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A sustainable solution of coffee husk waste disposal for soil stabilization

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ABSTRACT

Sustainable engineering conserves energy and resources for future generations. Natural resources have deteriorated because of the rapid increase in global population. Similarly, the waste amount released parallels population growth. The waste that does not decompose will be buried for hundreds of years, causing harm to the environment, and contributing to the environmental and financial challenge of waste disposal. Introducing more eco-friendly materials is of essential relevance in geotechnical engineering. Coffee is among the most highly valued commodities today. Its production has increased drastically in recent years, but so have its waste by-products. Unfortunately, handling coffee husk waste has become a major issue due to increased coffee production and consumption. This study examines the influence of coffee husk ash (CHA) on the mechanical and compressibility properties of stabilized clayey soil. Five different samples of soil were made, containing 5, 10, 15, 20, and 25% of CHA. The physical and mechanical properties of the CHA-clay will be described in detail in the paper. The presence of CHA in clayey soil improved both the Atterberg limits and the compaction properties. In addition, it was found that the unconfined compressive strength (UCS) and California bearing ratio (CBR) values of CHA-modified soil showed better performance than untreated soil. The potential of replacing conventional resources with waste products such as CHA offers significant technical, financial, and environmental benefits in the current context of sustainability, especially in the road construction industry.

Keywords: coffee waste, compressibility, environment, stabilization, sustainable.

1 INTRODUCTION

In the past half-century, the social, economic, and physical infrastructure of the world has been challenged by rapid urbanization. With a forecasted, 2.7 trillion tons of waste that will be generated by 2050, the world's waste production has never been higher as a result of growing populations (Maddalena et al. 2018). This will have a considerable effect on ecological life, especially public health, due to the production of harmful gases during biological and chemical decomposition (Rivera et al. 2020). In addition, harmful greenhouse gases cause significant global warming and ecological problems. Accordingly, applying more efficient strategies for sustainable solutions, especially in the construction and manufacturing industries, will boost environmental and economic systems greatly. Moreover, it will also benefit overall cost variables by optimizing resource usage and reducing waste that would alternatively be dumped (Janissen & Huynh, 2018).

Sustainable and cost-efficient infrastructure projects, including roads, buildings, and trains, require the utilization of locally sourced materials. In the past few years, extensive research has been done on how agricultural by-products can be used to produce environmentally friendly building materials (Abdelkader et al. 2022; Kumar & Barbato, 2022; Munirwan et al. 2022; Wu et al. 2022). Also, it is well known that agricultural wastes like palm oil fuel ash (POFA), rice husk ash (RHA), and eggshells can be used for soil stabilization (Mumtaz et al. 2020). These have mostly been done to help with soil problems like low bearing capacity and soil expansion. One of the by-products that could be utilized for soil stabilization is coffee husk, which is a by-product of the coffee industry. As shown in Figure 1, although coffee waste, for instance, has various practical uses (Borghesi et al. 2016; Chairgulprasert & Madlah, 2018; Kosaiyakanon & Kungsanant, 2020), it is commonly dumped in landfills in developing countries due to a lack of proper regulations and technical expertise for its use. Currently, utilized coffee husks have no equivalent market demand, resulting in disposal problems. The coffee husks are abandoned in landfills or burned, resulting in environmental degradation (Zhang et al. 2020). The inappropriate dumping of coffee waste has poor effects on the environment, including water contamination and land degradation, which are harmful to humans (Acchar et al. 2016). Therefore, it is essential to establish sustainable options for reusing waste to improve the sustainable production of the coffee service. There are three typical coffee wastes: coffee husk, coffee husk ash, and spent coffee ground. A schematic illustrating current coffee by-product usage is illustrated in Figure 1.

