Research article

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Advancing geotechnical engineering via sustainable biomass-based soil stabilization

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Abstract. This research investigates the potential influence of mixing biomass resources, cow bone ash, in various percentages into the untreated kaolinitic soil in altering the geotechnical parameters. The nature of clayey soil frequently triggers the prevailing issues, such as uneven settlement, insufficient soil-bearing capacity, and abnormal compressibility coefficient. Several fundamental laboratory approaches were deployed to obtain information on grain size distribution, consistency limits, proctor behaviors, and specific gravity. The optimum moisture content of kaolin stabilized with cow bone ash was discovered at 6 %, and this value was utilized for the assessment of unconfined compression data. The examination of shear strength parameters was implemented via the fabrication of a cylindrical sample, dimensioned at 38 mm in diameter and 76 mm in height. The kaolin samples were altered using 3 %, 6 %, 9 %, and 12 % of cow bone ash content, and cured for periods of 7 and 14 days, respectively. The discoveries revealed that associating all portions of cow bone ash enhanced the kaolin shear strength significantly, ranging from 81.15 % to 578.10 %. The accuracy was verified by the utilization of the correlation technique, where all the curing periods of the samples possess a coefficient of determination greater than 0.9. Furthermore, the establishment of cost-analysis calculation generates a thorough framework for optimizing the total cost of stabilization, with the efficiency reaching 49.56 %. In short, using cow bone ash in soil stabilization resulted in positive implications that advance the technology of the geotechnical industry, proposing a promising development practice via the application of sustainable material.

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1. Introduction

From the ancient to modern era, the responsibility of civil engineering has been enormous for the quality of life of people, being a catalyst in fostering the global civilization. Previous research data have proven that the significance of modernization is coherent with the advancement of building technology, which links to sustainable [1]. Possessing an excellent infrastructure system that complies with the Environment, Social, and Governance (ESG) is a huge challenge for a country, as it costs a huge amount of money to overcome myriad challenges. Correspondingly, Mochida et al. [2] and Li et al. [3] reported the association of the ESG concept in construction activities is crucial, which is consistent with the 17

Sustainable Development Goals (SDGs). Historically, Leknoi and Likitlersuang [4] emphasized the significance of ideas in handling soil erosion and slope stabilization that aligns with Goal 11, sustainable cities and communities. Abundant data from previous studies have verified the possibility of advancing the construction projects while practicing the SDGs, whereby utilizing recycling waste, industrial by-products, and disposal items has become evidence [5], [6]. In completing an infrastructure project, the soil condition is the fundamental consideration for the parties involved, such as engineers, developers, and contractors. The physicochemical behaviors of soil, particularly clayey minerals are always complex, dealing with the evolution of architecture beneath the ground [7]. Naturally, clayey soil is categorized as a low-performing soil, as compared to other soils like gravel [9]. The reported problems include soil particle dispersion, abnormal coefficient of compressibility, insufficient soil-bearing capacity, Plasticity Index (PI) exhibited higher values, excessive pore water pressure, and sensitivity to moisture content. Analyzing its grain size, the clay soil has an overall grain size (>50 %) of less than 2×10^{-6} mm, which makes the entrapped water not easily to escape via its adjacent drainage boundaries [10]. The research data of clay properties provided by Hasan et al. [11] and Hoque et al. [12] confirmed the results, in which the authors classified kaolin clay as a less permeable soil via the determination of its coefficient of hydraulic conductivity. Chemically, the formula of kaolin clay is $Al_2Si_2O_5(OH)_4$, composed of the elements of aluminium, silicon, oxygen, and hydroxide. The hydrophobic behavior of kaolin is due to the hydroxyl group (–OH) of kaolin, connected by a hydrogen bond that makes it attractive to water mode [13]. The authors summarized that the polarity of partial positive (H+) and negative (OH−) from oxygen and hydrogen elements elaborates the excellence of water retention capability. Based on a report published by Abbaslou et al. [14], at least 75 countries around the world, like Malaysia, Thailand, Iran, South Africa, etc., have expressed their concerns about the dispersive clayey minerals discovered, along with the detected issues. It implies that the problematic clay soil is a worldwide problem, not restricted to respective regions only. Corresponding to that, there are a lot of studies being implemented to alter the weak clay soil properties by discharging the additional water retained in the soil mass. Through chemical approach, Karkush and Ali [15] reported that changes in soil pH via electroosmosis in pore water, combined with chemical grouting in the electrokinetic method, can improve the shear strength of soil. This finding is supported by Al-Ani et al. [16] who observed that altering the magnetic field from 500 to 2000 Gauss reduced the plasticity of soil, particularly its Liquid Limit (LL) and Plastic Limit (PL). Similarly, Jawad and Karkush [17] obtained comparable results to those reported in the literature, demonstrating that the use of magnetized water is an effective technique for treating soft clay soil. Other than these approaches, Jun Shen et al. [18] enhanced the soil through bottom ash, and Baldin et al. [19] mixed the soil with rich husk and proved to raise the strength. Concerning the mentioned statements and data, the ground remediation works are continuously improved by the parties involved around the work, and they should vigorously participate in the development of sustainable buildings.

Conventionally, there are many existing ground amelioration techniques that are applied to treat the soft soil. Regardless of the type of techniques, Vakili et al. [20] discovered that the purpose of the soil stabilization method is to reduce the potential of magnesium and calcium particles to detach from each other, and decrease the magnitude of repulsive inter-particle forces that resulted in the instability of particles. Azimi et al. [21] reported that the chemical stabilization is an effective approach, provided in a controlled condition, specifically in the supervision of environmental impact. Referring to Herrmann and Bucksch [22], the adoption of a technique should be based on the type of soil (cohesive or non-cohesive soil) and the cost of the foundation. In this case, the choices of cohesive soil are vertical drains, vacuum dewatering, stone columns, and the in-situ mixing method. From the perspective of the economy and laboratory scale, the in-situ mixing method is mostly practiced by researchers due to its convenience of application. However, traditional soil stabilization approaches mostly involve the use of chemical admixture and mechanical modification, which can be substantially detrimental to the environment. Almuaythir et al. [23] summarized the effective materials but harmful substances for conventional stabilization are cement and lime, which have remarkably high carbon dioxide emissions due to the huge energy demand. In contrast, the authors implemented the cost analysis on the usage of clamshell ash as the source of lime silica-fume stabilized kaolin for the source of silicon and aluminium, which can optimize the cost of stabilization up to 10.06 %. It is deduced that the association of clamshell ash raises the pH condition of soil swiftly via the hydration process when contacted with moisture content, and generates the calcium hydroxide compound. It yields an identical effect as compared to quicklime (CaO), which accelerates the dissolution of amorphous compounds such as Si^{4+} and Al^{3+} ion. This statement is supported by Hashim Mohammed et al. [24], the production of Calcium Silicate Hydrate (CSH) and Calcium Aluminate Hydrate (CAH) is a significant product. Other products, such as nano-silica, are also widely applied and recognized for activating and accelerating pozzolanic activity to produce the aforementioned hydrated compounds [25]. The refinement of the properties of clay, persistently manifesting in pore refinement, particle bonding, and water mobility due to pozzolanic reaction. As the curing period extends, the CSH is gradually undergoing densification, which fills the capillary pores of soil through the procedure of sluggish polymerization. However, the CAH exists in a better crystallized state, which only contributes to the early strength development, and presents insignificant improvement of shear strength corresponding to the curing factor.

Therefore, all the above-mentioned studies have accentuated that traditional stabilizers or materials such as cement and sand are appropriate in altering clay properties, but also that greenery substituents can be utilized for improvement purposes, which aligns with the real-world construction industry.

Cow bone, being a source of biomass is appropriate to extract the calcium compound for various purposes [26]. The primary content of cow bone is Hydroxyapatite (HPA) or $Ca_{10}(PO_4)_6(OH)_2$, a type of stabilized crystalline structure that is held strongly by the three-dimensional lattice. Baroutkoob et al. [27] verified the effectiveness of cow bone as it is a sustainable source of nano-phosphorus in the increase of tomato yield by amending the biochemical and physiological properties of clayey soil. Norrahim et al. [28] utilized the advantage of cost-effective, renewable, and high stiffness in the polymer composites, acting as a reinforcement filler. Awotemi et al. [29] discovered the ideal proportion of Cow Bone Ash (CBA) is approximately 10 % of the total weight of concrete, where the maximum flexural strength was observed. The authors concluded that the rise of concrete strength is attributed to the high-water demand by CBA, which increases the Optimum Moisture Content (OMC). It stimulates the mobilization of ions and, therefore, the period of hydration is shortened. Coherently, the formation of CBA is done through the calcination process with the purposes of (1) removing impurities and organic matter, (2) transition of complex compounds to reactive minerals such as calcium oxide, (3) initiating the pozzolanic potential, and (4) transformation of biomass into a stabilizing agent. However, the temperature of calcination influences the productivity of calcium oxide, in which the factor of temperature and its yield is in a directly proportional relationship. Oluniyi et al. [30] reported that heating within the range of 800–900 °C yields calcium oxide contents of 87–99%. Due to its calcium-based biominerals, they are efficient in the absorption of contaminants, or catalyzing the decomposition of heavy metals, dyes, fluorides, surfactants, etc [31]. With the prior references of applying CBA, Yilmazoğlu [32] reported the curing period of 7 days, 14 days, and 28 days presented a significant alteration of unconfined compressive strength (UCS) as compared to the raw kaolin soil. The authors recorded the fluctuation of UCS was from 4.47 % to 23.34 %, and the negative results were due to the procrastination of pozzolanic reaction, transition of pore fluid, and the breakdown of kaolin fabric. The above data are verified by Parihar and Gupta [33] as the authors obtained a similar condition when using CBA as a substituent. The result of shear strength was raised drastically from 27 kPa to 257 kPa or 851.85 % after 28 days of curing, which densified and interlocked the soil matrix productively.

