Magazine of Civil Engineering

ISSN
2712-8172

journal homepage: http://engstroy.spbstu.ru/

Research article

UDC 624

DOI: 10.34910/MCE.130.3

Effects of chicken bone powder mixed with limestone and cement on the clayey soil geotechnical characteristics

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Keywords: clayey soil, soil stabilization, waste chicken bone powder, strength improvement, unconfined compressive strength

Abstract. Soil stabilization is aiming to enhance the geotechnical properties of soils. Traditionally, it has relied on conventional materials, such as cement and lime. However, the growing awareness of environmental sustainability has prompted researchers to explore alternatives, including waste. The employment of waste helps reduce waste deposited in landfills and decrease greenhouse gas emissions. The literature revealed that adding wastes to clay significantly improves clay's mechanical characteristics. This study has identified alternative methods of trash disposal that would be economically and environmentally beneficial. The effect of chicken bone powder with limestone and cement on clay has been investigated. Liquid limit and plasticity index have decreased, and unconfined compressive strength of samples treated with 10%CBP+5%LS and 10%CBP+5%C up to 28 days have been increased by 2.69-fold and 4.82-fold, respectively. A reduction in the soil's cohesion from 37.079 to 35.115 kPa and an increment in the internal frictional angle from 0.66° to 2.10° has been discovered for the mix of 10%CBP+5%LS. Compression and swell index reductions were observed with the addition of 10%CBP+5%LS and 10%CBP+5%C. From scanning electron microscopy, the binder materials caused the samples to indicate a dense and compact matrix and reduced the porosity.

Citation: Salih, A.G., Rashid, A.S., Salih, N.B. Effects of chicken bone powder mixed with limestone and cement on the clayey soil geotechnical characteristics. Magazine of Civil Engineering. 2024. 17(6). Article no. 13003. DOI: 10.34910/MCE.130.3

1. *Introduction*

Soil quality is an essential consideration in infrastructure development [1]. The geotechnical challenges associated with varying site conditions can be mitigated through adjustments in foundation design and soil stabilization techniques [2, 3]. By adapting these methods to the specific needs of a project, engineers can ensure the long-term stability and safety of buildings, roads, and foundations, contributing to sustainable infrastructure development [4, 5]. Soil stabilization techniques might be the most cost-effective way to solve the issue depending on the required particulars. Soil stabilization is the process of modifying soils physically and chemically to improve their mechanical characteristics [6]. The primary objectives of soil stabilization include increasing load-bearing capacity, reducing soil settlement, enhancing soil durability, and mitigating environmental impacts.

To enhance the shear strength of soils, numerous stabilizing methods and additives have been used for a period of time. The two main techniques used nowadays to increase shear strength are either stabilization techniques can be mechanical or chemical. Compaction or the addition of fibrous and other non-biodegradable reinforcement to the soil are two examples of mechanical stabilization. Further, chemical stabilization involves the addition of chemicals or other materials to enhance the ongoing soil.

Portland cement (C), lime (L), fly ash, bitumen, calcium chloride, cement kiln dust, steel slag, limestone (LS), enzymes, and many other natural materials are a few of the chemicals or materials used today [7–15].

The majority of frequently used soil-stabilizing substances, such as C, L, and coal fly ash, all contain variable amounts of calcium. One of the most common, widely applicable, and simple methods for improving the geotechnical characteristics of clayey soils is by using L and C stabilization [16, 17]. Calcium, the essential component required for stabilizing soil and enhancing its strength, can be provided by both L and C. The availability of calcium varies depending on the type and purity of L employed as a stabilizing agent. The chemical reaction between L and soil consists mostly of two phases. When adding L, the first phase, sometimes referred to as an immediate or short-term treatment or stabilization, starts to take place within a few hours or days. At this step, three primary chemical processes occur – cationic exchange, flocculation-agglomeration, and carbonation. It may take months or years to finish the second phase, which makes up the majority of the pozzolanic reaction. It is regarded as a long-term treatment [4, 16, 18]. While L has some benefits in lowering the plasticity index (PI) of very plastic soils [19], C has the feature of enhancing soil strength in addition to decreasing the PI. The reaction between the silica from the soil and the $Ca(OH)_2$ from the L might result in the formation of C-S-H in L-soil systems [15]. A pozzolanic reaction is the name for this process. Additionally, calcium and alumina may combine to form the cementitious compound C-A-H [20, 21]. In this context, when C hydrates, it composes C-S-H and produces $Ca(OH)_2$, whereas the pozzolanic reaction produced known as C-S-H has been proven to be crucial for maintaining and enhancing soil's engineering qualities [19, 21, 22]. Generally, the C stabilization method demands the addition of 5 to 14 % C by the volume of the compacted mixture being stabilized [23, 24]. Bhuvaneshwari et al. [25] and Anggraini et al. [26] reported that 5 % L additive is a sufficient amount for the stabilization of dispersive soils.

Basically, conventional stabilizers like C and L have been widely used but raise concerns related to carbon emissions and resource consumption. As a result, there is a growing interest in utilizing waste materials as alternatives for soil stabilization, aligning with the principles of sustainability and circular economy.

Many studies revealed that the characteristics of soil strength, compaction, and settlement are considerably enhanced by the addition of various waste materials to parent clay. Essentially, the resulting mechanical properties depend mainly on the type of the added mineral and treatment duration [27, 28]. When bones are burned (calcinated), white, powdery ash is remaining. Calcium phosphate is the main component. Tricalcium phosphate, or $Ca_5(OH)(PO_4)_3$, represents the hydroxyapatite form of bone ash [29, 30]. Ayininuola and Akinniyi [29] stated that bone ash is chemically inert, free of organic matter, and has very high heat transfer resistance; it also has good non-wetting features. Ayininuola and Shogunro [31] carried out laboratory investigations to study the influence of bone ash on soil shear strength and revealed that bone ash had a significant role in increasing its shear strength. The shear strength of the soil was increased by between 22.4 and 105.2 % above the strengths of the corresponding control tests when bone ash was added to soil samples. On the other hand, all samples reached their highest shear strengths at 7 % stabilization with bone ash [31, 32]. However, there is still cause for concern regarding the embodied energy used to produce bone ash. This is because, notwithstanding the benefit of minimizing the environmental pollution caused by these wastes, calcining bone ash at a temperature of between 650 and 900 °C after open-air burning has a high cost [33, 34].

