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Mineral Content of Clay Soil and Coffee Husk Ash for Soil Stabilization Applications in Geotechnical Engineering

Arissa Sabilla[1], Rajib Muammar[2], Ari Juanda[3]
[123]Teknik Sipil/Sains dan Teknologi, Universitas Samudra, Indonesia
[1]arissasabilla@unsam.ac.id , [2]rajibmuammar@unsam.ac.id , [3]arijuanda@unsam.ac.id

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ABSTRACT

This study aims to analyze the mineral composition of clay soil and coffee husk ash, as well as to evaluate the effect of coffee husk ash as a stabilizing agent for clay soil. The main problem addressed is the high plasticity of clay soil, which causes volume changes and reduces bearing capacity, making stabilization methods necessary. The research was conducted by collecting clay soil samples from Kebun Kurma Barbate, Aceh Besar, and coffee husk ash from Aceh Tengah. Mineral composition was analyzed using gravimetric, titrimetric, spectrophotometric, and AAS methods, while soil plasticity was examined through Atterberg limits and specific gravity tests. The results indicate that clay soil contains dominant Silica Oxide (SiO_2) at 42.99% and Aluminum Oxide (Al_2O_3) at 5.63%, contributing to its high plasticity. Meanwhile, coffee husk ash contains 8.30% SiO_2 and 5.22% Calcium Oxide (CaO), which play crucial roles in stabilization. The addition of 5–25% coffee husk ash reduced the plasticity index from 38.42% to 34.29%, increased soil specific gravity from 2.587 g/cm³ to 2.690 g/cm³, and transformed soil classification from clay to silt. These findings confirm the potential of coffee husk ash as an effective, and sustainable stabilizing material for geotechnical engineering applications

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A. BACKGROUND

In modern infrastructure development, soil plays a crucial role as a load-bearing medium for construction, whether in the form of roads, bridges, buildings, or other transportation infrastructure (Rudiansyah, 2024). The quality and characteristics of soil as a basic material greatly determine the stability and service life of a construction (Sumner, 2018). Inadequate soil conditions or low bearing capacity often become sources of problems that lead to structural damage or decreased construction performance in the long term (Aslam & Gofar, 2022). Therefore, geotechnical engineering seeks to provide solutions to varying soil quality problems through a series of approaches, one of which is soil stabilization techniques. Soil stabilization is necessary to improve the technical properties of poor soil so that it can meet the technical requirements for supporting construction loads safely and sustainably (Ekaputri dkk., 2021). One of the most widely developed stabilization methods is the addition of additives containing active minerals, which can interact with the soil to produce binding compounds such as calcium silicate hydrate (C-S-H), which significantly improves soil cohesion and strength (Munirwan, Taha, dkk., 2022; Munirwan, Taib, dkk., 2022).

The use of agricultural waste as a soil stabilizer is an interesting and sustainable approach in civil engineering. Coffee husk ash is a waste product resulting from the burning of coffee husks, which has not been optimally utilized (Artigos, 2025; Rosyad & Pranata, 2024). As the world's largest coffee producer, Indonesia generates a significant volume of coffee waste each year (Utamy, 2025). Coffee husk ash contains various important minerals such as silica (SiO_2), calcium oxide (CaO), magnesium oxide (MgO), and potassium oxide (K_2O), which have the potential to function as stabilizers in improving soil properties (Citra dkk., 2022; Diler, 2014). Recent research shows that coffee husk ash can improve the physical and mechanical properties of clay soil, including reducing the liquid limit, plasticity index, and increasing the cohesion and shear strength of the soil (Hardi, 2021). In addition, mineralogical analysis using XRD and XRF methods revealed that the main mineral content of clay soil, such as kaolinite, montmorillonite, illite, and quartz, contributes significantly to the plasticity and bearing capacity of the soil (Artigos, 2025). The pozzolanic reaction between amorphous silica in coffee husk ash and soil calcium produces binding compounds that improve soil structure and stability (Karurukan dkk., 2022).

Beyond the technical aspects, using coffee husk ash as a soil stabilizer provides economic and environmental added value (Bhandary dkk., 2023; Huri dkk., 2022). The utilization of this waste helps reduce pollution caused by the accumulation of coffee waste and supports the principles of the circular economy and sustainable development (Elhassan dkk., 2022; Ouyang dkk., 2021). By replacing conventional additives that are more expensive and have a high carbon footprint, coffee husk ash offers an environmentally friendly and economical soil stabilization solution, which is highly relevant for infrastructure development in coffee-producing areas (Munirwan, Taib, dkk., 2022). This also contributes to improving the welfare of farmers and coffee industry players through the utilization of waste as a productive resource.

