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Evaluation of clay soil stabilization with coffee husk ash for sustainable geotechnical applications

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ABSTRACT

This study evaluates the use of coffee husk ash (CHA) as a stabilizer for improving the physical and mechanical properties of low-plasticity clay soils. CHA was incorporated at 4%, 6%, and 8% by weight. Laboratory tests included compaction, unconfined compressive strength (UCS) under dry and saturated conditions, California Bearing Ratio (CBR), resilient modulus, matrix suction, and soil expansion. Results showed significant improvements: CBR increased by 356%, soil expansion was reduced by 24%, and UCS improved by 17.4% (dry) and 28.0% (saturated) compared to natural soil. Higher ash content led to greater water retention and lower matrix suction, enhancing internal cohesion and stiffness under varying moisture. The resilient modulus also increased with curing time and ash content, reaching up to 25% after 28 days. These findings demonstrate that CHA can significantly enhance both mechanical and hydromechanical behavior of clay soils, making it a suitable alternative for road and infrastructure applications. One challenge addressed in this study is the lack of standardization in the use of agricultural ashes for soil stabilization. Since coffee husk ash is often discarded or underutilized, its application in geotechnical contexts may offer a promising alternative to reduce waste and promote the use of locally available materials.

Keywords: coffee husk ash; soil stabilization; mechanical performance; durability; suction; expansion.

1. INTRODUCTION

The stabilization of soils with high plasticity is a topic of growing interest in geotechnical engineering due to the inherent limitations of this type of soils, such as their low bearing capacity and high deformations under load. These characteristics make them unsuitable for infrastructure applications, which has led to the search for sustainable alternatives that improve their physical and mechanical behavior [1, 2]. At the same time, agricultural processes generate a large amount of unused waste, the inadequate management of which represents a significant environmental problem [3, 4]. In this context, vegetable ashes, such as rice husk ash (RHA), sugarcane bagasse [5], coffee husk ash (CHA) [6, 7] and cow dung ash [8, 9], corn by-products [10–12], jute fibers [13], rice husk [14, 15] and ash. The use of peanut shell ash (CMA) [16, 17], have been shown to have pozzolanic properties that make them effective stabilizers for high plasticity soils.

Recent studies have expanded the understanding of the behavior of soils treated with agricultural residues, emphasizing the need for sustainable approaches adapted to local conditions [18, 19]. CHA, obtained by burning rice husks at high temperatures, contains up to 95% silica, which makes it highly pozzolanic. Studies have reported that it increases the uniaxial compressive strength (UCS) of clay soils from 48.5 kPa to 166.0 kPa, reduces the plasticity index from 120% to 27% and decreases volumetric expansion by 51% [7, 20]. Similarly, cow dung ash significantly improves bearing capacity and reduces expansion of plastic soils [9], while peanut shell ash (CMA) decreases plasticity and increases strength, with optimum results when used at 2% to 6% in mixtures with soil [16].

Among the available options, coffee husk ash (CHA) emerges as a promising stabilizer, especially in coffee-growing regions such as Colombia. This by-product is generated during the drying of the coffee fruit,

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and possesses pozzolanic properties derived from its chemical composition rich in calcium, potassium and magnesium oxides [21]. In Colombia, the annual production of coffee husks exceeds 1,094 tons, which represents a significant opportunity for its use in soil stabilization [22]. Studies carried out in Ibagué showed that the incorporation of CHA in road subgrades significantly increased the bearing capacity of pavement structures [8], while research in Indonesia reported improvements in maximum dry density and shear strength when CHA was combined with cohesive soils [4]. The optimum percentage of CHA in cohesive soils is estimated at 15%, although it may vary depending on soil and ash characteristics [2]. In addition, recent investigations emphasize the importance of characterizing not only the strength but also the dynamic stiffness of stabilized soils—key aspects that are comprehensively addressed in recent studies [23, 24].

This experimental study evaluates the stabilization of silty-clay soils with CHA in the region of Liberia, Viotá, Cundinamarca. The objective of the research was to analyze the influence of the addition of CHA in proportions of 4%, 6% and 8% on key soil properties, including plasticity index, maximum dry density, optimum moisture content, UCS and CBR. These evaluations were performed using standardized methodologies such as ASTM D698-07 for compaction tests and ASTM D1632-17 for unconfined compression tests.

Despite the growing body of literature on the use of agricultural waste ashes in soil stabilization, several challenges persist. First, there is a lack of standardization in technical regulations regarding the use of specific types of biomass ashes—most guidelines refer generally to fly ash, without considering the variability in chemical composition, particle size, and behavior of ashes like CHA. This makes it difficult for practitioners to determine safe and effective dosage ranges. Second, the availability and current use of ashes such as CHA—often applied as fertilizer or discarded—poses logistical constraints that may limit their adoption in engineering applications. Lastly, many existing studies focus solely on strength parameters, omitting hydromechanical variables critical for real-world performance. This study addresses these gaps by analyzing both mechanical and hydromechanical behavior of CHA-stabilized soils under standardized laboratory conditions, and by exploring realistic application percentages (4–8%) based on the local context and material availability.

This study responds to the current demand for sustainable and locally available soil stabilizers. While materials like rice husk ash and sugarcane bagasse have been studied, coffee husk ash (CHA) remains underexplored despite its pozzolanic potential. Recent studies support the use of agricultural ashes to enhance soil strength and reduce expansion with CHA and enset fiber [25], and MIRZABABAEI *et al*. [26] with nano-additives improving cohesion via C-S-H formation. Calcium-rich ashes were also shown to improve hydration and long-term strength in LUAN *et al*. [27], while NAZIR *et al*. [28] highlighted gains in shear strength and dimensional stability using GGBS and dolomite. These findings align with this study's approach, which incorporates matric suction and resilient modulus for a deeper evaluation of stabilized soil behavior

The present research offers two essential contributions to the scientific community. First, it provides a comprehensive analysis of the physical and mechanical properties of soil stabilized with CHA, highlighting significant improvements such as a 356% increase in CBR and a 28% improvement in UCS under wet conditions. Second, it demonstrates the potential of CHA as a sustainable and economically viable alternative to conventional stabilizers, leveraging an abundant agricultural by-product in coffee-growing regions to address infrastructure challenges while promoting environmental sustainability and contributing to circular economy practices in geotechnical engineering

This article is divided into four main sections. The first corresponds to the introduction, where the problems of high plasticity soils, their impact on infrastructure and the relevance of stabilization using CHA are presented. The second section, materials and methods, describes the physical and chemical properties of the soil and the CHA, together with the experimental procedures employed. The third section, results and discussion, analyzes the effect of CHA on properties such as CBR, compressive strength and maximum dry density, discussing their relationship with previous research. Finally, the fourth section includes the conclusions, which synthesize the findings of the study and propose future lines of research.