To address problems related to soil instability, researchers are now creating and investigating effective uses for agricultural and environmental waste products. This study has identified alternative methods of trash disposal that would be economically beneficial and environmentally friendly. Thus, the study aims to investigate the possibility of utilizing waste chicken bone powder (CBP) – which is yet material containing calcium – as a soil stabilizer. Therefore, to improve clayey soils, the utilization of waste CBP as well as LS and C as partially eco-friendly alternatives was investigated in the current study. For samples of clayey soil, the additives were put in a variety of percentages. Then, to investigate the potential of such additives in reducing the LS and C content as well as improving the engineering properties of the clayey soil, a comparative analysis was made between the CBP-LS-treated soil mix and the CBP-C-treated soil mix.

2. Materials and Test Methods

2.1. Materials

2.1.1. Soil

The clayey soil in southern parts of Sulaimaniyah City was investigated for this research. As a result of weathered portions of the parent rock and foraminifera in the soil, the deposit in this location is primarily made up of soft dark grey, silty clay, and clayey silt. Soil samples were taken from a depth near the surface, put in plastic bags, and transferred to the laboratory. Classification tests were carried out based on the ASTM standards [35–38] to determine the priority geotechnical properties of the collected soil. The natural water content in the soil sample used in this investigation ranged from 23 to 34 %. As illustrated in Fig. 1(a), the preliminary observation of the soil revealed that it is fine-grained soil. By performing the basic tests required for soil classification, the characteristics of the soil were determined. The soil sample contains 51.17 % clay, 45.44 % silt, and 3.39 % sand, according to the results of the sieve analysis and the grain distribution curve shown in Fig. 2. Moreover, the basic properties of the soil sample are 2.67 specific gravity, 48 % liquid limit (LL), 23 % plastic limit (PL), and 25 % PI. Table 1 lists the geotechnical characteristics of the soil. The natural soil sample was classified as low plasticity clay (CL) by the Unified Soil Classification System (USCS) [39]. The compaction test was conducted to obtain the optimum moisture content (OMC) and maximum dry density (MDD) of the natural soil sample as presented in Table 1. These results were used for the preparation of remolded soil samples for the study tests. Fig. 3 present the scanning electron microscope (SEM) micrograph and its elemental spectrum of the studied soil.

2.1.2. Chicken bone powder

Chicken bones were collected from the waste of food. The bones were carefully washed with water multiple times, released from the meat, and then rinsed once more repeatedly to get eliminate any surface impurities. Firstly, the bones were air-dried and then put in the oven at 50–60 °C to ensure they were fully dry. Then a grinder was used to crush the dried bones into a homogeneous mixture as presented in Fig. 1(c). Accordingly, the study employed an average particle size of less than 425 μm, which was obtained using a sieve size of 425 μm (sieve No. 40).

2.1.3. Crushed limestone

The sample of crushed LS used in this study was obtained from the Tlazait crusher in Iraq, which is located 30 kilometers to the southeast of Sulaimaniyah city. The crushed LS was chosen as a waste material. The waste LS used was easily crushed, whitish, and had a sub-rounded particle shape. To employ the crushed rock for laboratory use, it was passed through sieve No. 40 (425 μm) as indicated in Fig. 1(b). The sample of crushed LS had a specific gravity of 2.81 according to the ASTM standard [38].

2.1.4. Cement

For the present study, the required amount of Bazyan Portland cement was obtained locally and used as a soil stabilizer additive. Both C and LS have a pozzolanic reaction that requires a period of time. They will create bonds among soil particles that tie them together and hence result in a strong soil structure.

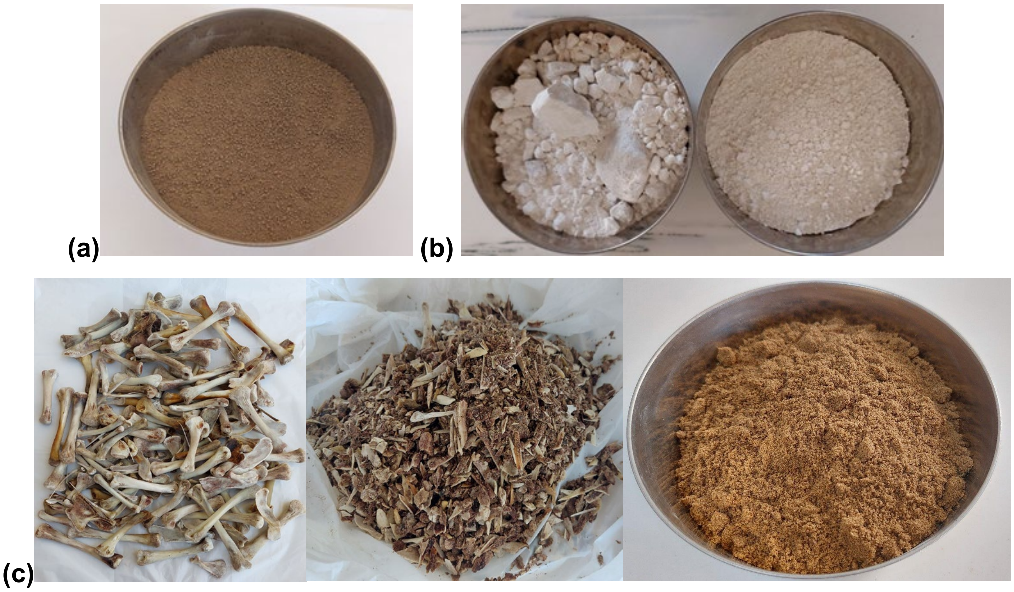

Figure 1. The materials used (a) clayey soil, (b) limestone, and (c) waste chicken bone.

Table 1. Geotechnical properties of clayey soil.