Previous research by Santoso (2020) focused on the stability of montmorillonite clay soil structure with the addition of coffee waste. The results of this study showed that coffee grounds can reduce the expansive properties of montmorillonite soil and improve soil structure stability. However, this study did not examine the mineral content of the soil or coffee grounds in detail, so the chemical mechanisms and mineralogical interactions that occur during the stabilization process were not explained in depth. Meanwhile, the study Karurukan (2022) examined the effect of adding coffee grounds to clay soil on increasing soil bearing capacity. The study showed an increase in bearing capacity (CBR) after mixing coffee grounds, but it also did not trace the mineral composition of the soil and stabilizer, nor did it evaluate changes in plasticity or soil classification in detail.

Research on the mineral content of clay soil and coffee husk ash as materials for soil stabilization needs to emphasize a deep understanding of the chemical and physical interactions between these two materials. Detailed observations of mineralogy and changes in soil properties through laboratory tests are important aspects in developing effective and reliable stabilization technology. Combining knowledge about the mineralogical properties of clay soil with the potential of agricultural waste as a stabilizing material provides an innovative solution that not only improves soil quality but also balances social, economic, and environmental aspects.

Although various studies on clay soil stabilization have been conducted using lime, cement, or other pozzolanic materials, clay soils in many areas of Aceh still exhibit high plasticity, volume changes, and low bearing capacity. These conditions have a direct impact on the performance of building foundations, roads, and geotechnical structures, which are prone to deformation and premature damage. At the same time, coffee husk waste in Central Aceh continues to increase in line with high coffee production, but has not been optimally utilized as an engineering material. Therefore, this research is urgent to provide technical and environmental solutions through the use of local waste as a soil stabilization material.

The research gap lies in the lack of studies linking the chemical-mineral composition of clay soil and coffee husk ash with systematic changes in plasticity and specific gravity due to the stabilization process. Most current studies only focus on mechanical testing without exploring how certain mineral contents such as SiO_2 and CaO affect the pozzolanic mechanism in clay soil. This study aims to analyze the mineral content of clay soil and coffee husk ash, as well as evaluate the effect of adding coffee husk ash on the plasticity, specific gravity, and changes in the classification of clay soil as an approach to sustainable soil stabilization. This study is expected to broaden knowledge and serve as a basis for the development of sustainable soil stabilization applications based on local resources.

B. RESEARCH METHOD

This research was conducted in the Barbate Aceh Besar Palm Garden area, focusing on the analysis of clay soil and coffee husk ash mineral content, which is important for soil stabilization in geotechnical engineering applications. Clay soil samples were taken directly from the research site for mineral testing. Mineral testing was carried out using analytical procedures in accordance with standards to produce accurate and reliable measurements of the main components of the soil.

1. Sample Collection and Preparation

The samples used in the analysis were taken directly from the Barbate Aceh Besar Palm Garden area. Clay soil samples were taken from various points in the garden to ensure representation of the soil characteristics at that location. Coffee husk ash was obtained from a local processing unit in Central Aceh.

Samples were prepared by mixing soil and coffee husk ash as the main ingredients of the mixture. Coffee husks taken from the site were dried and then burned to produce black charcoal. The burnt husks were then ground until they passed through a #200 sieve to produce coffee husk ash, which was used for soil stabilization mixtures. Coffee husk ash and soil were mixed with several ratios of coffee husk ash to soil, namely 5%, 10%, 15%, 20%, and 25%.

