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Enhancing the Geotechnical Behavior of Expansive Soil-Coconut Fiber Mixtures with Various Agricultural Ash Waste: A Comparative Study

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ABSTRACT

Expansive soil is classified as problematic because it has a high plasticity index, high swelling shrinkage due to water content fluctuations, and low bearing capacity. This research focused on stabilizing it with coconut fiber and three different types of agricultural ash: sugarcane bagasse ash (SBA), rice husk ash (RHA), and coir-wood ash (CWA). Coconut fiber made up 0.75% of the material and acted as reinforcement. The three types of ash were used in varying proportions (0%, 2%, 4%, 6%, 8%, and 10% of the mixture's total weight) to reduce swelling shrinkage and enhance bearing capacity through cementation. The mixture was compacted to the soil's Maximum Dry Density and Optimum Moisture Content. Then, the specimens were cured for different durations. The California Bearing Ratio (CBR) testing specimens were cured for 7 days and 14 days, while those for Unconfined Compressive Strength (UCS) testing were cured for 14 days and 28 days. All testing complied with ASTM standards. The results showed that strengthening coconut fiber and stabilizing with three different types of ash in expansive soil increased CBR and UCS values and significantly reduced swelling. These improvements were directly proportional to increases in the ash content and curing time. Optimal outcomes were achieved with all three types of ash at a similar content level, ranging from 8% to 10%. For specimens cured for 14 days, CBR values increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil. For specimens cured for 28 days, UCS values increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil. A swelling value of 0% was achieved in the soil-coconut fiber mixture stabilized with a 10% concentration of RHA/SBA/CWA. These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling. By utilizing agricultural waste for expansive soil stabilization, significant benefits can be achieved for the government, industry, and local communities. Developing technical guidelines for using agricultural waste as a soil stabilizer will greatly facilitate its practical application in the field.

HIGHLIGHTS

This study compares three agricultural ashes from industrial waste widely available in Indonesia as stabilization materials for expansive soil-coconut fiber mixtures.

1. INTRODUCTION

Expansive soil is problematic, characterized by a high plasticity index and swelling shrinkage due to water content fluctuations. This soil swells during the rainy season and shrinks during the dry season. Consequently, structures built on such soil are prone

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to damage (Ikeagwuani, 2019). Technological advances have led to the development of various techniques for improving expansive soil, including mechanical and chemical stabilization methods (Rani and Chandra, 2021; Tamiru et al., 2025). Mechanical stabilization improves soil's mechanical properties by incorporating highly tensile materials. Chemical stabilization, on the other hand, involves adding specific chemicals to the soil, which then undergo a chemical process that produces new materials with enhanced physical and mechanical behavior. Commonly used chemicals include cement and lime, which have proven effective in improving soil quality (Al-Kalili et al., 2022). Anburuvel (2024) states that the California Bearing Ratio (CBR) and unconfined compressive strength (UCS) of soils (excluding peat), stabilized with either cement or lime at a 5% content, can reach values of 30-60% and 700-1,500 kPa, respectively. These values depend on the soil type, degree of compaction, and curing conditions. However, using cement and lime is costly and contributes to global warming due to substantial carbon dioxide emissions (Gowthaman et al., 2018; Sekar and Kandasamy, 2019). The production of one ton of Portland clinker cement releases approximately one ton of CO_2 into the atmosphere. Additionally, Portland cement is responsible for about 7% of global CO_2 emissions, contributing to the depletion of the ozone layer (Chakraborty and Roy, 2016). Indeed, the principles of sustainable development must always be considered. Environmental protection should be prioritized throughout the planning, implementation, and maintenance of infrastructure projects. Therefore, it is essential to consider environmental sustainability when employing soil stabilization materials. Utilizing recycled materials can help reduce costs and promote sustainable development (Darwis, 2017).

