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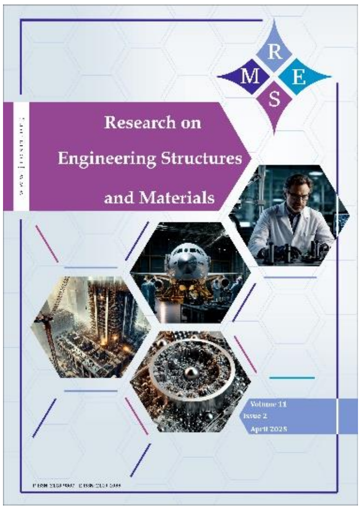

Sustainable soil stabilization using coffee husk ash and limestone: An eco-friendly approach

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Research Article

Sustainable soil stabilization using coffee husk ash and limestone: An eco-friendly approach

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Abstract

The geotechnical properties of soils vary depending on the regional and environmental diversity in which they are found. Therefore, remediation methods for troubled soils depend on the environmental conditions and material sources found in that area. However, the soil layer must have sufficient bearing capacity to be suitable to withstand the applied loads. The parameters of elasticity, cohesion, strength, and durability are part of soil optimization in this study. To do this, the soil is stabilized by treating it with a mixture of coffee husk ash and limestone powder in proportions of (3, 5, 7, and 10) % for three types of additives (coffee husk ash, limestone powder, and coffee husk ash mixed with limestone powder) and for periods of (1, 7, 14, and 28) days. The extent of improvement in geotechnical properties was determined using the unconfined compressive strength test and Atterberg limits. Two mathematical equations were predicted, one relating soil cohesion to plasticity index and the other relating plasticity index to unconfined compressive strength. The experimental results indicated that the soil cohesive strength improved from 30 to 52 kN/m^2, and it was also observed that the soil activity decreased from 0.9 to 0.25. At 28 curing days, the 7% of CHA+L mixture reduced PI from 30 to be 6.8 and increased UCS from 60 to be 94 kN/m^2. Nevertheless, predictive equalities were developed to re-count plasticity index with strength then cohesion, their applicability is limited to the type CH - soil and stabilizer contents within the range of 0–10%. The best improvement occurred at 7% coffee husk ash and limestone powder.

1. Introduction

Since the construction is where construction begins, it is the most important part of a building. Many influences, including subsurface lateral pressure, horizontal development on the divider, air activity, unequal subsurface settling of the craftsmanship, subsurface horizontal settlement, and moisture buildup in the subsoil [1]. Structures that contact the ground in harsh or corrosive settings must be waterproofed. Subterranean constructions are protected from moisture and groundwater contamination by waterproofing the basic materials [2]. For waterproofing solutions to be effective, proper installation and regular maintenance are essential. Ignoring these elements might eventually lead to deterioration and compromise the structural integrity. Since most traditional materials are expensive and harmful to the environment, researchers are currently investigating the use of eco-friendly and cost-effective methods to remediate soil before construction [3–12]. The present studies examine the economic consequences of the risks associated with applying traditional methods to enhance the properties of base soil. Studies have

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also begun to demonstrate other methods for enhancing the qualities of the underlying soil by employing recycled environmental waste. This is a wonderful alternative to the more costly traditional methods of improving the foundation soil. Particularly the inclination towards sustainability [13].

Exploration of pozzolanic materials has been a serious obstacle to the advancement of national development. Laterite soil is a common choice for long-term construction projects due to its widespread local accessibility, which contributes to its considerable significance as a reliable and long-lasting building material. [14–16]. Although recycling techniques are relatively new, they are gaining popularity in the Global South. These methods are more thorough, environmentally sustainable, and have a positive influence on both human well-being and the environment than older methods [17]. Many studies have looked into the use of industrial waste feasibility as an input material at various stages of the Portland cement production process [18]. Pozzolanic addition of materials to soil improve its chemical stability through increasing the soil particles size, declining plastic index, and dropping the soil's inclination to consolidate and expand. [19]. Adding pozzolanic materials, such as cement, is the traditional way to reinforce soil [20], although doing so comes with a higher cost [21].

After conversion, low-cost pozzolanic materials were utilized instead of more expensive ones, such as peanut shells. Compared to conventional Portland cement, which has a higher overall composition, this produced a lower CaO concentration [22,23]. Recent studies in a few nations have examined the pozzolanic qualities of coffee husk ash. Certain substitution percentages have been found to improve mortar, and concrete properties, such as water tightness, compressive strength, and fineness [24] and [25]. It was found that adding coffee husk ash to concrete significantly decreased slump and workability characteristics, also compressive strength decreased with higher coffee husk ash percentage, even though it improved through curative percentage up to a 10% coffee husk ash. Coffee husk ash plays a major role in strength development, although its effects on the physical and chemical properties of coffee husk ash and coffee husk ash-modified cement, and the flexural strength, durability, and concrete tensile, were not investigated in earlier studies. This study's primary goal is to describe, both chemically and physically, how coffee husk ash improves soil foundation instead of cement. The new method mixed limestone with coffee husk ash to improve the construction.

