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Evaluating coconut fiber and fly ash composites for use in landfill retention layers

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Graphical abstract

The plasticity index (PI) significantly increased from 19.10% to 22.15%. The three composites have met the requirements for liquid limit and plasticity index values for landfill covers, namely LL 20≥% and ≥PI 7%. The coefficients on the three composites meet the requirements, with values ranging from 10^{-5} cm/s. . Composite has the best value with a cohesion value of 55 kPa and a shear angle of 22°. The addition of fiber can increase the free compressive strength of the entire sample at all tested ratios

Abstract

This study utilized a series of experimental tests, including the Atterberg limit, standard Proctor, permeability, and direct shear tests. Three composites were investigated: 85% fly ash-10% bentonite (V1), 90% fly ash-5% bentonite (V2), and 95% fly ash-0% bentonite (V3). All composites contained 5% coconut fiber. The plasticity index (PI) increased significantly from 19.10% to 22.15%, with a change in bentonite content from 0% to 10%. All composite met the landfill liner plasticity index standards. The permeability values were low and satisfied local criteria, namely 1.052 x 10^{-5} (V1), 1.260 x 10^{-5} (V2), and 1.394 x 10^{-5} (V3). Composite V2 has the best value with a cohesion value of 55 kPa and a shear angle of 22°.Therefore, composite V3 was the most promising composite as an alternative covering material for landfills because it has the lowest atterberg limits results, the lowest OMC, and the results from the direct shear test that meet the criteria even though it is not the best result among the three variations. However, by supporting the OMC value and good plasticity, the V3 composite was chosen. This study is beneficial and valuable in the engineering, selection, and design of materials used for the construction of landfill liners.

Keywords: Stability, landfill liner, coconut fiber, bentonite

1. Introduction

The exponential increase in municipal solid waste owing to population growth, urbanization, and economic development has prompted the construction of engineered landfill sites with three primary methods for managing large quantities of municipal solid waste. These methods include stockpiling, burning, and composting (Turisno *et al.*, 2021). In comparison to burning and composting, the landfilling of waste is the most prevalent and widely employed method by communities (Kiruba-Sankar *et al.*, 2018). In addition, according to Zohoori and Ghani (2017), waste management issues in a number of countries constitute environmental, technical, and economic challenges (De Corato *et al.*, 2018). Many industrialized and European Union countries continue to include landfills as integral components of their waste management infrastructure (Ilman *et al.*, 2016).

Integrated waste management necessitates a landfill that complies with relevant standards. The linear stability of the landfill leachate system in terms of bearing capacity and soil strength is one of these standards. Landfill instability can result in landslides and environmental damage (Bhomia *et al.*, 2016). Thus, various studies have focused on investigating the prevention of landfill instability. The efficacy of a leachate retention system can be improved by changing the type of soil used; this variation results in an increase in soil density. The liner system functions as a semipermeable layer that prevents the infiltration of leachate or contaminants into the soil (Turisno *et al.*, 2021). Low-permeability materials are typically used for the construction of landfill liners in order to minimize infiltration (Rubinos and Spagnoli, 2018). According to the Minister of Public Works Regulation No. 03/PRT/M/2013, landfill leachate-retaining liners must have a permeability coefficient value of less than 10^{-6} cm/s. Another study found that the hydraulic conductivity of the final landfill cover should be less than or equal to 1 x 10^{-5} cm/s (Purnama and Marfai, 2012). This permeability coefficient value is influenced by several factors, including Atterberg limits, water content, energy density,

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compressive conditions, and viscosity (Falamaki *et al.*, 2018). However, the stability of leachate-containing liners in landfills is inversely proportional to their permeability (Ko *et al.*, 2021).