Using recycled materials or waste derived from natural sources has been promoted as an alternative to traditional soil-stabilizing materials. These abundant natural substances are cost-effective, environmentally friendly, and biodegradable (Alqaisi et al., 2020). Various types of agricultural waste are effective as soil-stabilizing materials (Ishola et al., 2019). Widianti et al. (2022) studied the contribution of coconut fiber waste to the mechanical characteristics of soft clay. Introducing coconut fiber into the soil randomly could improve the soil's shear, bearing, and tensile strength. The percentage of fibers with high tensile strength ranged from 0.6% to 0.8%, but it did not reduce water-induced swelling. Therefore, additional research was conducted by combining coconut fiber with agricultural ash waste to create a coir-wood ash (CWA) mixture. This combination has proven highly effective in stabilizing soft clay. When CWA is added to the soil, it can eliminate swelling and significantly improve the values of CBR, UCS, tensile strength, elastic modulus, and shear strength by up to 534%, 349%, 105%, 824%, and 210%, respectively (Widianti et al., 2023; Widianti et al., 2024).

Food and Agriculture Organization of the United Nations (2022) shows that Indonesia is the world's largest coconut producer with total production of 17.19 million tons, the world's 4th largest rice producer with total production of 54.75 million tons, and the world's 8th largest sugar producer with total production of 32.40 million tons. The waste generated from coconuts, rice, and sugarcane is 35%, 15%, and 90%, respectively (Trikarlina et al., 2018; Asfar et al., 2021; Sudibandriyo and Lydia, 2011). This waste is commonly used as a fuel source in various industries, producing ash waste. Typically, this ash waste is discarded, leading to environmental disruption (Al-Ghouti et al., 2021), even though sugarcane bagasse ash (SBA) and rice husk ash (RHA) have the potential to be soil stabilizers (Yadav et al., 2017; Daarol et al., 2023). RHA and SBA are characterized by their notable SiO_2, Al_2O_3, and Fe_2O_3 content. Silica, a primary constituent in cement manufacturing, exhibits pozzolanic characteristics, resulting in increased hardness over time when reacted with Al_2O_3 and CaO in clay soil. Apart from that, the ash grains' very loose structure makes mixing evenly with clay soil easy. Although extensive research has been conducted, the conventional approach involves combining RHA and SBA with lime or cement. Numerous experiments have been conducted, mostly involving mixtures of RHA or SBA with lime or cement (Dang et al., 2016; Eliaslankaran et al., 2021; Gandhi and Shukla, 2021; Pushpakumara and Mendis, 2022; Raja et al., 2022; Barwar et al., 2022).

Based on the studies, it is necessary to investigate the combination of reinforcing with coconut fiber and chemically stabilizing with RHA and SBA, both industrial wastes. The findings were compared with the results from Widianti et al. (2023), who used coir-wood ash (CWA) to evaluate its effectiveness and impact on expansive soil's bearing capacity and swelling.

2. METHODOLOGY

2.1 Materials

2.1.1 Soil

The physical and mechanical properties of the soil used in this investigation were analyzed by Widianti et al. (2020) according to ASTM. The analysis showed that the soil composition consisted of sand (13.36%), silt (70.58%), and clay (16.68%). Additionally, the soil exhibited a liquid limit of 89.91%, a plastic limit of 38.86%, and a shrinkage limit of 16.33%. According to AASHTO, the soil was categorized as clay (A-7-5), while USCS identified it as clay with high plasticity (CH).

Soil with a liquid limit value of >60% and a plasticity index of >35% is categorized as expansive clay with high swelling potential (National Standardization Agency, 2018). The level of potential for clay to swell can also be analyzed using the plasticity index value and the clay percentage (Skempton, 1953). This data was used to calculate the activity value (A), and a value of 3.18 was obtained. According to Das and Sobhan (2016), soil with an A value of >1.25 is categorized as active clay. According to Bowles (1992), soil with an A value between 1 and 7 is categorized as clay, containing clay minerals called montmorillonite. The unstabilized soil produced a CBR value of 1.25%, which Bowles (1992) classifies as very poor. The unconfined compressive strength (UCS) value was determined to be 41.70 kPa. Das and Sobhan (2016) classifies soil with UCS ranging from 25 to 50 kPa as soft soil.

The soil had granules passing through sieve No. 4 (for the CBR test) and sieve No. 40 (for the UCS test).