2. Mineral Testing Method

The mineral content of clay soil and coffee husk ash is analyzed using laboratory methods that have been proven to be accurate:

a. The Gravimetric Method is used to determine the percentage of Silica Oxide (SiO_2), Aluminum Oxide (Al_2O_3), Magnesium Oxide (MgO), and Loss on Ignition (LOI). These minerals are important for understanding soil composition and its ability to withstand volume changes due to moisture variations.

b. The Titrimetric method is used to test the content of Iron Oxide (Fe_2O_3) and Calcium Oxide (CaO). This method is widely used in soil testing due to its accuracy in determining the concentration of minerals that affect the physical and chemical properties of soil.

c. Atomic Absorption Spectrometry (AAS) is used to measure the content of Sodium Oxide (Na_2O), Potassium Oxide (K_2O), and Manganese Oxide (MnO). AAS provides precise detection of trace elements in soil samples.

d. Spectrophotometry is used to determine the content of phosphorus pentoxide (P_2O_5), as this method allows for highly sensitive and accurate detection of phosphorus levels, which are very important for soil fertility

3. Atterberg Limit Test Method

The Atterberg limit test method is used to measure soil plasticity, which is the ability of soil to retain its shape when subjected to force. This test includes two main limits, namely the liquid limit (LL) and the plastic limit (PL), which are used to calculate the Plasticity Index (PI) (Sivakumar dkk., 2025).

a. Liquid Limit (LL): The liquid limit is the moisture content of soil at the point where soil transitions from a plastic state to a liquid state. At this point, soil cannot retain its shape, and the Casagrande apparatus is used to measure this limit.
b. Plastic Limit (PL): The plastic limit is the soil moisture content at the point where the soil transitions from a solid state to a plastic state. At this point, the soil can be shaped but still retains cohesion.
c. Plasticity Index (PI): The Plasticity Index is calculated as the difference between the Liquid Limit (LL) and the Plastic Limit (PL), using the formula:

$$PI = LL - PL \tag{1}$$

Where:
LL = Liquid Limit
PL = Plastic Limit

4. Specific Gravity Method

Soil density is calculated using the following formula (Astrid dkk., 2023):

$$Gs = \frac{W2-W1}{(W4-W1)-(W3-W2)} \times K \tag{2}$$

Where:
W1 = Weight of the pycnometer (grams)
W2 = Weight of the pycnometer and dry soil (grams)
W3 = Weight of the pycnometer, soil, and water (grams)
K = Relationship between the relative density of water and the conversion factor K in Temperature

C. RESULT AND DISCUSSION

1. Mineral Content of Clay Soil

An in-depth analysis of the samples has revealed the diversity of minerals found in this clay soil. The complete details of the mineral composition, along with their percentages or levels, can be seen in Table 1.

Table 1 Clay Soil Mineral Test Results

No	Test Parameter	Unit	Test Method	Test Results
1	Silicon Dioxide (SiO_2)	%	Gravimetry	42,99
2	Aluminum Oxide (Al_2O_3)	%	Gravimetry	5,63
3	Iron Oxide (Fe_2O_3)	%	Titrimetry	2,67
4	Calcium Oxide (CaO)	%	Titrimetry	3,01
5	Magnesium Oxide (MgO)	%	Gravimetry	1,69
6	Sodium Oxide (Na_2O)	%	AAS	0,05
7	Potassium Oxide (K_2O)	%	AAS	0,10
8	Manganese Oxide (MnO)	%	AAS	0,03
9	Phosphorus Pentoxide (as P_2O_5)	%	Spectrophotometry	0,28
10	Loss on Ignition (LoI)	%	Gravimetry	1,50

The results of clay soil mineral analysis show a dominant SiO2 content of 42.99%, supported by Al2O3(5.63%) and Fe2O3(2.67%), which chemically and physically give clay soil high plasticity with relatively low bearing capacity. Silica and aluminum oxide strengthen the mineral structure of the soil, but clay soil naturally has high cohesion and plasticity, which causes the soil volume to change due to variations in moisture. Calcium oxide (3.01%) and magnesium oxide (1.69%) contribute to stability, but these levels are not sufficient to reduce the expansive properties and high plasticity of the soil.

In civil engineering, soils with these mineral contents typically have less than ideal mechanical properties as foundation materials or construction materials without treatment. Highly plastic clay soils have the potential to experience significant shrinkage and volume expansion, causing cracks, deformation, and reduced stability of building structures. The low loss on ignition value of 1.5% indicates a low organic content, meaning that the soil is predominantly inorganic, but it still has high plasticity potential.

Due to the high plasticity and cohesiveness of this type of clay soil, it requires stabilization to be used effectively in construction. Stabilization methods such as the addition of lime, cement, or rice husk ash have been proven effective in reducing the plasticity index, increasing soil bearing capacity, and reducing the potential for soil expansion and shrinkage. Without stabilization, this soil is not suitable for direct use as a building foundation or civil engineering structure due to the risk of significant deformation due to moisture changes that can cause long-term structural failure. Clay soils with this mineral composition and high estimated plasticity must undergo a stabilization process first. The use of soil without stabilization treatment can result in problems such as large volume expansion, decreased mechanical strength, and foundation instability in civil construction.