In today's engineering landscape, there has been a surge in research interest focused on the interaction of sustainable materials or the combination of other greenery materials in the application of soil stabilization. CBA, a biomass material sourced from the restaurants and poultry industry, has gained prominence as an origin of calcium replacement, such as quicklime and limestone. The major component of CBA, calcium carbonate ($CaCO_3$), occupies almost the entire volume of its component, with at least 90 % of occupancy depending on the calcination procedure. Resultantly, there are myriad potentials, benefits, values, and promises that can be explored in the construction industry. Without ambiguity, it can be stated that the replacement proportion must be in a commanded condition, refraining from obtaining unnecessary negative results. Established literature has confirmed the association of cow bone-derived substituents, suggested that further tailored materials are robust, and reduces the volume of disposal from the respective industries. Highlighting the civil-geotechnical area, the mixture of CBA into clayey soil has gained a huge momentum from the related parties, particularly the researchers. Previous investigations have tested and verified the suitability of CBA in altering the properties of soil, cement, and so on [29]–[31]; but there is no exact focus on the direct substitution of CBA with percentage in stabilizing the kaolinitic clay, along with the cost-analysis framework.

The current study emphasizes and carries out the association of CBA with the increment of 3% and 9 % by referring to previous analyses [21], [34]. It analyzes the engineering properties of kaolin, CBA, and refined kaolin with CBA through geotechnical approaches. These properties are significant in generating the relationship between kaolin and CBA, and provide new insight to readers regarding the soil stabilization effect corresponding to the curing periods of 7 days and 14 days. According to the experimental framework, several hypotheses can be drawn: (1) The mixture of CBA as a foreign material can react effectively with kaolin soil through the pozzolanic reaction, producing cementitious-behaved products; (2) regardless of the percentage of CBA used, the shear strength parameters of refined kaolin can be modified; (3) a comprehensive cost-analysis system can be established based on the comparison between conventional soil stabilizers and CBA materials. To highlight the advancement of this study relative to the literature data, the objectives are established to provide new knowledge to readers: (1) determine the geotechnical properties of the research materials (kaolin and CBA) utilized in this study; (2) obtain the shear strength parameters of kaolin and refined kaolin with CBA in various percentages; (3) establish the cost-analysis framework to verify the effectiveness of sustainable refined kaolin in actual construction sites via a prediction model.

2. Materials and Methods

The study (soil stabilization) is conducted on the scale of laboratory scale with the aim of modifying the shear strength properties of soil, which suits the common practice of research. The preparation of relevant materials is purely carried out in a controlled environment, complying with the BS and ASTM standards.

2.1. Materials

This section reveals the interaction of the investigated materials between the soft soil and the substitute. For the structurally deficient candidate, the kaolin soil with grade S300 is chosen, as depicted in Fig. 1. The selection of this grade material is due to several reasons: (1) homogeneous property, (2) cost-effectiveness, and (3) empirically validated material. The general formula of kaolin is $Al_2Si_2O_5(OH)_4$, and the geotechnical characteristics is tabulated in Table 1. Remarkably, the coefficient of permeability of kaolin is explored at 4.0×10^{-8} m/s, which fulfills the criteria of treatment-required material [5]. This material is sourced from Kaolin (M) Sdn. Bhd, a Malaysian clay leading company that specializes in supplying silica sand, China clay, mica powder, and sericite. The chemical composition of kaolin and CBA is listed in Table 2. Located in Puchong, Selangor, the company is approximately 19 km from Kuala Lumpur, the capital of Malaysia. The price of consideration for the above-mentioned kaolin is purchased at RM1.20 per kg (≈0.28USD), and the total usage of kaolin in this study is around 3.5 kg, which encompasses the potential wastage that occurred during the execution of the experiment.

Figure 1. Kaolin clay type S300.

Table 1. Geotechnical characteristics of kaolin

Characteristic	Unit	Data
LL	41	%
PL	33	%
PI	8	%
Gravel	0	%
Sand	39	%
Silt and clay	61	%
Specific gravity	2.64	NA
Optimum moisture content	19.77	%
Maximum dry density (MDD)	1.53	Mg/m^3
Permeability coefficient	4.0×10^{-8}	m/s

Table 2. Compound percentage of research materials

Sample	Composition (%)					
	SiO$_2$	CaO	Al$_2$O$_3$	K$_2$O	MgO	Fe$_2$O$_3$
Kaolin	66.1	0.1	20.2	2.9	1.2	0.7
CBA	12.6	61.0	16.8	0.6	1.5	1.2

Furthermore, the integrated reinforcement to the weak soil is the cow bone member, acting as a soil stabilizer to facilitate the pozzolanic reaction. The raw cow bone is collected from the local restaurants in Kuantan. It is washed with tap water to remove the impurities present on the surface, and air-dried for 7 days. As shown in Fig. 2, the clean cow bone is crushed into smaller pieces via a jaw crusher, ensuring an effective calcination process due to a higher surface-to-volume ratio. Afterwards, the crushed cow bone

was heated under a chamber furnace at 900 °C for 10 hours, following the standard procedure of calcination. The white color product is obtained, signifying the complete conversion of calcium carbonate into calcium oxide. The CBA is left in a desiccator for 24 hours, which avoids unnecessary reactions such as hydration due to the atmospheric moisture.

Figure 2. Preparation of CBA

2.2. Methods

This section discusses the entire flow of research work, beginning from the preparation of unrefined and refined kaolin, followed by the setup of experiments. The flow of preparation of unrefined and refined kaolin is shown in Fig. 3. The preparation of unrefined kaolin signifies the use of air-dried kaolin soil, weighing 110 g. The volume of water is set at 20.00 % of its total soil mass, determined from the OMC value as stated in Table 1. The dimension of the steel mold is measured at 38 mm in diameter and 76 mm in height for the sample fabrication process. As demonstrated in Fig. 3(a), the prepared kaolin mixture is transferred into the mold and undergoes compaction. The compaction effort varies accordingly, depending on the stiffness of the materials. Afterwards, an extruder (see Fig. 3(b) is used to extrude out the sample before storing it in a suitable container for stabilization purposes. Referring to the literature, the refined kaolin presents the unrefined kaolin mixed with the respective percentage of CBA, including 3 %, 6 %, 9 %, and 12 % [34]. Regarding the CBA material, it was selected for several reasons, including its proven effectiveness in rectifying the shear strength parameters of various types of soil with only a mild amount substituted under specific curing periods [33]. Previous studies highlighted that the CBA substitution has great potential to act as a supplementary material for cementitious and pozzolanic applications, such as concrete and soil enhancement [29]. The authors mentioned that the replacement of a certain portion of soil (not more than 20 %) with CBA accelerates this reaction mechanism for the production of cement hydration products. In addition, the utilization of CBA material is considered sustainable. Correspondingly, this material was obtained from disposed food waste from a local restaurant in Kuantan, Malaysia, and hence it did not incur additional cost.

The sample coding of refined kaolin is tabulated in Table 3. Correspondingly, the curing day of kaolin is chosen at 7 and 14 days, and measuring the rate of change of shear strength within this timeframe is significant to notice the reactivity of amorphous contents. The selection of these respective curing periods is attributed to literature remarks and results. The 7-day and 14-day curing periods are the common practice in soil stabilization methods, during which the reaction mechanism between kaolin soil and CBA has already demonstrated early to mid-term strength development through the formation of gel calcium compounds. In terms of practicability, timeline, and construction practice, the data acquired from the optimum curing periods of 7 days and 14 days are sufficient to evaluate the pozzolanic reaction, while subsequent curing periods record only mild improvement in engineering properties. A longer curing period (for example, 28 days) was not deployed in this study because it is more appropriate for cement-based materials, such as Ordinary Portland Concrete.


Figure 3. Procedure of kaolin preparation.