2. MATERIALS AND METHODS

2.1. Materials

2.1.1. Silt-Clay soils

This study focuses on the analysis and stabilization of soils from a specific area in the town of Viotá, Cundinamarca, Colombia. For this purpose, a section of the road that connects the village of Liberia with the region of Las Brisas, at an altitude of approximately 230 meters above sea level, was selected. This site, shown in Figure 1, was identified as the place of extraction of the natural soil used in the experimental tests. These

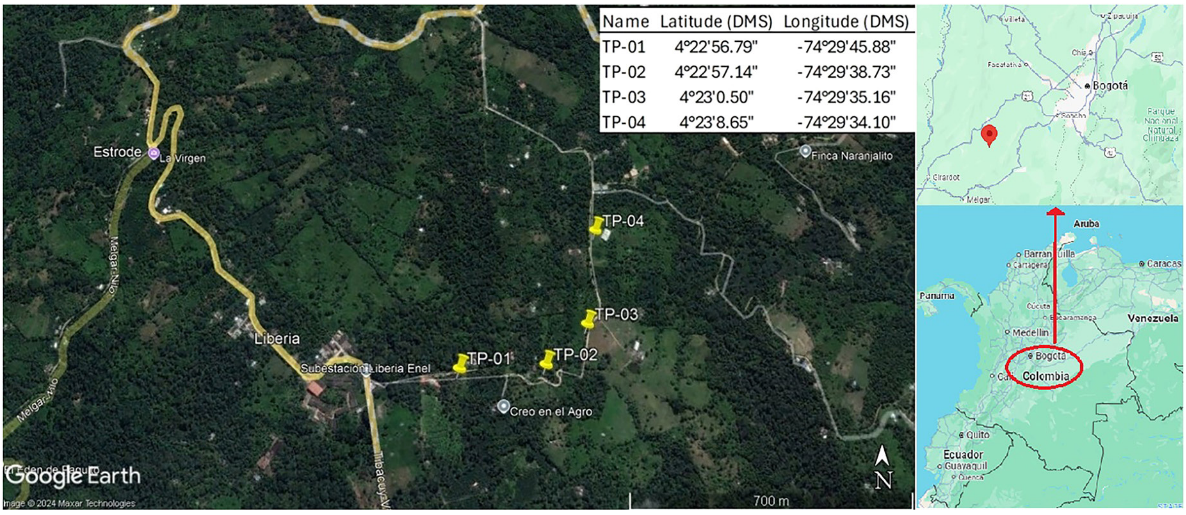

Figure 1: Location in the municipality of Liberia, Cundinamarca, Colombia. Soil extraction site.

sampling sites are labeled TP-01 to TP-04 and are georeferenced in Figure 1, which shows their distribution using Google Earth imagery. The coordinates in degrees, minutes, and seconds (DMS) are provided for each point. All samples were obtained from shallow depths (approximately 0.5–1.0 meters), where the clayey-silt layer was visibly exposed and accessible.

The site selection responds to its representative characteristics of the region, both in terms of geological and environmental conditions, providing a realistic context to evaluate the potential for soil stabilization through the use of coffee husk ash.

Figure 2 shows the grain size distribution and characteristics of two materials analyzed. Based on the ASTM particle size classification, the soil contains approximately 16.3% sand, 49.4% silt, and 34.3% clay (with size ranges as in your original). This distribution confirms its classification as a fine-grained, plastic soil, consistent with the CL designation under the Unified Soil Classification System (USCS). This distribution confirms its classification as a fine-grained, plastic soil, consistent with the CL designation under the Unified Soil Classification System (USCS), presents a liquid limit (LL) of 38.5%, a plasticity index (PI) of 17.0% and a specific gravity of 2.47. The grain size curve shows a continuous gradation with a significant proportion of particles smaller than 75 micrometers (fines) and a moderate sand content. These characteristics provide cohesion, stability and water resistance, making it suitable for construction applications.

MUNIRWAN *et al*. [29] found that coffee husk ash (CHA) has a particle distribution in which 78.90% corresponds to sand size, and 21.90% are fine particles. This material, with a specific gravity estimated at 2.54, is suitable for construction applications, since density directly influences its behavior in soil stabilization

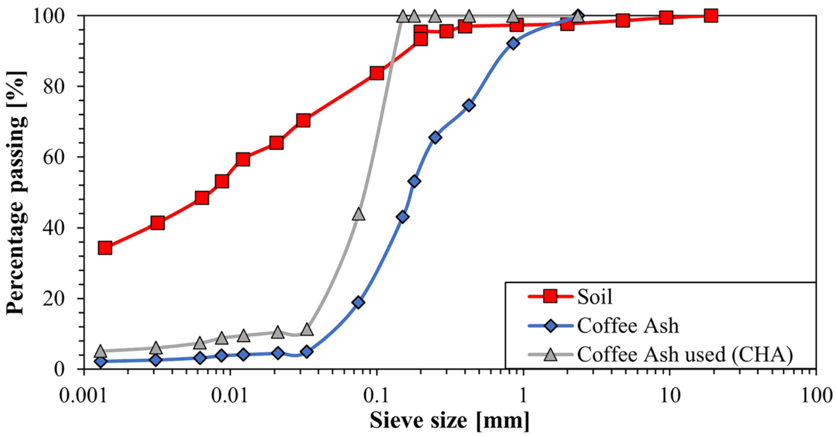

Figure 2: Soil and Coffee Husk Ash granulometric curve.

processes. With a plasticity index of 0.99%, CHA has a low plasticity, which is advantageous to avoid excessive deformations when mixed with soils, improving the stability of the mixture.

2.1.2. Coffee husk ash (CHA)

This study analyzes the impact of the inclusion of coffee husk ash (CHA) on the improvement of the physical and mechanical properties of silt-clay soils. The main objective is to evaluate how stabilized mixtures with different percentages of CHA influence the hydromechanical behavior, compressive strength and water holding capacity of treated soils. Coffee husk ash (CHA) is a by-product generated during the coffee drying and roasting process. In these traditional processes, the husk—constituting the outer covering of the coffee bean—is burned in furnaces or open combustion systems to take advantage of its calorific value, typically as biomass fuel for energy generation. The ash used in this study was obtained from local facilities in the rural area of Viotá, Cundinamarca, a coffee-growing region in Colombia. It is important to note that the ash was not produced under controlled laboratory calcination, and therefore the exact burning temperature was not recorded. However, based on similar studies, combustion temperatures in such traditional systems are estimated to range between 400 °C and 600 °C, which is considered sufficient to activate the pozzolanic properties of the ash.

MUNIRWAN *et al*. [29] found that coffee husk ash (CHA) has a particle distribution in which 78.90% corresponds to sand size, and 21.90% are fine particles. This material, with a specific gravity estimated at 2.54, is suitable for construction applications, since density directly influences its behavior in soil stabilization processes. With a plasticity index of 0.99%, CHA has low plasticity, which is advantageous to avoid excessive deformations when mixed with soil, improving the stability of the mixture. For the stabilization process, only the CHA fraction passing the No. 100 sieve (0.15 mm) was selected, representing 43% of the total ash. This decision was based on recommendations from previous research suggesting that ash particles used in soil stabilization should be fine enough to ensure uniform dispersion and effective pozzolanic activity, similar to cement or fly ash behavior [4].