Previous studies have extensively investigated the use of agricultural and industrial wastes such as rice husk ash, groundnut shell ash, fly ash, and eggshell ash for soil stabilization. These studies primarily focused on single stabilizers and short-term strength improvement. However, limited attention has been given to the combined use of coffee husk ash and limestone as a hybrid stabilizing system. In addition, the time-dependent behavior of CHA–lime treated soils and the development of predictive regression-based relationships between plasticity index, unconfined compressive strength, and cohesion remain insufficiently explored. Therefore, the present study aims to address these gaps by investigating the combined effect of CHA and limestone on clay soil over different curing periods and by proposing empirical equations for strength prediction.

2. Methodology and Materials

2.1. Coffee Husk Ash (CHA)

The coffee husk from India. After being exposed to sunshine to eliminate surface moisture, the resulting sample was burned for three hours at 550°C to turn it into ash. To assess the physicochemical characteristics of the resultant Coffee Husk Ash. After cooling and being ground with a crushing tool, the crushed coffee husk ash was sieved in a 75 µm sieve [25].

2.2. Limestone Powder (L)

Locally procured limestone is crushed in a jaw crusher and then ground in a ball mill to create limestone powder. A No.200 sieve (75 µm) was used to sift all of the limestone powder.

2.3 Chemical Physiognomies

The chemical properties of the additives are displayed in Table 1, which shows the % quantitative analysis of composition silica oxide and other for coffee husk ash chemical compounds similar Fe2O3, SO3, K2O, and MnO.

Table 1. The chemical characteristics

Chemical Composition (%)	CHA	Lime
CaO	17.7	92
Fe_2O_3	2.8	0.9
Al_2O_3	0.6	0.89
SiO_2	15	3
MgO	4.51	4.2
$K_2O + Na_2O$	46.7	0.8

The CHA oxide composition and L is shown in Table 1, respectively. According to Table 1, that CHA has 2.8% Fe_2O_3, 0.6 Al_2O_3, and 15% SiO_2. This results in 18.4% SiO_2+Al_2O_3+Fe_2O_3. Because CHA contains SiO_2, Al_2O_3, Fe_2O_3, and CaO, it is therefore fundamental to use it as a cementing material rather than as a pozzolanic material [26]. When lime and coffee husk ash are combined, the mechanical properties of the soil can be enhanced. Silica along with the other pozzolanic components contained in coffee husk ash have the ability to counter with calcium hydroxide to formula new compounds such as aluminates and calcium silicates, which are beneficial for enhancing soil. The silica and alumina composition of coffee husk ash causes it to react with calcium hydroxide when mixed with lime to create cementitious materials that increase stability and strength. The mechanism of CHA-lime reaction in soil stabilization is dominantly pozzolanic reaction. Lime (CaO) reacts exothermically with water in moist soil and forms calcium hydroxide ($Ca(OH)_2$). Its derived $Ca(OH)_2$ result in initiating the SiO_2 and Al_2O_3 of CHA within them is activated by holding a basic environment. These reactive oxides then react with the calcium ions chemically forming C–S–H and C–A–H compounds which are primarily the responsible constituents for providing strength of treated soil due to lesser plasticity. This is a classic pozzolanic reaction. According to ASTM C618 [26], CHA qualifies as a pozzolanic material based on its oxide composition. However, some studies suggest that CHA may also exhibit partial self-cementing behavior due to its relatively high content of CaO and alkalis. For instance, [14] found that CHA can develop cementitious bonds even in the absence, thus, the stabilization mechanism in this study is primarily pozzolanic, with a possible minor contribution from self-cementing effects inherent to CHA.

2.4 Soil

The soil samples were brought up from Al-Hilla city, south of Iraq. The soil is classified as high plasticity clay soil (CH) according to ASTM 2487-17. Table 2 displays the results of the laboratory tests.

Table 2. Soil classification

Property	Value	Specification
Water content	8.9%	[27]
Gs	2.7	[28]
Sand	41.0%	
Clay	43.0%	
Silt	13.0%	
Gravel	3.00%	
Soil Classification	CH	
PL	35%	[29]
LL	74%	
PI	39%	
Activity	0.9	
Optimum moisture content	15%	

Property	Value	Specification
Dry density	1.65 gm/cm^3	[30]
Cohesion, c_u	30 kN/m^2	[31,32]
UCS	60 kN/m^2	

2.5 Sample Preparation

2.5.1 Atterberg Limits Tests Preparation

The Atterberg limits tests, soil samples were prepared in accord thru (ASTM D4318). The air-dried soil was first crushed and passed from a 425 µm sieve. The required mixture percentages (coffee husk ash, limestone powder, or their mixture) were dry-mixed carefully with the soil to confirm uniform the stabilizing agent's distribution. Water was then and there additional gradually while mixing up until the soil reached the target moisture content equal to15% the optimum moisture content (OMC), as determined from the Standard Proctor compaction test. The prepared soil paste was sealed and allowable to equilibrate to conducting the liquid limit and plastic limit tests.