Physical properties	Clay	Standard
Liquid limit, %	48	ASTM D 4318
Plastic limit, %	23	
Plasticity index, %	25	
Sand content, %	3.39	ASTM D 422
Silt content, %	45.44	
Clay content, %	51.17	
Passing sieve no. 200, %	96.61	
Soil classification	Lean Clay	ASTM D 2487
Optimum moisture content, %	20	ASTMD 698
Max dry density, g/cm^3	1.694	
Specific gravity, G_s	2.67	ASTM D 854

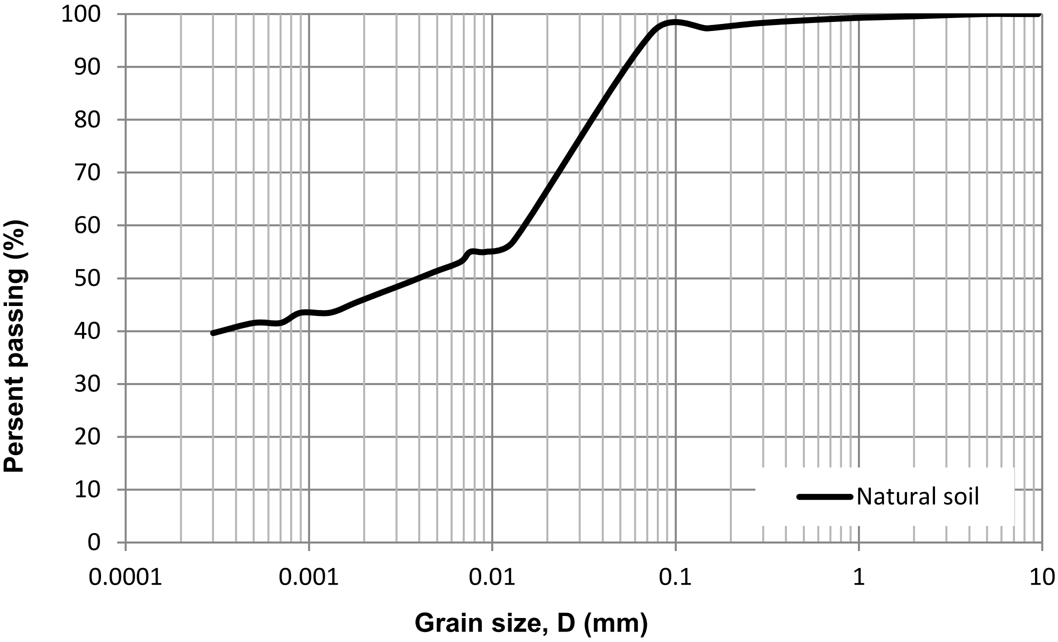

Figure 2. Grain size distribution curve for the natural clayey soil.

Table 2 lists the materials' chemical compositions by the weight percentage of the total chemical composition as determined by X-ray fluorescence (XRF) testing. Table 2 shows that the clay soil sample has a high content of silica (SiO_2 = 49.4 %) and a lower content of alumina (Al_2O_3 = 9.25 %).

On the other hand, the oxide composition of the LS showed that it consisted of majorly of calcium oxide (87.12 %) with traces of magnesium oxide (0.96 %), silicon oxide (0.6 %), and potassium oxide (0.1 %). Furthermore, C was mostly consists of calcium oxide (65.03 %) and silicon oxide (18.4 %), whereas CBP mostly consists of calcium oxide (53.25 %), phosphorus pentoxide (37.46 %), and silicon oxide (1.5 %). Ojuri et al. [4] reported that cow bone powder does not contain enough calcium oxide to be considered a cementitious material.

However, Adeyemi et al. [40] have noted that when employed that cow bone powder as a partial substitute for L in the presence of water at room temperature, it produces insoluble compounds with cementitious capabilities.

Table 2. The chemical composition obtained from (X-ray fluorescence analysis) of the natural soil and the additives for soil stabilization under study.

Chemical compound	Minerals	Clay soil, %	Chicken bone powder, %	Limestone, %	Cement, %
Silicon dioxide	SiO_2	49.4	1.5	0.6	18.4
Sulfur trioxide	SO_3	0.44	1.74	0.58	
Iron (III) oxide	Fe_2O_3	6.37	0.26	0.15	2.537
Aluminum oxide	AL_2O_3	9.25	0.7	0.49	3.439
Calcium oxide	CaO	16.45	53.25	87.12	65.03
Magnesium oxide	MgO	9.003	1.77	0.96	2.748
Potassium oxide	K_2O	4.28	0.48	0. 1	
Chlorine	Cl	0.7		0.0013	0.013
Sodium oxide	Na_2O	–	0.016	0.0031	
Phosphorus pentoxide	P_2O_5	0.07	37.46	0.02	
Tricalcium aluminate	C_3A	–	–	–	4.83

The SEM micrograph of untreated clay is displayed in Fig. 3. The image illustrates the detection of hexagonal particles and the flaky texture of the clay, which almost disappeared after the addition of additives as presented in Fig. 10.

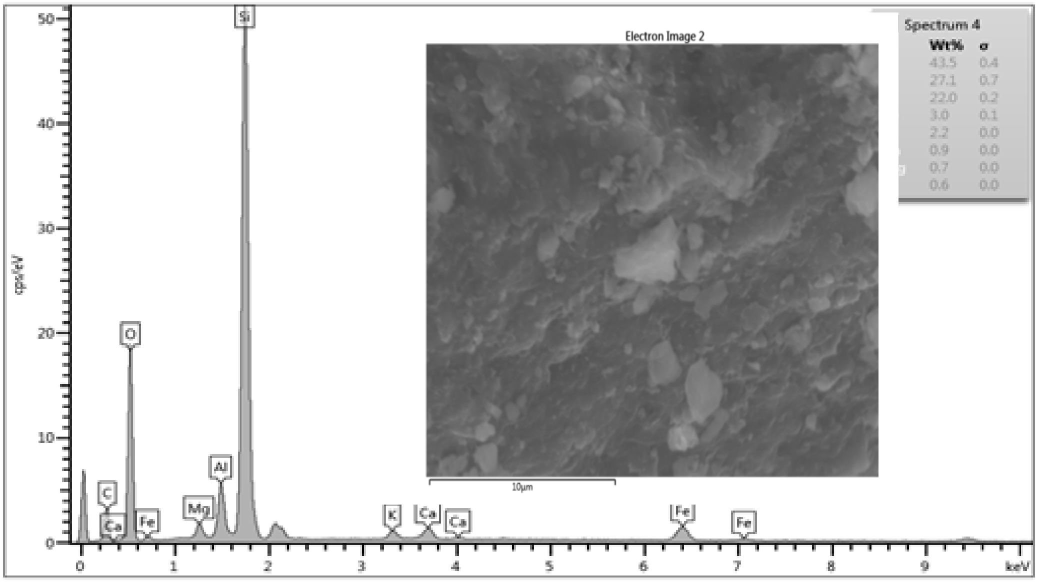

Figure 3. SEM image of clay soil.