2.1.2 Coconut fiber

The coconut fiber waste exhibited tensile strength ranging from 108.6 MPa to 238.6 MPa and strain ranging from 28.70% to 34.25%. The fiber was separated from the husk and then dried in an oven at 100°C. Afterward, the fiber was cut into pieces of approximately 5 cm in length.

2.1.3 Agricultural ash

This study utilized three different types of agricultural ash: sugarcane bagasse ash (SBA), rice husk ash (RHA), and coir-wood ash (CWA). SBA is the residue from sugarcane bagasse after extraction and is used as a fuel source in sugar mills (Figure 1(a)). RHA, derived from rice husks, is used as a fuel source in brick and tile manufacturing (Figure 1(b)). CWA is a by-product of a mixture of coconut fiber and wood used as a fuel in the tofu production industry (Figure 1(c)). The combustion process carried out is categorized as uncontrolled burning. The selected ash sample was gray, consisting of grains that passed a 200-mesh sieve. Table 1 presents the SBA, RHA, and CWA oxide composition test results from the GetIn-CICERO Laboratory, Department of Geological Engineering, Universitas Gadjah Mada, Indonesia. Testing was conducted using a Spectro Xepos XRF.

The oxide composition test results for all agricultural waste indicate that SBA, RHA, and CWA are excellent pozzolanic materials due to their high combined proportions of silica (SiO_2), iron oxide (Fe_2O_3), and alumina (Al_2O_3). According to ASTM C618-22 (ASTM International, 2022), both SBA and RHA fall under Class F because they meet the criteria of having a minimum of 50% for the combined content of SiO_2, Al_2O_3, and Fe_2O_3, a maximum of 18% for CaO, and a maximum of 5% for SO_3. Materials in Class F are known for their pozzolanic properties. Conversely, CWA does not fit into Class N, F, or C because its SiO_2, Al_2O_3, and Fe_2O_3 content is only 37.42%, below the required content of 50%. However, CWA does have a high CaO content of 27.58%, exceeding the 18% limit. This high CaO content gives it cementitious properties.

(a) (b) (c)

Figure 1. Types of agricultural ashes (a) sugarcane bagasse ash, (b) rice husk ash, (c) coir-wood ash

Table 1. Test results for the oxide composition of SBA, RHA, and CWA

Component		Result		
		Sugarcane bagasse ash (SBA)	Rice husk ash (RHA)	Coir-wood ash (CWA) (Widianti et al., 2023)
SiO_2	Silicon oxide	81.12%	85.89%	33.52%
Al_2O_3	Aluminium oxide	6.18%	2.65%	1.93%
Fe_2O_3	Iron oxide	5.36%	2.27%	1.97%
CaO	Calcium oxide	4.29%	5.52%	27.58%
MgO	Magnesium oxide	1.84%	1.81%	4.96%
P_2O_5	Phosphorus oxide	1.33%	2.33%	3.95%
K_2O	Potassium oxide	3.62%	3.52%	15.23%
SO_3	Sulfideoxide	0.94%	1.49%	3.67%
Na_2O	Sodium oxide	0.45%	0.41%	1.21%

2.2 Laboratory testing

Soaked CBR and UCS tests were performed at the Geotechnical Laboratory of Universitas Muhammadiyah Yogyakarta, Indonesia. Table 2 lists the specimen dimensions and the standards implemented for the tests.

The coconut fiber content was 0.75% of the total mix weight. This value is based on previous studies by Widianti et al. (2020) and Widianti et al. (2021). Different ash concentrations were added to the mixtures, with ash content at 0%, 2%, 4%, 6%, 8%, and 10%. This variation refers to the research by Widianti et al. (2023). The amount of water added during mixing was based on the Optimum Moisture Content value. The mixture was compacted to the soil's Maximum Dry Density.Then, the specimens were cured for a different length of time. The specimens for CBR testing were cured for 7 days and 14 days, while those for UCS testing were cured for 14 days and 28 days. This curing time aligns with the guidelines specified by The Ministry of Public Works of the Republic of Indonesia (2007). Table 3 presents the detailed design of the specimen variations. Figure 2 shows the laboratory CBR test performed on the soaked samples. The soaked CBR testing aims to simulate rain or the most severe conditions in the field, resulting in the addition of water to the soil.