Table 3. Design of kaolin mixture with CBA

Sample coding	Percentage of association (%)		
	Kaolin	CBA	Total
7K	100	0	100
7K3CBA	97	3	100
7K6CBA	94	6	100
7K9CBA	91	9	100
7K12CBA	88	12	100
14K	100	0	100
14K3CBA	97	3	100
14K6CBA	94	6	100
14K9CBA	91	9	100
14K12CBA	100	12	100

*7K3CBA – 7 days of curing kaolin sample with 3 % of CBA mixture

Afterwards, the research process proceeds to the introduction of physical and mechanical investigations, as shown in Fig. 4 and Fig. 5. As demonstrated in Fig. 4(a), the dry sieving process begins with the selection of the relevant sieve size, including 5 mm, 3.35 mm, 1.18 mm, 0.6 mm, 0.3 mm, 0.15 mm, 0.063 mm, and a pan. The CBA is mechanically shaken for 15 minutes, and the percentage passing through its sieve size is plotted algorithmically. The subsequent analysis of grain size distribution (GSD) involves the use of hydrometer test, testing for the particle size of kaolin. This wet sieving process utilizes the same technique of data interpretation, as shown in Fig. 4(b) and the significant amount of kaolin particles retained is referred to as the final value. The execution of Atterberg limit is categorized into 2 sections: the LL and PL determination. Referring to Fig. 4(c), the LL value is obtained via the assistance of Casagrande device, and the PL value is yielded through the rolling method and oven drying at 100 °C. Last but not least, the small pycnometer is applied for the evaluation of the specific gravity of kaolin and CBA confined in the pycnometer. This technique subtracts the loss of water vapor, the change in mass between the material, soil, and pycnometer, to determine the average specific gravity.
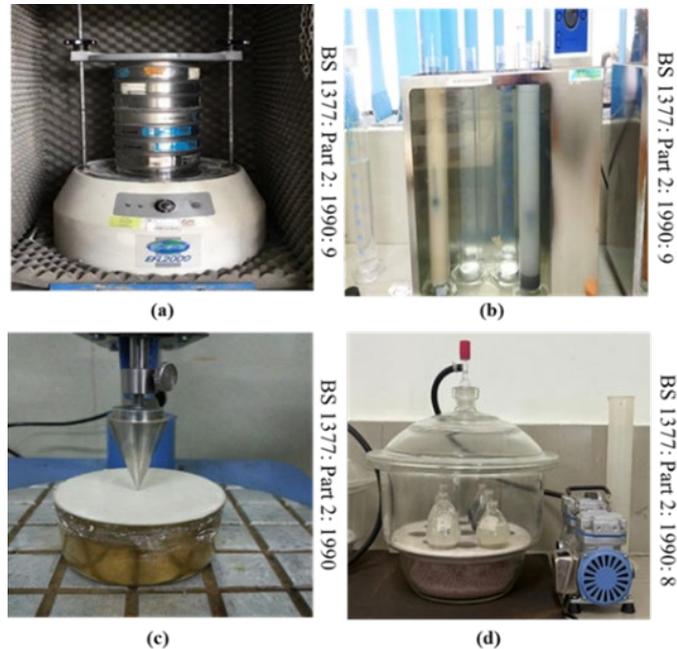
Figure 4. Physical experiments (a) Sieve analysis (b) hydrometer (c) cone penetrometer (d) small pycnometer.

Figure 5. Mechanical experiments (a) Standard compaction (b) falling head test.

As shown in Fig. 5(a), the mechanical characterization of unrefined and refined kaolin is acquired through the execution of standard compaction test. The raw kaolin soil is first analyzed to obtain the OMC and MDD values, followed by the mixture of relevant percentage of CBA as tabulated in Table 3. It ensures the homogeneity, accuracy, and reliability of data upon executing the UCT. For all designs, the range of moisture content addition is from 5 % to 30 %, with the 5 % of increment for the subsequent analysis. For calibration purposes, the hammer used for compaction is weighted at 2.5 kg, and the height and diameter of the compaction mold are measured for accurate dry density calculation, following the BS standard. Besides, the oven temperature was calibrated between 100 °C and 105 °C during the drying process. The compaction hammer is used to reduce the air voids of soil, measured from a distance of 15 cm from the steel mold. The turning point of graph is marked as the reference for OMC and MDD determination. In addition, the rate of water flow across the kaolin particle is expressed via the coefficient of hydraulic conductivity. As depicted in Fig. 5(b), the falling head approach is implemented to acquire the data. This method computes the flowrate of water within a stipulated timeframe, assisted by a burette. After obtaining the significant geotechnical properties, the samples of unrefined and refined kaolin are investigated under the approach of UCT (see Fig. 6). Before beginning the test, the load frame is calibrated to zero indication which shows no load being applied. Referring to the dimension of specimen, the constant strain rate is fixed at 1 %, following the ASTM standard. Thus, the specimen undergoes 1 mm/min. This machine shears the specimen at a constant rate of deformation, with the calibration ring factor of 0.00167 kN/div. The axial stress strain, unconfined compression stress, and undrained shear strength are calculated concerning this value. This method complies with the ASTM D 2166, in which the examination is halted when column failure is observed, for instance, column bulging. For the purpose of accuracy, each specimen from Table 3 is examined for 3 times, and the average value is picked up as the final value.

Figure 6. Determination of shear strength parameters through the execution of UCT.

3. Results and Discussion

This chapter demonstrates thoroughly the geotechnical engineering properties of kaolin clay and CBA, and the alteration of their characteristics when kaolin mixes with CBA at 3 %, 6 %, 9 %, and 12 %,

respectively. These samples are tested without curing, by approximating real-world soil behavior under the experimental settings. Their performance under the fixed rate of deformation is also evaluated. The use of statistical analysis presents entirely their relationship, correlation, and strength align to all the involved variables.

3.1. Effect of CBA on the Modification of Kaolin Particle Size

Fig. 7 demonstrates the graph of kaolin, CBA, and kaolin + 6 % CBA, corresponding to their percentage passing and particle size. It is noticed that without the addition of CBA, the curvature of graph is positioning outwards, indicating a bigger variation in terms of particle size. From the results, there are only 3 types of grain size detected from this category, which are 0.15 mm, 0.063 mm, and less than 0.063 mm. The largest occupancy of particle size is from 0.063 mm, which represents 62.82 %. The above discovery is coherent with the findings by Shen and Hasan [35], in which 50 % or more 0.063 mm kaolin particle is anticipated to obtain. In contrast, the graph of cow bone is curved inwards, as compared to kaolin soil. It is predicted to occur due to its calcined properties, where the bone microstructure is naturally dense, attributed to HPA component [26]. The largest portion of particle size discovered is at 0.3 mm, followed by 0.6 mm which holds 32.34 % and 26.73 %, respectively. However, Norrahim et al. [28] emphasized the moderate size of CBA can enhance the mechanical properties of soft clay soil effectively, due to its larger surface area exposure to undergo cementitious and pozzolanic reaction.

Due to the acquisition of optimum shear strength parameters result from the inclusion of 6 % CBA in kaolin, this specific design is only selected to quantify the degree of dispersion across the dataset. Interestingly, the 6% substitution yields particle sizes ranging from 0.15 mm to 0.3 mm at 93.08%, which validates the literature data. According to Abdulwahab et al. [36] mentioned surpass the optimum addition percentage of CBA, it induces the chemical saturation condition, where the calcium oxide has no longer demanded by the amorphous oxide. The current findings deduce that 6 % CBA mixture is effective and the occurrence is due to physical mixing influence as well as vigorous flocculation and agglomeration. The calcium oxide extracted from CBA is adequate to facilitate the cation exchange in kaolin particle efficiently.
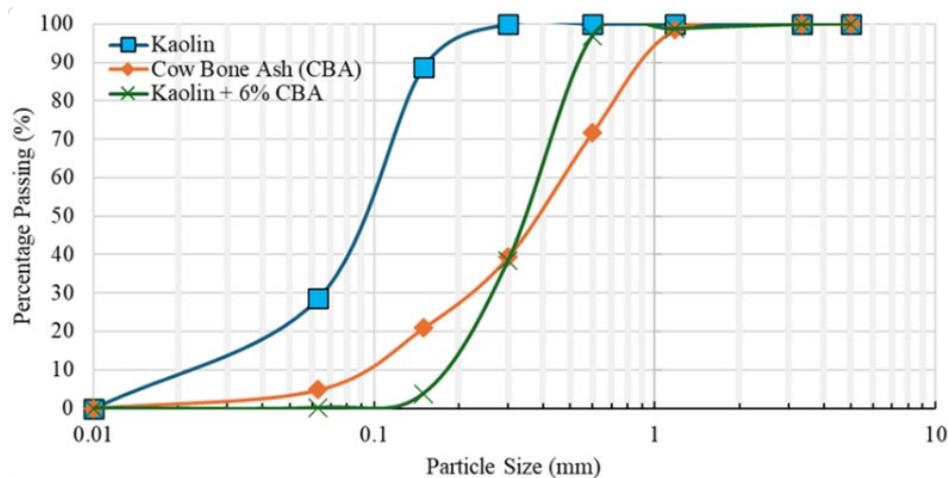

Figure 7. Modification of particle size of kaolin and kaolin with CBA.

