

Splitting Tensile Strength of Soft Clay–Coconut Coir Fiber Mixtures Soaked in NaOH at Various Concentrations

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Abstract.

Soil strength plays a crucial role in construction and geotechnical engineering. Weak soils, such as soft clay, often exhibit low bearing capacity, necessitating ground improvement techniques to ensure structural stability. One promising method for soil reinforcement involves the use of natural fibers, particularly coconut coir, which can be chemically treated to enhance its bonding with soil particles. This study investigates the effect of sodium hydroxide (NaOH) treatment on coconut coir fibers and its influence on the splitting tensile strength of a soil–fiber mixture. Coconut coir fibers, measuring 3–5 cm in length and incorporated at a content of 0.6%, were soaked in NaOH solutions of varying concentrations (0%, 5%, 10%, 15%, and 20%) for three hours prior to mixing. The treatment aimed to roughen the fiber surface and improve mechanical interlocking with the soil matrix. Splitting tensile strength tests were conducted following the SNI-2491 standard, with three specimens prepared for each NaOH concentration. The results indicate that NaOH treatment did not significantly enhance the splitting tensile strength of the soil–fiber mixture. The highest average splitting tensile strength, 33.48 kPa, was observed in samples reinforced with untreated fibers (0% NaOH). These findings suggest that, for coconut coir fibers of this size and content, chemical treatment with NaOH may not be necessary for improving soil tensile performance.

Keywords: *Soft clay; Coconut coir fiber; NaOH and Splitting tensile strength.*

I. INTRODUCTION

Soil is an essential component widely utilized by humans, particularly in the field of Civil Engineering. In this discipline, soil serves as the foundation for supporting structures, including both building and road constructions. According to (Bowles, 1994), soil is a construction material readily available in the field, making it highly economical and easily obtained. Despite these advantages, soil quality must be properly evaluated prior to its use as a construction material to prevent structural failure. Problems may arise when structures are built on unsuitable soil conditions; therefore, the influence of soil properties must be carefully considered in construction planning. Soil improvement is commonly undertaken to enhance soil strength and its geotechnical properties. Various methods, both mechanical and chemical, can be applied for soil stabilization. The success of these efforts depends on the methods, materials, and equipment employed. Soil reinforcement is an approach aimed at improving or modifying unfavorable subgrade conditions, particularly in terms of bearing capacity to support the intended structure. Unfavorable soil conditions include high plasticity index and significant swelling–shrinkage behavior, characteristics commonly associated with clay soils. When subjected to moisture reduction, clay soils tend to shrink and crack; conversely, when the moisture content increases, they expand. With advancements in soil mechanics, such conditions can be addressed through various ground improvement techniques.

One alternative material for soil reinforcement is coconut coir fiber treated with a NaOH solution. Coconut coir fiber is selected due to its high permeability and its widespread availability throughout Indonesia. According to (Arsyad et al., 2015), coconut coir fiber contains cellulose, hemicellulose, and lignin, and exhibits hydrophilic properties (compounds capable of binding with water). The surface of coir fiber often contains impurities and substances that affect its bonding capacity with soil; therefore, treatment is required prior to use. One common treatment method involves soaking the fibers in a NaOH (sodium hydroxide) solution. NaOH is capable of removing impurities and other surface substances, resulting in a rougher fiber surface due to the reduction of adhered contaminants. According to (Brígida et al., 2010), one method of fiber treatment is immersion in a chemical solution such as NaOH. Soaking green coconut coir

fibers in a NaOH solution for 1 hour at 30°C produced a cleaner fiber surface compared to untreated fibers. A similar treatment was conducted by (Maryanti et al., 2011), in which coconut fibers were immersed in NaOH solutions with concentrations of 2%, 5%, and 8% for 1 hour and then air-dried at room temperature for 8 hours. Tensile strength testing indicated that the highest value, 97.356 N/mm², was obtained at a 5% concentration.