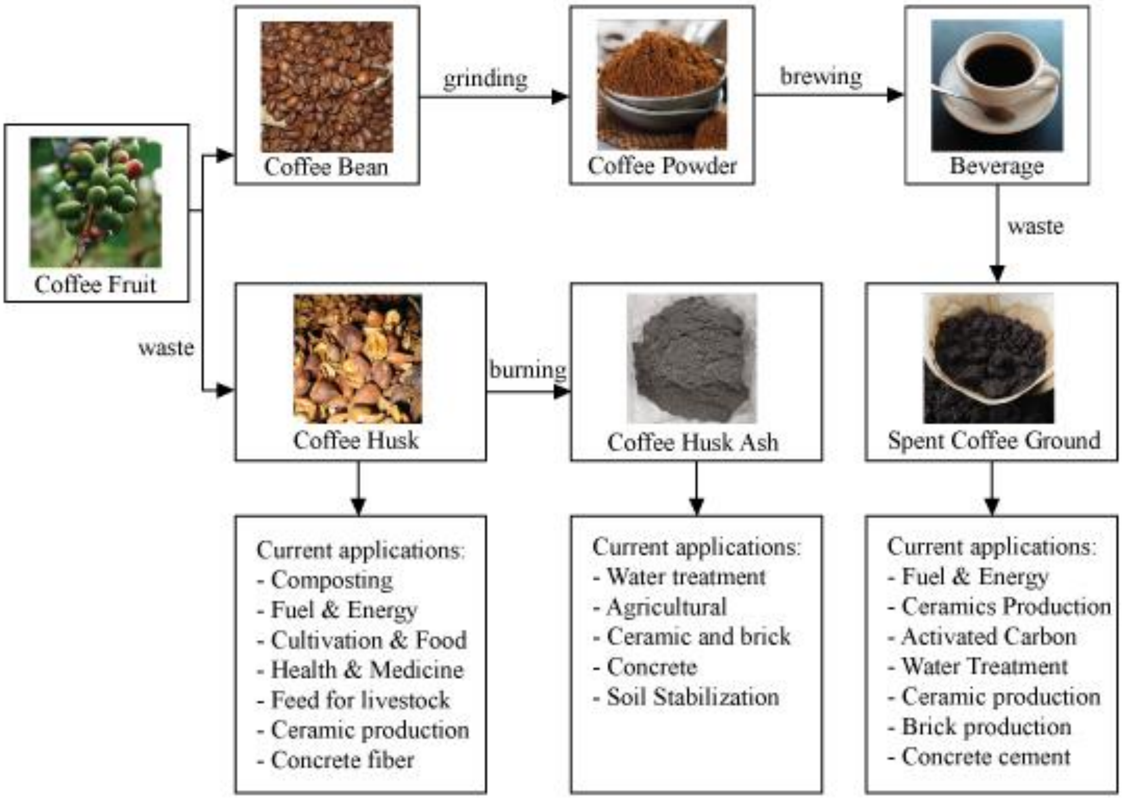

Figure 1. *A diagrammatic illustration of current coffee by-product uses* (Munirwan et al. 2022)

Coffee is the second most traded commodity in the world. Therefore, it is the most available and second-most consumed drink in the world (Kovalcik et al. 2018; Saberian et al. 2021). Brazil is the top coffee-producing country in the world, followed by Vietnam, Colombia, Indonesia, and Ethiopia. Significant amounts of waste are produced during the industrialization of coffee. The coffee industry is reported to make about 6 million tons of waste every year (Massaya et al. 2019). Furthermore, the coffee industry generates a large number of by-products, like coffee husks and spent coffee grounds (Munirwan et al. 2022). Recent investigations of coffee husk ash (CHA), a waste of the coffee husk burning phase, for its potential use as a geomaterial, have been studied (Acchar et al. 2016; Atahu et al. 2019; Demissew et al. 2019). Acchar et al. (2016) examined the effects of incorporating CHA and granite waste into clay-based composite ceramic. Moreover, Atahu et al. (2019) investigated the influence of CHA on the compressibility and consolidation of black cotton soil. Both untreated and CHA-treated samples were put through the California bearing ratio test and the one-dimensional consolidation test. The results of the analysis show that the CHA-treated soil displays an overall increase in soil strength. In addition, Demissew et al. (2019) examined if coffee husk ash (CHA) could partially replace ordinary Portland cement (OPC) in standard concrete production. This study demonstrates that concrete made from CHA has great importance as a source of environmentally friendly material that offers a viable option for managing coffee waste.

The main objectives of this experimental study are to determine the influence of CHA on the geotechnical performance of clayey soil and to investigate the interrelated processes. Essentially, the higher quantity of potassium and silica concentrations in CHA could assist the pozzolanic processes that happen during hydration and lead to the production of cement composites. These compounds are responsible for the improvement of soil engineering properties as the pozzolanic reaction progresses (Atahu et al. 2019). Due to its accessibility and low commercial value, the revolution of CHA in civil engineering will receive great interest. Accordingly, the goal of this research is to examine the influence of CHA application as an agricultural by-product on the geotechnical properties of clayey soils. Different geotechnical tests were conducted to assess the physical and mechanical characteristics of the CHA-modified soil.