3.2. Effect of CBA on the Modification of the Consistency Limit of Kaolin

Fig. 8 displays the data generated by Atterberg limit, presenting the value of LL, PL, and PI. From the dataset, the total change of LL, PL, and PI is recorded at 16.62 %, 24.96 %, and 157.39 %, respectively. Without the inclusion of CBA content, the raw kaolin has the value of LL and PL at 41 % and 33 %, which is not favorable for construction activities [39]. It proves that the raw kaolin is subjected to high compressibility and sensitive to moisture content, aligning to its LL value. Furthermore, the undisturbed kaolin is potentially to lose its plasticity when exposing to continuous water supply. Nonetheless, the utilization of CBA does not guarantee a continuous improvement of consistency limits, where the LL, PL, and PI magnitude demonstrate a fluctuating condition. For 3 % and 9% CBA embracement, the magnitude of consistency limits rectifies moderately, in which the improved LL and PL value compromise each other.

Notably, both the maximum LL and PL values were recorded at 12% CBA inclusion, which yielded the smallest PI value across the study. The above condition is similar to the experiment conducted by Jamhuri et al. [34], in which the authors mentioned the dissolution process of cow bone into cations and anions, comprising of calcium ion (Ca^{2+}) and hydroxide ion (OH^-) displace hydrogen ion (H^+) to accelerate the process of kaolin flocculation. This condition is explained by the overdose of CBA substituent, which produces an insignificant effect on reducing water affinity but worsens the surface roughness of the soil matrix. Consequently, the modified soil mass with 12 % CBA content tends to trap more moisture content

on the kaolin particle lining wall. The calcium compounds are also potentially to interrupt the original soil matrix structure, transforming the state of soil into a mixture of kaolin-silt. Hence, as proven by the result from UCT, the optimum inclusion percentage fells to 6 % CBA, in which the demonstration of LL, PL, and PI figures are in ideal status.

The validation of accuracy of consistency limits is carried out by the deployment of correlation technique, and the cubic function is chosen to establish the equation for LL, PL, and PI as shown in Eq. 1, Eq. 2, and Eq. 3. According to the R^2 parameter, the values are 0.986, 0.975, and 0.9938, respectively, as recorded in Eq.1, Eq.2, and Eq.3. This signifies that more than 95 % of the variables can be explained by these models. In addition, the regression analysis on LL, PL, and PI generated p-values of 0.2485, 0.1634, and 0.5972. Hence, the findings verify that CBA content is effective in the development of shear strength while showing insignificant modification of plasticity.

$$LL = -0.0283(CBA)^3 + 0.5794(CBA)^2 - 2.7064(CBA) + 40.831; \qquad (1)$$

$$PL = -0.0076(CBA)^3 - 0.0163(CBA)^2 - 0.3841(CBA) + 33.173; \qquad (2)$$

$$PI = -0.036(CBA)^3 + 0.5953(CBA)^2 - 2.3069(CBA) + 7.6507. \qquad (3)$$
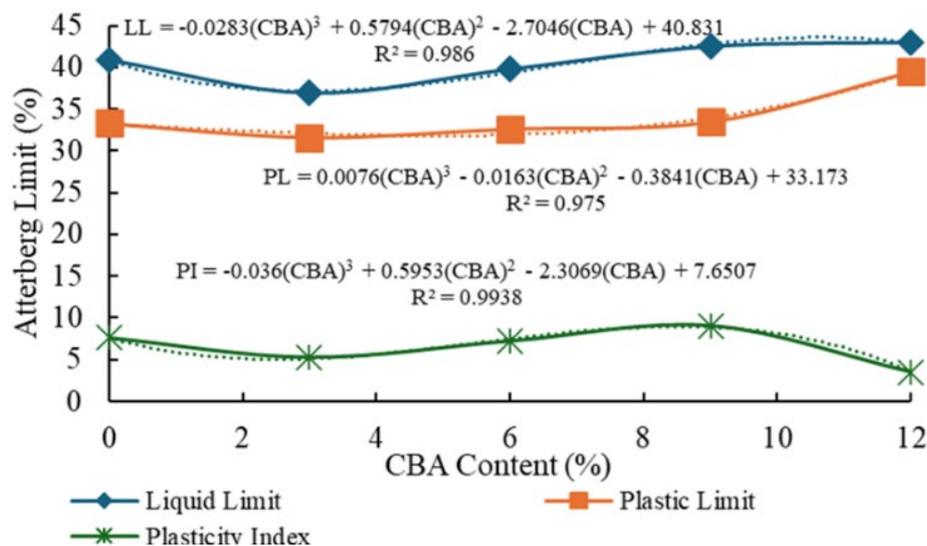

Figure 8. Consistency limits of kaolin altered with varying content of CBA.

3.3. Effect of CBA on the Proctor Test Properties of Kaolin

The association of CBA content in varying content modifies the proctor characteristic of kaolin soil, causing the inconsistent movement of OMC and MDD across the proportion. As displayed in Fig. 9 and Fig. 10, all the designs show decreasing trend after achieving its ideal proctor parameters. Referring to the data, the highest OMC and MDD value recorded is at 19.97 % and 2.53 Mg/m^3, extracted from the refined kaolin at 3 % and 6 % CBA content, respectively. Table 4 summarizes the ideal value of OMC and MDD concerning the unrefined and refined kaolin sample. Remarkably, it is discovered that there is a sharp reduction of OMC at 6 % of CBA content used, dropped from 19.77 % to 9.42 %. In contrast, the MDD value is increased drastically from 0.79 Mg/m^3 to 2.53 Mg/m^3. Therefore, this study concludes that the optimum content of CBA is fixed at 6 %, corresponding to the reported data. Previous experiment data discovered that the optimum value of lime-based stabilized material inclusion should not exceed 10 % of its total soil volume, as the unreacted CBA content introduces micro-voids to the soil particles [37]. It explains the reason of obtaining the MDD at 2.53 Mg/m^3 when the 6 % of CBA is utilized. The effective densification process by the calcined CBA stimulates the volume occupant of voids which then requires a better compaction effort to attain the respective MDD value. A greater value of MDD is favorable for mega infrastructure project, which caters for a better load bearing capacity [9], [38].

Table 4. Summary of the compaction features from distinct samples

Sample	OMC (%)	MDD (Mg/m^3)
K	19.77	1.53
K3CBA	19.97	0.79
K6CBA	9.42	2.53
K9CBA	14.49	1.61
K12CBA	15.44	1.59