2. Mineral Content of Coffee Husk Ash

In-depth analysis of the samples has revealed the diversity of minerals present in this coffee husk ash. The complete details of the mineral composition, along with their percentages or levels, can be seen in Table 2.

Table 2 Mineral Test Results of Coffee Husk Ash

No	Test Parameter	Unit	Test Method	Test Results
1	Silicon Dioxide (SiO_2)	%	Gravimetry	8.30
2	Aluminum Oxide (Al_2O_3)	%	Gravimetry	0.04
3	Iron Oxide (Fe_2O_3)	%	Titrimetry	5.10
4	Calcium Oxide (CaO)	%	Titrimetry	5.22
5	Magnesium Oxide (MgO)	%	Gravimetry	1.03
6	Sodium Oxide (Na_2O)	%	AAS	0.03
7	Potassium Oxide (K_2O)	%	AAS	0.09
8	Manganese Oxide (MnO)	%	AAS	0.05
9	Phosphorus Pentoxide (as P_2O_5)	%	Spectrophotometry	4.98
10	Loss on Ignition (Lol)	%	Gravimetry	2.83

For coffee husk ash samples, all mineral composition data were also obtained from methods performed in the laboratory. Through gravimetric analysis, the Silica Oxide (SiO_2) content in coffee husk ash was obtained at 8.30%, followed by Aluminum Oxide (Al_2O_3) at 0.04%, Magnesium Oxide (MgO) at 1.03%, and LOI at 2.83%. The content of Calcium Oxide (CaO) of 5.22% and Iron Oxide (Fe_2O_3) of 5.10% was determined through the titrimetric method, indicating the reactive capacity of coffee husk ash to play a role in the soil stabilization process. Trace minerals such as Na_2O, K_2O, and MnO, at 0.03%, 0.09%, and 0.05%, respectively, were obtained through AAS analysis, which is sensitive to metals in very small concentrations. The P_2O_5 content of 4.98% was obtained from spectrophotometry, indicating the presence of higher amounts of phosphate components than in clay soil.

In civil engineering and soil stabilization, the chemical composition of coffee husk ash is highly relevant as a specific additive for clay soils, which are typically problematic due to their high plasticity and expansivity. The high SiO_2 and CaO content indicates that coffee husk ash has the potential as a natural pozzolan material that can interact with water molecules and soil minerals to form a binding matrix that increases shear strength and reduces soil plasticity. The addition of coffee husk ash to clay soil can improve mechanical properties such as increasing the CBR value, decreasing the plasticity index, and reducing the risk of soil shrinkage-expansion that causes instability in foundations and building structures. Therefore, coffee husk ash is an environmentally friendly stabilization material alternative that utilizes agricultural waste while improving soil performance for civil construction.

3. Soil Stabilization Result Using Coffee Husk Ash

Calculations to obtain physical property test values are presented in Table 3.

Table 3 Physical Property Test Results

No	% Coffee Ash	Plasticity Index (%)	Specific Gravity (gr/cm3)	Soil Type
1	0	38.42	2.587	Clay
2	5	35.72	2,623	Clay
3	10	35.59	2,642	Silt
4	15	35.26	2,674	Silt
5	20	34.56	2,681	Silt
6	25	34.29	2,690	Silt

The results of physical soil tests with varying amounts of coffee ash added showed significant changes in the plasticity index (PI), specific gravity, and soil classification. The original soil without coffee ash added had a high plasticity index of 38.42% and a specific gravity of 2.587 g/cm^3, classified as clay soil. The addition of coffee ash ranging from 5% to 25% gradually reduced the plasticity index to 34.29%, with an increase in specific gravity to 2.690 g/cm^3. This decrease in plasticity index indicates a reduction in soil plasticity, thereby reducing the risk of volume changes due to drying and water saturation cycles. The decrease in plasticity index can be seen in Figure 1.