(Arsyad and Soenoko, 2018) investigated coconut coir fiber treatment using NaOH solutions with concentrations of 0%, 5%, 10%, 15%, and 20%, as well as potassium permanganate solutions at concentrations of 0.25%, 0.5%, 0.75%, and 1%. The fibers were soaked for 3 hours and subsequently oven-dried at 90°C for 5 hours. Observations using a Scanning Electron Microscope (SEM) showed that NaOH-treated fibers exhibited different surface roughness characteristics compared to untreated fibers. Although previous studies have demonstrated that NaOH treatment can improve the cleanliness and surface roughness of coconut coir fibers, most of these investigations have focused primarily on the individual characteristics of the fibers, such as surface morphology and tensile strength. Studies examining the effect of NaOH treatment on the mechanical behavior of fiber-reinforced soil, particularly in terms of splitting tensile strength, remain limited and have not been extensively reported. Therefore, further research is necessary to determine the extent to which NaOH treatment at various concentrations influences the performance of soil–fiber mixtures as reinforcement materials. This study aims to analyze the effect of immersing 0.6% coconut coir fiber in NaOH solutions with concentrations of 5%, 10%, 15%, and 20% for 3 hours on the splitting tensile strength, maximum strain, and lateral deformation of soil–fiber mixtures, and to determine the optimum NaOH concentration that yields the maximum splitting tensile strength.

II. METHODS

2.1. Research Design

This study commenced with the preparation of the testing equipment to be used throughout the research process. Subsequently, material preparation was carried out, consisting of clay soil and coconut coir waste. The clay soil was first sieved using a No. 40 sieve and then oven-dried to remove its natural moisture content (Das, 2013). Meanwhile, the coconut coir was cleaned prior to conducting fiber tensile strength testing. The fibers were then cut to lengths of 3–5 cm and weighed at 0.6% of the dry weight of the soil mixture (Shalchian & Arabani, 2023). The prepared coconut coir fibers were immersed in sodium hydroxide (NaOH) solutions with concentration variations of 0%, 5%, 10%, 15%, and 20% for 3 hours (Khan et al., 2018). After soaking, the fibers were oven-dried at 90°C for 5 hours. The next stage involved the preparation of soil–fiber mixture specimens using fibers treated with the respective NaOH concentrations. Specimen preparation was conducted at the Maximum Dry Density (MDD) and Optimum Moisture Content (OMC) of the clay soil. The prepared specimens were then subjected to splitting tensile strength tests. The test results were analyzed to determine stress–strain behavior, splitting tensile strength, and lateral deformation. The final stage of the study involved compiling and discussing the results based on the data obtained. The results of the physical properties tests of the soil are presented in Table 2.1.

Table 2.1. Results of Soil Physical Properties Tests (Widianti et al., 2021)

Parameter	Testing Standard	Value
Specific Gravity, G _s	ASTM D854-10	2.63
Liquid Limit, LL (%)	ASTM D4318-10	89.91
Plastic Limit, PL (%)		38.86
Shrinkage Limit, SL (%)		16.33
Plasticity Index, PI (%)		51.05
Maximum Dry Density, MDD (g/cm ³)		ASTM D698-12
Optimum Moisture Content, OMC (%)	29.9	
Silt Fraction (%)	ASTM D422-63 and ASTM D6913-04	70.58
Clay Fraction (%)		16.06
Sand Fraction (%)		13.36
Soil Classification (USCS)	CH (Organic clay with high plasticity)	
Soil Classification (AASHTO)	A-7-6 (Clay with poor bearing capacity)	
Soil Activity (Skempton)	3.18 (Active clay / montmorillonite)	

The soil properties presented in the table indicate that the tested material is a highly plastic, fine-grained clay with significant engineering challenges. The specific gravity (Gs) of 2.63 is typical for clay minerals, suggesting a dense mineral structure. The liquid limit (LL) of 89.91% and plastic limit (PL) of 38.86% result in a plasticity index (PI) of 51.05%, which is very high and indicates a soil with extreme plasticity, prone to large volumetric changes with moisture variations. The shrinkage limit (SL) of 16.33% further supports the soil's tendency to undergo significant contraction and expansion, typical of expansive clays. The maximum dry density (MDD) of 1.28 g/cm³ and optimum moisture content (OMC) of 29.9% reflect the soil's low density and high moisture retention capacity, which are characteristics of soft, compressible clays.

Particle size distribution shows a predominance of silt (70.58%), with smaller fractions of clay (16.06%) and sand (13.36%), highlighting the soil's fine-grained nature. Classification according to the Unified Soil Classification System (USCS) identifies it as CH, an organic clay with high plasticity, while the AASHTO classification as A-7-6 indicates poor bearing capacity, unsuitable for supporting heavy structures without improvement. Skempton's activity value of 3.18 classifies the soil as active clay, primarily montmorillonite, confirming its susceptibility to shrink-swell behavior. Overall, these parameters suggest that the soil is highly compressible, expansive, and has low strength, necessitating stabilization or reinforcement methods such as fiber inclusion or chemical treatment before construction. Its high plasticity and active clay content indicate that careful attention must be paid to moisture control and compaction during foundation design to prevent structural settlement or cracking.