Observing from 9 % CBA content onwards, the recovery of OMC value from its trough signifies the subside of MDD value from its crest. It is deduced that the OMC and MDD possess an inverse proportional relationship, regardless the inclusion of CBA content. As explained by Hasan et al. [39], the rise of OMC indicates the increase of degree of water molecule mobilization and therefore, pore pressure volume increases. This causes the decrease of compaction effort to achieve the MDD value under the identical soil matrix. Therefore, the generation of R^2 are at 0.9551, 0.8893, 0.987, 0.8168, 0.8168, and the functions are presented in Eq. 4, Eq. 5, Eq. 6, Eq. 7, and Eq. 8. Coherent with this, the modification of Proctor properties by CBA leads to higher accuracy in variability explanation, increasing from 81.68 % to 98.70 % according to the R^2 values. Furthermore, the p-values for each function are recorded at 0.613, 0.2187, 0.1609, 0.4622, and 0.3241, respectively. These data support the rejection of the alternative hypothesis, indicating an insignificant relationship between MDD and OMC, although the regression model fits the variables properly. The current results confirm that the Proctor properties of soil and refined soil are governed by their size distribution and texture.
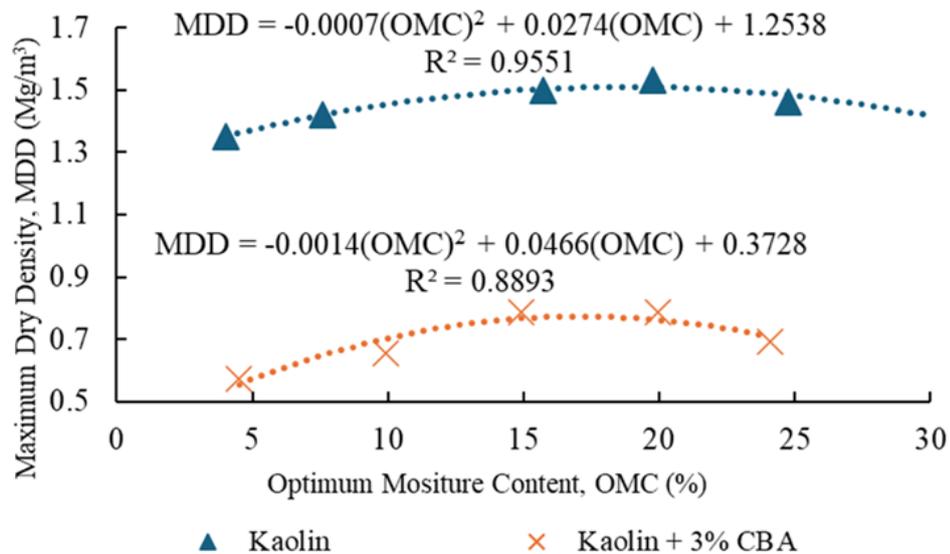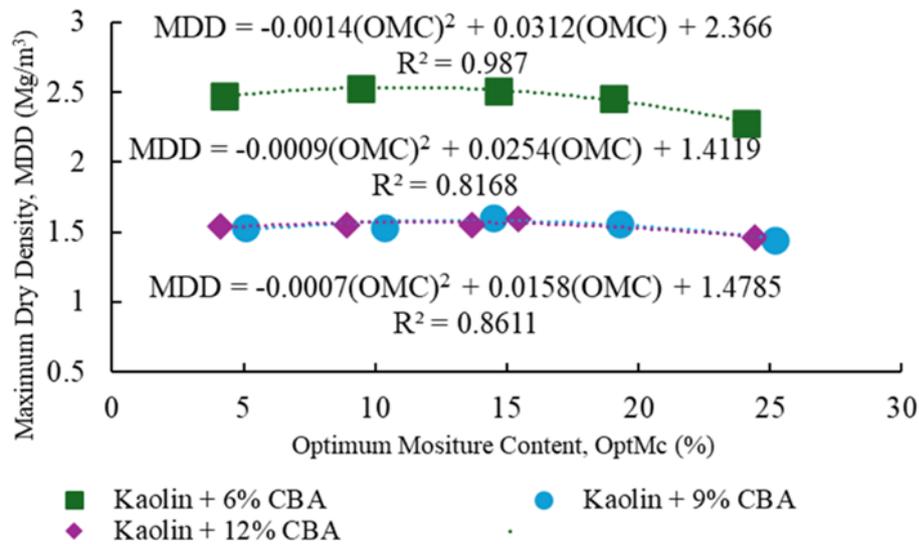
$$MDD = -0.0007(OMC)^2 + 0.0274(OMC) + 1.2538; \tag{4}$$

$$MDD = -0.014(OMC)^2 + 0.0466(OMC) + 0.3728; \tag{5}$$

$$MDD = -0.014(OMC)^2 + 0.0312(OMC) + 2.3660; \tag{6}$$

$$MDD = -0.0009(OMC)^2 + 0.0254(OMC) + 1.4119; \tag{7}$$

$$MDD = -0.0007(OMC)^2 + 0.0158(OMC) + 1.4785. \tag{8}$$

Figure 9. Proctor characteristics of kaolin and refined kaolin at 3% CBA content.

Figure 10. Proctor characteristics of refined kaolin at 6 %, 9 %, and 12 % CBA content.
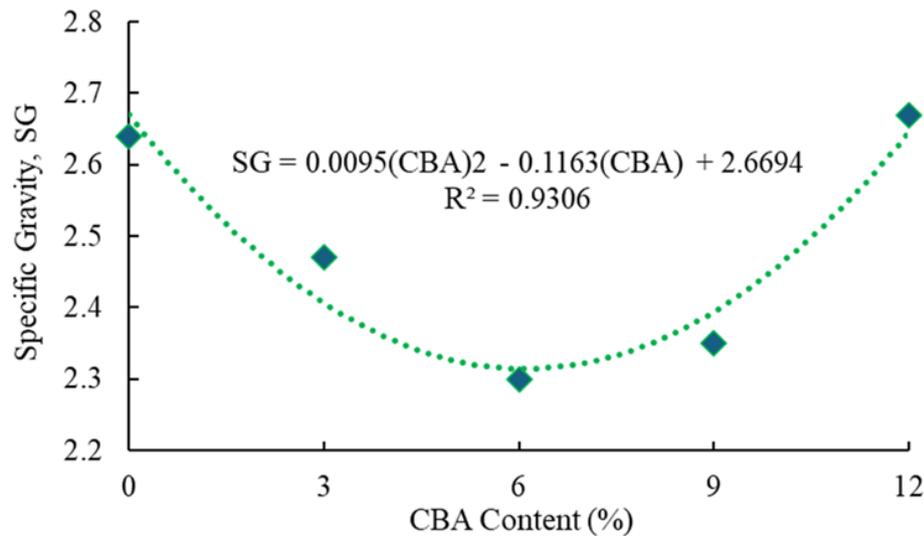
3.4. Effect of CBA on Kaolin Specific Gravity

This section expresses specifically the details of specific gravity, referring to its raw value of kaolin soil and CBA. From the study, the specific gravity of kaolin and CBA is obtained at 2.64 and 0.89, respectively. Bozyigit et al.[40] reported the value at 2.62, Hoque et al. [12] discovered at 2.68, and Hasan and Yee [8] mentioned 2.64. Thus, it is concluded that the undisturbed kaolin soil has a small variation, and can be attributed to the impurities found on the pycnometer surface. Furthermore, the CBA specific gravity is influenced by its calcination process, and exert a greater fluctuation value corresponding to the temperature control in the furnace [41]. Based on the results, it interprets that the kaolin soil is 2.64 times heavier than the water, while CBA is lighter than the water due to its value less than 1.

The addition of varying CBA contents rectifies the specific gravity of undisturbed kaolin, as shown in Fig. 12. As referred to the initial value of specific gravity of kaolin, the variation of specific gravity value ranges from 2.67–14.78%, smaller undulation as compared to other geotechnical characteristics. From the graph, it is noticed the gradual increment of CBA content (up to 6 %) produces the lowest value of specific gravity of refined kaolin. This situation confirms that the refined kaolin has become a porous and lightweight structure, which is ready to absorb more moisture content due to its enlargement of volume tolerance. In addition, at 6 % CBA content, the refined kaolin possesses a better dispersion behavior or an ideal blend density, where it can react more vigorously with the calcium compounds, such as calcium oxide.

This trend is reversed when the CBA content increases to 9 %, causing the specific gravity to rise 2.17 %. It shows that the refined kaolin begins to densify, where the unreacted calcined CBA has predominantly occupied the pore of kaolin particles. Furthermore, the above condition also signifies the density gradient is restored, in which the ideal dosage of CBA has been surpassed. Similarly, the kaolin mixes with 9 % CBA content onwards got a better capability in modifying the moisture content, as the pore water being entrapped in the soil mass can be eliminated more effectively. The subsequently increment of CBA content to 12 % has expected to rise the specific gravity to the highest among this research, recorded at 2.67. It is possible to hinder and reduce the efficiency of pozzolanic reaction, because of the deceleration of ion exchange during hydration process. Besides, it expresses the refined kaolin has a heavier weight, which has limited usage and not practical in actual construction industry. Thus, the current findings propose 6 % CBA content is the appropriate proportion for kaolin soil substitution. The R^2 is calculated at 0.9306, and its function is displayed in Eq. 9. Correspondingly, the p-value of this function is calculated at 0.9275, suggesting the acceptance of the null hypothesis. This result indicates that the research is consistent with findings in the literature, where substituents such as CBA and cementitious materials act chemically rather than physically altering particle density. On the other hand, the variation in specific gravity depends on its mineral composition relative to the water ratio.

$$SG = 0.0095(CBA)^2 - 0.1163(OMC) + 2.6694. \tag{9}$$

Figure 11. Specific gravity of kaolin and refined kaolin at 6 %, 9 %, and 12 % CBA content.

3.5. Effect of CBA on the Kaolin Shear Strength

Via the execution of UCT, the average value of kaolin shear strength (KSS) is obtained from 3 identical samples, and the improvement rate is calculated according to the unrefined kaolin sample, as displayed in Fig. 12. Based on the data, all the refined kaolin specimens with 3 %, 6 %, 9 %, and 12 % CBA content produce shear strength enhancement, ranging from 81.15 % to 578.10 %. Notably, the significant rise in shear strength is attributed to the extremely low baseline strength of unrefined kaolin, whose soil matrix is primarily comprised of pore water, contributing to higher compressibility. The complete formation of CSH and CAH compounds within the soil structure results in a denser matrix, thereby providing better resistance against axial force. It is also observed that this value occurs at the highest CBA content, 12 %, which supports the statement regarding the complete formation of hydrated calcium compounds. The potential sources of error in this value include material handling issues, material variability, and the preparation process. The refined kaolin sample is categorized into 2 categories, 7 days and 14 days curing samples. Remarkably, the highest KSS value is generated from 7K6CBA, which yielded a KSS value at 57.36 kPa. In contrast, the smallest KSS value is produced from 14K3CBA, recorded at 20.09 kPa. The numerical difference is calculated at 37.27 kPa, which translates into 64.98 %. The huge gap of difference is predominantly attributed to the curing process, in which the rapid strength development is noticed at 7 days. Furthermore, the optimum amount of CBA substitution accelerates the surge of shear strength, where the calcium compound has been fully mobilized to form the gel substance, mainly the silicate and aluminate hydrate. This in turns produce the environment which has no excessive calcium compounds that can possibly disturb the soil matrix which leads to the over-densified condition.