Table 2. Specimen dimensions and testing standards

Test type	Specimen dimension		Testing standard
	Height (cm)	Diameter (cm)	
Soaked CBR and swelling	17.8	15.3	ASTM D1883-07e2 (ASTM International, 2007)
Unconfined compressive strength (UCS)	7.2	3.6	ASTM D2166-06 (ASTM International, 2016)

Table 3. The design of specimen variations

Specimen variation		Sugarcane bagasse ash (SBA)		Rice husk ash (RHA)		Coir-wood ash (CWA) (Widianti et al., 2023)	
		Soaked CBR	UCS	Soaked CBR	UCS	Soaked CBR	UCS
Soil + 0.75% coconut fiber + varying types and content of ash	0%	X	•	X	•	X	•
	2%	X	•	X	•	X	•
	4%	X	•	X	•	X	•
	6%	X	•	X	•	X	•
	8%	X	•	X	•	X	•
	10%	X	•	X	•	X	•

Description: X: 7 and 14 days of curing; •: 14 and 28 days of curing

3. RESULTS AND DISCUSSION

3.1 Effects of the type and content of ash on the CBR value

Figure 3 illustrates CBR values after soaking for each specimen reinforced with 0.75% coconut fiber; stabilized with varying RHA, SBA, and CWA contents, and cured for 7 and 14 days. For CWA testing results, the data is obtained from Widianti et al. (2023).

The unstabilized soil acquired a soaked CBR value of 1.25%, falling to the extremely low-quality soil, as categorized by Bowles (1992). Figure 3 shows that after being reinforced with coconut fiber, the CBR value increased significantly to 2.12% (an increase of 0.7 times compared to the unstabilized soil). This improvement in the strength of expansive soil reinforced with coconut fiber is attributed to the interactions and interlocking between the fibers and between the fibers and soil particles within the compacted specimens. The rough surface of the fibers enhances friction between particles and helps bind soil particles together (Dang et al., 2016). These bonds transfer stress from the soil to the fibers, which possess high tensile strength (Singh and Bagra, 2013).

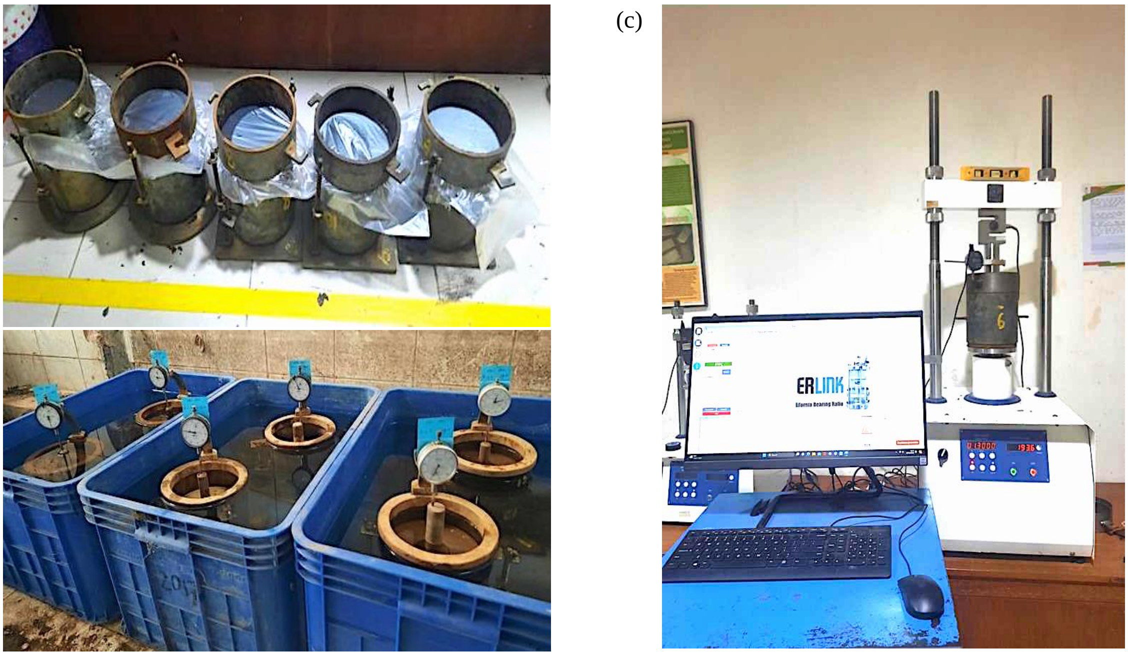

Figure 2. Soaked CBR testing: (a) curing for 7 and 14 days, (b) soaking for 4 days, (c) CBR testing

