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Enhancement of Shear Strength Properties of Soft Clay Using Coir Fiber-Coconut Husk Ash-Wood Ash Mixture

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ABSTRACT

Soft clay is a problematic type of soil because it has high water content, low shear strength, low bearing capacity, and high compressibility. This study explores the effectiveness of stabilizing soft clay using a combination of coir fiber, coconut husk ash, and wood ash. This research investigated the impact of incorporating 0.75% coir fiber and varying levels of a coconut husk ash-wood ash mixture (ranging from 0% to 10%) on the shear strength properties of soft clay. The study applied two different curing times: seven and 21 days. An unconsolidated-undrained triaxial test was conducted following ASTM D2850-03. The results demonstrated that combining coir fiber reinforcement with chemical stabilization through the ash mixture significantly enhanced the deviatoric stress, cohesion, internal friction angle, shear strength, and elastic modulus of soft soil. Specifically, an 8% ash content with a 21-day curing time achieved the highest deviatoric stress and shear strength. This highest shear strength value was 210% greater than soil solely reinforced with coir fiber.

1. INTRODUCTION

Soft clay is a problematic type of soil because its water content is high, so its shear strength is low. As a result, the compressibility level is high, and the bearing capacity is low (Hejazi et al., 2012). Hence, stabilization is necessary before employing soft soil as a structural base or fill (Karkush and Yassin, 2020). Adding a material with a high tensile strength is one of several stabilization methods. The materials that can be used are very diverse, including waste organic materials in the form of natural fibers from plants (Suffri et al., 2019).

Soil reinforced using randomly distributed fibers will behave as a composite material similar to plant roots, which is then known as an eco-composite. Fibers that can be used include coir, palm, sugar cane bagasse, rice husk, sisal, jute, barley straw, bamboo, and sawdust. These fibers have been proven to improve soil's geotechnical properties, such as bearing capacity, shear strength, and tensile strength (Hejazi et al., 2012; Medina-Martinez et al., 2022). Coir fiber is a widely used alternative due to its abundance in tropical countries, low cost, low environmental impact, and relatively lightweight (Das et al., 2016; Lone and Bawa, 2018). Cellulose accounts for 54% of coir fiber, lignin makes up 40%, and other water-soluble compounds constitute 6% (Khatri et al., 2017). The high cellulose concentration of coir fiber gives it superior flexural and tensile strength compared to other plant fibers (Gowthaman et al., 2018). Compared to synthetic fibers, natural fibers have a higher coefficient of friction and are more elastic (Maurya et al., 2015; Upadhyay and Singh, 2017). Fiber disintegration is slower than with other natural fibers and can take up to ten years because of the high lignin content, rendering coir fiber resistant to microbes (Hejazi et al., 2012).

Several studies have revealed that coir fiber mixed into the soil randomly will behave like plant roots. These fibers will increase friction between soil particles and the fiber surface, boosting its shear strength and bearing capacity. The mixture of fiber and

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soil will increase the bond or interlocking between the two. Fibers with relatively high tensile strength will help soil grains withstand horizontal forces (Peter et al., 2016; Upadhyay and Singh, 2017; Bhatt et al., 2017; Gupta et al., 2017).

Widianti et al. (2020) demonstrated that adding 0.75% coir fiber increased the soil's shear strength to its maximum value. However, it turns out that coir fiber cannot prevent air-induced swelling. Thus, it needs to be complemented with chemical stabilization, as demonstrated in subsequent research by Widianti et al. (2022). For this reason, Widianti et al. (2023) have mixed coconut husk ash and wood ash waste with coir fiber. This experiment combined the soil with 0.75% coir fiber and coconut husk ash-wood ash at varying levels (0%, 2%, 4%, 6%, 8%, and 10%). The test findings revealed that the highest values of California Bearing Ratio (CBR), Unconfined Compressive Strength (UCS), and tensile strength were achieved with a combination of coir fiber and coconut husk ash-wood ash with a content ranging from 6% to 8%. Additionally, the swelling was reduced to 0% with an ash content of 6-10%.

Trikarlina et al. (2018) explained that burning waste coir fiber produces coconut husk ash containing pozzolanic silica, calcium, and alumina. Multiple studies have proven that soil stabilized by coconut husk ash has superior physical and mechanical properties (Onyelowe, 2016; Chakraborty and Roy, 2016; Yusuf and Zava, 2019). This stabilization process is influenced by the ash concentration and curing time (Barman and Dash, 2022).