The chemical analysis of CHA, performed by X-ray fluorescence (XRF) is shown in Table 1 and revealed its high concentration of essential compounds that support its use in soil stabilization applications. The results obtained highlight that the main chemical components are calcium oxide (CaO), with a percentage of 49.15%, potassium oxide (K_2O), with 16.44%, and magnesium oxide (MgO), with 9.31%. These compounds are responsible for the pozzolanic properties of the ash, allowing it to react chemically with water and soil compounds to form cementitious products that improve the cohesion, densification and durability of the treated material. In addition, other relevant elements were identified, such as silicon dioxide (SiO_2) at 5.29%, sulfur oxide (SO_3) at 6.52%, and phosphorus pentoxide (P_2O_5) at 5.30%, which broaden the applicability of CHA in other areas of civil engineering, including sustainable construction.

Previous studies have corroborated the variability in the chemical composition of CHA depending on the region and coffee roasting method. ARULRAJAH *et al*. [30] reported higher values of K_2O (60.09%) and SiO_2 (8.30%) in ash from recycled coffee waste, which reinforces its pozzolanic character and its effectiveness in improving geopolymeric blends. On the other hand, OKWADHA *et al*. [21] highlighted that the combination of CaO and MgO enhances the stabilizing properties of CHA, improving cohesion and reducing the plasticity index of the treated soil. This study highlighted its usefulness in clayey soils, especially as a material for road sub-bases. Likewise, MOON *et al*. [31] analyzed CHA in the context of remediation of lead-contaminated soils, identifying high percentages of carbon (46.1%), potassium (33.1%) and calcium (11.9%), which allowed it to be effectively employed to improve the structure and stability of problematic soils.

The XRD pattern of the coffee husk ash (CHA) reveals a predominantly amorphous structure, accompanied by several crystalline peaks indicative of mineral phases with pozzolanic potential. A strong reflection near 26.6° 2θ confirms the presence of silicon oxide (SiO_2), mainly quartz, which contributes to the reactivity of the ash when combined with calcium sources. Additional peaks observed around 23°, 30°, and 33° 2θ correspond to potassium sulfate (K_2SO_4) and calcium silicate sulfate ($Ca_3(SiO_4)(SO_4)$), while signals at 27°, 31°, and 35° 2θ suggest the presence of magnesium phosphate oxide ($Mg_3(PO_4)_2$) and iron silicate (Fe_2SiO_4). These phases, though not hydrated, indicate that the ash contains reactive oxides such as SiO_2, CaO, K_2O, and MgO, which are essential for pozzolanic activity under alkaline or lime-rich conditions. The presence of these minerals suggests

Table 1. Chemical composition of coffee husk ash.

CHEMICAL COMPOST	CONCENTRARION BY WEIGHT (%)							
	CaO	K_2O	MgO	SO_3	P_2O_5	SiO_2	Fe_2O_3	Al_2O_3
Coffee Husk Ash	49.15	16.44	9.31	6.52	5.3	5.29	3.17	2.02

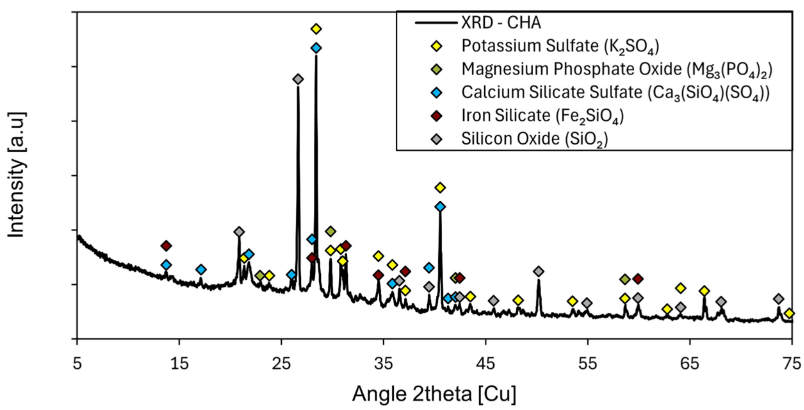

Figure 3: XRD pattern of coffee husk ash (CHA).

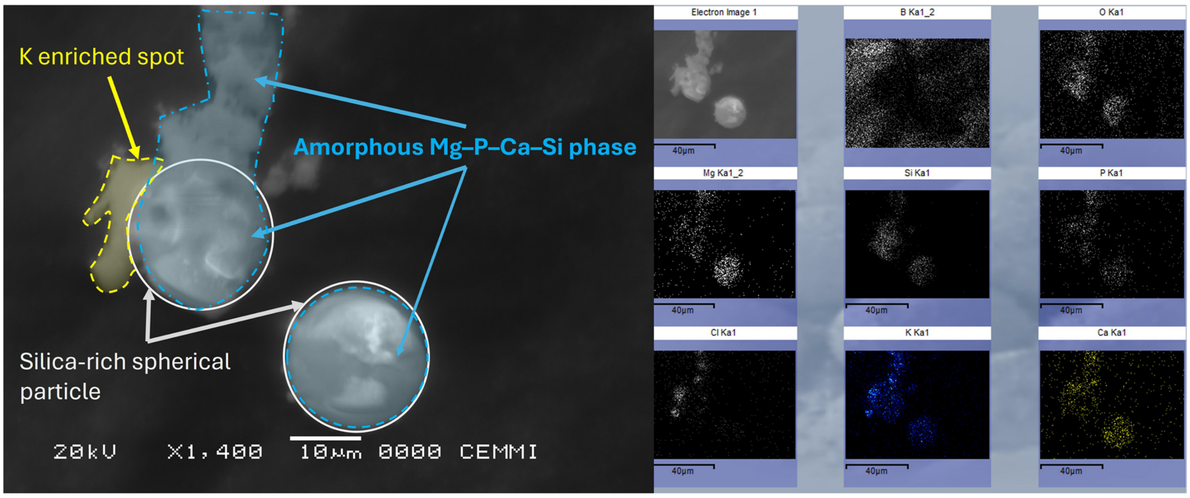

Figure 4: SEM–EDS Analysis of CHA Microstructure.

that CHA has the potential to develop cementitious compounds when properly activated, making it suitable as a complementary material in soil stabilization as shown in Figure 3.

The scanning electron microscopy (SEM) image (see Figure 4), obtained using a JEOL JSM-6460LV scanning electron microscope coupled with an Oxford Instruments INCA x-act EDS detector, reveals predominantly spherical particles rich in silicon, characteristic of a vitreous or non-crystalline phase, likely formed during the calcination of an agro-industrial byproduct. These particles are surrounded by amorphous phases with less defined morphology, which, according to the elemental mapping, contain magnesium, phosphorus, oxygen, calcium, and silicon. This suggests the presence of magnesium phosphate and calcium silicate compounds. Additionally, localized inclusions with high potassium and chlorine content were detected, consistent with the formation of potassium sulfate or potassium chloride. This heterogeneous distribution and the coexistence of secondary crystalline and amorphous phases highlight the complexity of the material and support its potential pozzolanic behavior in cementitious environments.