(a)

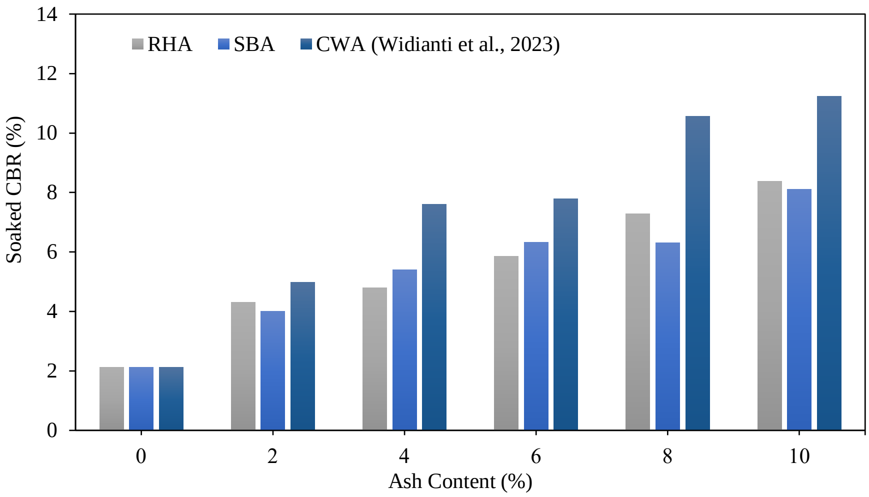

Figure 3. Effects of the type and content of ash on the CBR value of mixed soil with varying curing durations: (a) 7 days, (b) 14 days

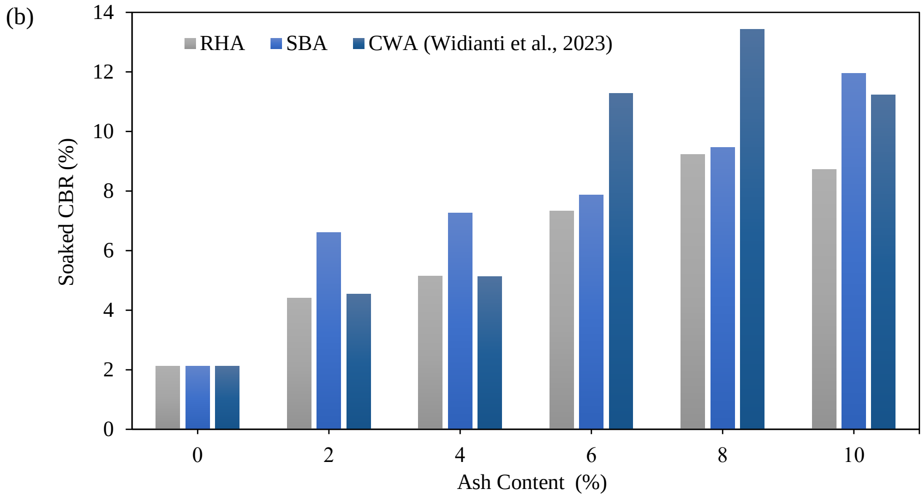

Figure 3. Effects of the type and content of ash on the CBR value of mixed soil with varying curing durations: (a) 7 days, (b) 14 days (cont.)

Figure 3 also illustrates the trend of increasing soaked CBR values upon stabilization with three different types of agricultural ash. A higher ash content and a longer curing duration resulted in higher CBR values, with 8% to 10% ash content leading to the highest values. For specimens cured for 14 days, the CBR value increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil. According to Bowles (1992), soil with a CBR value ranging from 7% to 20% is considered fair soil.