This study examined soft clay's shear strength and elastic modulus when mixed with 0.75% coir fiber and coconut husk ash-wood ash with varying contents. Higher shear strength values are expected due to combining chemical stability and strengthening with environmentally friendly additives. Soil shear strength is a significant parameter to consider when determining the bearing capacity of the soil and the stability of embankment slopes.

2. METHODOLOGY

2.1 Materials

This study utilized soft clay soil from Yogyakarta, Indonesia. Data on the physical and mechanical properties of the soil were obtained from previous research by Widianti et al. (2021a) and Widianti et al. (2021b). The data are shown in Table 1.

According to the particle size distribution and consistency limits test findings, the soil is categorized as clay with high plasticity, abbreviated as CH. Das and Sobhan (2016) defined soil as soft if its unconfined compressive strength (UCS) value fell within the 25 to 50 kPa range.

The coir fiber was sourced from waste at the market. The tensile strength test results exhibited tensile strength values from 107.4 MPa to 240.8 MPa, with strain values ranging from 20.53% to 34.10%. Before mixing with the soil, the fiber was cut into pieces about 5 cm long.

Table 1. The physical and mechanical properties of the soil (Widianti et al., 2021a; Widianti et al., 2021b).

Parameters	Values
Particle size distribution:	
Sand (%)	13.36%
Silt (%)	70.58%
Clay (%)	16.06%
Consistency limits:	
Liquid Limit	89.91%
Plastic Limit	38.86%
Shrinkage Limit	16.33%
Plasticity Index	51.05%
Specific Gravity	2.63
Proctor standard compaction:	
Maximum Dry Density	12.64 kN/m^3
Optimum Moisture Content	29.90%
Unconfined compressive strength	41.70 kPa
Cohesion	43.26 kPa
Internal friction angle	2.35°

The research utilized a combination of coconut husk ash and wood ash derived from the waste of burning coconut husk and wood in the tofu home industry. The ash had been passed through a 200-mesh sieve and was dried in an oven for 24 h. Table 2 illustrates the chemical element content of the coconut husk ash-wood ash mixture examined at the GetIn-CICERO Laboratory, Department of Geological Engineering, Faculty of Engineering, Universitas Gadjah Mada, Indonesia. Several researchers stated that elements of the oxides SiO_2, Al_2O_3, Fe_2O_3, and CaO are essential to evaluate pozzolan characteristics (Muntohar et al., 2016).

2.2 Specimen preparation

This study utilized coir fiber at 0.75% of the mixture's overall weight and the coconut husk ash-wood ash mixture at different levels (0-10%) to determine the optimal mix yielding the maximum shear strength. Each specimen had a diameter of 3.5 cm and a height of 7 cm. Each variant was tested with three specimens. Curing occurred for seven and 21 days before testing.

Table 2. Chemical element test results for a mixture of coconut husk ash-wood ash

Chemical element		Result
SiO_2	Silicon oxide	33.52%
CaO	Calcium oxide	27.58%
MgO	Magnesium oxide	4.96%
P_2O_5	Phosphorus oxide	3.95%
Fe_2O_3	Iron oxide	1.97%
Al_2O_3	Aluminium oxide	1.93%

2.3 Testing procedure

Unconsolidated-undrained triaxial testing was performed on the hardened specimens following STM D2850-03 (ASTM International, 2003). Each specimen was subjected to a specific cell pressure: 98.1 kPa, 196.2 kPa, and 294.3 kPa. Subsequently, the specimens were subjected to deviatoric stress with a 1 mm/minute loading speed until the soil collapsed or until the strain reached 15%. Testing was conducted at the Geotechnical Laboratory, Faculty of Engineering, Universitas Muhammadiyah Yogyakarta, Indonesia.

3. RESULTS AND DISCUSSION

3.1 Effect of ash content and curing time on deviatoric stress

Unconsolidated-undrained triaxial testing produces axial stress values in the form of deviator stress, which causes the specimen to collapse or the strain that occurs to reach 15%. Figure 1 summarizes the deviatoric stress values for each soil sample stabilized with coir fiber and varying ash content during the 7-day and 21-day curing.

Figure 1 demonstrates that the deviatoric stress value increased when the ash content and curing time rose. For a specimen containing 0.75% fiber and 10% ash, the maximum value obtained at a cell pressure of 294.3 kPa was 622.5 kPa.