2.2. Sample Preparation and Methods

The soil sample was put in the oven at 110 °C, then left to be dried for 24 hours. The soil sample was well mixed after being pulverized with a plastic mallet and then passed through a No. 4 sieve on a flat surface to achieve a uniform distribution. In order to investigate the geotechnical characteristics of the treated clayey soil, and look into the impact of the CBP with a separate mix of LS, or C, some of the geotechnical experiments, such as the Atterberg limit, unconfined compressive strength (UCS), direct shear, and 1-D consolidation tests were conducted. All samples were remolded using the moist tamping method with a dry density of 1.694 g/cm^3 (95 % of MDD), and 20 % water content (OMC). The compaction characteristics of soil samples were evaluated using the Standard Proctor test and as presented previously in Table 1. Manual mixing was used in every part, and each step was monitored carefully to ensure a uniform mixture. The samples, which had been carefully compacted in particular molds prepared for each experiment, were taken out of the molds, placed in plastic bags, and kept in safe containers at about 25 °C in the laboratory for various treatment periods.

SEM and X-ray diffraction (XRD) analysis were carried out to obtain a better understanding of the microscale's interaction mechanism of the CBP and the soil particles, in addition to the LS and C mixture. The central zone of the samples was used to collect the specimens.

According to ASTM D2166/D2166M-16 [41], the UCS tests were carried out on cylindrical samples with dimensions 38 mm in diameter and 76 mm in height for both the untreated and treated remolded soil samples. The samples were remolded and then sealed in plastic bags and cured at constant humidity and room temperature of 25 °C to allow for chemical reaction. The soil was mixed with the specified distilled water to produce the necessary water contents.

Firstly, the soil was treated with CBP of 2.5, 5, 7.5, and 10 % of the total dry weight of the soil at curing time periods of 7 days in order to evaluate the effect of time on the strength of the treated materials for UCS tests. To compare the UCS behavior of the tested samples, the stress-strain curves were plotted.

Secondly, other samples were prepared for each additive with the optimum value of the CBP, obtained from the results of UCS tests as mentioned in the previous step. Both crushed LS and C were added individually to the optimum value of CBP with the clay soil mix by utilizing the replacement method with percentages of 5 % in order to increase the soil's bearing capacity and stiffness. This dosage was selected for subsequent experiments and tests.

In a similar manner, separated mixtures of soil, 10%CBP+5%LS, 10%CBP+5%C, and 20 % of water content were prepared in order to be used for the direct shear tests. The prepared mixtures were then placed into the direct shear test squared mold of 60 × 60 × 20 mm in accordance with ASTM D3080 standard [42]. The direct shear test samples were made, sealed with a plastic bag, and allowed to cure for 28 days. To determine the shear strength parameters, shear stress-normal stress curves were developed (internal friction angle and cohesion).

The intention of the 1-D consolidation test is to determine the compressibility characteristics of the soil samples on the remolded samples of treated and untreated soil. The ASTM D2435 standard [43] provides the basis for the test. The consolidation tests were carried out over a single curing time period of 28 days. Brass oedometer rings of 50 mm in diameter and 19 mm in height were used for all consolidation tests. The additional load that was imposed was twice as much as the previous one. Thus, with a loading interval of 24 hours, the samples were loaded gradually as 2, 4, 8, and 16 kg. At 2 kg of normal stress, the unloading was accomplished. In order to plot the compression curves (void ratio versus applied vertical stress), the deformations of the samples during the test were recorded.

However, these materials and additives percentages were used and compared in order to address the strength development of materials to evaluate the best combinations of soils and stabilizing agents.

3. Results and Discussion

3.1. The Effect of the Additives on the Consistency Limits

The results obtained from this study showed that the LL and PI decreased with the addition of binders. For the sample treated with 10%CBP+5%LS, there was a reduction in the PI values from 25 to 20.59 % due to the LL value decrease from 48.1 to 43.09 %, and the PL value decreased from 23 to 22.5 %. In addition, in the treated sample with 10%CBP+5%C, the PI value decreased from 25 to 11.07 % due to the LL value decrease from 48.1 to 39.1 %, and the PL value increased from 23 to 28.03 %.

The remarked behavior may be due to the partial replacement of the plastic soil particles with CBP and other binders that are non-plastic material with a reduction in clay content. Basically, the amount of clay in the soil controls its plasticity, which decreases as the percentage of clay fractions decreases [1, 29, 44, 45]. Further, chemical reactions between the soil and the binders may be responsible for this reduction. The significant reduction in LL for the sample treated with 10%CBP+5%C may be caused by the rapid hydration of the C that leads to a decrease in the amount of water available in the mixture to be absorbed by the other contents.

Abdalqadir et al. [46] reported in their study on clayey soil stabilization with LS that the reduction in the double-layer thickness of clay particles was the matter of this reduction in constancy limits, which was caused by the cation exchange reaction, which increases the attraction force and causes the particles to flocculate.

3.2. The Effect of the Additives on the Unconfined Compressive Strength

Unconfined compressive strength values are considered the primary criterion for evaluating the enhanced strength of the treated soil [47, 48]. Fig. 4 displays the relation stress versus axial strain for treatment duration of 7 days for samples containing soil with CBP of 2.5, 5, 7.5, and 10 % mix. These curves illustrate the effect of CBP on the UCS of clay soil samples. The UCS of the untreated sample was 66.6 kPa. However, there are considerable increases in the UCS values of all CBP-clay samples. It can be seen that the UCS increased and reached its maximum resistance with the addition of CBP of up to 10 % as the UCS was 120.133 kPa, and the UCS of the clayey soil was increased by 80.29 %.

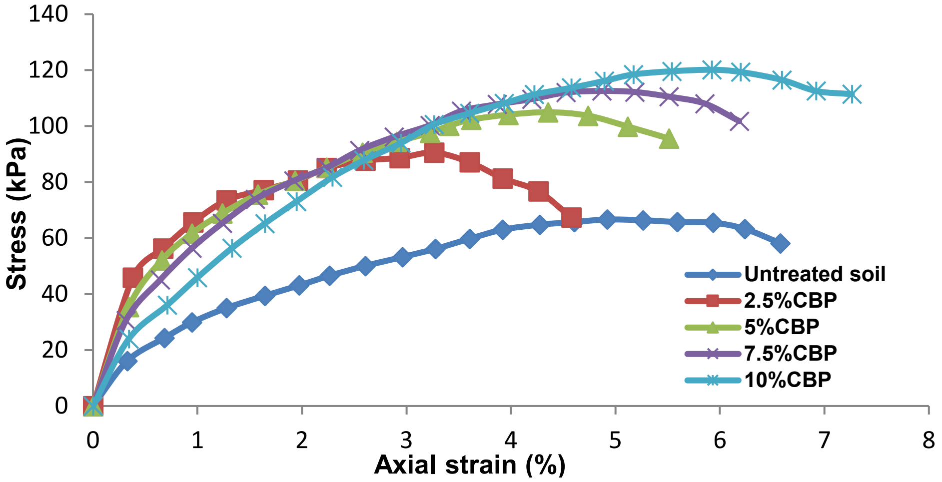

Figure 4. UCS results for different CBP % contents.