SBA and RHA have high silica (SiO_2) and alumina (Al_2O_3) content, measuring 87.30% and 88.54%, respectively. This presence of silica and alumina makes them good pozzolanic materials. With the help of water, silica and alumina will react with calcium oxide (CaO) present in the soil and ash to produce calcium silicate hydrate and calcium aluminate. These compounds are crucial parameters for cementitious behavior (Yadav et al., 2017).

Soil stabilized with CWA resulted in a higher soaked CBR value. Its silica and alumina content is only 37.42% (below 50%), but its calcium oxide (CaO) content is high, namely 27.58%. This material will function as cementitious with self-cementing properties that can subsequently harden.

As Darwis (2017) outlined, the reaction between silica-alumina and CaO is a two-stage process over time. The first stage, known as the immediate reaction, occurs within hours. Mixing CaO with water results in the formation of hydrated lime ($Ca(OH)_2$), which serves as the precursor for cementitious compound development and consequently reduces the water content in the soil. The reaction is shown below:

$$CaO + H_2O \dashrightarrow Ca(OH)_2 + heat$$

After this initial reaction, flocculation and/or agglomeration of clay particles occurs, leading to a coarser texture and decreased plasticity. This condition enhances the soil matrix's shear strength and improves the soil's workability. The second phase involves medium and long-term reactions, spanning days, weeks, months, or years. The reaction characteristic of this phase is the pozzolanic reaction, shown below:

$$Ca(OH)_2 + H_2O + SiO_2 \ \& \ Al_2O_3 \dashrightarrow \text{C-S-H \& C-A-H}$$
(cementitious materials)

Through the pozzolanic reaction, silica and alumina react with calcium to create new cementitious compounds, specifically calcium silicate hydrate (C-S-H) and calcium aluminate hydrate (C-A-H). This process transforms the very fine clay particles, causing them to crystallize into relatively larger and coarser particles. As a result, the contact area between grains grows, and the bonding between them strengthens, significantly improving the bearing capacity.

3.2 Effects of the type and content of ash on the swelling behavior

The swelling value was assessed through the soaked CBR test. Figure 4 illustrates the swelling values for each specimen reinforced with 0.75% coconut fiber and stabilized with varying RHA, SBA, and CWA contents after 7-day and 14-day curing durations.

Figure 4 illustrates agricultural ash waste's significant effectiveness in reducing clay's swelling potential. The swelling value decreased as the ash content increased, and the curing duration was extended. The swelling value of expansive clay was 3.25% when reinforced with coconut fiber. Adding RHA and SBA as much as 2% resulted in a considerable reduction in the swelling value, which decreased by 79% of the initial value after a curing duration of seven days and further by 91% after 14 days. The reduction in the swelling value becomes more pronounced at higher ash percentages, reaching nearly 0% within the 8-10% ash content range. In contrast, soil reinforced with coconut fiber and stabilized with CWA showed a progressive reduction in the swelling value as the CWA concentration increased. When the concentration of CWA was raised by 2% and 4%, the swelling value decreased by 33.2% and 56.6% after seven days of curing and by 36.3% and 58.5% after 14 days of curing, respectively. At a 6% CWA content, the swelling was effectively eliminated.

The observed reduction in the swelling value is attributed to the flocculation and agglomeration of soil particles, which reduce the surface area of clay grains and make the soil less plastic and coarser. Basma and Tuncer (1991) noted that adding additives decreases the soil's swelling potential from high to low, with increased ash content and curing duration contributing to changes in the soil's physical properties. The pore spaces within the stabilized soil become significantly smaller than those in the unstabilized soil (Ikeagwuani, 2019). Based on the Scanning Electron Microscopy (SEM) analysis, unstabilized soil exhibits a loose particle arrangement, evidenced by many pores (Figure 5(a)). In contrast, the soil, fiber, and ash mixture displays a denser and more compact microstructure. The number of pore voids is substantially reduced (Figure 5(b)).