2.5.2 Unconfined Compressive Strength (UCS) Tests Preparation

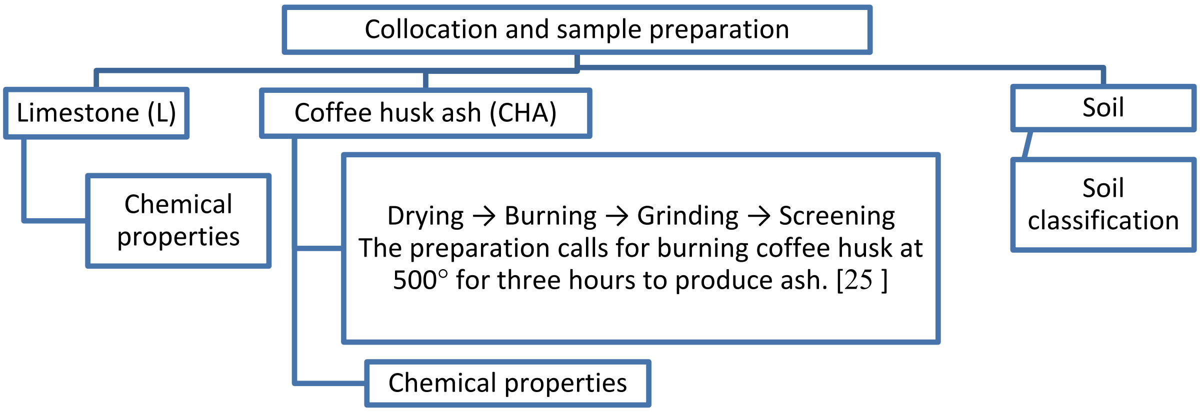
The unconfined compressive strength (UCS) tests, soil specimens were prepared for compaction following (ASTM D698) (Standard Proctor method) and for UCS (ASTM D2166) testing. Initially, the air-dried soil was pulverized and mixed in a dry state with the specified percentages of additives until a homogeneous mixture was achieved.

Water was then added incrementally to reach the mark 15% (OMC) moisture content. using standard Proctor compaction to find the moist soil mixtures were compacted energy to achieve approximately 95% of the maximum dry density (MDD) gotten from the Proctor test.

The compacted specimens were cylindrical in shape and were cautiously extruded from the molds immediately after compaction. To each specimen was sealed in plastic bags to prevent moisture loss and cured at room temperature (25 ± 2°C) for the designated curative times of (1, 7, 14, and 28) days previous to UCS testing.

2.6 Time-Dependent Testing Plan

In addition to studying the effect of additive percentages, the experiment also evaluated the strength development over time. For the 7% CHA+L mixture, unconfined compressive strength (UCS) tests were conducted at curing durations of 1, 7, 14, and 28 days to assess the time-dependent behavior of the treated soil. This time-based testing was intended to track the progressive improvement in strength due to pozzolanic reactions between the coffee husk ash and lime. For this mix, both Atterberg limits (LL, PL, PI, and A%) and also unconfined compressive strength (UCS) were slow at curative times of (1, 7, 14, and then 28) days, below identical preparation and curing conditions.



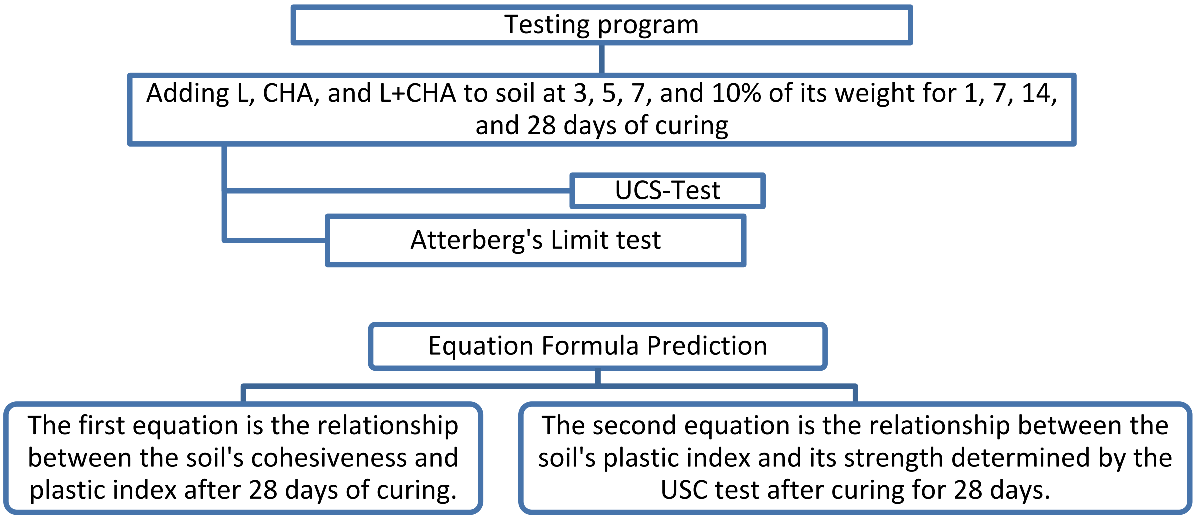


Fig. 1. Methodology of study

This testing program was intended to quantify the progressive enhancement in mechanical properties and also consistency of the treated soil over time, resultant of mainly from pozzolanic reactions stuck between coffee husk ash and limestone. The time-dependent study results are explained as a summarized in Table 3, despite the detail the overall sample preparation then testing procedure is illuminated in Figure 1.

2.7 Replication and Testing Procedure

Three identical samples were prepared and tested to guarantee the reliability of experimental results for each testing condition. All soil samples were compacted at Standard Proctor energy according to ASTM D698 using a 2.5-kg rammer with 25 blows per layer (applied over three layers). Uniaxial Compressive Strength (UCS) specimens were prepared in the form of cylinders as described by ASTM D2166 having diameter 38 mm and height 76 mm.