Furthermore, the achieved results showed that by increasing the CBP dosage, the strength increased and the failure strain increased accordingly, besides, the treated sample stiffness was decreased. The failure strain of the treated soil increased from 3.26 to 4.35, 4.86, and 5.92 % for the 2.5, 5, 7.5, and 10 % of CBP mix, respectively, showing an increase in flexibility. Overall, the treated soil samples exhibited more stiffness than the untreated soil samples. Therefore, the addition of LS or C was suggested for the soil stiffness and brittleness enhancement.

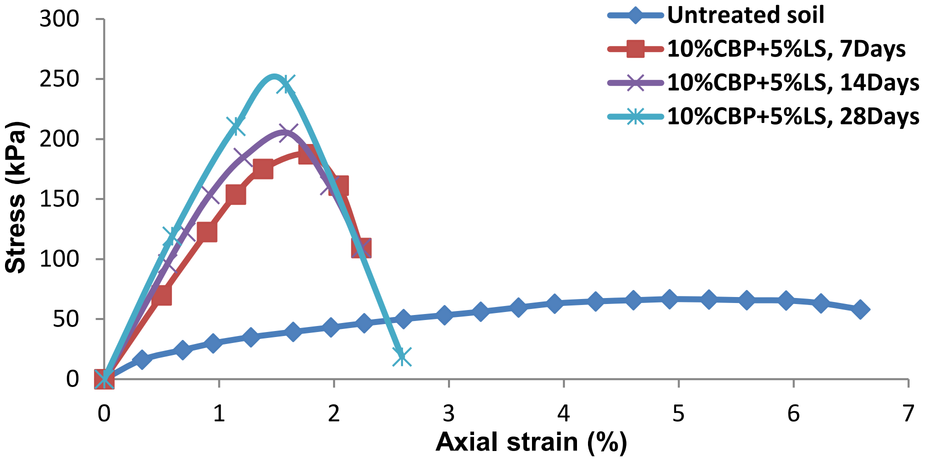

Figure 5. UCS results of 10%CBP+5%LS contents with different curing ages.

Fig. 5 illustrates the UCS results for samples treated with 10%CBP+5%LS contents. By comparing the result of UCS as presented in Figs. 4 and 5 for curing ages of 7, 14, and 28 days; all samples provided more strength and less ductility at failure strain compared to the untreated soil sample and the samples treated with CBP only. The failure strain decreased from 4.92 % for untreated soil to less than 2 % for treated soil showing decreased flexibility, thus, the brittleness of the treated samples with 10%CBP+5%LS further increased and subsequently resulted in non-plastic deformation.

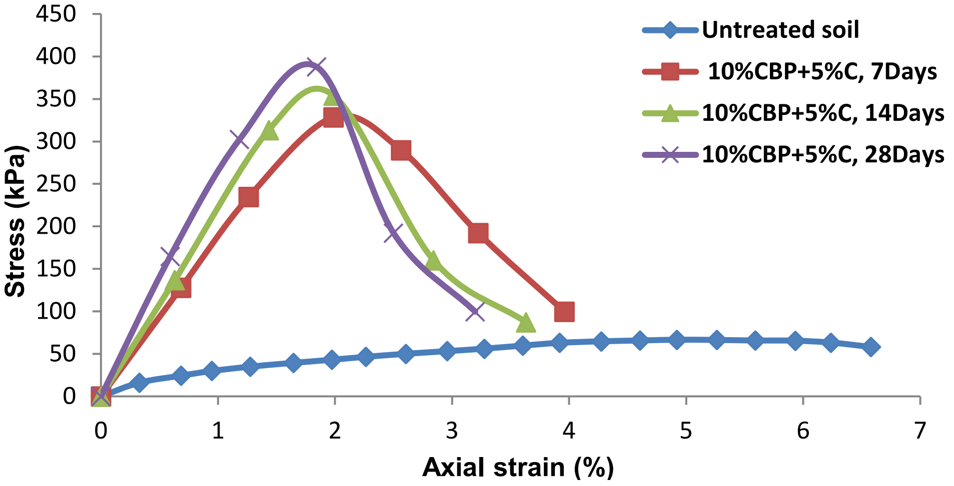

Figure 6. UCS results of 10%CBP+5%C contents with different curing ages.

The pozzolanic reaction property of the LS and C increases the strength of the treated soil, but as the plasticity of the soil is decreased by the addition of additives, the soil sample becomes more brittle.

Similarly, after the treatment duration of 7, 14, and 28 days, samples treated with 10%CBP+5%C represented more UCS strength but less ductility at failure strain compared to the untreated samples and samples treated with only CBP as presented in Fig. 6. The failure strain decreased from 4.92 % for untreated soil to less than 2 % for treated soil showing less flexibility and more brittleness. This behavior may come as a result of the influence of cementation reactions on the reduction of soil plasticity.

Due to the time effect, which created the environment for long-term pozzolanic reactions, the specimens' ductility decreased, therefore, extending the curing time improved the development of mechanical strength, which was caused by the completion of chemical reactions.

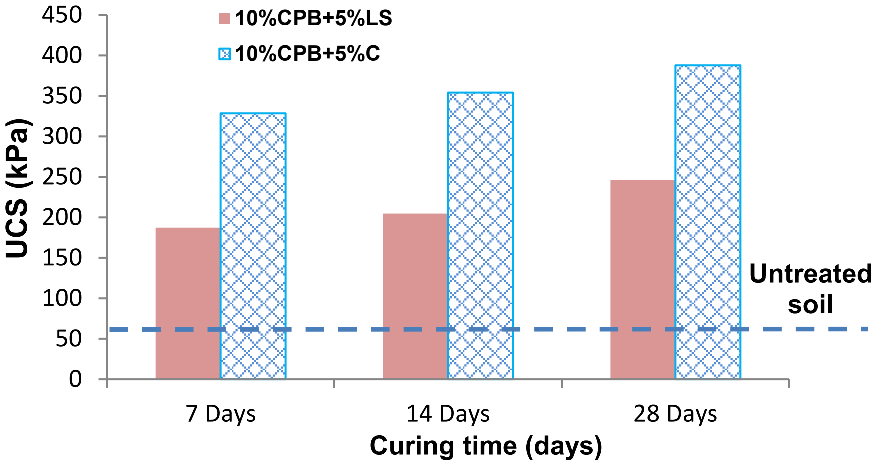

Figure 7. Effect of additives on the UCS of clayey soil.