The majority of Indonesian landfills are susceptible to leachate infiltration into the soil. Landfill leachate constitutes liquid waste that is generated from the percolation of rainwater through solid waste disposed of at landfill sites as well as water vapor within waste and degradation products (Javankhoshdel and Bathurst, 2017). The transported material is a product of biological decomposition; it contaminates soil and groundwater and causes odor nuisances (Riser-Roberts, 2020). Given their affordability and accessibility, alternative building materials, such as fly ash, bottom ash, and bentonite, have been utilized as composite materials in landfill retaining layers. Bentonite is used because its rheological properties produce low-permeability and high-metal ion adsorption (Huang *et al.*, 2016). However, bentonite is prone to shrinkage cracking when dried and has a low compressive strength (Wu *et al.*, 2019). Consequently, a combination of alternative materials is required to improve soil stability. This study used several combinations of fly ash and coconut fiber. Fly ash can be used as a landfill liner in conjunction with other materials, such as bentonite, which can then reduce the permeability coefficient of the mixed material (Pandey and Jain, 2017). In addition, the use of coconut fiber can effectively control and prevent shrinkage cracking (Akindahunsi *et al.*, 2021). Thus, it is necessary to adapt testing methods and combine materials in order to obtain the permeability and desiccation values that meet the standards for landfill liners. Fly ash is mixed with bentonite material with a low conductivity value in order to create a landfill liner composite. In this study, the incorporation of additional materials, such as coconut fiber, was able to control shrinkage cracking; therefore, coconut fiber was selected as a composite material to determine the optimal blend of materials that could be employed in the landfill leachate retention layer system. According to Priyankara *et al*. (2016), the incorporation of coconut husk into soil mixtures reduces the plasticity properties of the soil, and soil volume changes caused by cracks can be minimized and controlled (Priyankara *et al.*, 2016). In addition, Budihardjo *et al*. (2021) conducted a similar study using fly ash, bentonite, and 1% quicklime at bentonite concentrations of 0% (FAB0), 15% (FAB15), 20% (FAB20), and 25% (FAB25) (Budihardjo *et al.*, 2021). The results showed that the addition of greater quantities of bentonite to fly ash reduced the shear stress and decreased the permeability coefficient values of soils. A mixture of fly ash and 25% bentonite (FAB25) had the lowest permeability value of 1.584 x 10^{-7} cm/s, which met the prescribed landfill liner standards. The addition of bentonite to fly ash improved the properties of the material intended for use as a landfill liner. The results of this study indicated that FAB25 produced the maximum safety factor value of 1.674. These outcomes satisfy the safety standards for the utilization of these materials as landfill liners. However, an evaluation of the mechanical stability of the soil utilizing fly ash as a landfill liner has not been conducted. In this study, we aimed to investigate the use of fly ash, bentonite, and coconut fiber composites as alternative landfill covering materials. We utilized the Atterberg limit, standard Proctor, composite permeability, and direct shear tests in our investigation. The increasing volumes of waste in landfills constitute the primary reason why this research is relevant. It is evident that because of poor management, leachate produced by waste persists as a considerable issue for communities and the environment adjacent to landfill sites. This research can be utilized as a scientific reference framework for designing a leachate-retaining system at a landfill site by using composite materials as landfill liners.

2. Methodology

2.1. Materials

This study used fly ash from coal waste acquired from one of the industries in Malang City, Indonesia. The composite materials used to modify fly ash as landfill cover materials were bentonite and coconut fiber. Fly ash consists of excellent and small particles (usually silt-sized) and is non-plastic or possesses inadequate shrinkage properties (Islam and Bhuiyan, 2018). Fly ash consists of various minerals, including silicates, aluminum, and iron oxides (Cokca, 2001). This pozzolanic property is the reason that fly ash can be used as a construction material, and it has been extensively investigated (Porbaha *et al*., 2000; Kim *et al*., 2005; Khan *et al*., 2013). In addition to being employed in construction material mixtures, fly ash is widely used to stabilize soft and expansive soils (Cokca, 2001; Tastan *et al*., 2011). Fly ash is a highly porous and permeable material that requires a blend of low-permeability materials, such as bentonite, for landfill cover applications (Islam and Bhuiyan, 2018). Fly ash is typically a non-plastic material that does not expand when used as a foundation material for structures without the addition of other materials (Bhatt *et al*., 2019). Moreover, the permeability of fly ash varies considerably, ranging from 10^{-4} cm/s to 10^{-7} cm/s, and the friction angle can range from 25° to 40° (Bhatt *et al*., 2019).