All specimens were sealed in plastic bags to avoid moisture loss and cured at room temperature (25 ± 2°C) under controlled laboratory conditions. To maintain consistency of data Atterberg limits tests and UCS tests were performed for specimens made from the same soil batch for each curing period with varying additive content.

3. Results and Discussion

3.1 Atterberg's Limits

This effect on the consistency of the soft clay with addition of reinforced material is shown in Figure 2. For 7% CHA, the liquid limit decreased from 74% to 67%, and for 7% (CHA+L), it was reduced to 60. Plus, to 64% a.c. @ 7% (L). Before mixing, the value of plastic limit was 35 as seen in Fig. 3. After mixing this value increased to 44 after 7% CHA was added. The increase carried on, up to 48 with 7% CHA and L together, topping a remarkable 49 when we added in only 7% of L. Moreover, from Figure 4 it is noted that for the soil, 39% of the sample produces a plasticity index (PI) as being very plastic. The soil became less flexible upon the addition of the chemicals according to (15, 9 and 11). The soil modulus declined when chemicals were mixed with the soil, as noted by (15, 9 and 11). This shows that at 7 % C, 7 % RHA bound with L and 7 % CHA, the plasticity of soil transforms to (low plastic), low. and medium plastic respectively [33]. The inclusion of RHA in the soil lead to a reduction in plastic index after CHA was added due to moisture adsorption by adding RHA.

From these results the decrease of soil activity can be seen, this occurs gradually until reaching a value of 0.98 that represents normal activity in soil and a value equal to 0.31 that presents inactive behavior for the case with 7% of cement content (Fig. Soil activity level was decreased to 0,30 with the use of 70% L + CHA, indicators of dormancy and inactivity. With an index of 0.42 at 7% CHA, it is remarkable that the soil can be considered inactive. Soil behavior is an important factor that greatly affects the stability/safety of a project. This characteristic is representative of the soil dynamic capability to shrink and swell with changes in water content. It is common to experience large volume changes in highly active soils which shift and resettle causing possible damage and instability. Low activity side casts, on the other hand, are also providing a secure starting point; they remain solid and not easily moved compared to high-risk material.