Notably, the 14K sample has a bigger value of KSS as compared to the value of KSS produced by 7K. The difference of KSS value is recorded at 2.63 kPa, or 23.72 %. It signifies that without the interruption of foreign material, the strength of kaolin is gradually built up corresponding to the curing period. However, when the introduction of calcium source is carried out, a guarantee of certain period of curing is necessary, regardless the type of lime introduction [42]. The authors deduced that the emerging of cementitious compounds require a longer time for the treated materials to stabilize, for the purpose of interlocking the particles in an undrained condition. The variation observed in the current research data arises from two factors, namely the curing period and the column dimension. According to Jamhuri et al. [34], the column diameter generates a substantial influence to the reinforcement member, in which a rise of column dimension leads to the surge of reinforcement magnitude, in a vice versa condition. Nonetheless, Shen and Hasan [35] reported the above-mentioned relationship is only applicable when the substituent possesses the following criterions, including identical or similar particle size, bulk density, proctor properties, and coefficient of hydraulic conductivity. Hence, the current result concludes that a 6 % CBA replacement into the kaolin soil sample which has a 38 mm diameter and 76 mm height is ideal, practical, and sustainable for the rectification of soil-bearing capacity. The comparison of CBA with other biomass materials is summarized in Table 5, corresponding to varying curing periods and its maximum improvement in shear strength (SSI) value.

Table 5. Different type of biomass in soil stabilization corresponding to its curing periods

| Biomass substituent	Curing periods (0, 7, 14, and 28 days)				
	Max SSI$_{0\ day}$ (%)	Max SSI$_{7\ days}$ (%)	Max SSI$_{14\ days}$ (%)	Max SSI$_{28\ days}$ (%)	Reference
CBA	NA	278.10	296.92	NA	Current
Rice husk	35.46	NA	NA	NA	[19]
Grinded coconut shell	28.51	NA	NA	NA	[43]
BA + rice husk ash	NA	16.77	NA	80.22	[32]
Cockle shell ash	NA	90.52	91.35	NA	[44]

The correlation equation is outlined in Eq. 10 and Eq. 11 according to the UCT result in 7 and 14 days of curing. The corresponding R^2 values were 0.9794 and 0.9464, respectively, based on Fig. 13. Using the same approach, the p-values for both curing periods were obtained at 0.005 and 0.008, which reject the null hypothesis. This validates the previous data and literature findings regarding curing periods, substitution percentage, cementitious reactions, and pozzolanic mechanisms. It also suggests to readers the formation of hydrated compounds over time, binding the dispersive particles together and leading to an increase in shear strength magnitude.

$$SSI = 0.3772(CBA)^3 - 15.438(CBA)^2 - 168.91(CBA) - 7.7924; \qquad (10)$$

$$SSI = 0.7357(CBA)^3 - 8.2163(CBA)^2 + 20.79(CBA) - 7.0607. \qquad (11)$$
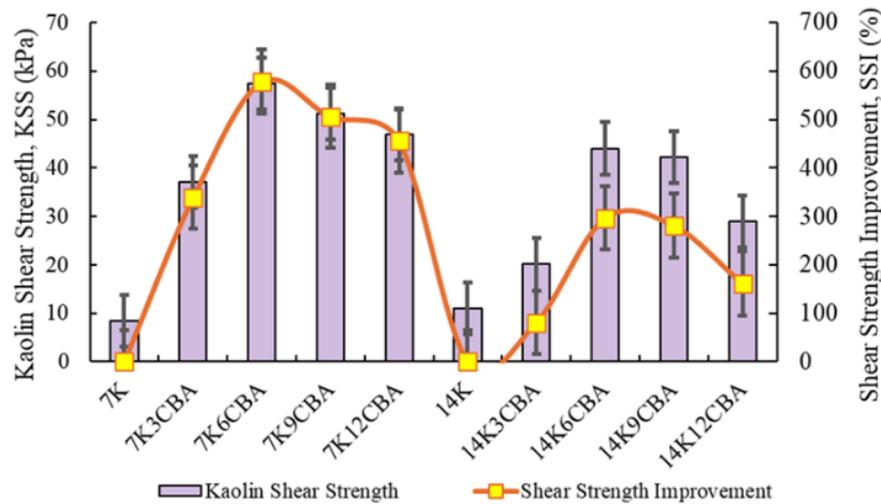
Figure 12. *Relationship between KSS and SSI rate.*
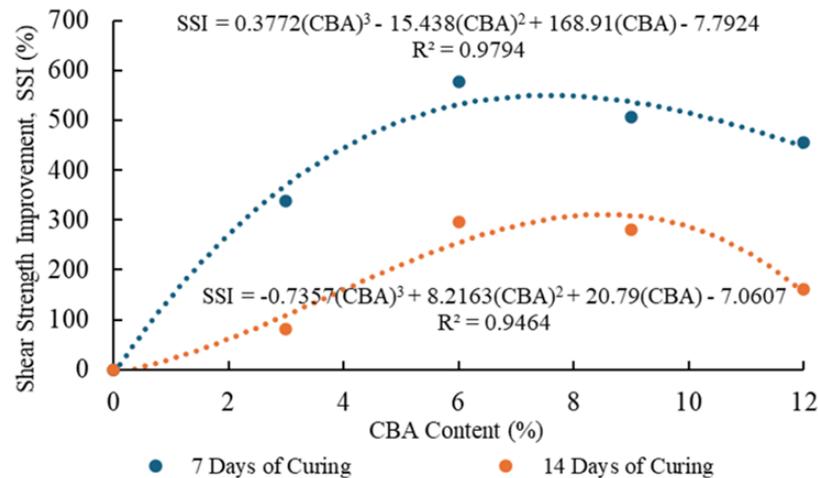
Figure 13. The correlation of SSI and its CBA content.

3.6.   Effect of CBA on the Kaolin Stress-Strain Relationship

This section discusses the stress-strain relationship of raw kaolin and refined kaolin soil, which examines their ductility, brittleness, and the peak strength across the pre-determined curing periods, 7 days and 14 days, respectively. Fig. 14 demonstrates the stress-strain relationship of raw kaolin and refined kaolin across all the CBA content, at 3 %, 6 %, 9 %, and 12 %, respectively. The maximum stress produced by 7K sample yielded at 17.29 kPa, corresponding to the strain value at 2.17 %. These data provide a comprehensive understanding that after 17.29 kPa or its peak strength, the soil failure occurs but deformation continues. It is noticed by the condition of column, and at this case, bulging of 7K sample is observed. As explained by Hasan and Yee [8], other common column failure observation under the UCT includes shear failure, buckling failure, and compression failure. With the addition of CBA content, the stress value from 7K3CBA, 7K6CBA, 7K9CBA, and 7K12CBA rise significantly. The recorded magnitude of its peak value are 61.38 kPa, 113.1 kPa, 99.28 kPa, and 68.45 kPa, aligning with the strain value of 6.32 %, 4.58 %, 6.36 %, and 8.85 %, respectively. Coherently, the optimum value of CBA content is at 6 % for the acquisition of peak stress magnitude, and the ideal substitution CBA content for obtaining strain value is at 12 %. It validates that at 6 % CBA content, the cementitious compounds, CSH and CAH have an optimum ratio, which densifies the particles evenly. In addition, the gel produces a stiffer kaolin specimen but brittle in catering shear force. Interestingly, the 12 % CBA content leads to a deformable behavior of kaolin, absorbing slowly the pressure imposed by the axial loading. On the other hands, 7K12CBA specimen possesses a systematic soil particle configuration due to the mild cementitious behavior exist on the soil mass. According to literature, the overdose CBA content causes the unreacted calcium compounds remain within the soil matrix.
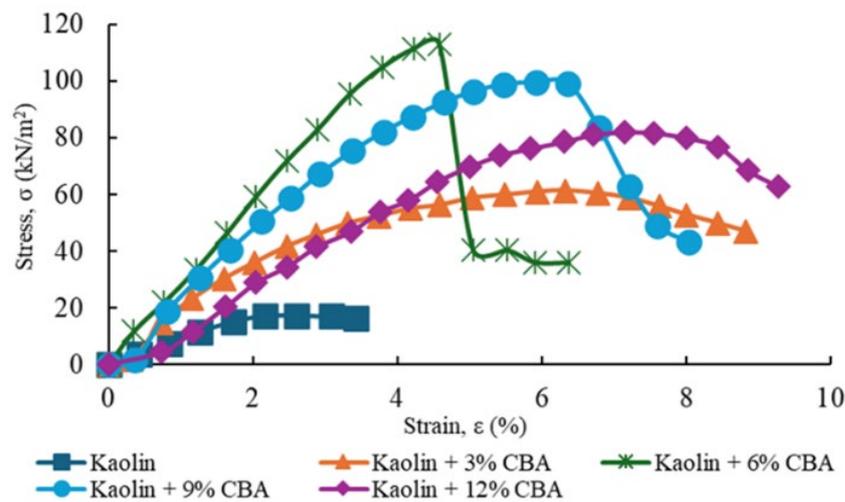
**Figure 14. Stress-strain relationship of 7 days curing kaolin
and refined kaolin at 3 %, 6 %, 9 %, and 12 % CBA content.**