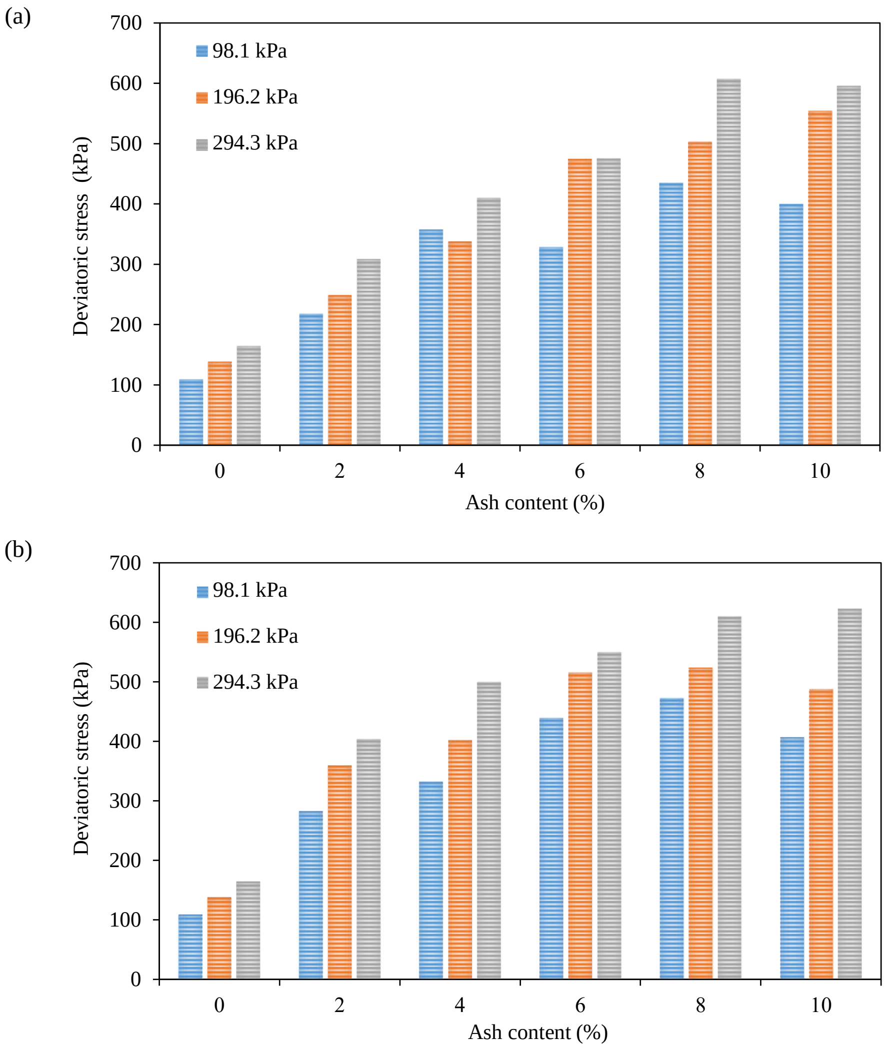

Figure 1. Effect of ash content on deviatoric stress values (a) seven-day curing, (b) 21-day curing

3.2 Effect of ash content and curing time on cohesion and internal friction angle

As demonstrated in Figure 2, the cohesion and internal friction angle values were examined by drawing a Mohr's circle graph based on the minor principal stresses (cell pressure) and the major principal stresses (cell pressure plus deviatoric stress). Figures 3 and 4 summarize the internal friction angle and cohesion values obtained from Mohr's circle.

Figure 3 illustrates the difference in cohesion values between the soil reinforced with coir fiber before and after adding ash. The cohesion value of soil reinforced with coir fiber alone (with no ash) was 36.31 kPa, and it rose as the ash content was added and the curing time increased. The addition of 8% ash content and a curing time of 21 days resulted in the highest cohesion value, 154.92 kPa, indicating an increase of 327%.