The composite material used in this study was bentonite, which was sourced from the Indrasari Company, Semarang City. Bentonite is produced from the chemical decomposition of common volcanic ash in the presence of water (Islam and Bhuiyan, 2018). It has a low hydraulic conductivity because of its ability to expand when in contact with water. According to Likos and Bowders (2010), there are two types of bentonite swelling: crystal and osmotic swelling (Sidik *et al*., 2018). In the context of crystal swelling, water enters the interlayer region upon crystallization and forms bonds with the exchanged cations. This swelling phase occurs regardless of the nature of the cations exchanged for all bentonite types. Osmotic swelling is caused by pore water flow driven by a solute concentration gradient. This phase occurs when cations with a radius-to-valence ratio greater than 300 (e.g., Na^+) occupy the exchange sites. Based on the research of Cokca *et al*. (2004), which employed bentonite compositions of 5%, 7%, 10%, 15%, and 20%, it was discovered that the addition of bentonite significantly decreased the permeability coefficient of the composite material, increased its cohesion, and decreased its internal friction angle (Cokca and Yilmaz, 2004). Meanwhile, the research of Budihardjo *et al*. (2021) with bentonite compositions of 0%, 15%, 20%, and 25% resulted in increases in the plasticity value and the optimum water content and decreases in the permeability coefficient of the composite mixture (Budihardjo *et al*., 2021). Therefore, the composition utilized to modify fly ash consists of a mixture of fly ash, bentonite, and coconut fiber divided into three variations presented in Table 1.

Table 1. Composite material variations.

Variable	Composition
V_1	85% Fly ash + 10% Bentonite + 5% Coconut fiber
V_2	90% Fly ash + 5% Bentonit + 5% Coconut fiber
V_3	95% Fly ash + 5% Coconut Fiber

The coconut fiber used in this study was acquired from an organic fertilizer business in Semarang. According to the findings of Chauhan *et al*. (2008), the addition of 0.75% coconut fiber to the composite mixture increased the free compressive strength of the soil (Chauhan *et al*., 2008). This indicated the optimal soil moisture content. These findings are supported by the research of Gray and Ohashi (1983), which revealed that coconut fiber could increase shear strength by increasing the number of fibers or by having a relatively low modulus fiber area ratio (Gray and Ohashi, 1983) .

2.2. Methods

In this study, a preliminary test was undertaken as a preliminary step to determine several parameters that could potentially affect the primary research outcomes. Preliminary tests that were conducted included an Atterberg limit test and a standard Proctor test. The Atterberg limit test was carried out in accordance with the American Society for Testing and Materials (ASTM) D-4318 standard to determine the shrinkage, plasticity, and limiting restrictions (Kollaros,.2016). The standard Proctor test was conducted to establish the optimum moisture content (OMC) in each composite (Khaleghnejad Tabari *et al*., 2019). This test involved the compaction of the composite material, followed by the gradual addition of water, which functions as a wetting agent or lubricant between particles. Insufficient water content would cause the soil texture to be dispersed, whereas low water content would cause the soil texture to flocculate [31]. When the composite exceeds the OMC level, soil strength decreases significantly (Syafrudin *et al*., 2023).

In addition to the preliminary testing, core testing was conducted in the form of permeability and shear strength tests. Permeability or hydraulic conductivity indicates the capacity of the soil to transmit water both horizontally and laterally (Doro *et al*., 2017). The permeability test was carried out using the falling head method of the AS 1289.6.7.2-2001 standard. The falling head method was selected because it is intended for particles of a suitable size, and the permeability can be low. The test was conducted by passing water through the composite sample until the water level in the vertical pipe reached a specified unit of height in order to quantify the amount of water that flowed through the sample. Direct shear testing was carried out as a core test to determine the stability of the composite material. This test required the following calculations: conversion from average load to normal stress, shear force, and shear stress. The shear stress and normal stress data provided the cohesiveness values and internal shear angles of the composite material. Shear strength was calculated using the Mohr–Coulomb formula shown as Formula (1) below (Budihardjo *et al*., 2021).

$$\tau = c + \sigma n. \operatorname{Tan} \emptyset \qquad (1)$$

The following is noted in the above formula (1): τ represents the shear strength of the soil; c indicates soil cohesion; σ denotes the effective soil stress in the soil plane; and $\emptyset$ represents the internal shear angle. In direct shear testing, a metal box containing a soil sample was split horizontally into a square or circle with two equilateral parts. The soil collapsed as a result of the shear force exerted on the top of the box.

Table 2. Atterberg limit test results.