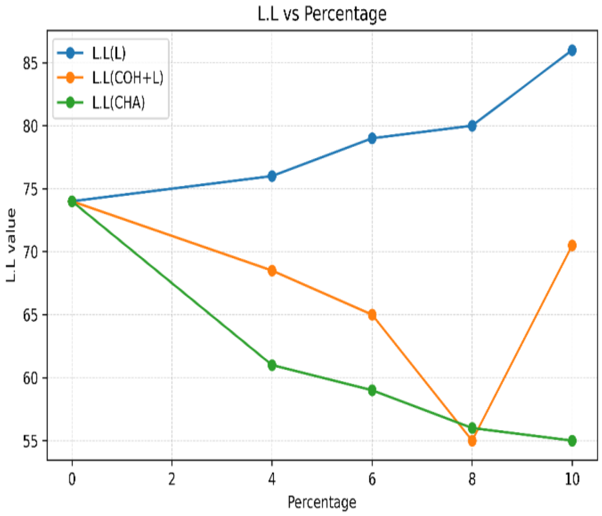


Fig. 2. Liquid limit of soil mixtures

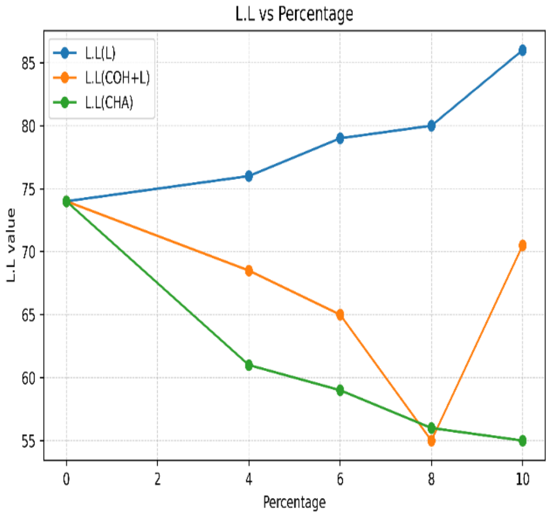


Fig. 3. Plastic limit of soil mixtures

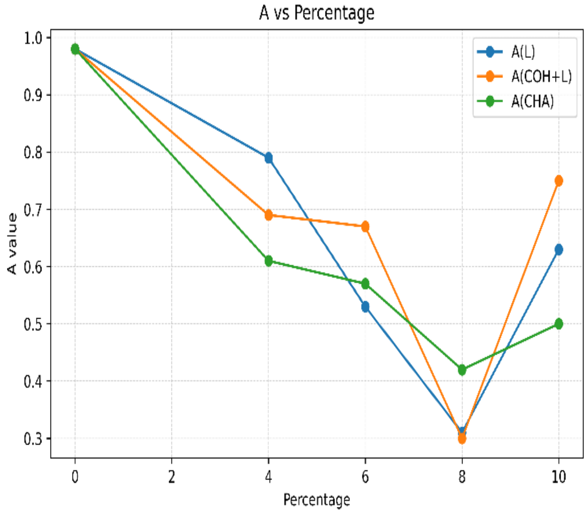


Fig. 4. Plasticity index of soil mixtures

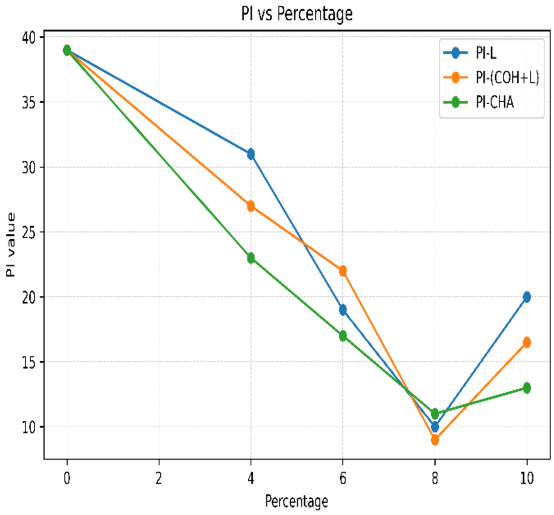


Fig. 5. Activity of soil mixtures

The most suitable option proved to be - addition of coffee husk ash (7 wt%) mixed up with limestone powder, after verification. Interaction impact of three amendments and soil over twenty-eight days correlation studies on cohesive soils and flow ability. This additive increased the binding of the soil. The work was designed to assess the overall effectiveness, porosity and water retention capacity of the soil for 1, 7, 14 days and over a period of up to 28 days in order to investigate how the combined system changes with time. The effect of 7% CHA with L is provided in Table 3.

It should be noted that the slight increase in the plasticity index observed at 10% CHA does not indicate a deterioration in soil behavior, but rather reflects a non-monotonic response at higher additive contents. At elevated CHA percentages, part of the ash acts as a non-reactive filler due to insufficient available calcium to sustain further pozzolanic reactions. Consequently, the excess ash particles may increase the fine fraction, leading to a marginal rise in plasticity index. Similar behavior has been reported in previous studies on agricultural ash stabilization, where an optimum additive content exists beyond which performance gains diminish.

Table 3. Atterberg's limit effect of 7% CHA combined with limestone

Curative time	L.L (%)	P.L (%)	P.I (%)	A (%)
First day	57	48	9	33
Seven days	54	46	9	30
Fourteen days	55	47	8	29
Twenty-eight days	54	47	7	25

3.2 Unconfined Compressive Strength

Figure 6 displays the soil mixture after 28 days of curing of11 unconfined compressive strength data. According toward the untested result, the soil's strength was 60 kN/m^2 before treatment, but it increased to 90 kN/m^2 during a 28-day curative period with 7% limestone treatment. 7After 28 days of curing, soil treated by 7% coffee ash gained strength to 70 kN/m^2. After 28 days of curing using 7% coffee husk 7 and limestone, the strength of soil reached 101 kN/m^2. Figure 7 depicts the soil cohesiveness results after 28 days of curing. The soil's cohesiveness was 30 kN/m^2 before curing, according to the most recent results. Adding 7% limestone to the soil after 28 days of curing significantly increased its cohesion (36 kN/m^2). Adding 7% coffee husk ash to 30 KN/m^2 of the soil yielded cohesiveness at Adding coffee husk ash seven percentage and limestone powder enhanced soil cohesiveness to 45 kN/m^2. As a result, incorporating coffee husk ash and lime into soil type clay improves soil qualities, including strength and cohesiveness.