Correspondingly, the stress-strain relationship of 14 days curing specimen is displayed in Fig. 15. The 14 days of curing generates the similar data as compared to 7 days of curing. Aligning to that, the gradient of all designs (includes 14K, 14K3CBA, 14K6CBA, 14K9CBA, and 14K12CBA) are less steep than the gradients of 7 days cured kaolin samples. It expresses the 14 days of curing samples possess the behavior of low stiffness and rigidity, or a lower value of Young's modulus. The peak stress from these specimens were generated at 20.21 kPa, 48.45 kPa, 81.86 kPa, 92.53 kPa, and 57.06 kPa, with the strain value of 1.97 %, 6.00 %, 4.15 %, 7.59 %, and 5.49 %, respectively. It proves that the 14 days curing is an intermediate duration for the reaction of calcium compounds and the kaolin particles to enhance its cementitious properties. Soyemi and Soretire [45] mentioned sufficient curing process leads to the value surge of rectifying parameters, however, it decreases over time because the cementitious reaction is getting completed. Although the previous data validate that the 6 % CBA content is the optimum ratio, but 14 days of curing data present the optimum percentage is at 9 % CBA content. The data discrepancy above has yielded a different of 3 % CBA content, which is minor to quantify. The mild variation of CBA proportion also provides a better understanding that curing duration has indeed imposed a substantial effect to the enhancement of stress-strain value. Conspicuously, the stress magnitude of 7K6CBA and 7K9CBA are higher than 14K7CBA and 14K9CBA, with the difference of 31.24 kPa and 6.75 kPa, respectively. Therefore, the interpretation of stress-strain relationship data deduce that 6 % CBA content association is optimum under 7 days of curing, and beyond this percentage, a longer curing period is required to stabilize the substituent and the soil.
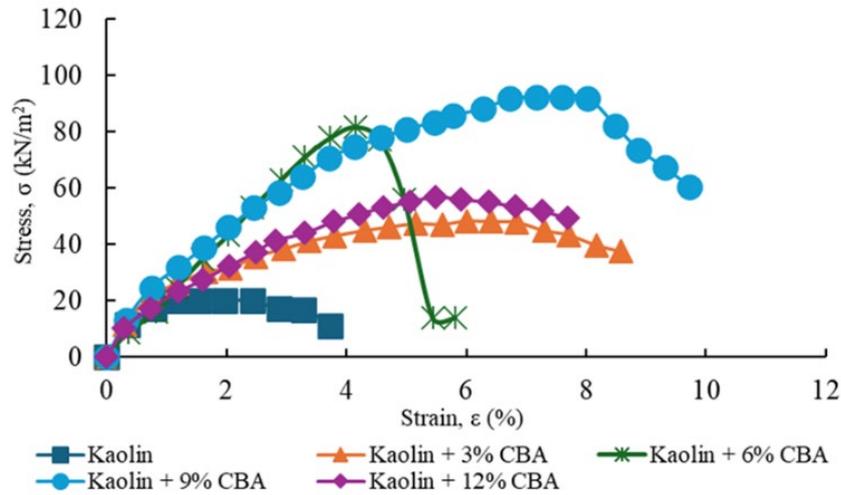
**Figure 15. Stress-strain relationship of 14 days curing kaolin
and refined kaolin at 3 %, 6 %, 9 %, and 12 % CBA content.**

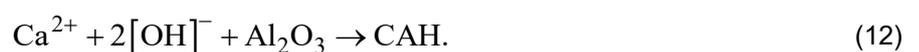### 3.7. Effect of CBA on the Kaolin Stabilization Mechanism

The generation of the greater KSS difference is attributed to the curing process, CBA association percentage, and the preparation process. However, the percentage used depends on the type of lime introduction, and the preparation procedure exerts insignificant influence if it is not mixed with reactive chemicals. Analyzing from the perspective of CBA mixture, it facilitates the cation exchange, flocculation, and pozzolanic reaction. These reactions exert a significant role in the evolution of strength via the necessary chemical and physical transformation [36]. Cation exchange is a displacement process where the introduction of CBA provides Ca^{2+} ion to displace other cation like Na^+ ion and K^+ ion which has a lower charge density. The addition of CBA has effectively raised the pH to appropriate alkaline condition, proceeding through the hydration of calcium oxide to form calcium hydroxide [46], as shown in Eq. 10. Simultaneously, the flocculation process occurs due to the electrostatic interactions between the kaolin surface and Ca^{2+} ion which clumps the dispersive kaolin particles together. The production of sufficient amount of this compound is important to source the quantity of CSH and CAH, which is CBA amount dependent variable.

Hydration reaction:

$$CaO + H_2O \rightarrow Ca(OH)_2. \tag{10}$$

Parihar and Gupta[33] emphasized the sufficient curing day can lead to a surge of rectified parameter. However, the authors also mentioned the design of curing day should correspond to the use of soil stabilizer, due to the influence of compaction efforts required to achieve the ideal proctor properties. The above statement is coherent with the current findings, where the 14 days of curing does not project a continuous rice of KSS magnitude. As reported by Jamhuri et al. [34], the sudden rise of KSS value can be due to the unacknowledged behavior of CSH, which fills the capillary pores of kaolin soil gradually. The establishment of silica link by the CSH requires a longer period to achieve a completed densified condition [32]. The rectification of soil-bearing capacity of kaolin expresses the effective pozzolanic reaction has taken place after 7 and 14 days of curing, regardless the design. The production of cementitious material accelerates the initial build-up of KSS value, causing the continuous increment at the period of 7 days. However, the 14 days of curing has somewhere probably led to the microcrack on the refined kaolin samples, which impair the soil matrix currently. The detection of microcrack can lead to the delayed pozzolanic reaction which undermines the effectiveness of CSH gel densification. Nonetheless, during the stipulated curing periods, the silicon oxide and aluminium oxide react efficiently with the calcium hydroxide, yielding sufficient concentration of CSH and CAH for the growth of kaolin strength. The chemical equations for the reactions involving calcium, hydroxide, and silicon oxide, which produce hydrated calcium compounds (CSH and CAH), are outcomes of the soil-stabilizing agent [46] and are presented in Eq. 11 and Eq. 12.

Pozzolanic reaction:

$$Ca^{2+} + 2[OH]^- + SiO_2 \rightarrow CSH; \tag{11}$$

$$Ca^{2+} + 2[OH]^- + Al_2O_3 \rightarrow CAH. \tag{12}$$

3.8.   Cost Analysis of Kaolin Stabilization Mechanism

In the focus of applying the cost-effective material, CBA in civil engineering world, developing a comprehensive data within the constraint budget is essential for the construction, development, and maintenance activities. To examine the efficiency of CBA in the technique of soil stabilization as a replacement of calcium source, it is compared with the conventional treatment which has similar characteristics, mainly the cement material. A financial viability occurs as a crucial factor that governs the decision makers across diverse alternatives. Table 5 summarizes the cost of each required materials, aligning to the relevant sources and data. The price of water and excavation are determined according to the rate set by the Malaysian government, all the prices may vary according from time to time, currency exchange, and across countries. Because of the collection method of CBA was from the local restaurants (disposal site) and was complementary, the price of CBA was considered RM0.00. However, the price of biomass varies according to collection methods, national policies, global commodity price movements, and environmental factors. Changes in any of these factors may result in additional costs for relevant parties, such as engineers seeking to replicate the current experimental program and its findings. Thus, as compared to the traditional stabilizing agent, cement, the price difference is RM0.45/kg. Table 6 is significant to outline the budget for stabilizing the clayey soil, with the details of portion and amount of soil stabilizer. Referring to the data, the amount of stabilizer required is corresponding to the portion of stabilizer, varying across the design. Therefore, Table 7 presents the total stabilization cost for cement and CBA, relative to the assumed soil quantity. As discussed by previous studies, the total amount of soil that requires to be stabilized in the current research was 10 m^3 or equivalent to 10,000kg [47].