Property	Test Method	Unit	V1	V2	V3
Liquid limit (LL)	ASTM-D423	%	40.06	38.83	34.83
Plastic limit (PL)	ASTM-D424	%	17.91	17.08	15.73
Plasticity index (PI)	ASTM-D2487	%	22,15	21.75	19.10

3. Results and discussion

3.1. Atterberg limits

As demonstrated in Table 2, the liquid limit (LL), plastic limit (PL), and plasticity index (PI) of the composite increased with increasing bentonite content. With the addition of 10% bentonite, the PI significantly increased from 19.10% to 22.15%. This shows that the addition of more bentonite increased the LL, PL, and PI. According to the findings of Rashid *et al*. (2021), the LL and PI increased with the addition of bentonite to the mixture (Islam and Bhuiyan, 2018). Pure bentonite has a PL value of 34%, whereas pure fly ash is a non-plastic material. Alla *et al*. (2017) employed plasticity criteria of LL 20% and PI 7% as parameters for composite material used as landfill cover (Alla *et al*., 2017). According to research by Gupt *et al*. (2020), composite materials for landfill coatings must have a conductivity of 1×10^{-7} cm/s, a PI of 7%, and a LL of 20% (Gupt *et al*., 2020). In this study, the three composites fulfilled the LL and PI standards for materials used as landfill covers.

The high mixed plasticity index is caused by changes in the soil and water systems that disrupt the balance of forces in the soil structure (Budihardjo *et al*., 2021). The fine-sized clay particles form a strong bond with the silt-sized particles, and bentonite undergoes flocculation, which increases the number of coarser particles by removing the finer particles (Islam and Bhuiyan, 2018).

3.2. Proctor standard test

A standard Proctor compaction test was performed on each composite variation in accordance with the ASTM D-698 standard. The determination of OMC and maximum dry density (MDD) in composites is important since it is used to determine the permeability of a mixture (Bhatt *et al.*, 2019). This test was conducted to determine the OMC and MDD. The standard Proctor test revealed that the first composite variation, composed of 85% fly ash, 10% bentonite, and 5% coconut fiber, yielded the highest OMC value. In contrast, the composite variation comprised of 95% fly ash and 5% coconut fiber yielded the lowest OMC value (Table 3).

Table 3. Standard Proctor test result

Variable	Composition	OMC (%)	MDD (gr/cm^3)
V_1	85% FA + 10% B + 5% C	19.80	1.600
V_2	90% FA + 5% B + 5% C	18.40	1.636
V_3	95% FA + 5% C	13.40	1.700

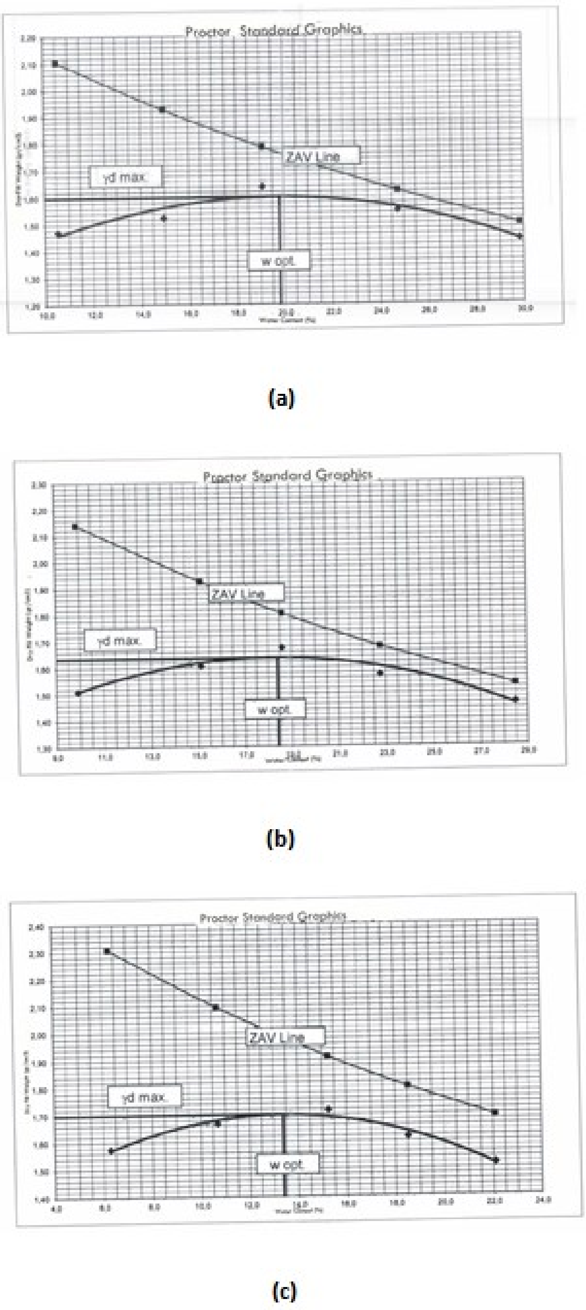
As shown in Figure 1, the MDD (γdmax) increases with the addition of bentonite and decreases the value of fly ash. The OMC and the MDD values decreased in correlation with the addition of bentonite and a decrease in the fly ash content. According to the findings of Meer and Benson (2007), an increase in MDD (γdmax) is expected with the addition of a percentage of bentonite and a decrease in fly ash because bentonite particles occupy the pore spaces in fly ash particles, reducing the pore volume and preventing an increase in the MDD of the composite (Meer and Benson, 2007). The lower density of fly ash and the formation of cement products owing to the action of pozzolanic fly ash are regarded as some of the most influential factors on MDD and OMC in mixtures (Islam and Bhuiyan, 2018). Pure fly ash is a non-cohesive material that remains in a non-plastic state in mixtures up to a 20% bentonite-fly ash content; thus, a mixture containing up to 20% bentonite can be used to improve the geotechnical properties of fly ash (Alam *et al.*, 2012).