Overall, for the resulting material, the UCS values of C-treated soil were higher than the LS-treated soil at all curing days as illustrated in Fig. 7. For samples treated with 10%CBP+5%LS and 10%CBP+5%C up to 28 days; the strength was increased by more than 2.69-fold and 4.82-fold, respectively, compared to the UCS of the untreated sample. Thus, using C is ideal when strength improvement is required. Two elements may be involved in Portland cement's ability to acquire increased strength. Firstly, the $Ca(OH)_2$ crystals produced as a by-product of the hydration of calcium silicates are significantly more reactive as they are pure and fine. This gives the required calcium for the ion exchange process. Secondly, with the hydration of C, a stiff network was created similar to that in mortar or concrete which mainly depends on the amount of the added C. This variation in the utilized material may be of significant employ when various properties are required from the same soil.

A study conducted by Ojuri et al. [4] concluded that the cow bone powder and L efficiently reacted to form cementitious materials that improved the soil's strength properties. The results obtained from the present study agree with the findings of Ojuri et al. [4], and Adeyemi et al. [40].

3.3. The Effect of the Addition on Shear Strength Parameters

Fig. 8 shows the effect of different additives on clay soil results from the direct shear test. Cohesion and angle of internal friction are each determined by the y-intercept and line gradient, respectively. With the addition of CBP and LS or C, the strength of soil samples increased. This strength increase was due to water content reduction in the treated samples. While the pH-raising additives create an ideal environment for the stabilizing process, so the soil density tends to increase upon stabilization. Based on Table 3, the samples treated with the CBP-C content reached the highest shear strength with the cohesion of 48.143 kPa in comparison with the strength of samples treated with CBP-LS or untreated clayey soil strength. As well known, soil plasticity is a factor that controls the corresponding cohesion of the samples. It was presented earlier that the addition of 10%CBP+5%LS and 10%CBP+5%C reduced the PI of the mixture by 17.64 and 55.72 %, respectively. Therefore, with the addition of CBP-C content, there is a noticeable increase in cohesion, and further, the angles of internal friction increased up to 1.54°.

In contrast, the addition of 10%CBP+5%LS reduced the cohesion to 35.115 kPa, while the internal friction increased to 2.1°. Results indicated that the LS content had a greater influence on the friction angle than the cohesion and that relatively controlled by the surface friction of the particles, which has a great impact on the structure and stability of the sample. It is evident that because of the relatively significant amount of coarser particles in samples that had appeared, the larger particles in the samples were broken and filled with pores during the shearing test process, which makes the adhesion between particles lesser, and further decreases the soil's cohesion. Thus, the friction force on the particle surface is increased and soil cohesiveness is decreased as a result of the particles' evident edge angle.

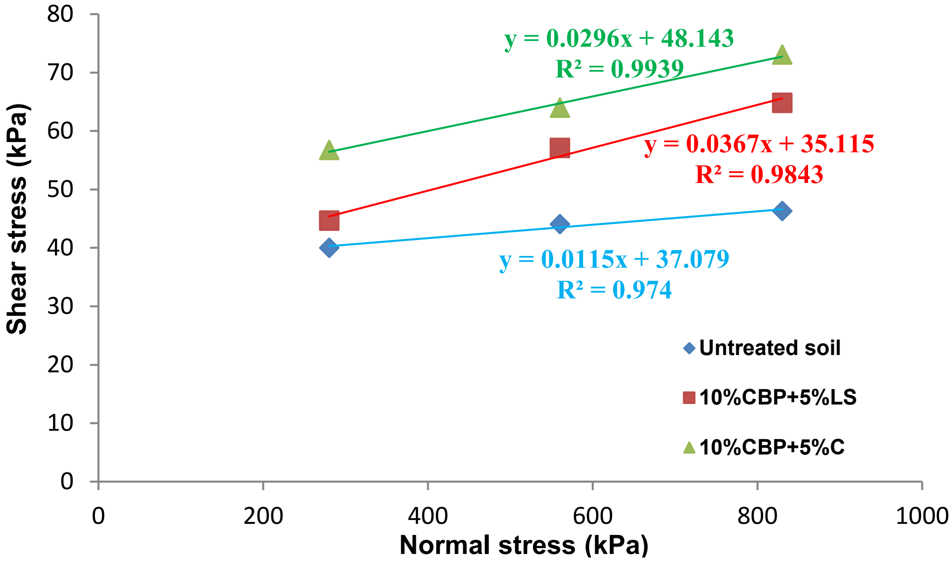

Figure 8. Strength envelope lines of untreated and treated soil.

Table 3. Cohesion and angle of internal friction for samples with different material additives.

Sample description	Untreated sample	Soil+10%CBP+5%LS	Soil+10%CBP+5%C
Cohesion (kPa)	37.079	35.115	48.143
Angle of shear resistance (°)	0.66	2.10	1.54

These results showed a good agreement with results obtained by Ojuri et al. [4]; the 10%L addition improved the internal friction while reducing the soil cohesiveness. Moreover, 6% L + 7 % cow bone powder + 1 % plastic waste stabilized low plasticity soil showed a similar pattern thus, with the addition of additive materials, the soil cohesiveness decreased, while the angle of internal friction increased [4].

3.4. The Effect of the Addition on Compressibility Characteristics

As seen in Fig. 9, the coefficients of consolidation (C_c) and the expansion index (C_r) decreased with the addition of the stabilizing binder 10%CBP+5%LS and 10%CBP+5%C. With the addition of 10%CBP+5%LS, the values of C_c and C_r decreased by 71.07 and 1.84 %, respectively. Likewise, the value of C_c and C_r decreased by 74.21 and 54.6 %, respectively for samples treated using 10%CBP+5%C. The reduction in C_c and C_r comes as a result of the influence of the stabilizing additives on reducing the void ratio among the clay soil particles in the treated samples, as well as the stiffness increase contributed to this reduction. From all curves, it can be observed that clayey soil with CBP achieved the lowest C_c and C_r

with the addition of C compared to LS. Therefore, the addition of 10%CBP+5%LS and 10%CBP+5%C to the clayey soil will reduce its settlement potential. These results agree with the findings of Ojuri et al. [4].