2 MATERIALS AND METHODS

2.1 Materials

The clayey soil utilized in this study was sourced from Paya Kameng area in Aceh, Indonesia. The disturbed soil sample was collected by manual digging with a hoe. The soil sample was initially stored at laboratory temperature to air dry before being placed in the oven for 24 hours to ensure that it was completely dried. A homogenous sample was then obtained by passing the dried soil through a 4.75mm sieve (Figure 2). The coffee husk used in this research was retrieved from factories and farms in the Takengon region, Aceh Province, Indonesia before being burned for three to four hours to produce the ash. Takengon is well-known as one of Indonesia's largest coffee-producing areas (Fadhil et al. 2018). In order to eliminate coarser particles, the dry ash grain size was sorted to the necessary fineness by sieving through a 2-mm sieve.

Figure 2. *Coffee husk ash (CHA) used for the study (left). Clay soil passing sieve No. 4 (right)*

2.2 Methods

A range of experiments were conducted to determine the soil's physical and mechanical properties. All laboratory tests were performed in accordance with ASTM standard specifications. In addition, following drying at 30–35 °C at room temperature, the soil was crushed into a powder and passed through a 4.75-mm sieve. The CHA and soil were mixed for ten minutes and homogenized. In order to get the optimum levels of CHA for stabilization, the CHA percentage was varied from 5% to 25% based on the soil's dry weight at intervals of 5%. The physical parameter tests of index consistency and compaction tests were carried out on treated and untreated soil in compliance with the ASTM standards. The maximum dry density (MDD) and optimum moisture content (OMC) were 1220 kg/m^3 and 36.3%, respectively.

A set of unconfined compression tests (UCS) and California bearing ratio (CBR) tests were carried out on clay samples with CHA concentrations ranging from 5% to 25%. The mixtures were then compressed using a static compression apparatus to form a test specimen. In order to optimize strength, samples were compacted at the OMC indicated by the compaction test. The UCS test was conducted in accordance with ASTM D2166. The CBR test was utilized to assess the compressibility of compacted soils. Tests were done on samples prepared at a moisture content equal to that of untreated soil at various dry densities following standard compaction by the ASTM D1883 method.

3 RESULTS AND DISCUSSION

The grain size distribution of clay soil is presented in Figure 3. Generally, the soil is composed of 56.9% clay (< 0.002 mm), 32.4% silt (0.002-0.075 mm), and 10.7% sand (> 0.075 mm). The untreated soil has an LL of 70.9% and a PL of 27.77%, giving a PI of 43.13. Therefore, the soil was classified as high plastic clay (CH) and A-7-6 by the Unified Soil Classification System (USCS) and The American Association of State Highway and Transportation Officials (AASHTO) soil classification systems, respectively.