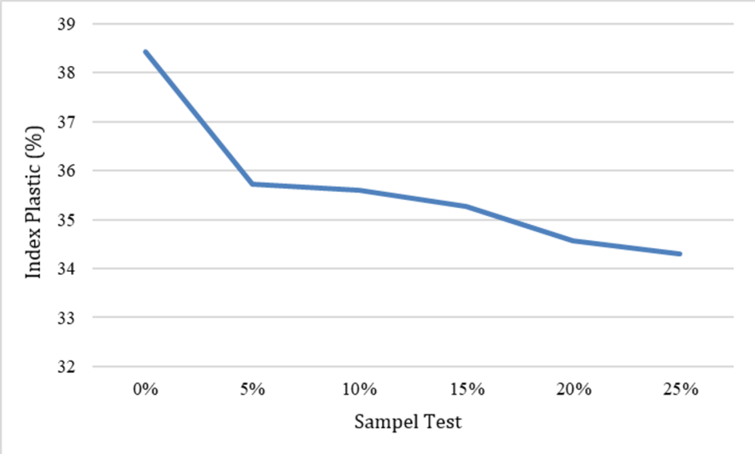

Figure 1 Effect of Coffee Ash Addition on the Decrease in Clay Soil Plasticity Index

The change in soil type from clay to loam with increasing coffee ash content indicates a change in soil particle structure that is more stable and less cohesive. This is directly related to the mineral composition of coffee ash, which is rich in silica oxide (8.30%) and calcium oxide (5.22%), as also found in the mineral test results. Silica acts as a filler that increases soil density and compactness, while calcium aids in the flocculation and binding of soil particles, which reduces plasticity and increases the mechanical strength of the soil. This reduction in plasticity is very important in clay soils, which have high natural plasticity, so that without stabilization treatment, there is the potential for problems such as shrinkage, expansion, and structural failure of buildings. With the addition of coffee ash, the soil becomes more suitable for use as a base material for civil construction because its strength and stability increase, and the risk of soil deformation decreases. These physical test results are in line with the mineral results of coffee ash, which show its potential as an effective stabilizing material, especially in overcoming clay soil problems.

D. FINDINGS OR DISCUSSION

The results of the study show that the clay soil at the research site has a dominant mineral content of 42.99% silicon oxide (SiO_2), 5.63% aluminum oxide (Al_2O_3), and 2.67% iron oxide (Fe_2O_3). This mineral composition explains the characteristics of soil with high plasticity, making it susceptible to volume changes due to variations in water content. This condition indicates that clay soil without stabilization treatment is not suitable for direct use as foundation construction material because it has the potential to cause a decrease in bearing capacity and deformation.

Analysis of coffee husk ash shows a silica oxide (SiO_2) content of 8.30% and calcium oxide (CaO) content of 5.22%. These contents play an important role as natural pozzolanic materials that can interact with soil minerals to produce binding compounds. Physical testing results show that the addition of coffee husk ash at levels ranging from 5% to 25% has a significant effect, namely reducing the plasticity index from 38.42% to 34.29%, increasing the specific gravity from 2.587 g/cm^3 to 2.690 g/cm^3, and changing the soil classification from clay to loam.

These findings prove that coffee husk ash is effective in improving the physical properties of clay soil, while also supporting the reduction of agricultural waste. The results of this study are in line with previous studies which state that coffee husk ash can function as an environmentally friendly stabilizing material to improve the performance of clay soil in geotechnical engineering applications.

E. CONCLUSION AND RECOMMENDATION

Based on the results of the study, it was concluded that the clay soil at the study site had a main mineral content of 42.99% silica oxide (SiO_2), which caused high plasticity and had the potential to cause problems with volume change and low bearing capacity. This type of clay soil requires stabilization treatment to be suitable for use as a construction material. Coffee husk ash has been proven to contain 8.30% silica oxide (SiO_2) and 5.22% calcium oxide (CaO), which can act as a natural pozzolanic material. The addition of coffee husk ash at variations of 5%, 10%, 15%, 20%, and 25% had a significant effect on the physical properties of clay soil, namely reducing the plasticity index from 38.42% to 34.29%, increasing the specific gravity from 2.587 g/cm^3 to 2.690 g/cm^3, and changing the soil classification from clay to loam. This shows that coffee husk ash is effective as an environmentally friendly and sustainable soil stabilizing material that can support infrastructure development based on local resources.

The recommendation from this study is the need for further testing with coffee husk ash percentages above 25% to determine the optimum limit for its use in soil stabilization.

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