2.1.3. Sample preparation

In defining the CHA content percentages (4%, 6%, and 8%) used in this study, we relied on previous research that identified these ranges as optimal for improving geotechnical behaviour in clayey soils stabilized with agro-industrial ashes. Studies such as MUNIRWN *et al*. [6], ALAVÉZ-RAMÍREZ *et al*. [32], JAYASHREE and YAMINI ROJA [33], and MORA-RUIZ *et al*. [5] reported favorable results with dosages generally ranging from 5% to 10%. These findings guided the selection of the 4–8% interval used here, as a balance between expected performance, workability, and compatibility with the soil characteristics. A summary of parameter selection from prior studies is presented in Table 2.

Table 2: Summary of Coffee Husk Ash (CHA) dosages and key findings from previous studies.

STUDY	TYPE OF ASH	SOIL TYPE	ASH CONTENT USED (%)	REPORTED OPTIMAL RANGE (%)	CALCINATION TEMPERATURE
Marwin et al. (2022)	Coffee husk ash	High plasticity clay	5%–25%	5%–10%	600 °C
Alavéz-Ramírez et al. (2012)	Sugarcane bagasse ash	Silty clay	5%–15%	5%–10%	600 °C
Jayashree & Yamini Roja (2019)	Rice husk ash	Expansive soil	4%–10%	6%–10%	500–600 °C
Mora-Ruiz et al. (2022)	Sugarcane bagasse ash	Clay	5%–10%	5%–10%	Not reported

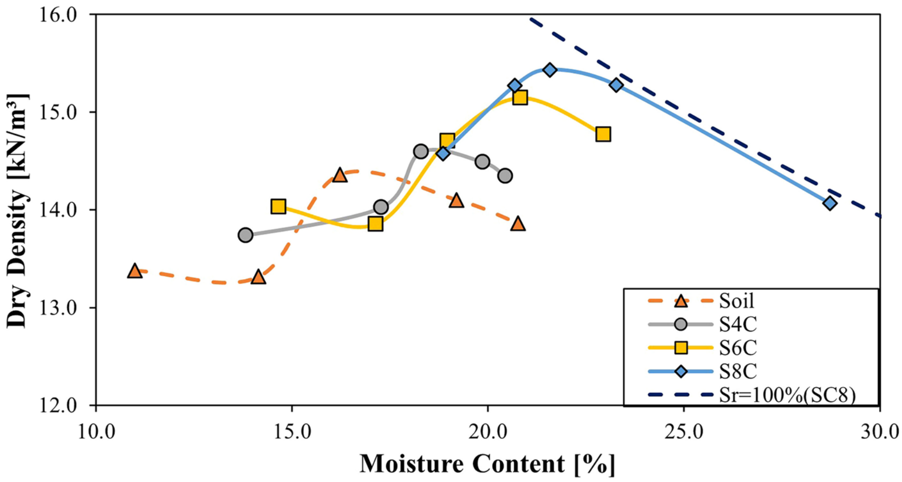

Figure 5: Compaction curve of soil with coffee husk ash.

Once the ash content percentages were defined, a standard compaction test was conducted to evaluate their effect on the physical behavior of the mixtures. The relationship between moisture and dry density was determined. shown in Figure 5. The results indicate that, as the coffee husk ash (CHA) content in the soil increased, both the maximum dry density and the optimum moisture content showed specific behaviors. Sample S8C reached a maximum dry density of 15.3 g/cm^3, while the untreated soil presented the lowest value, 14.2 g/cm^3. This behavior can be explained by the pozzolanic properties of the ash, its higher specific gravity and its capacity to act as a filler, improving soil compaction and cohesion. As shown in other studies, ashes tend to increase the water demand due to their porous and absorbent nature. However, having a higher specific gravity than the natural soil and inducing flocculation processes between particles, the ash promotes a denser packing structure. As a result, the dry density increases progressively as the ash content rises, even when more water is needed for compaction.

Research by MUNIRWAN *et al*. [29] reported consistent results when analyzing a clayey soil of high plasticity, where the maximum dry density reached 1220 kg/m^3 when incorporating up to 25% CHA. They also reported an optimum moisture content of 36.3%, explained by the porous nature of the ash, which increases the demand for water to lubricate the particles and improve their cohesion. On the other hand, ARULRAJAH *et al*. [30] also observed that the use of CHA mixed with by-products, such as recycled glass, significantly improved soil compaction characteristics. Although specific numerical values were not provided, they highlighted that the chemical interaction between ash and soil particles increased the bearing capacity. In addition, OKWADHA *et al*. [21] worked with a red clay loam soil and found that CHA improved compaction properties by reducing soil plasticity. They also mentioned that the optimum moisture content tends to increase due to the water absorption capacity of the ash, although specific quantities were not reported. Furthermore, ALAVÉZ-RAMÍREZ *et al*. [32] showed that the incorporation of sugarcane bagasse ash increased both the optimum moisture content and dry density of compacted soil blocks, due to its fine texture, absorbent nature, and interaction with the soil matrix. Likewise, JAYASHREE and ROJA [33] confirmed similar behavior when using rice husk ash and lime to stabilize expansive soils, reporting improved compaction properties related to higher moisture demand and densification In addition, they mentioned that the optimum moisture content tends to increase due to the water absorption capacity of the ash, although specific quantities were not reported.

2.2. Methodology

The general methodology adopted in this study is illustrated in Figure 6, which outlines the procedures from soil and ash collection through characterization, mixture preparation, and performance evaluation. This study evaluated the stabilization of a clayey soil of low plasticity through the incorporation of coffee husk ash (CHA). First, the physical characterization of the ash was performed. The organic matter content was determined using the ignition method in an oven at 450°C, following ASTM D2974-20 [34]. Particle size distribution was evaluated by two methods: sieve analysis for the coarse fraction, according to ASTM D6913-04 [35], and hydrometer analysis for the fine fraction, according to ASTM D7928-17 [36]. The specific gravity of the ash particles was determined by the water pycnometer method, according to ASTM D854-10 [37]. In addition, the particle size was analyzed by the sieving and hydrometry methods, following ASTM D 422-63 [38].

Subsequently, the physical and mechanical properties of the natural soil, a clayey soil of low plasticity, were evaluated. Classification tests included granulometry, according to ASTM D 422-63 [38], consistency limits according to ASTM D 4318-10, organic matter content, following AASHTO 267-86 [39], and specific gravity, according to ASTM D854-10 [37]. The compaction test was performed following ASTM D698-07 [39] to determine the maximum dry density and optimum moisture content of the soil. To evaluate the strength properties, the California Bearing Ratio (CBR) test, according to ASTM D1883-07 [40], and the unconfined compression test, according to ASTM D1632-17 [41], were used In addition, the resilient modulus test was conducted in accordance with AASHTO T307, and the matric suction of the specimens was measured using the WP4C dew point potentiometer.