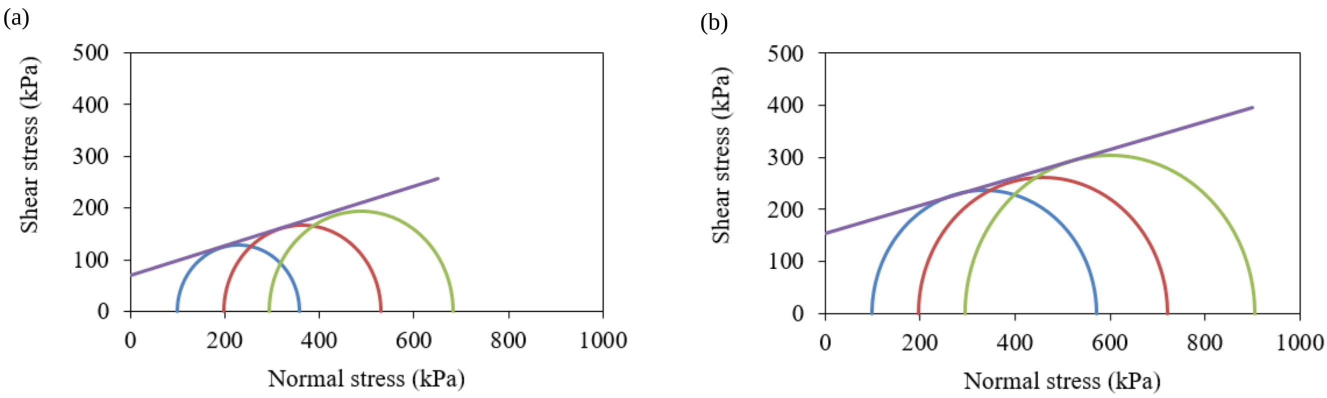

Figure 2. Mohr's circle of specimens (a) with 0.75% coir fiber and 0% ash, (b) with 0.75% coir fiber and 8% ash at 21 days of curing

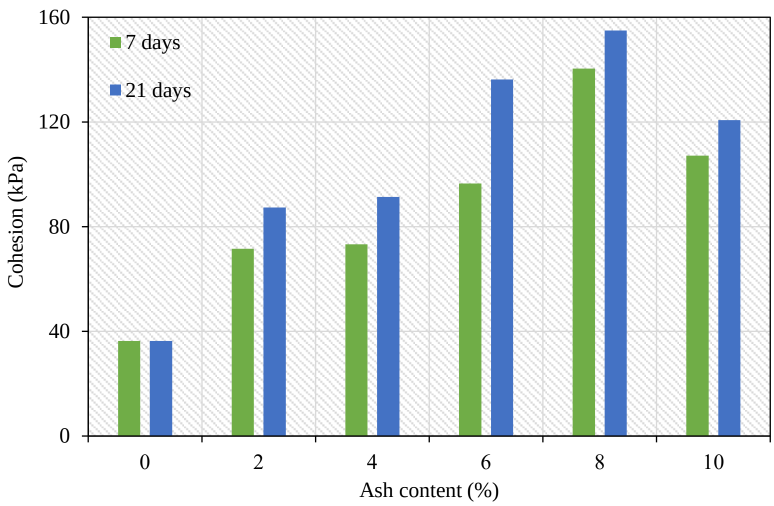

Figure 3. Effect of ash content on mixed soil cohesion values with curing times of seven and 21 days

The chemical reaction between the two raised the cohesion. When the calcium oxide (CaO) in coir fiber ash reacted with the silica (Si) in clay, the following pozzolanic reaction occurred.

$$Ca(OH)_2 + H_2O + SiO_2 \text{ \& } Al_2O_3 \rightarrow CSH \text{ \& } CAH$$

CSH and CAH are cement materials forming cementation in soil grains, raising the binding force between soil granules (Darwis, 2017; Tan et al., 2020).

The ash content and the curing time affected the internal friction angle, which tended to rise, as illustrated in Figure 4. Soil grains underwent flocculation and cementation due to a chemical reaction with ash, leading to this rise. As a result, the soil grains grew larger, and their surfaces became less smooth and flexible, leading to more friction between them (Fondjo et al., 2021).