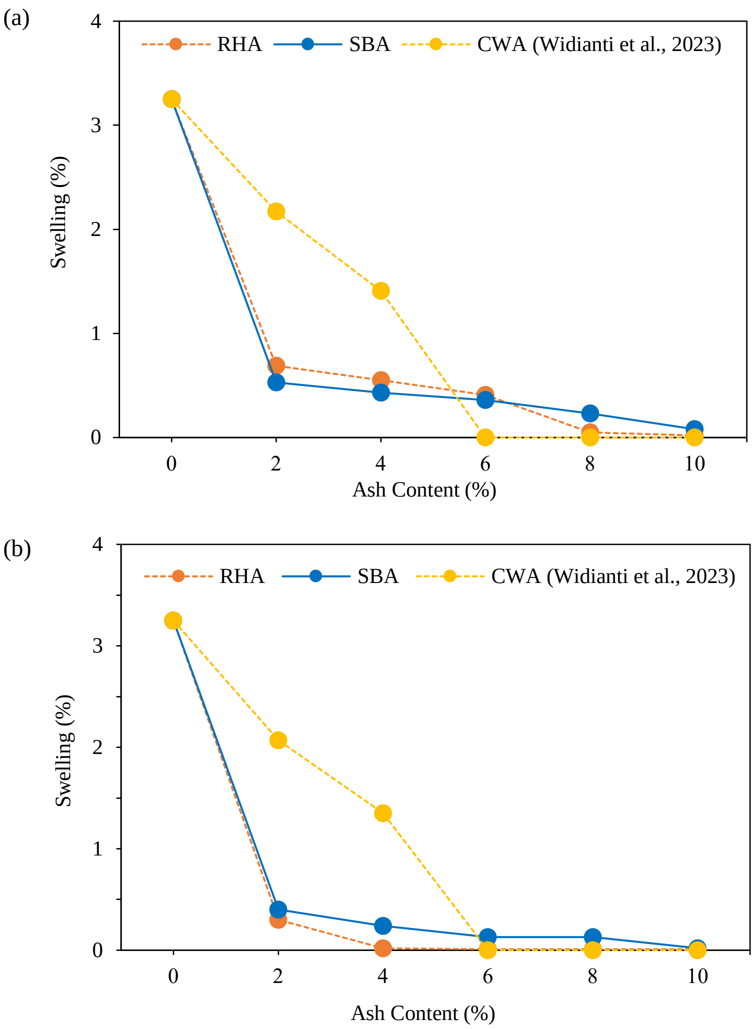

Figure 4. Effects of the type and content of ash on the swelling behavior of mixed soil with varying curing durations: (a) 7 days, (b) 14 days