3.3. Permeability Test

The hydraulic conductivity (k) of a material is used to determine its suitability as a liner material [18]. Permeability or hydraulic conductivity denotes the capacity of the soil to transmit water both horizontally and laterally (Bhatt *et al.*, 2019). This test was performed on all composite variations using the remainder of the standard Proctor test and the falling head method. The falling head method was selected since it is designed for fine-sized particles with low permeability. In this method, the rate of water flow in the burette, which is channeled into the ground tube without any pressure, is measured. This flow velocity is converted into a permeability coefficient.

Table 4. Permeability test result.

Variable	Composition	Permeability (cm/s)
V_1	85% FA + 10% B + 5% C	1.052×10^{-5}
V_2	90% FA + 5% B + 5% C	1.260×10^{-5}
V_3	95% FA + 5% C	1.394×10^{-5}



(a)

(b)

(c)

Figure 1. Standard Proctor test: (a) composite variation V1; (b) composite variation V2; and (c) composite variation V3.

According to Table 4, the composite variation, composed of 85% fly ash, 10% bentonite, and 5% coconut fiber, had the lowest permeability value. In comparison, the V3 composite, composed of 95% fly ash and 5% coconut fiber, had the highest permeability value. According to the test results for the three composites, mixing fly ash with bentonite significantly reduced the permeability value of each composite. The decrease in the permeability coefficient value in the composite variation consisting of fly ash and bentonite was because of the bentonite expansion process, which narrows the pores between the particles. This reduction in pore size impedes the flow of water through the composite. Similar to the research findings of Jembise *et al*. (2014), an increase in bentonite content frequently decreases permeability (Jembise *et al*., 2014). The permeability of fly ash impacts soil properties when utilized as a stabilizing soil agent. The permeability coefficient of pure fly ash varies between 10-^{4} to 10^{-7} cm/s (Bhatt *et al*., 2019). According to Bhatt, Priyadarshini (Bhatt *et al*., 2019), the permeability of a composite should be between 10^{-5} cm/s and 10^{-7} cm/s for landfill cover and coating applications. All composite variations in this study fulfilled the permeability criteria; the resulting permeability coefficient values ranged from 10^{-5} cm/s to 10^{-7} cm/s. In addition, the increase in the PI was in line with the decrease in the permeability value because it indicates the possibility of water seeping into the composite and improving plasticity. Therefore, as the value of the PI increased, the permeability value decreased. The addition of lime would reduce the permeability value because lime has stronger binding qualities than those of a composite consisting of bentonite and fly ash. Furthermore, it followed the notion that lime would become an imperative particle for sand particles with smaller pores.