To evaluate the impact of coffee husk ash on soil behavior, mixtures were prepared with concentrations of 4%, 6% and 8% by weight of CHA. Physical tests were repeated for each mixture, including determination of specific gravity, consistency limits and compaction test. In addition, mechanical tests, such as CBR and simple compression test, were performed.

Specimens were manufactured for compaction and mechanical tests, with standard dimensions for each type of test. For the unconfined compressive strength tests on soil–cement mixtures, cylindrical specimens of 5 cm in diameter and 10 cm in height were prepared. Additionally, specimens for resilient modulus tests were molded with 7 cm in diameter and 14 cm in height and subjected to controlled loading conditions. For the matric suction tests, disc-shaped specimens were prepared using a specialized mold with 37.5 mm in diameter and

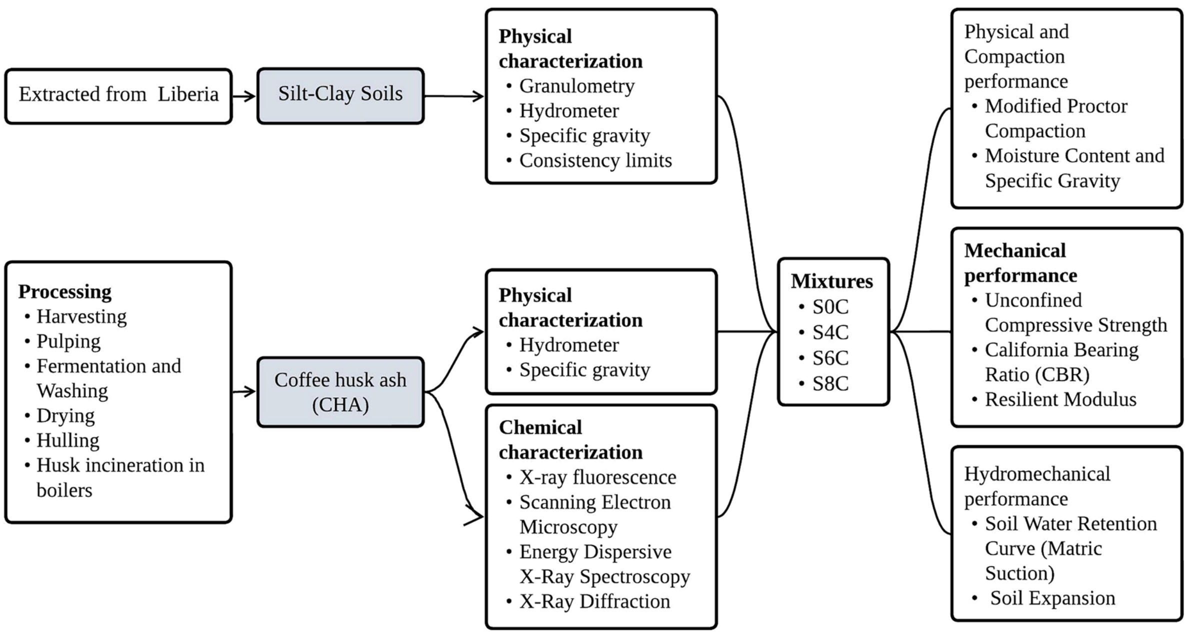

Figure 6: Experimental methodology for soil stabilization with coffee husk ash.

9.25 mm in height, allowing proper fitting in the suction testing apparatus. These different geometries ensured appropriate conditions for evaluating the hydromechanical behavior of the stabilized soil under varying moisture and stress levelsFinally, moisture retention curve tests were performed using a WP4C hygroscope, and resilient modulus tests were carried out using a GDS triaxial tester. The results obtained allowed establishing correlations between the suction parameters and the resilient modulus of the stabilized soil.

3. RESULTS AND DISCUSSIONS

This section presents and analyzes the results obtained from the tests carried out to evaluate the stabilization of clayey soil with coffee husk ash. The results are discussed in terms of the physical and mechanical properties of the soil, as well as the impact of the different concentrations of coffee husk ash (4%, 6% and 8%) on the behavior of the material.

Figure 7 shows the results of the moisture content and specific gravity of the different soil-ash mixtures: S4C, S6C and S8C. The results show that the liquid limit is in the range of 38 to 40%, and the plastic limit varies between 20% and 22%, resulting in a slight decrease in the plasticity index, from 18% to 17%. Although these changes are not significant, a slight trend towards a reduction in the plasticity of the stabilized soil can be observed. This observation is in line with previous studies reporting an improvement in the plastic properties of soils upon incorporation of CHA. TESSEMA *et al*. [8] in their study on the stabilization of expansive soils with coffee husk ash and gypsum, observed a reduction in the plasticity index with the addition of CHA, improving the stability and bearing capacity of the soils.

Regarding specific gravity, a value of 2.95 was obtained for coffee husk ash, while the natural soil presented a value of 2.47. According to previous studies, such as those of GIDEBO *et al*. [3], soils treated with coffee husk ash present an increase in specific gravity due to the densification of the stabilized soil particles, which reinforces the improvement in soil density with the addition of CHA. These results are also consistent with those found in the study by OKWADHA *et al*. [21] on the use of rice ash to stabilize soils, where an increase in specific gravity was reported upon incorporation of the stabilizing material.

Figure 8 shows the analysis of two fundamental properties in soils stabilized with coffee husk ash (CHA): the California Bearing Ratio (CBR) and soil expansion. The results obtained from the CBR tests, performed according to ASTM D1883-07 [40], show that as the percentage of ash in the soil increases, the CBR increases significantly. This behavior is consistent with that reported by previous studies, such as those of JARJUSEY *et al*. [42] and LI *et al*. [43], who found an increase in CBR with the addition of stabilizers such as rice ash and palm ash. In both studies, the incorporation of ash improved the bearing capacity of the soil, which allows the stabilized material to withstand higher loading stresses, crucial for its use in pavements and other engineering applications.

In addition, the measurement of soil expansion, taken at 96 hours after saturation, showed that as ash content increases, soil expansion decreases. This behavior is consistent with the results obtained in the research of JARJUSEY *et al*. [42], where it was observed that treatment with palm ash and rice ash reduced expansion in clay soils, which improves soil stability under wet conditions. In the case of the soil stabilized with the highest percentage of CHA (S8C), a 24% reduction in expansion was achieved with respect to the natural soil, suggesting a significant improvement in its volumetric behavior.