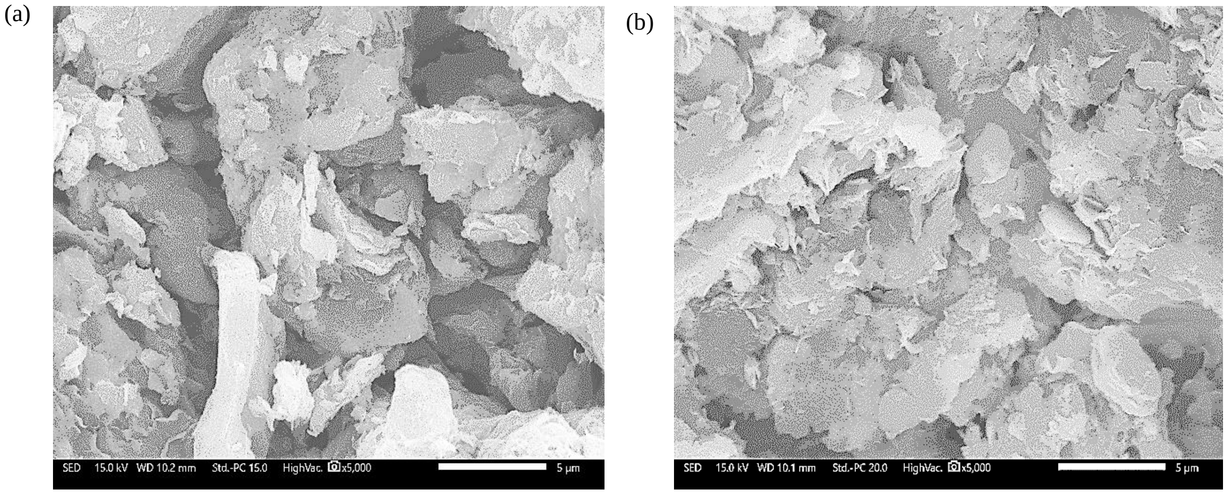

Figure 5. The microstructure of expansive soil (a) unstabilized, (b) stabilized

3.3 Effects of the type and content of ash on the UCS value

In addition to the soaked CBR test, the impact of ash was also assessed through Unconfined Compressive Strength (UCS) measurements. Figure 6 shows the UCS values for each specimen reinforced with 0.75% coconut fiber and stabilized with varying RHA, SBA, and CWA contents. The curing durations for these specimens were either 14 days or 28 days.

As shown in Figure 6, the UCS values display a consistent trend across all types of ash. The UCS value increased significantly with higher ash content and longer curing duration. This increase is attributed to the cementation between the soil and the ash, which forms agglomerates and enhances the bonding between individual soil particles. The existing voids in the soil were partially filled with a more rigid cementitious material, leading to more excellent compression resistance and reduced water permeability. The highest UCS value was recorded for soil with 0.75% coconut fiber and 8% ash content. However, at a 10% ash content, the UCS value decreased. The soil particles become larger at this concentration, and reducing soil density (Herman et al., 2021). Despite this decrease, the UCS value remains significantly higher than the soil reinforced with coconut fiber alone (Chakraborty and Roy, 2016; Yusuf and Zava, 2019).

Figure 6. Effects of the type and content of ash on the UCS value of soil mixtures with varying curing durations: (a) 14 days, (b) 28 days

Figure 6. Effects of the type and content of ash on the UCS value of soil mixtures with varying curing durations: (a) 14 days, (b) 28 days (cont.)

The classification of clay consistency was determined based on the UCS value (Das and Sobhan, 2016). The unstabilized clay soil had a UCS value of 41.70 kPa, which classified it as soft soil. Incorporating 0.75% coir fibers increased the UCS value to 98.10 kPa, representing an improvement of 1.4 times compared to the unstabilized soil, thus categorizing the soil as medium soil. Stabilization involved combining coir fibers with ash. The soil exhibited high rigidity with ash content ranging from 2% to 6% and showed significant hardness with ash content between 8% and 10%. For specimens cured for 28 days, the UCS value increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil. Hardiyatmo (2014) states that soil is hard if its UCS value exceeds 400 kPa, indicating an exceptionally high load-bearing capacity.

While the soaked CBR value was higher for soil stabilized with CWA, this treatment resulted in the lowest UCS value. These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling.

4. CONCLUSION

The study led to the following conclusions:

1) Strengthening coconut fiber and stabilizing with three different types of ash increased CBR and UCS values and significantly reduced the swelling of expansive soil. These improvements were directly proportional to increases in the ash content and curing duration.

2) Optimal outcomes were achieved with all three types of ash at similar contents, ranging from 8% to 10%.

3) For specimens cured for 14 days, CBR values increased to 9.24% (RHA), 11.96% (SBA), and 13.44% (CWA), representing an improvement of 6.4 to 9.8 times compared to unstabilized soil.

4) A swelling value of 0% was achieved in the soil-coconut fiber mixture stabilized with a 10% concentration of RHA/SBA/CWA.

5) For specimens cured for 28 days, UCS values increased to 440.69 kPa (CWA), 472.45 kPa (SBA), and 482.96 kPa (RHA), representing an improvement of 9.6 to 10.6 times compared to unstabilized soil.

6) These findings suggest that each type of ash has advantages and disadvantages, but all ultimately contribute to increasing soil strength and eliminating swelling.

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AUTHORS CONTRIBUTION

Conceptualization, Methodology, Validation, Supervision, and Writing Original Draft Preparation, Anita Widianti; Experimental run, Data Collection, and Formal Analysis, Muhammad Hatta; Visualization, Review and Editing, Anita Rahmawati and Dian Eksana Wibowo.

DECLARATION OF COMPETING INTEREST

The authors declare no conflict of interest.

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