Table 6. The data of soil stabilization framework, corresponding to its materials and prices

Material & process	Unit price (RM/kg)	Reference
Clay	0.00	[46]
Cement	0.45	[48]
CBA	0.00	NA
In-place stabilization	0.02	[47]
Water	0.00286	Suruhanjaya Perkhidmatan Air Negara (SPAN)
Excavation	0.032	Jabatan Kerja Raya (JKR)

Table 7. Details assumption of stabilizer portion and its amount based on the soil quantity at 10m³ Volume = 10,000 kg. Cement (Ce); clay soil (K); CBA

Design	Portion of stabilizer (%)		Amount of stabilizer (kg)	
	Ce	CBA	Ce	CBA
K3CBA	N/A	3	N/A	300
K3Ce	3	N/A	300	N/A
K6CBA	N/A	6	N/A	600
K6Ce	6	N/A	600	N/A
K9CBA	N/A	9	N/A	900
K9Ce	9	N/A	900	N/A
K12CBA	N/A	12	N/A	1200
K12Ce	12	N/A	1200	N/A

Table 8. Tabulation of cost analysis based on the designs, in comparing with the cement and CBA material. Total cost = (Stabilizer quantity × unit price of materials) + (In-place stabilization × soil quantity) + (Water times [OMC × stabilizer quantity] + Soil quantity) + (Excavation × soil quantity)

Design	Amount of stabilizer (kg)		Total cost (RM)
	Ce	CBA	
K3CBA	N/A	300	548.77
K3Ce	300	N/A	683.64
K6CBA	N/A	600	548.76
K6Ce	600	N/A	818.69
K9CBA	N/A	900	548.97
K9Ce	900	N/A	953.73
K12CBA	N/A	1200	549.13
K12Ce	1200	N/A	1088.77

Based on the calculated cost obtained, the price of stabilization is ranging from RM548.77 to RM1088.77, or a difference of RM540 between the type of soil stabilizer, cement and CBA across the percentage of 3 %, 6 %, 9 %, and 12 %. For stabilizing the quantity of 10 m³ of clay soil, the difference in total cost for all designs are discovered at RM134.87, RM269.93, RM404.76, and RM539.64, respectively. This in turns translates to an additional cost at 19.73 %, 32.97 %, 42.44 %, and 49.56 %. Fig. 16 depicts the cost comparison between both materials, represented by CBA stabilized-soil (red color) and cement stabilized-soil (grey color). It is deduced that when the percentage of cement increases, the total cost for soil stabilization increases more than 10 %. In contrast, the rise of CBA content does not subject to double digit cost increment, attributing to the cost-effective factor of CBA. Analyzing from the optimum portion of CBA, the total cost of stabilization is found at RM548.76. Comparing with the identical percentage of traditional soil stabilizer, cement, the total cost is calculated at RM818.69, which is equivalent to approximately 33 % of the work efficiency. The OMC of ordinary concrete is selected at five %, according to the research implemented by Pongsivasathit et al. [49]. Therefore, because of the cost-effectiveness of CBA and its lime-identical properties, it is an ideal alternative to act as a soil stabilizer in rectifying the expansive clay soil.
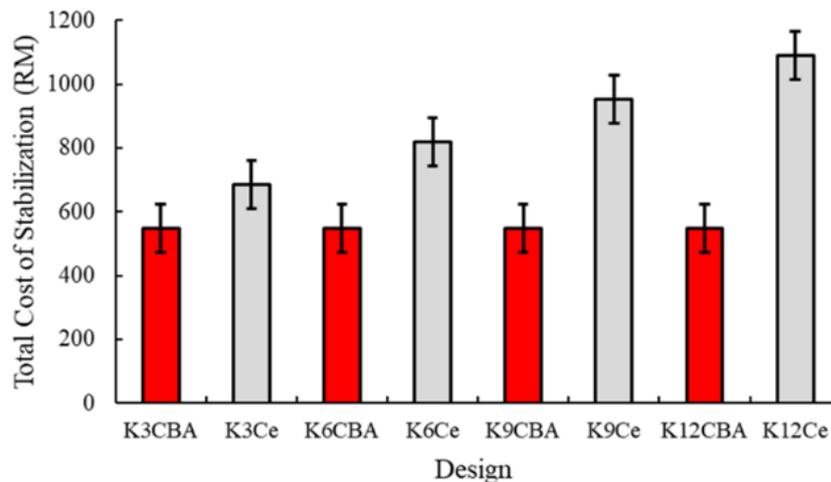

Figure 16. Cost comparison between cement and CBA for each design in this research.

4. Conclusions

A spectrum of laboratory approaches had been implemented to confirm the geotechnical properties of kaolin, CBA, and refined kaolin with different CBA content. The investigation has involved the determination of particle size gradation, consistency limits, proctor behaviors, specific gravity, rate of shear strength improvement of kaolin and kaolin-stabilized CBA soil. According to the data, there are several conclusions and recommendations can be deduced.

1. The kaolin soil particles are dispersive, with a larger proportion of grain size variation, specifically in a smaller size, for instance, 0.063 mm. With the addition of CBA at 6 % to its total mass, the grain size of kaolin has improved significantly, with more than 90 % of particle size detected at 0.15 to 0.3 mm. In addition, the consistency limits of raw kaolin proved to be unfavorable for construction activitie because of its high compressibility behavior. By adding the CBA content from 3 –12 %, the ideal substitution content is deduced at 6 %, validated by its improvement percentage of consistency limit. The LL, PL, and PI values have enhanced 2.76 %, 2.28 %, and 5.00 %, respectively. Analyzing from the standard compaction test, the promising proctor behaviors exhibited by the refined kaolin is also discovered at 6 %, provided by its OMC and MDD value at 9.42 % and 2.53 Mg/m³. It verifies that at 6 % CBA content, the pozzolanic reaction is effective to occur due to the lower value of OMC or low consumption of water. In addition, a high MDD shows that this refined kaolin has a stabilized soil matrix, even under constant compaction force. The specific gravity of kaolin is improved from 2.64 to 2.30, which yields a difference of 0.3 % or 12.88 %. It expresses a sign of dead load reduction and reinforced compaction characteristic.

2. With the assistance of UCT machine, the influence of constant rate of deformation on the soil specimen is evaluated. For 7 days of cured refined kaolin, the SSI value is recorded from 339.00–578.10 %. Similarly, the 14 days of cured refined kaolin samples present a SSI value ranges from 81.15–296.92 %. Interestingly, the largest SSI is yielded from 7 days cured samples, 7K6CBA while the smallest SSI is produced from 14 days cured samples, 14K3CBA. The above condition is attributed to the rapid grain of shear strength provided by the CAH, which leads to a sudden surge of KSS value when the CBA content is at 6 %. Coherently, the identical design of refined kaolin at

14 days reduces the KSS value drastically to 20.09kPa or a loss of 64.98%. At 14 days of curing, the moisture content inside the soil particle is still in the balancing and drying stage, which restraints certain degree of pozzolanic reaction. Therefore, the strength contributed by the expansion of silica chains link is not sufficient to compromise this situation. Combining all the above-mentioned factors and the reduction of 50 % of CBA content, the 14K3CBA specimen contributes a mild improvement in terms of shear strength. Thus, it is concluded that 6 % CBA content cured at 7 days produces an optimum value of shear strength.

3. The establishment of cost-analysis framework provides a comprehensive set of data by comparing the utilization of conventional material and sustainable substituent. For the sake of aligning experimental program with industry-scale execution, the materials and processes applied in the fieldwork are extracted based on the actual costing in the market. By replicating the current designs, the total cost of stabilization for cement ranges from RM683.63–RM1088.77 for a quantity of 10,000 kg clayey soil. Notably, the total cost of stabilization using CBA is from RM548.77–RM549.13 for the same volume of soil stabilization. Based on this system, it optimizes the cost from 19.73–49.56 %, concerning the replacement ratio of 3 %, 6 %, 9 %, and 12 %, respectively.

4.1. Limitations and Recommendations for Future Research

1. The study assumes that all kaolin and refined kaolin specimens with CBA were prepared homogeneously, with no impurities contained within the specimens. The specimen dimensions were fabricated at 50 mm and 100 mm; therefore, any insignificant variations were disregarded during the execution of the UCT.

2. The entire experiment was conducted at laboratory scale, and the procedures can be conveniently replicated using other types of biomass and industrial materials to verify their effectiveness in soil stabilization.

3. Similarly, incorporating advanced geotechnical approaches, such as triaxial testing, may provide a more comprehensive understanding of the engineering behavior of kaolin, CBA, and refined kaolin with varying proportions of CBA content.

4. A detailed analysis of market price fluctuations, including acquisition costs, transportation costs, currency variations, and international trade policies should be undertaken before replicating the cost analysis results derived from this research.

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