3.4. Direct shear test

The direct shear strength test was conducted to determine the stability of the composite mixture material in the leachate retention layer (Lin *et al*., 2018). Direct shear tests were conducted with applied normal stresses of 41.15 kPa, 82.30 kPa, and 300 kPa. Table 5 shows the results of the direct shear strength test on the three composites. The highest cohesiveness value was obtained in the V2 composite, which consisted of 90% fly ash, 5% bentonite, and 5% coconut fiber. In comparison, the lowest value was obtained in V1, which consisted of 85% fly ash, 10% bentonite, and 5% coconut fiber. The internal shear angle decreased; The V1 composite had the lowest value, while the V3 composite produced the highest value.

Table 5. Direct shear strength test result.

Variable	Normal Stress	Shear Stress (σ)	Cohesion (c')	Internal Friction Angle(Ø)	Safety Factor
	KPa	kg.cm^{-2}	kPa	°	
V_1	41.15	50.21	42	10	3.430
	82.30	54.32			
	123.46	64.20			
V_2	41.15	71.60	55	22	
	82.30	86.42			6,817
	123.46	104.53			
V_3	41.15	64.20	45	26	
	82.30	85.60			5,360
	123.46	104.53			

The results showed that the addition of bentonite affected the shear strength of the composite mixture. In the V2 (90% fly ash, 5% bentonite, and 5% coconut fiber) and V3 (95% fly ash and 5% coconut fiber) composites, the cohesiveness values in the mixtures increased following the addition of bentonite. The increase in shear stress was caused by the formation of a pozzolanic reaction in the composite, namely the reaction between calcium in fly ash with aluminum and silicate in the soil, resulting in a hard and rigid mass (Furlan *et al*., 2018). Previous research by Budihardjo *et al*. (2021) demonstrated that the addition of bentonite increased the cohesiveness of a composite mixture of fly ash and bentonite (Budihardjo *et al*., 2021). Furthermore, the addition of bentonite affected the value of the internal shear angle, which showed a decreasing trend. This finding was similar to that of Slim *et al*. (2016), which demonstrated that the addition of bentonite altered the internal shear angle in the leachate-retaining material mixture (Slim *et al*., 2016).

This study also utilized coconut fiber as a composite material since its addition increased the free compressive strength of the soil. This finding was consistent with research by Saini *et al*. (2021), which showed that increases in cohesiveness and friction values were proportional to the addition of coconut fiber and increased non-linearly with the coconut fiber content. The addition of cohesiveness was a result of the fibers entering the soil (Saini and Sharma). The addition of coconut fiber increased the shear compressive strength of the composite. Consoli *et al*. (2010) found that the addition of fiber could increase the free compressive strength of the entire sample at all tested ratios (Consoli *et al*., 2010).

The last step in this research is Geoslope/W analysis using Geostudio software, which aims to determine the safety factor possessed by the composite when it is used as a landfill liner. The greater the safety factor of the composite, the more stable the composite. Data analysis using the Geoslope/W application was performed on all composites. The data input to the application was specific gravity, internal shear angle, and cohesion value. The safety factor values presented in Table 5 indicate that the decrease in the safety factor, along with the addition of bentonite, is caused by a decrease in the shear strength represented by the cohesion value and the internal shear angle of the composite. Thus, the cause of the high and low factor of safety is caused by the factors causing the high and low internal shear angles and the cohesion value of the composite (Javankhoshdel and Bathurst, 2017).

4. Conclusion

Analyzing several mixtures of fly ash, bentonite, and coconut fiber revealed that these materials were suitable for use in the construction of landfill liners. Three composites with bentonite contents of 10%, 5%, and 5%, each containing 5% coconut fiber, displayed plastic properties. The PI value significantly increased from 19.10% to 22.15% with the change of bentonite content from 0% to 10%. The three composites satisfy the LL and PI standards for landfill covers, which are LL 20% and PI 7%, respectively. Permeability test with Falling Head showed that the addition of bentonite significantly reduced the permeability value of the composite. The result is that the coefficients on the three composites meet the requirements, with values ranging from 10^{-5} cm/s in accordance with the stability of previous studies between 10^{-5} cm/s and 10^{-7} cm/s. While the results of the shear strength test showed that the cohesiveness of the mixture increased after the addition of bentonite. Composite V2 has the best value with a cohesion value of 55 kPa and a shear angle of 22°. The increase in shear stress is caused by the formation of a pozzolanic reaction in the composite. Adding coconut fiber to the composite increased the cohesiveness value, hence increasing its non-linearity. Coconut fiber increased the shear compressive strength of the composite. This was a result of the presence of coconut fiber in the soil.

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