Figure 9 shows the results obtained in the simple compression test, comparing the strength of the soil stabilized with coffee husk ash (CHA) in two conditions: dry (after 7 days of oven curing) and saturated through

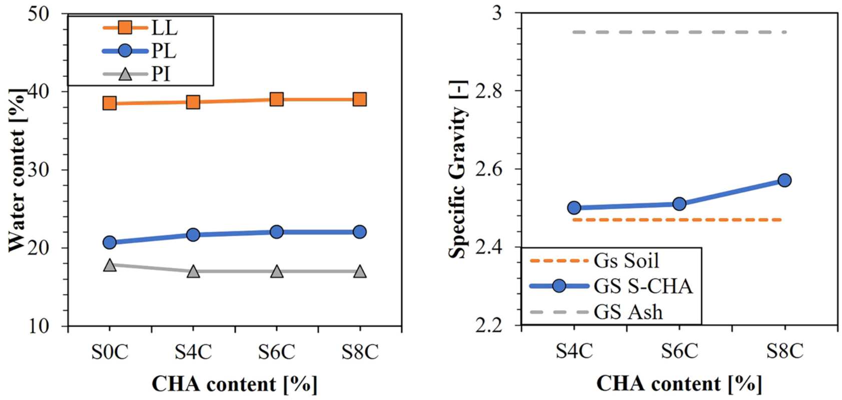

Figure 7: Moisture content and specific gravity of the mixes.

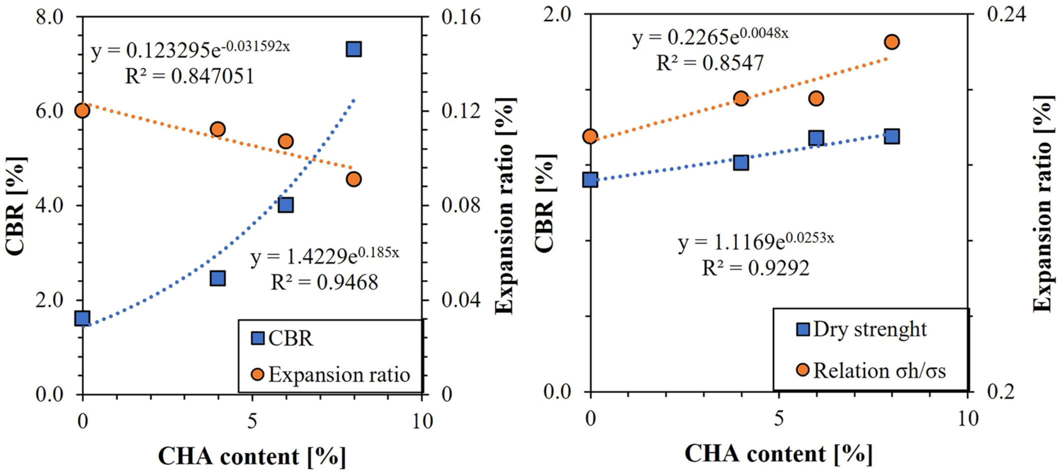

Figure 8: Influence of coffee husk ash on soil CBR and expansion behavior.

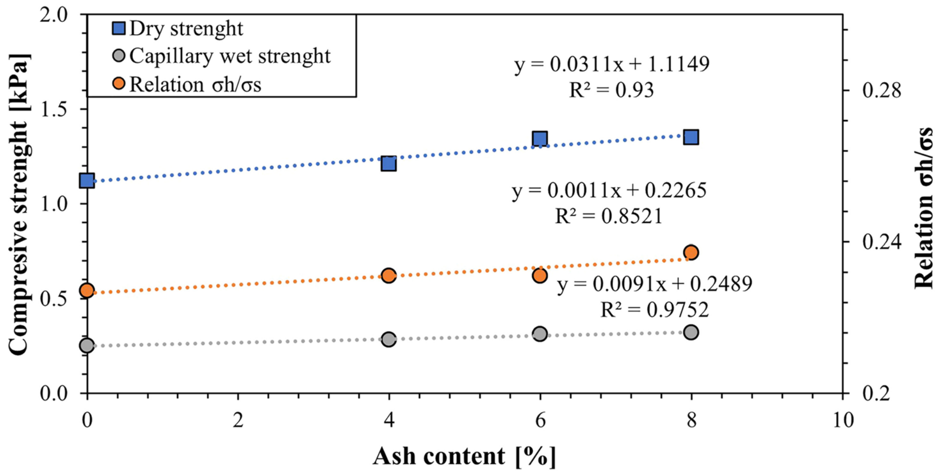

Figure 9: Effect of coffee husk ash content on compressive strength and expansion of soil.

capillary rise. The results indicate significant improvements in soil strength with the addition of ash in both conditions.

Under dry conditions, it was observed that the compressive strength of the soil increased as the ash content increased. Soil strength increased from 1.15 MPa in natural soil to 1.35 MPa with 8% ash, an increase of 20.5%. This behavior shows that the ash improves the bearing capacity of the soil, providing greater structural support. In addition, a linear trend in the increase in soil strength as a function of ash content is observed, reinforcing the positive relationship between the two factors. This linear increase in strength is consistent with previous studies, such as that of YU *et al*. [44], who also reported a linear increase in the compressive strength of soil stabilized with fly ash.

In the saturation condition by capillary rise, the resistance also showed an increase, going from 0.25 MPa for the natural soil to 0.32 MPa for the soil with 8% ash, which represents an increase of 25.9%. However, the resistance in this condition is lower than that obtained in dry conditions due to the high presence of water, which reduces the cohesion between soil particles. The strength trend in this condition follows an exponential pattern, suggesting that the increase in strength is more noticeable at the beginning, but stabilizes with higher ash concentrations. This behavior is consistent with the study of LI *et al*. [43], where it was observed that water content negatively affects the strength of stabilized soil, especially when organic stabilizers are used.

The ratio between the strength in dry and saturated conditions was approximately 0.23, indicating that, although both increases in strength are substantial, the difference between the two conditions is not as pronounced. This suggests that stabilization with coffee husk ash has a greater impact on the strength of the soil in its dry state. This behavior is consistent with the results obtained by YAN *et al*. [45], who also observed that water content negatively affects the strength of stabilized soil.

In terms of expansion, it was observed that ash content contributed to significantly reduce soil expansion. The soil with 8% ash showed a 24% improvement in expansion reduction compared to the natural soil. This behavior reinforces the idea that the addition of ash improves the dimensional stability of the soil, reducing its expansion under wet conditions. This effect is similar to that observed by YU *et al*. [44], who reported an improvement in the dimensional stability of soils stabilized with fly ash and cement.

The results obtained show that stabilization with coffee husk ash significantly improves both the strength in dry conditions and in conditions saturated by capillary infiltration. Although the effect is more pronounced in dry conditions, the ash also contributes to a considerable improvement in soil strength under saturation. In addition, the reduction of soil volumetric expansion with increasing ash content confirms the effectiveness of coffee husk ash as a stabilizer, improving both mechanical and volumetric properties of the soil. These findings are consistent with previous studies that have documented improvements in the strength and stability of soils stabilized with ash and other stabilizers.

