Hons.) Civil (Infrastructure) student project, Faculty of Civil Engineering, Universiti Teknologi MARA, Permatang Pauh, Pulau Pinang, Malaysia, 2018. [Online]. Available: https://ir.uitm.edu.my/id/eprint/39663

[48] [48] S. H. Park, J. An, A. Koutsospyros, and D. H. Moon, “Assessment of the stabilization of Cu-, Pb-, and Zn-contaminated fine soil using cockle shells, scallop shells, and starfish,” *Agriculture*, vol. 13, no. 7, p. 1414, 2023, https://doi.org/10.3390/agriculture13071414.

[49] N. N. A. N. Aziz, M. Hasan, M. S. I. Zaini, S. N. A. Mohamed, and M. J. Winter, “Hydrated lime and cockle shell ash: A sustainable approach to soft kaolin clay improvement,” *Journal of Advanced Research in Applied Mechanics*, vol. 138, no. 1, pp. 37–45, 2025, https://doi.org/10.37934/aram.138.1.2745.

[50] D. Tunega and A. Zaoui, “Mechanical and bonding behaviors behind the bending mechanism of kaolinite clay layers,” *Journal of Physical Chemistry C*, vol. 124, no. 13, pp. 7432–7440, 2020, https://doi.org/10.1021/acs.jpcc.0c00843.

[51] N. Kumari and C. Mohan, “Basics of clay minerals and their characteristic properties,” in *Clay and Clay Minerals*, N. Kumari and C. Mohan, Eds. *IntechOpen*, London, United Kingdom, 2021, https://doi.org/10.5772/intechopen.97672.

[52] C. Teerawattanasuk, P. Voottipruex, S. Maneekaew, R. Sukkarak, W. Sramoon, and I. Meepon, “Engineering properties of treated clay by kaolin-rice husk ash geopolymer activated with sodium hydroxide solution,” *Transportation Infrastructure Geotechnology*, vol. 11, no. 5, pp. 3293–3313, 2024, https://doi.org/10.1007/s40515-024-00412-8.

[53] M. S. I. Zaini, M. Hasan, S. Almuaythir, and M. Hyodo, “Experimental investigations on physico-mechanical properties of kaolinite clay soil stabilized at optimum silica fume content using clamshell ash and lime,” *Scientific Reports*, vol. 14, no. 1, p. 10995, 2024, https://doi.org/10.1038/s41598-024-10995-1.

[54] M. S. I. Zaini, M. Hasan, L. S. Yie, K. A. Masri, R. P. Jaya, M. Hyodo, and M. J. Winter, "The effect of utilizing silica fume and eggshell ash on the geotechnical properties of soft kaolin clay," *Jurnal Teknologi*, vol. 84, no. 1, pp. 159–170, 2022, https://doi.org/10.11113/jurnalteknologi.v84.17115.

[55] W. Xu, T. Y. Lo, W. Wang, D. Ouyang, P. Wang, and F. Xing, "Pozzolanic reactivity of silica fume and ground rice husk ash as reactive silica in a cementitious system: A comparative study," *Materials*, vol. 9, no. 3, p. 146, 2016, https://doi.org/10.3390/ma9030146.

[56] A. E. Ahmed and F. Adam, "Indium incorporated silica from rice husk and its catalytic activity," *Microporous and Mesoporous Materials*, vol. 103, no. 1–3, pp. 284–295, 2007, https://doi.org/10.1016/j.micromeso.2007.02.001.

[57] M. Nehdi, J. Duquette, and A. El Damatty, "Performance of rice husk ash produced using a new technology as a mineral admixture in concrete," *Cement and Concrete Research*, vol. 33, no. 8, pp. 1203–1210, 2003, https://doi.org/10.1016/S0008-8846(03)00038-3.

[58] N. Van Tuan, G. Ye, K. Van Breugel, and O. Copuroglu, "Hydration and microstructure of ultra-high-performance concrete incorporating rice husk ash," *Cement and Concrete Research*, vol. 41, no. 11, pp. 1104–1111, 2011, https://doi.org/10.1016/j.cemconres.2011.06.002.

[59] V. Pham, W. R. L. van der Star, L. van Paassen, and G. Ye, "Rice husk ash with high carbon content proves favourable for soil stabilization," in Jaarboek van de Mijnbouwkundige Vereeniging te Delft: *Shifting Sources–Long Term Supplies*, Delft University of Technology, Delft, The Netherlands, 2015, pp. 158–173. https://resolver.tudelft.nl/uuid:8a3b9363-7d72-4a1d-bfbb-d6e0cb1fb132.