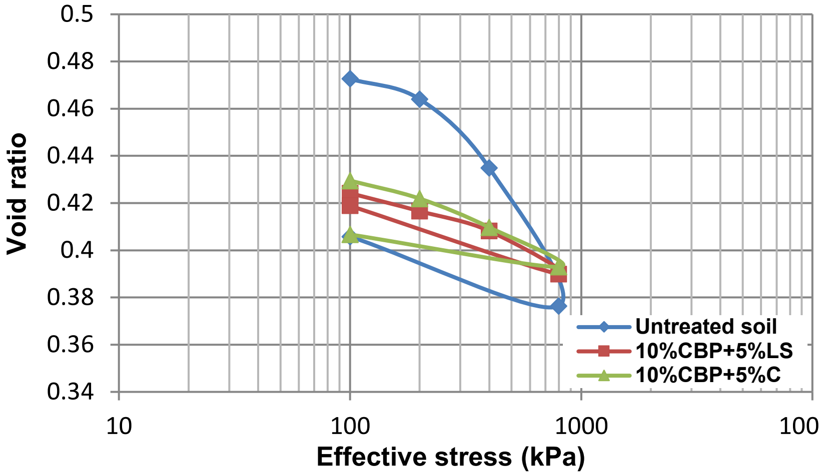

Figure 9: Void ratio versus effective stress curves from the consolidation test on untreated and treated soil with 10%CBP+5%LS and 10%CBP+5%C.

3.5. Microstructural Mechanisms of the Additives Mix on the Microstructure

As seen in Fig. 10(a), untreated clayey soil has large voids between the soil particles to appear as dark patches. The microstructural analysis utilizing SEM indicated denser materials for the treated samples which resulted in decreasing the voids between the soil particles as shown in Fig. 10(b), (c), and (d). The particles of these denser materials have closer contact and stronger bonding due to the addition of 10 % of CBP as the soil stabilizer as clarified in Fig. 10(b). Thus, increasing the soil density will enhance the compressive strength of the treated clayey soil as presented in images (c) and (d) for samples treated with 10%CBP+5%LS and 10%CBP+5%C, respectively.

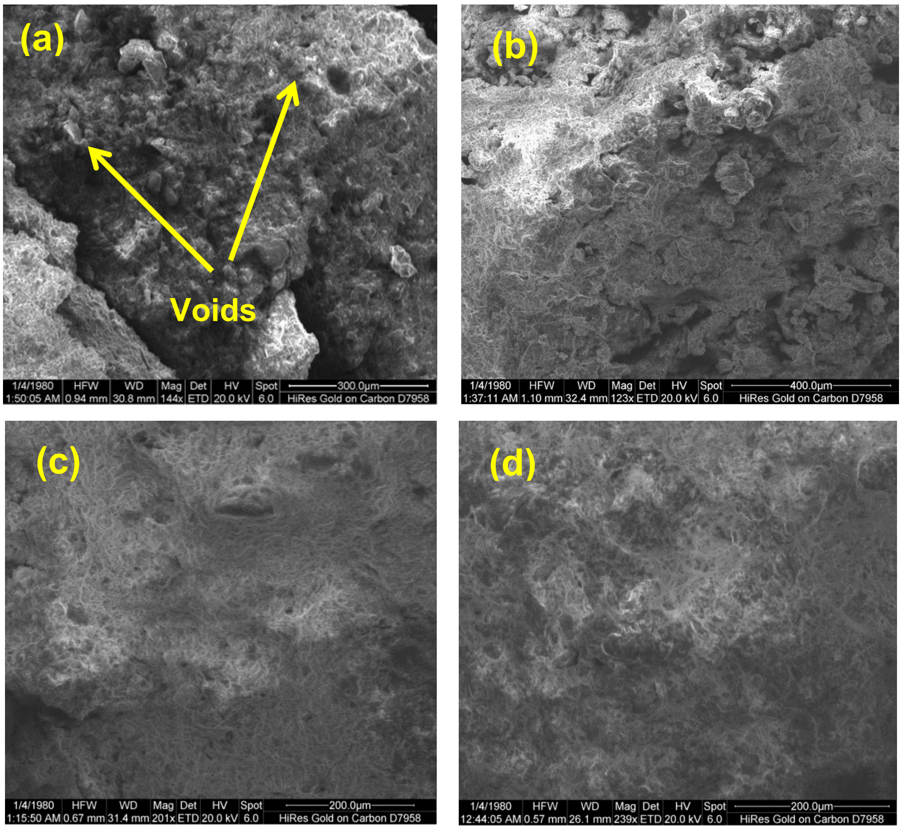

Figure 10. SEM images of (a) untreated soil, (b) sample treated with 10%CBP after 7 days, (c) sample treated with 10%CBP+5%LS after 28 days, and (d) sample treated with 10%CBP+5%C after 28 days.

The effect of LS and C relies mainly on their chemical reaction with soil components when there is water present, as well as the quantity of stabilizer agent, which is used. In this regard, the SEM analysis was employed to observe the structural changes and to better understand the interactions between the soil and additives.

It is noteworthy that the primary aspect affecting the void ratio of the texture is the shape of the particles. Among the analysis of particle matter, it is found that the arrangement of texture particles in the treated sample in image (d) is relatively dense, and multiple paths for cemented bonds (C-SH gel) are formed between particles in different forms of contact. In the texture particle system, numerous of these cemented bonds crisscross one another to create a network that is adequate to resist both the weight of the particle system and external loads. The production of C-S-H has a significant effect on the mechanical properties of the sample which is reflected in the strength development of the soil sample. Fewer voids remain as a result of the particle's range in angularity, which lowers the void ratio.

In general, as calcium-based stabilizers, L, and C are usually utilized to strengthen the soil during the hydration and pozzolanic processes [49].