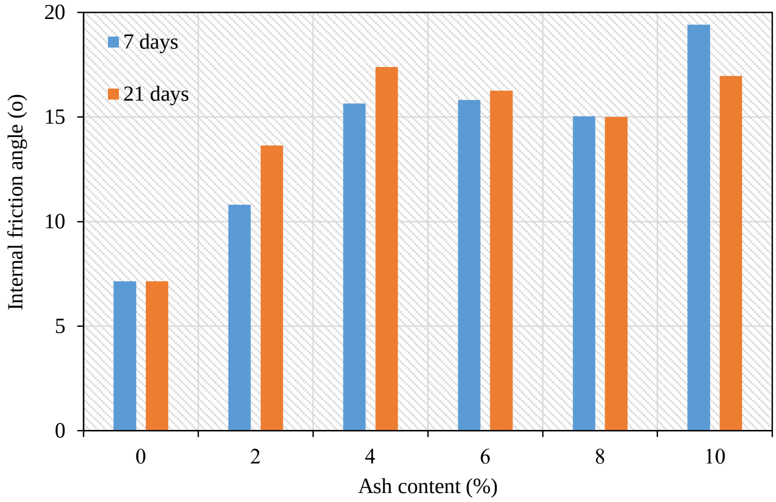

Figure 4. Effect of ash content on the internal friction angle of mixed soil with curing for seven and 21 days

3.3 Effect of ash content and curing time on shear strength

The tangent line depicted on the Mohr circle (Figure 2) is the failure envelope. If the soil has a normal stress value and the shear stress value is still below the failure envelope, then shear failure will not occur, and vice versa. In this study, the failure envelope for each specimen is shown in Figure 5. It can be seen that the failure envelope increases with each rise in ash content. An additional 8% ash content maximized the failure envelope.

Soil shear strength indicates how well soils resist moving or collapsing in the shear plane that cuts through them. According to Mohr (1980) in Das and Sobhan (2016), a material will only fail when shear stress and normal stress reach a critical combination. The shear strength values at specific normal stresses can be calculated using the cohesion and internal friction angle values pulled from Mohr's circle graph. Figure 6 exhibits the shear strength values of mixed soil at a curing time of seven and 21 days when a normal stress of 350 kPa was applied. The shear strength value in soil reinforced solely with coir fiber (and not with ash) was 80.21 kPa. The shear strength value rose over many days of curing in an ash mixture with varied concentrations. Adding 0.75% fiber and 8% ash to the soil elevated its shear strength to 248.73 kPa after 21 days of curing, signifying a 210% increase above the shear strength of fiber-reinforced soil.

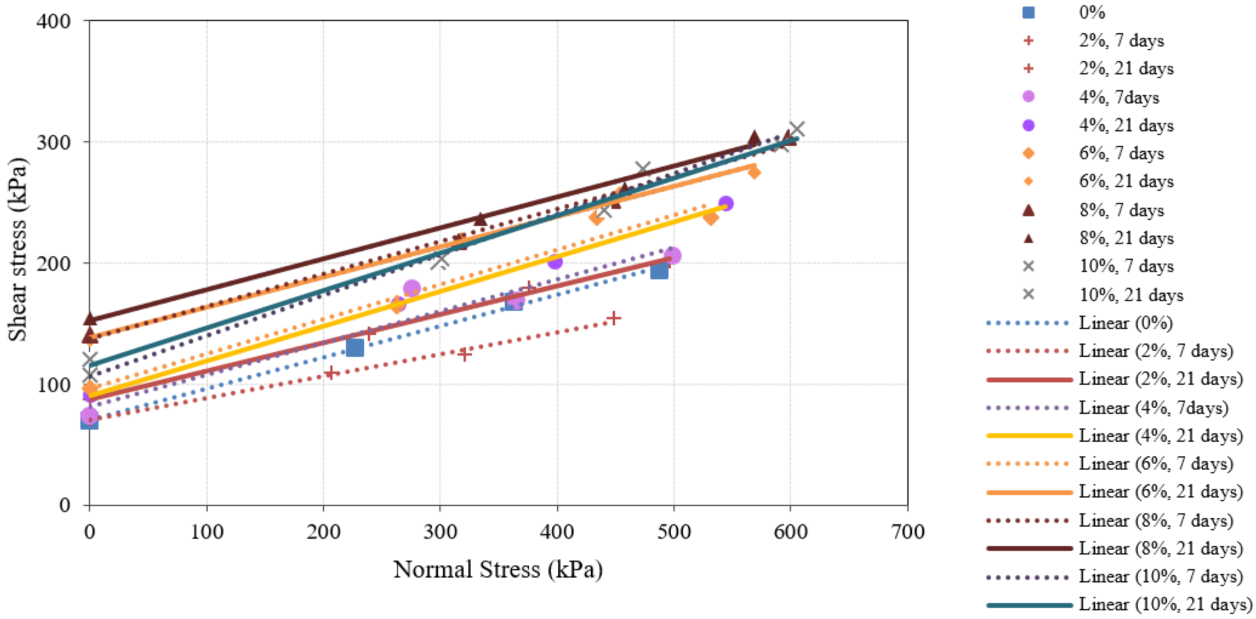

Figure 5. The failure envelope of the specimens during the curing time of seven days and 21 days