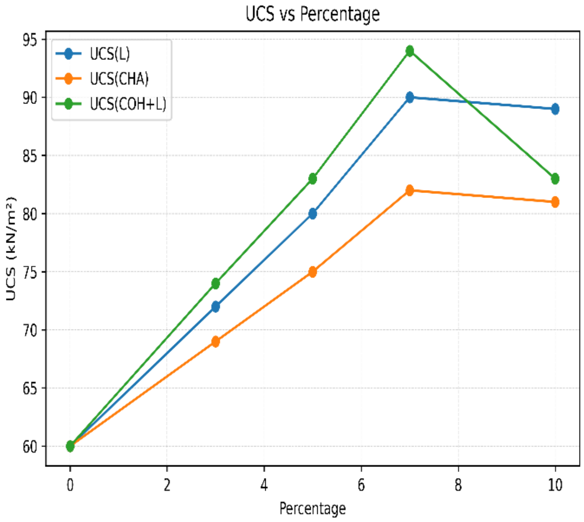


Fig. 6. UCS of soil mixture after 28 days of curing

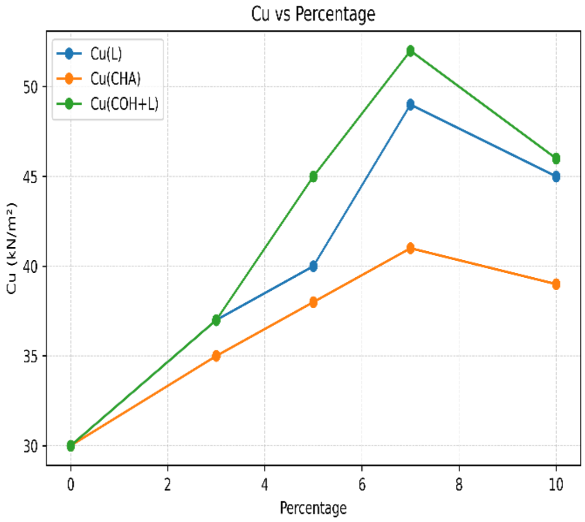


Fig. 7. Cohesion of soil mix. after 28 d. of curing

The results demonstrate that the unconfined compressive strength was rise than before 101 after using a mixture of coffee husk ash and limestone powder for a 28-day curing period, which improved long-term strength in particular [34]. This study shown that coffee husk ash combined with limestone powder can be effectively reprocessed as a soil preservative, hence reducing ecological contamination. The results of this study are similar to [35]. The research mentioned about the coffee husk ash effect such being linked by there. It acts similar to a partial replacement for cement and strength, durability goes up by 10% by its weight. Additionally, comparisons may be made through 36 with regards to the coffee husk ash effects on soil characteristics. The icing on the cake is that we used consistent mixing, compaction and curing procedure for all specimens to have consistency in results. and Each value is the mean of repeated tests.

3.3 Proposed Equations

The reduction of model development costs and laboratory requirements that this study will achieve is significant, because mechanisms through which the soil behaves during treatment are studied in detail. It nicely emphasizes the importance of a strong link between bearing capacity (cumulative loading) and soil property dynamics as both are needed to improve our comprehension and management of soil systems. Graphical representations were used to obtain the foregoing equations. The first equalization represented by Figures 4, 6 and 8 is a clear attempt to make the operation more efficient from both a time and cost perspective. It details a 28-daygradedtreatmentwhich and U, is based on Ux The latter heal mud index (Subhedarlb /Ii-X) Edict as well of the soil strength line with plasticity that correlation, in particular with unconfined compressive soil strength Index ucs). The second equation is shown in Fig 9 and confirms the evidences provided by Figs 4 and 7. The model was established to obtain a mathematical relationship between soil cohesive features and PI at the same 28-day period of treatment. By providing a complete representation of soil-behavior during curing and emphasizing the important relationships between mechanical behavior of soil properties and their ability to carry increasing loadings, more efficient modeling in terms of costs and labor can be achieved. Graphical analysis and the development of appropriate equations is the key to these efforts. The formation of equations prediction and right factor are summarized in Table 5.

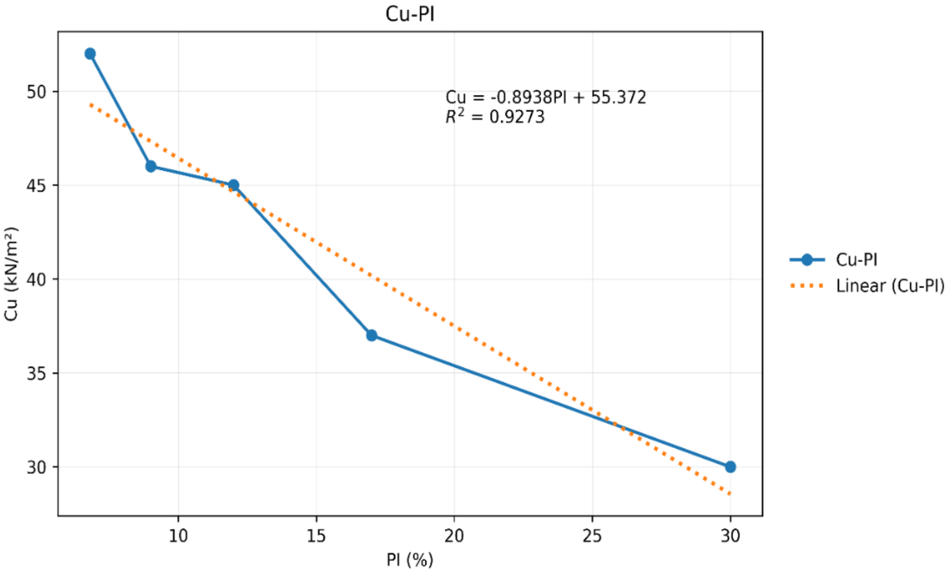


Fig. 8. Variation of PI with cohesion at 28 days of curing

The slight increase in plasticity index observed at 10% CHA can be attributed to the excess ash content acting as a non-reactive filler material rather than participating in pozzolanic reactions. At higher dosages, insufficient calcium availability limits further cementitious bonding, resulting in reduced efficiency of stabilization. This phenomenon has been reported in previous studies on agricultural ash stabilization. Table 4 explain that by reducing the plasticity index (PI) from 30 to 12 at a 7% ratio, increasing the unconfined compressive strength (UCS) from 60 to 90 kN/m^2, and increasing the cohesion (C) from 20 to 30 and then to 42 kN/m^2 at 10%, the improved rice husk ash (CHA) progressively improved the properties of the soil. The PI value stayed in the strong correlation range even with the apparent improvement. While cohesion recorded its maximum value at 10% (57.5 kN/m^2), lime (L) did not reach the same level of UCS, which stayed around 70 kN/m^2. But it was the plastic which reduced PI most (up to 9 at 7%) indicating quite good plasticity development. The possible chemical stabilization processes due to the presence of coffee-husk ash (CHA), limestone, and clay minerals are mainly pozzolanic reactions, cation exchange, agglomeration/flocculation bonding bond, and secondary less important carbonation.