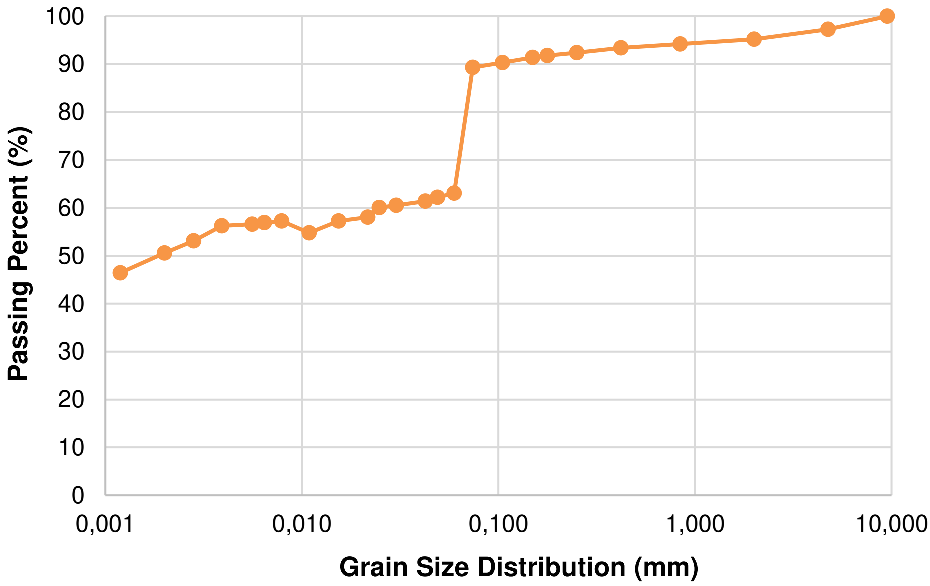

Figure 3. *Grain size distribution of untreated clay soil*

The CHA chemical compositions vary with temperature and combustion period, chloride and moisture, silica content, and ignition loss. Potassium oxide, iron oxide, silica, and phosphorus pentoxide represent most of the CHA's mineral composition as presented in Table 1. K_2O is the higher chemical composition of CHA followed by SiO_2, CaO, Fe_2O_3, and P_2O_5. Earlier studies have identified an identical range of CHA chemical component percentages (Acchar et al. 2016; Atahu et al. 2019). Furthermore, CHA is formed of a proportion of SiO_2, Al_2O_3, and Fe_2O_3, a concentration of CaO, and many other oxides with a high alkali content of K_2O (45–65%), and the loss on ignition rate of CHA is substantial of up to 20% due to the incineration and processing that was performed (Gedefaw, et al. 2022; Lima, et al. 2023).

Table 1. *Chemical content of the dry CHA used in this experimental study (in %)*

SiO_2	Fe_2O_3	CaO	MgO	Al_2O_3	Na_2O	K_2O	P_2O_5	MnO	LOI
8.30	5.10	5.22	1.03	0.04	0.03	60.09	4.98	0.05	2.83

Scanning electron microscopy (SEM) photographs are presented in Figure 4 to illustrate the micromorphological properties of CHA. The typical structure of CHA of 2,000 magnification from Samuel, (2017) is shown in Figure 4 (left). A similar structure was also captured for CHA at 4,000 magnification used in this research as in Figure 4 (right). The photos show that CHA has a rough base and that its granules are jagged, broken, irregular, and have rough surfaces. The morphology of their microstructure is an effective indicator of their effectiveness as a construction material, particularly for soil stabilization.

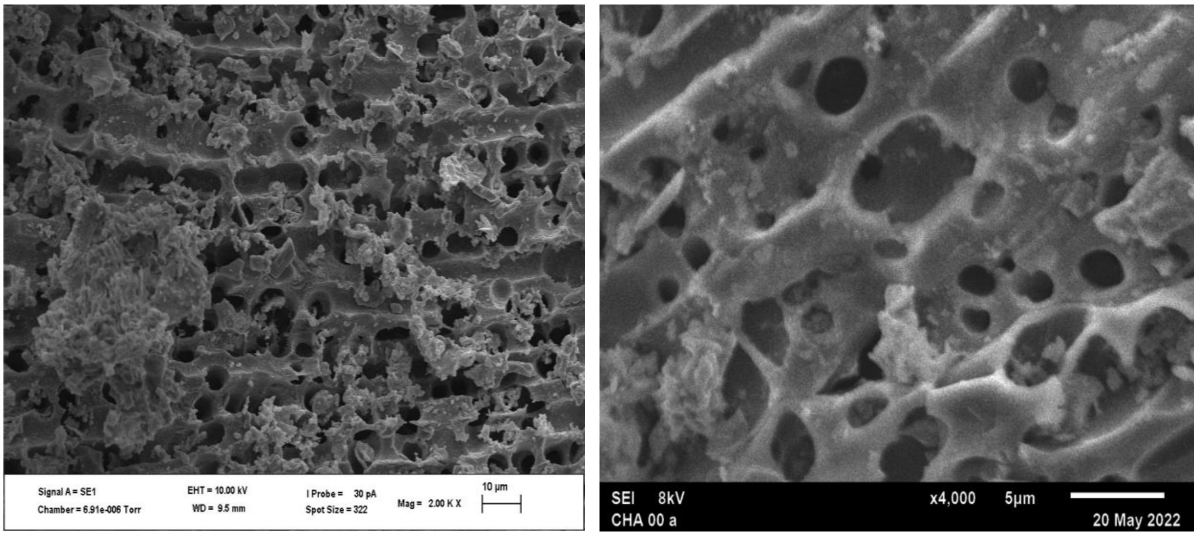

Figure 4. *Scanning electron microscopy (SEM) photograph of CHA. Typical CHA structures from* Samuel, (2017) *(left). CHA used in this study (right)*