[60] D. K. Datta, T. Biswas, E. Castonguay, and P. Ni, "Sustainable stabilizer derived from calcium- and phosphorus-rich biowaste for remediation of heavy metal-contaminated soil: A critical review," *Sustainability*, vol. 16, no. 20, p. 8841, 2024, https://doi.org/10.3390/su16208841.

[61] J. Z. Chong, N. M. Sutan, and I. Yakub, "Characterization of early pozzolanic reaction of calcium hydroxide and calcium silicate hydrate for nanosilica modified cement paste," *Journal of Civil Engineering, Science and Technology*, vol. 4, no. 3, pp. 6–10, 2013, https://doi.org/10.33736/jcest.120.2013.

[62] [62] L. Li, S. Li, W. Li, H. Xiao, K. Xu, and J. Yang, "Mechanical properties of soil reinforced by fiber and alkaline-activated rice husk ash, and rainfall erosion model tests," *Science of the Total Environment*, vol. 958, p. 178099, 2025, https://doi.org/10.1016/j.scitotenv.2024.178099.

[63] S. D. Sagala, S. Syahril, D. A. Purba, and A. Marques, "Sustainable soil improvement: Soft clay stabilization using rice husk ash and waste spent catalyst RCC 15," *Potensi: Jurnal Sipil Politeknik*, vol. 27, no. 1, pp. 23–32, 2025, https://doi.org/10.35313/potensi.v27i1.6518.

[64] N. Nahar, A. O. Owino, S. K. Khan, Z. Hossain, and N. Tamaki, "Effects of controlled burn rice husk ash on geotechnical properties of soil," *Journal of Agricultural Engineering*, vol. 52, no. 4, p. 1216, 2021, https://doi.org/10.4081/jae.2021.1216.

[65] M. Md Nujid, D. A. Tholibon, and M. H. Kushairi Rahman, "Effect of cockle shell powder as sustainable additive on geotechnical engineering properties of stabilized soil," *Arabian Journal of Geosciences*, vol. 15, p. 1306, 2022, https://doi.org/10.1007/s12517-022-10593-6.

[66] E. R. Sujatha, M. Abijayan, M. Vignesh, and V. Shriram, "Effect of rice husk ash on the behaviour of highly compressible clay," in *Proceedings of the Indian Geotechnical Conference 2019*, Lecture Notes in Civil Engineering, vol. 136. Singapore: Springer, 2021, https://doi.org/10.1007/978-981-33-6444-8_13.

[67] B. T. Kamtchueng, V. L. Onana, W. Y. Fantong, J. M. Ndzié, and G. E. Ekodeck, "Geotechnical, chemical and mineralogical evaluation of lateritic soils in humid tropical area (Mfou, Central-Cameroon): Implications for road construction," *Geo-Engineering*, vol. 6, p. 1, 2015, https://doi.org/10.1186/s40703-014-0001-0.

[68] S. S. D. Raavi and D. D. Tripura, "Predicting and evaluating the engineering properties of unstabilized and cement stabilized fibre reinforced rammed earth blocks," *Construction and Building Materials*, vol. 262, p. 120845, 2020, https://doi.org/10.1016/j.conbuildmat.2020.120845.

[69] K. Hung, U. J. Alengaram, M. Zamin, S. Cheng, W. Inn, and C. Wah, "Recycling of seashell waste in concrete: A review," *Construction and Building Materials*, vol. 162, pp. 751–764, 2018. https://doi.org/10.1016/j.conbuildmat.2017.12.009.

[70] M. Nujid, J. Idrus, D. A. Tholibon, N. F. Bawadi, and A. A. Firoozi, "Bearing capacity of soft marine soil stabilization with cockle shell powder (CSP)," *International Journal of Engineering and Advanced Technology*, vol. 9, no. 3, pp. 1490–1497, 2020, 10.35940/ijeat.B3989.029320.

[71] M. Amar, M. Benzerzour, J. Kleib, and N. E. Abriak, "From dredged sediment to supplementary cementitious material: Characterization, treatment, and reuse," *International Journal of Sediment Research*, vol. 36, no. 1, pp. 92–109, 2021, https://doi.org/10.1016/j.ijsrc.2020.07.001.

[72] A. A. A. Shehata, A. O. Owino, M. Y. Islam, and Z. Hossain, "Shear strength of soil by using rice husk ash waste for sustainable ground improvement," Discover *Sustainability*, vol. 5, no. 1, p. 64, 2024, https://doi.org/10.1007/s43621-024-00238-x.

[73] A. Atef and Z. Hossain, "Assessing the impact of rice husk ash on soil strength in subgrade layers: A novel approach to sustainable ground engineering," *Sustainability*, vol. 17, no. 12, p. 5457, 2025, https://doi.org/10.3390/su17125457.