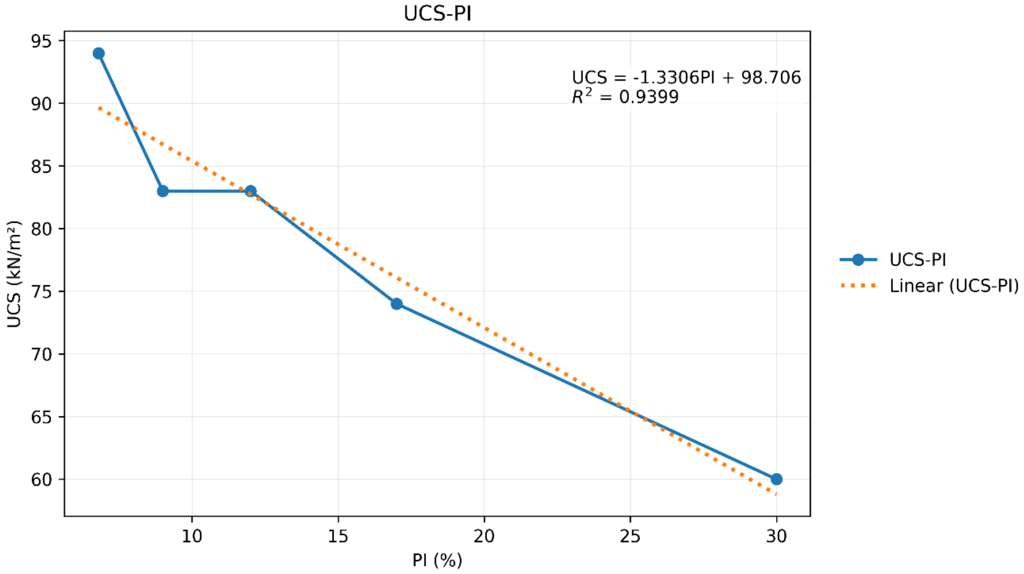


Fig. 9. Variation of PI with UCS at 28 days of curing

The CHA has highly reactive silica (SiO_2), alumina (Al_2O_3) and calcium oxide (CaO). In the presence of moisture, these compounds react with limestone-derived calcium hydroxide ($Ca(OH)_2$) to produce stable calcium silicate gels (C-S-H) and calcium aluminate gels (C-A-H). These gels manufacture to bind soil particles together, low plasticity and permeability as well as increase in strength of durability [37]. Cation exchange and flocculation result when the divalent calcium ion ($Ca^{2+)}$ released via limestone disrupts monovalent cation (e.g., Na+ or K+) adsorbed at clay edges. These cations directly offset the repulsion among particles and contribute to particle coalescence, improving soil structure and resistance of swelling [38]. Also, effects on long-term strength enhancement of carbonation reactions in which $Ca(OH)_2$ reacts with atmospheric CO_2 to form calcium carbonate($CaCO_2$) may be marginal. These reactions are, however, of lesser importance under \`short-term curing' conditions [39]) [L1].

Table 4. Physical and shear strength of tested soil samples at 28 -day curing

Additive (%)	Additive Type	LL (%)	PL (%)	PI (%)	Activity (A)	UCS (kN/m²)	c_u (kN/m²)
0	Soil without adding	76	46	30	0.90	60	30
3	CHA	66	44	22	0.75	69	35
5	CHA	52	39	15	0.60	75	38
7	CHA	50	38	12	0.42	82	41
10	CHA	56	42	14	0.50	81	39
3	L	58	40	18	0.70	72	37
5	L	58	44	14	0.55	80	40
7	L	58	49	9	0.31	90	49
10	L	56	46	10	0.40	89	45
3	CHA + L	60	43	17	0.60	74	37
5	CHA + L	57	45	12	0.45	83	45
7	CHA + L	54	47.2	6.8	0.25	94	52
10	CHA + L	61	46	9	0.38	83	46

The developed expressions which can predict for the UCS and cohesion based on the percent of additive (CHA, limestone) plant a beneficial initial indicator to recognize the effect of treated soils. Nevertheless, the high model R^2 values suggest that these models are only partly robust and can be interpreted with care. It should be noted, however, that the small number of data points and the single soil type (CH) prevent application of these equations at large scale. Because of this, these equations can be used to emphasize dominant features and sketch designs, however generalizing these soil types and conditions over other clays or varying climates needs more data and an extended range of soil types. Linear regression analyses were re-performed using the correct and complete dataset obtained after 28 days of curing, in Table 4 explained as summarized. Separate regression models were developed to evaluate the relationships between the plasticity index (PI) plus unconfined compressive strength (UCS), in addition between PI plus soil cohesion (Cu).

Figure 9 shows the relationship between PI and UCS, showing a strong inverse linear correlation. The derived regression equation is expressed as; $USC = -1.3306PI+98.706$, with a coefficient of determination $R^2 = 0.9399$, indicating a high degree of correlation between plasticity reduction and strength gain. That explain in Table 5. Figure 8 shows the link stuck between PI and cohesion (Cu). The regression analysis produced the following equality; $Cu = -0.8938PI+55.372$, , with $R^2 = 0.9273$, reflecting a strong correlation influenced by additional microstructural factors beyond plasticity alone. That explain in Table 5. The regression equations and corresponding R^2 values are summarized in Table 5. Although these models effectively capture the observed trends, their applicability is limited to the tested CH soil and additive contents within the range from 0 to 10 percentage.