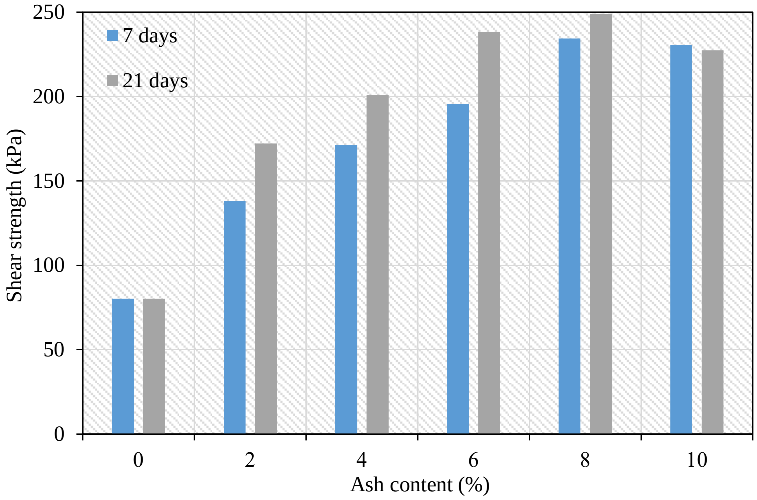

Figure 6. Effect of ash content on the shear strength of mixed soil with curing for seven and 21 days

3.4 Effect of ash content and curing time on the elastic modulus

Another parameter obtained from the triaxial test is the elastic modulus. This can be determined using the secant modulus method, obtained by comparing the deviatoric stress of 50% and the strain when it is 50%. Figure 7 displays a graph of the specimens' elastic modulus value at a cell pressure of 294.3 kPa.

As seen in Figure 7, the elastic modulus values continued to rise as the ash content increased. Curing the specimens for 21 days typically yielded a higher elastic modulus than curing it for seven days. The soil became stiffer as its elastic modulus rose (Widianti et al., 2021a).

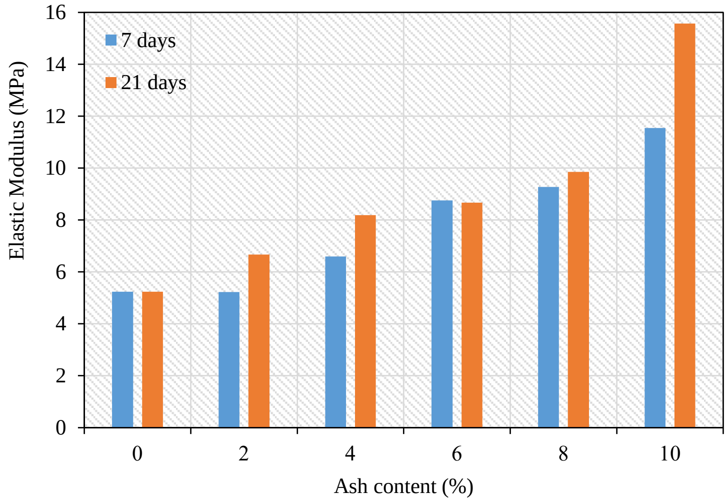

Figure 7. Effect of variations in ash content on the elastic modulus of mixed soil at a cell pressure of 294.3 kPa

4. CONCLUSION

The research yielded the following conclusions.

a) The combination of reinforcement using coir fiber and chemical stabilization using a mixture of coconut fiber ash and wood ash has significantly increased the deviatoric stress, cohesion, internal friction angle, shear strength, and elastic modulus of soft soil.

b) Cohesion, shear strength, elastic modulus, and internal friction angle all rose as cure time increased.

c) A mixture with an ash percentage of 8% and a curing time of 21 days achieved the highest deviatoric stress and shear strength. The highest shear strength value was 210% greater than soil solely reinforced with coir fiber.

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