The fitted regression models for each condition demonstrate a high degree of correlation ($R^2 > 0.85$), validating the observed trends. In particular, the dry strength follows a linear trend with respect to ash content, while the saturated strength exhibits an exponential behavior, confirming the greater influence of moisture on the early stages of stabilization. The dry-to-wet strength ratio also increases slightly with ash content, indicating an improvement in the material's resistance even under moisture intrusion. These patterns suggest that the coffee husk ash not only enhances the soil's bearing capacity under dry conditions but also contributes to maintaining mechanical performance under partially saturated states. This behavior can be attributed to the formation of cementitious phases (e.g., C-S-H), which improve particle bonding and reduce the negative effects of capillary water on cohesion.

Figure 10 shows the relationship between matrix suction (in MPa) and moisture content for the soil-ash mixtures. In this graph, it is observed that the suction decreases exponentially as the moisture content increases. Mixtures with higher ash content, such as S8C, show a higher water holding capacity compared to mixtures with lower ash content, such as S4C. This behavior is consistent with the results obtained in the compaction curve, where mixtures with higher amounts of ash have higher optimum moisture and higher maximum dry density. These results suggest that mixtures with higher ash content, such as S8C, could exhibit better hydromechanical performance under variable moisture conditions, providing greater stiffness and stability. This water-holding capacity and higher dry density correlate with improved stability and structural behavior of the stabilized soil, as demonstrated by other studies using agricultural residue ash or biomass [1, 46].

The results obtained are similar to those observed by other authors, such as MUNIRWAN *et al*. [4], who also reported improvements in the hydromechanical properties of soils stabilized with agricultural residue ash. This behavior suggests that increasing the amount of ash not only improves the bearing capacity and strength of the soil, but also its behavior against moisture fluctuations, which is crucial in the design of structures that must withstand changing moisture and loading conditions. Matrix suction is a fundamental parameter to evaluate the response of stabilized soils under variable moisture conditions, as observed in previous studies of stabilization with coffee husk ash.

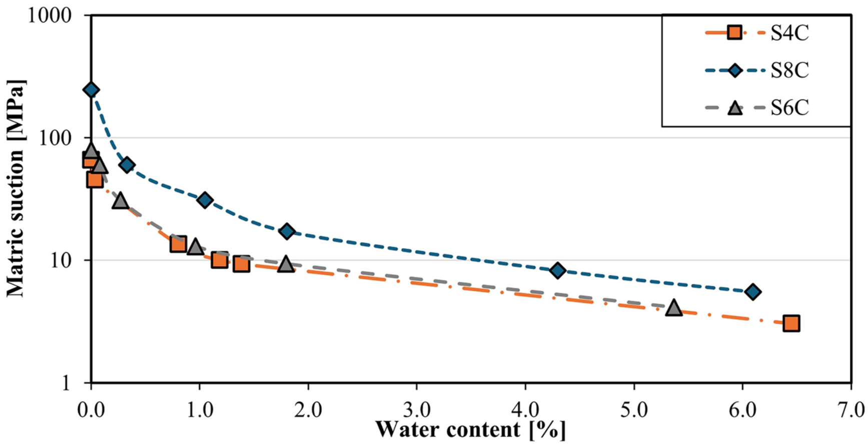

Figure 10: Soil water retention curves for mixtures stabilized with 4%, 6%, and 8% coffee husk ash (S4C, S6C, and S8C).

This trend is also consistent with the research of MELESE *et al*. [47], who analyzed the improvement of expansive soils with ash, finding that moisture content has a considerable impact on the water-holding capacity and, thus, on the structural stability of soils. From a physical-chemical standpoint, this improvement can be attributed to pozzolanic reactions between reactive oxides in the ash (e.g., CaO, MgO) and active clay minerals, leading to the formation of cementitious products such as calcium silicate hydrates (C-S-H), which enhance particle bonding and cohesion. These findings reinforce the conclusion that coffee husk ash significantly improves the mechanical and hydromechanical properties of the soil, increasing the stiffness and stability of the material, which is especially beneficial for use in variable moisture conditions, such as those found in road and other infrastructure applications.

Figure 11 shows the relationship between Resilient Modulus (Mr) and Stress Tensor (θ) for soil mixtures stabilized with different percentages of coffee husk ash (S4C and S8C) at two curing times: 7 and 28 days. In the graph, an increasing trend in the resilient modulus is observed as the stress tensor increases. This behavior is expected for materials that increase their stiffness as more stress is applied to them, which is characteristic of stabilized materials. It is noted that samples cured for 28 days show a significantly higher resilient modulus than those cured for only 7 days, with a 25% increase in resilient modulus. This increase is especially noticeable in the mixes with higher ash content. For example, the S8C mix (with 8% ash) at 28 days shows higher Mr values compared to the S4C mix, reflecting an improvement in the dynamic stiffness of the material, attributed to both the ash content and the longer curing time.

The positive effect of the higher ash content is evident, as the S8C-28 day mix shows an increase of approximately 20% in resilient modulus compared to the S4C-28 day mix. This behavior highlights how the addition of ash contributes to increased formation of cementitious products and a denser microstructure, which improves the internal cohesion and stiffness of the stabilized soil. This effect is consistent with the findings of FAROOQ *et al*. [48], who also highlighted that prolonged curing time favors the formation of a more cohesive structure in stabilized materials. In addition, samples with higher ash content, such as S8C, present a higher resilient modulus than mixtures with lower ash content, such as S4C, confirming that ash has a positive effect on the development of material stiffness. This behavior is in line with that found by NAZIR *et al*. [28], who observed that materials stabilized with other composites, such as GGBS (granulated blast furnace slag), also showed an increase in the stiffness of soils.

The analysis in Figure 11 reaffirms the positive influence of both ash content and curing time on the mechanical properties of stabilized soils. In particular, the increase in resilient modulus with curing time suggests that chemical reactions during curing, such as the formation of calcium silicate hydrate (CSH), improve the internal cohesion of the material, resulting in an increase in its stiffness. This phenomenon has also been documented in previous studies of soil stabilization with agricultural residues and cementitious materials, such as those conducted by FAROOQ *et al*. [48] and NAZIR *et al*. [28].

A chemical perspective, show an increase in stiffness can be attributed to the pozzolanic reactions between reactive oxides present in the ash (e.g., CaO, MgO, K_2O) and the active clay minerals. These reactions lead to the gradual formation of cementitious products, such as calcium silicate hydrates (C-S-H), which bind soil particles and fill microvoids, enhancing cohesion and reducing deformability. Furthermore, the granular nature of the ash modifies the soil texture, improving particle packing and internal friction, which contributes to the development of resilient behavior under repeated loading.