Table 5. The equation formula prediction at 28 -day curing

Information	Formulation	Right factor
The first equation is the relationship between the soil's plastic index and strength on the 28-day curing USC test.	$USC = -1.3306PI+98.706$	$R^2 = 0.9399$
The second equation is the relationship between the soil's plastic index and cohesion after 28 days of curing.	$Cu = -0.8938PI+55.372$	$R^2 = 0.9273$

The regression equations presented in this study describe the relationship between plasticity index (PI) and the mechanical strength parameters of the treated soil. The negative slopes in both equations indicate that soil strength increases as plasticity decreases, which reflects improved particle bonding and reduced clay activity due to stabilization. The fact that the slope for the PI–UCS is steeper than the PI–cohesion indicates UCS to be more sensitive to plasticity of soil than cohesion. These responses can be ascribed to the interactive influence of cementitious bonding and microstructural densification on compressive strength.

The intercept in the regression equations is a theoretical value at zero plasticity and provides rather a reference point than an achievable state. The high R^2 values ($R^2=0.95$) point to a good correlation between the factors in the range studied. Nevertheless, these equations are linear approximations performed from a limited database and this must therefore be only valid within the experimented content of CH soil and stabilizer varying between 0 to 10%. Their potential use on other soil types or under different conditions needs experimental support.

3.4 Chemical Stabilization Mechanisms of CHA–L Treated Soil

The stabilization mechanism of CHA and LS–treated clay soil seems to be dominated through both physical and chemical effects taking place over time. Calcium ions liberated from limestone, immediately after the mixing process, react with negatively charged surfaces of clay particles resulting in cation exchange. During this process monovalent ions are exchanged for divalent calcium and the clay particles flocculate and aggregate. As a result, soil plasticity and activity are minimized within the initial stages of treatment. Upon further curing, the flocculated clay particles redeposit to entrench a stiffer structure. The small ash particles can fill pores and lock the soil particles together, which not only may increase the stiffness of soils but also could improve load transfer between soil particles.

The long-term strength gain results from pozzolanic reactions between reactive silica (SiO_2), alumina (Al_2O_3) and ferric oxide (Fe_2O_3) content in coffee husk ash with calcium hydroxide generated due to hydration of limestone. These reactions result in the production of cementitious phases; calcium silicate hydrate (C–S–H), and calcium aluminate hydrate (C–A–H), helping to bond soil particles, are responsible for long-term enhancement in unconfined compressive strength and cohesion. The presence of CaO in lime stone (see Table 1) is necessary to induce these pozzolanic reactions and together they contribute definite contribution An important factors in governing the long-term behavior of stabilized soils. The enhanced strengthening of clay soil due to the presence of coffee husk ash and limestone is believed to be an interaction among physiochemically stabilization mechanisms namely cation exchange, flocculation, agglomeration, and pozzolanic reactions [36].

Cation exchange In the presence of limestone, cation exchange is taken place in the hydrate phase with respect to clay particle surfaces due to availability of calcium ions released from hydrated lime replacing monovalent cations (Na^+ and K^+). This reduces the width of diffuse double layer, weakens inter-particle repulsion and close up particle association so that PI and soil activity decrease [40]. Flocculation and agglomeration: after the cation exchange, divalent calcium ions yield in clays changing from a dispersed to flocculated state. This structural change leads to better packing of particles, higher plastic limit and lower liquid limit causing the improvement in soil consistency properties observed [41]. Pozzolanic reactions is the main stabilization mechanism in CHA–L treated soils in long term. The activity of SiO_2 and Al_2O_3 in coffee husk ash forms the pozzolanic part of rice husk ash and react with Ca(OH)2genrated from limestone hydration under alkaline environment. These reactions that cause the cementitious compounds to form, such as calcium silicate hydrate (C–S–H) and calcium aluminate hydrate (C–A-H), allow an unconfined compressive strength and cohesion to increasing with curing time [37].

Carbonation could also contribute slightly to strength gain by the reaction of calcium hydroxide with atmospheric carbon dioxide producing calcium carbonate. However, with the rather short curing times investigated in this study, carbonation is assumed to be secondary to pozzolanic reactions [36]. Overall, the cation exchange combined with the flocculation and pozzolanic reactions forms a tighter and more stable soil structure with reduction in plasticity and activity and improvement in strength parameters, which sustains that coffee husk ash and limestone can adequately be used as sustain ending agents for clays.

4. Conclusions

In the present work, coffee husk ash (CHA) and limestone as a sustainable stabilizer for high plasticity clay soil were explored. The test results showed that the incorporation of CHA–limestone dramatically decreased soil plasticity and activity, meanwhile increased strength performance.
The optimum stabilizer content was found to be 7% CHA – limestone stabilizer at this level of concentration result in the PI reduction from 35% 90 kN/m^2 up to 60 kN/m^2 unconfined compressive strength when lime and cement are used after twenty-eight -day curing. Soil cohesion also augmented from 30 to 45 kN/m^2 between untreated and optimum stabilizer content soil.
The observed enhancements were related to the mechanisms of physicochemical stabilization by sorption (cation exchange), flocculation, pozzolanic reaction. The developed regression equations have practical importance for the preliminary design of soil strength in the studied ranges.
Despite such promising results, the conclusions of this research are restricted to a single type of clay soil and to the short-term curing period. Further study is recommended to evaluate the long-term durability, microstructure by means of SEM and XRD techniques and performance evaluation in the laboratory for CHA–limestone stabilization under various environmental conditions.

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