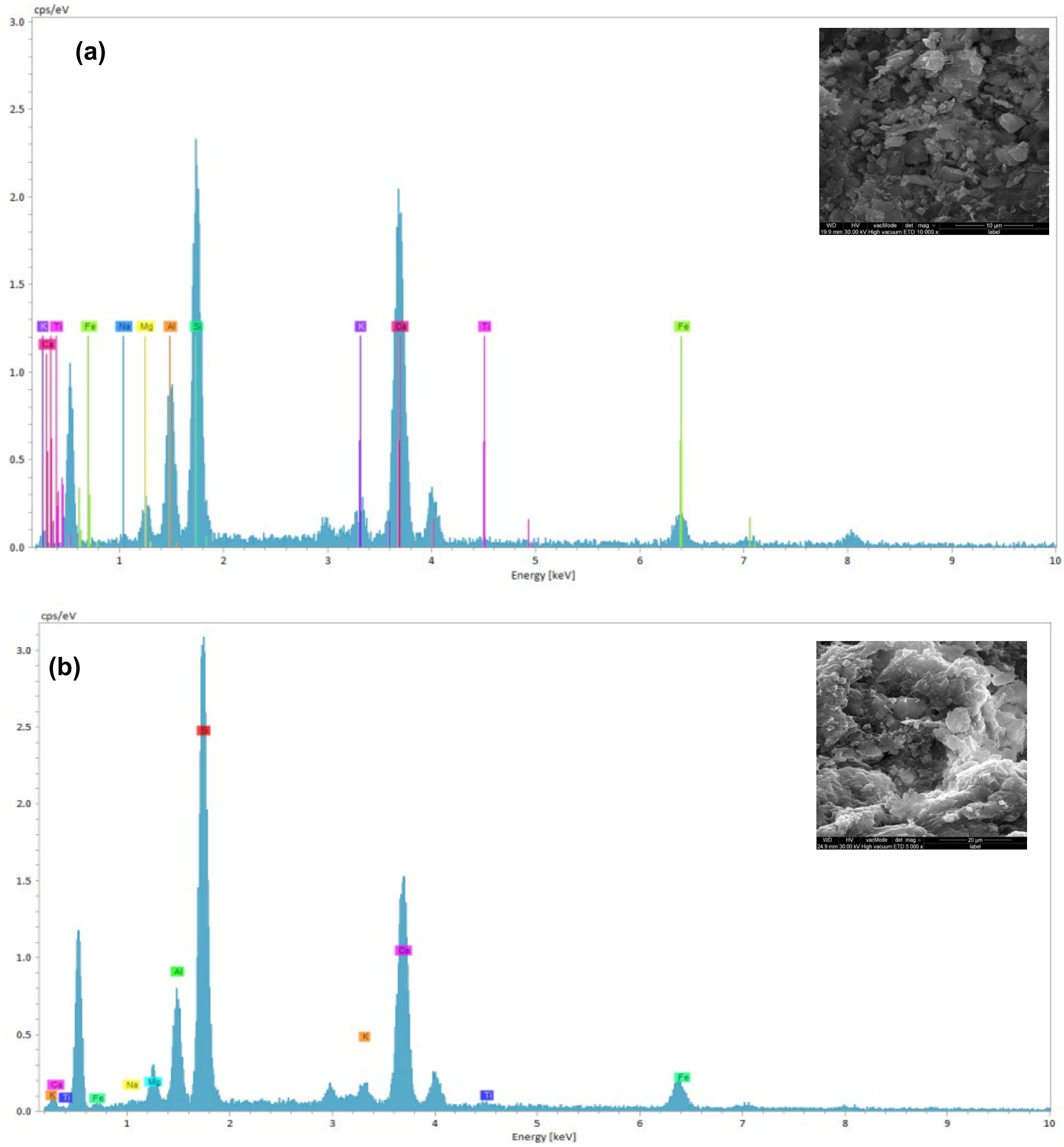

Figure 11. SEM micrograph and its elemental spectrum of a selected particle obtained by EDS analysis of sample: (a) 10%CBP+5%LS and (b) 10%CBP+5%C.

According to Fig. 11, this study found that the development of new hardened cementitious compounds has a principal effect that enhanced the UCS and shear strength characteristics of CBP-LS-treated soil and CBP-C-treated soil. The outcomes of the microstructural test revealed that the growth and deposition of cementing compounds caused morphological changes at the edges of soil particles. The soil texture changes when the soil particles get closer to one another. The clayey soil is mainly composed of silica (SiO_2) and alumina (Al_2O_3), while LS and C are mostly composed of calcium ions. The most important chemical composition values belong to calcium in LS and C; silicon and aluminum in the soil are presented in Table 2. The addition of LS or C (Ca+2) strengthens the bond between the soil particles. The soil mineralogy, LS content, and short-term reactions are the factors affecting LS-treated soil. On the other hand, C reactions are time-dependent and take a long time to complete since these reactions depend on temperature, the amount of calcium present, the pH level, and the proportion of silica in the soil minerals [50]. Substantially, SEM images revealed that the pozzolanic reaction coated the soil particles and created a closed matrix, which made the voids less evident and reduced the consolidation coefficient as well as the expansion index.

4. Conclusions

This research investigated the effect of CBP with the addition of LS and C individually to a clay matrix. The conclusions obtained throughout the investigations for this research can be listed as follows:

1. The study yielded in LL and PI values to be decreased with the addition of additives.
2. The results from UCS (which were considered the primary indicator to evaluate the effectiveness of CBP as a stabilizer) revealed that the 10%CBP mix produced the best improvement for the soil strength.
3. According to results obtained from UCS for samples treated with 10%CBP+5%LS and 10%CBP+5%C up to 28 days; the strength was increased by more than 2.69-fold and 4.82-fold respectively compared to the UCS of the untreated sample.
4. Generally, the rate of UCS development of the clayey soil samples stabilized with CBP and C or LS is enhanced as the curing duration is increased.
5. The direct shear components were notably achieved. The soil cohesion was reduced from 37.079 to 35.115 kPa, but the angle internal frictional was increased from 0.66° to 2.10° for the mix 10%CBP+5% of LS. While, for the mix 10%CBP + 5 % of C, the soil cohesiveness and the internal frictional angle were increased from 37.079 to 48.143 kPa, and from 0.66° to 1.54° respectively.
6. Reduction in both the compression index C_c and swell index C_s were observed with the addition of 10%CBP+5%LS and 10% CBP+5%C content.
7. Portland cement modification with CBP exhibited higher UCS and shear strength values than limestone modification for all samples when mixed with clayey soil and CBP for all curing ages.
8. According to the SEM analysis, the addition of the binder materials caused the stabilized samples to indicate a dense and compact matrix as well as reduced the soil porosity which resulted in increasing the mechanical strength.

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Received 15.02.2023. Approved after reviewing 08.02.2024. Accepted 10.09.2024.