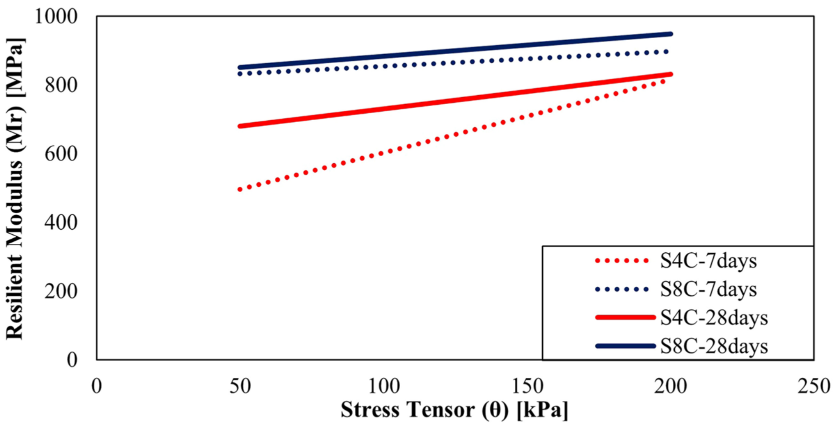

Figure 11: Resilient modulus versus tensile stress in soil–CHA mixtures.

The results obtained in this study align with and, in some cases, surpass those reported in previous research on soil stabilization using agricultural ashes. For instance, while ATAHU *et al*. [2] reported a 28.3% increase in unconfined compressive strength (UCS) with 10% coffee husk ash (CHA) after 28 days, our study achieved a comparable 28% increase under saturated conditions, highlighting the effectiveness of CHA even in less favorable moisture environments. Similarly, MUNIRWAN *et al*. [6] observed an improvement from 181 to 355 kPa using 8% CHA, which aligns with the strength gains recorded in our samples, particularly at higher dosages. TESSEMA *et al*. [8] noted UCS improvements from 245 to 310 kPa using 6% CHA with gypsum; although we did not use gypsum, similar magnitudes were achieved solely with CHA, emphasizing its potential as a standalone stabilizer.

Regarding bearing capacity, the 356% increase in California Bearing Ratio (CBR) observed in our study significantly exceeds the 95.5% gain reported by LISBET OLANO *et al*. [7] using 10% CHA, and even the 264% improvement obtained by TESHNIZI *et al*. [18] with a rice husk ash–gypsum mix. This indicates a particularly strong interaction between CHA and the tropical clayey soil tested in our research. MORA-RUIZ *et al*. [5] also reported progressive improvements in stiffness and resilient modulus using sugarcane bagasse ash; our results follow similar trends, showing that binder type and local compatibility play a crucial role. Lastly, although MANIMARAN *et al*. [17] highlighted the effectiveness of groundnut shell ash and blast slag, the environmental fit and magnitude of improvement in our study underscore the viability of CHA as a locally sourced, sustainable stabilizing agent for road subgrades in coffee-producing regions. Moreover, SILVA *et al.* [46] demonstrated that biomass ashes such as wood ash can be effectively used as partial cement replacements in soil–cement bricks, achieving competitive mechanical strength and environmental benefits. This reinforces the relevance of agro-industrial ashes not only in compacted soils but also in cemented matrix applications, and supports the broader applicability of CHA in sustainable soil improvement strategies.

The improvement in strength parameters such as CBR, unconfined compressive strength (UCS), and resilient modulus (Mr) with increasing ash content can be attributed to the physical and chemical interactions between the clay matrix and the coffee husk ash (CHA). From a chemical standpoint, the presence of reactive oxides such as CaO, MgO, and K_2O in the ash contributes to pozzolanic reactions, especially under moist conditions. These reactions lead to the formation of cementitious compounds such as calcium silicate hydrates (C-S-H) and calcium aluminate hydrates (C-A-H), which fill voids and bind soil particles together, resulting in increased cohesion and stiffness. Physically, the ash particles—being coarser and less plastic—modify the soil texture, reduce its plasticity and improve the particle packing, enhancing the load transfer capacity and reducing deformation. Furthermore, the higher water-holding capacity of ash-rich mixtures increases the internal suction and surface tension forces at lower moisture contents, which also contributes to the mechanical stability of the material. These combined effects explain the observed improvements in mechanical and hydromechanical performance with increasing CHA content.

4. CONCLUSIONS

It was demonstrated that coffee husk ash significantly improves the physical and mechanical properties of clay soils. Its pozzolanic capacity favors the cementation of the material, which makes it suitable for the improvement of roads in clayey soils, improving their behavior in the face of mechanical stress and variable environmental conditions.

The soil analyzed is classified as low plasticity clay according to the SUCS system, with a specific gravity of 2.47. Its granulometric composition indicates that it is a fine soil. Its granulometric composition indicates that it is a fine soil, since more than 50% of its particles pass the No. 200 sieve. The coffee husk ash, on the other hand, does not present plasticity and has a specific gravity of 2.95. Its granulometry shows mostly coarse particles, since more than 50% of its particles have a diameter greater than 0.075 mm. This makes it a suitable material for soil stabilization, especially because of its high calcium content, favoring its pozzolanic action.

The addition of ash did not affect the soil plasticity index. However, it increased the specific gravity of the soil from 2.47 in the natural soil (S0C) to 2.56 in the soil with 8% ash (S8C). In compaction tests, optimum moisture increased from 16.63% in the natural soil to 22.83% in the soil with 8% ash, representing an increase of 37.3%. However, the maximum dry density decreased slightly from 15.96 kN/m3 to 15.24 kN/m3, representing a reduction of 4.5%.

As for the load bearing ratio (CBR), an increase of 356% was observed, from 1.6% in the natural soil to 7.3% in the soil with 8% ash by weight. This increase highlights the high potential for improvement in soil strength with the addition of ash. In addition, a 24% improvement in expansion was evidenced, as expansion decreased from 0.120% in the natural soil to 0.091% with the 8% ash, reflecting greater dimensional stability of the soil.

In the simple compression test, it was observed that the addition of ash to the soil increased the strength in both conditions evaluated. In the dry condition, the strength increased from 1.12 MPa (S0C) to 1.35 MPa (S8C), which represents an increase of 17.4%. In the capillary infiltration condition, the strength increased from 0.25 MPa (S0C) to 0.32 MPa (S8C), an increase of 28.0%. These results show a significant improvement in the stiffness of the stabilized soil in both dry and saturated conditions, making it suitable for applications where high structural strength is required.

The analysis confirms that both curing time and coffee husk ash (CHA) content significantly enhance the resilient modulus (Mr) of stabilized soils. After 28 days of curing, mixtures showed up to 25% higher Mr values compared to those cured for only 7 days. In particular, the S8C mix (8% CHA) achieved the highest performance, showing a 20% increase in resilient modulus compared to the S4C mix (4% CHA) at the same curing time. This improvement is attributed to the intensified pozzolanic reactions over time and the greater availability of reactive oxides in the ash, which contribute to the formation of cementitious products such as C–S–H. As a result, the soil structure becomes denser and more cohesive, improving its stiffness and resistance to repeated loading.

The observed improvements in CBR, compressive strength, and resilient modulus are attributed to the combined physical and chemical effects of the coffee husk ash. The presence of reactive oxides such as CaO and MgO favors pozzolanic reactions, leading to the formation of cementitious compounds that enhance particle bonding. Simultaneously, the ash modifies the soil texture and improves its internal structure, contributing to greater cohesion, stiffness, and reduced deformation under load.

5. ACKNOWLEDGMENTS

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