The influence of CHA concentration on the physical properties of clay is shown in Table 2. The liquid limit (LL) value ranges from 67.0 to 70.9%, whereas the plastic limit (PL) value ranges from 27.77 to 32.42%, leading to a decline of 34.58 to 43.13% in the plastic index (PI) value. Often, a loss in the LL value of clay soil represents a drop in the soil swelling characteristics (Rahgozar et al. 2017). Furthermore, as more CHA is added, the specific gravity decreases from 2.670 for 0% CHA to 2.486 for 25% CHA. This was expected because CHA substances have a low specific gravity as mentioned by Atahu et al. (2019). Samples were also put through the standard Proctor tests to obtain their MDD and OMC. The highest MDD at 1250 kg/m^3 was observed for 25% CHA and the lowest OMC at 29.90%. On average, the MDD of clay soil samples treated with CHA was always greater than their initial dry unit weight. The improvement in MDD of the clay soil is related to the enhanced gradation of the soil resulting from the addition of CHA. In addition, increasing dry density enhances particle interlocking. On the contrary, when the concentration of CHA increased, the OMC of modified clay soil dropped marginally. The decrease in OMC can be attributed to the introduction of CHA to the soil, which reduces the interaction of clay soil particles with water particles. Similarly, previous researchers have shown an improvement in MDD and a reduction in OMC when CHA is introduced (Atahu et al. 2019; Woldegiorgis, 2019).

Table 2. *Physical properties of CHA-clay soil mixture*

Percentage (%)	Liquid Limit (%)	Plastic Limit (%)	Plastic Index (%)	Specific Gravity	Maximum Dry Density (kg/m^3)	Optimum Moisture Content (%)
0	70.90	27.77	43.13	2.670	1220	36.30
5	69.50	28.78	40.72	2.571	1224	34.00
10	69.00	29.33	39.67	2.531	1228	33.75
15	68.70	31.23	37.47	2.515	1235	33.10
20	68.00	32.43	35.57	2.501	1240	30.85
25	67.00	32.42	34.58	2.486	1250	29.90

Based on the USCS and AASHTO methods, Table 3 displays how the introduction of CHA modifies the morphology of clay soil grain. The treated samples began to change from clay to silt as the amount of stabilizing chemicals added to the soil increased. Overall differences in the consistency limits of stabilized soil led to a change in the soil classification system from CH to MH and from A-7-6 to A-7-5 for the USCS and AASHTO methods, respectively. According to the observed data, CHA stabilization forced the clay soil particles to agglomerate into larger aggregates, leading to the transformation into silt-sized particles.

Table 3. *Soil classification of CHA-clay soil mixture*

Percentage (%)	AASHTO	USCS
0	A-7-6	CH
5	A-7-6	CH
10	A-7-6	CH
15	A-7-5	CH
20	A-7-5	MH
25	A-7-5	MH

The results of UCS and CBR tests for untreated and treated clay soils with various CHA concentrations are presented in Figures 5 and 6. Results given in Figure 5 indicate that the UCS value of the clay soil rises steadily as the concentration of CHA increases from 89.17 to 130.83 kN/m^2 at a maximum of 25% CHA. The increased strength of CHA-clay soil can be linked to the interlock and interaction mechanism that developed between clay particles and CHA during sample preparation due to compacting efforts. Moreover, as indicated, the improvement in UCS value is attributable to the clay–CHA hydration interaction, which filled the void area and held the grains together, hence improving the strength of the clay soil. As was already stated, the development of strength is due to the existence of potassium carbonate, which stimulates the hydration reaction (Atahu et al. 2017; Lima, et al. 2023).

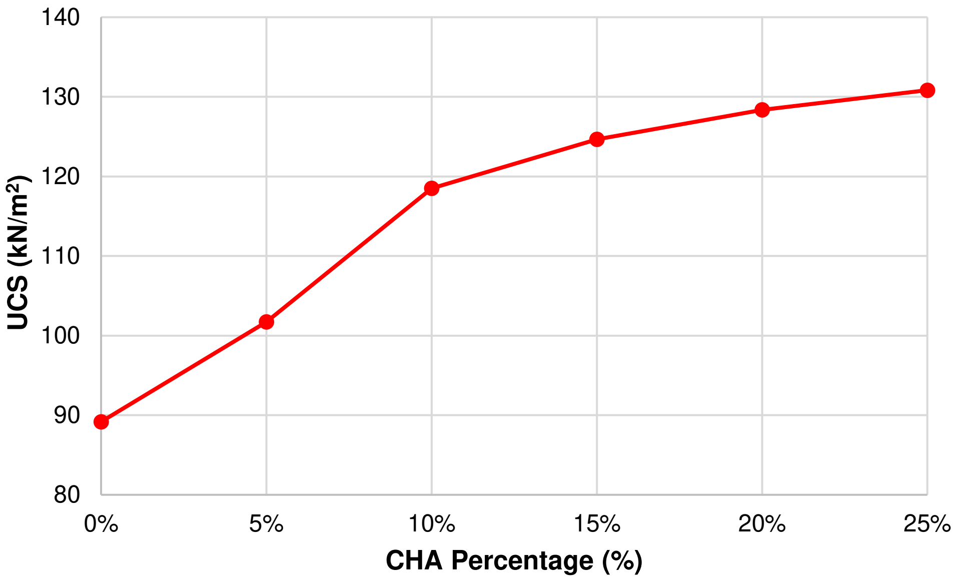

Figure 5. *UCS of clay-CHA mixture*

Figure 6 displays the unsoaked CBR values of untreated and treated clay soil with varying concentrations of CHA. The maximum CBR value of 26.4% was found for stabilized CHA soil containing 25% CHA. Several studies have found a similar pattern (Mamuye & Geremew, 2018; Atahu et al. 2019; Woldegiorgis, 2019). The occurrence of CHA around soil particles is associated with an improvement in CBR. Accordingly, soils may be able to withstand higher stresses and enhance their CBR value (Abdelkader et al. 2022; Rahgozar et al. 2017). Furthermore, the cementation responses of soil CHA may also support the improvement of CBR. Interactions between soil particles and CHA result in the development of a cementitious compound, which contributes to the improvement of soil strength. These results (UCS and CBR) show that the waste from the production of coffee has great potential as a suitable and sustainable resource/material in road or highway construction, especially in developing countries like Indonesia. The waste which would be just dumped and left without use can be introduced in construction reducing the use of precious natural resources and enhancing overall environmental sustainability.

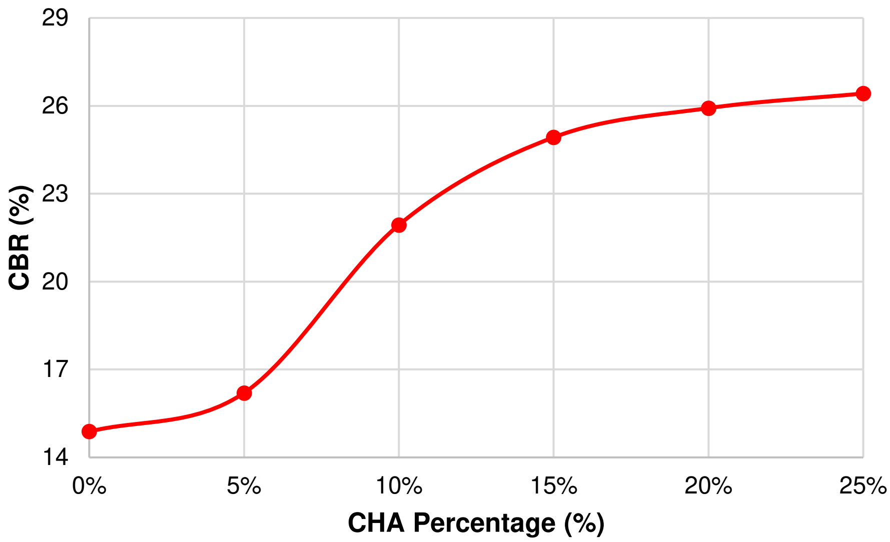

Figure 6. *CBR of clay-CHA mixture*

4 CONCLUSIONS

The innovative utilization of CHA in clay soil stabilization was investigated for the possibility of establishing a clean, eco-friendly, and greener environmental solution involving the reuse of waste material. The inclusion of CHA in clay soil changes the engineering properties of the soil, including the physical and mechanical properties. The study shows that adding CHA increases the MDD, UCS, and unsoaked CBR while lowering the OMC. In brief, CHA can improve the physical and mechanical properties of clay soil by triggering a particle interlocking and hydration response that fills clay voids and interlocks the particles of clay and CHA. Thus, CHA has promising potential and can be used effectively as a material for construction to reduce emissions into the atmosphere and construction costs. Furthermore, utilizing CHA, a by-product of coffee waste, in soil stabilization may result in highly acceptable results in terms of resolving issues associated with the disposal of coffee waste.

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