Table 2.2. Mix Design of Test Specimens

Specimen Code	NaOH Content (%)	Dry Soil Weight (g)	Fiber Weight 0.6% (g)	Water Content (ml)	Number of Specimens
A	0	86.28	0.52	25.95	3
B	5	86.28	0.52	25.95	3
C	10	86.28	0.52	25.95	3
D	15	86.28	0.52	25.95	3
E	20	86.28	0.52	25.95	3

The table presents the mix design for preparing soil–fiber specimens with varying NaOH concentrations to evaluate their effect on mechanical behavior. Each specimen consists of a consistent dry soil weight of 86.28 g, reinforced with 0.52 g of coconut coir fiber, which represents 0.6% of the soil weight. The water content for all mixtures is maintained at 25.95 ml to achieve uniform moisture conditions across specimens. The NaOH content in the fiber treatment is varied from 0% (untreated fibers) to 20% (specimens A to E), while the number of replicates for each variation is consistently three, ensuring statistical reliability of the results. The uniformity in soil weight, fiber content, and water content allows the study to isolate the effect of NaOH treatment concentration on the soil–fiber mixture properties, specifically tensile strength, strain, and lateral deformation.

Specimen A, with 0% NaOH, serves as the control, representing the baseline behavior of soil reinforced with untreated coir fibers. Specimens B through E investigate the influence of incremental NaOH concentrations (5%, 10%, 15%, and 20%) on the interaction between the fiber and clay matrix. Maintaining constant fiber and soil proportions ensures that differences in mechanical performance can be attributed primarily to NaOH treatment rather than variations in mix composition. Overall, this experimental design provides a controlled framework to evaluate the optimal NaOH concentration for enhancing soil–fiber interfacial bonding and mechanical performance while accounting for variability through multiple replicates. The approach is well-suited for examining the balance between chemical fiber treatment and soil reinforcement effectiveness.

2.2. Splitting Tensile Strength Test

In this study, the primary test conducted was the splitting tensile strength test to determine the tensile strength (T) of cylindrical specimens subjected to compressive loading applied along the vertical diameter until failure occurred. Failure was identified by the appearance of cracks along the vertical diameter of the specimen surface.

$$T = \frac{2 \cdot P_{max}}{\pi \cdot L \cdot d}$$

where:

- T = Tensile strength (kPa)
- P_max = Maximum applied load (N)
- L = Average length of the specimen (mm)
- d = Diameter of the specimen (mm)

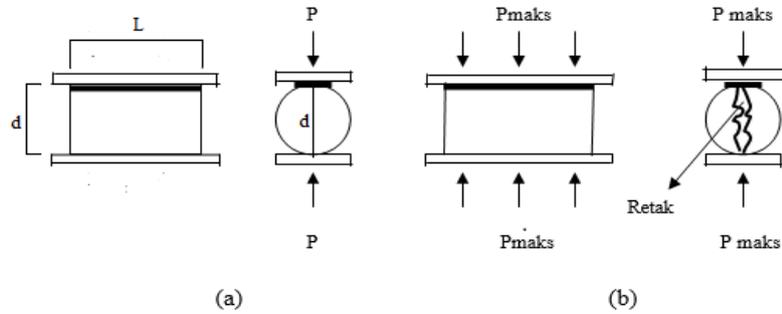
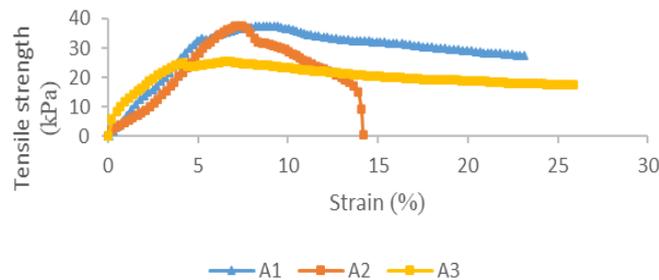


Fig 2.1. Configuration of the Splitting Tensile Strength Test
 (a) Splitting test during loading (b) Splitting test at failure

III. RESULT AND DISCUSSION

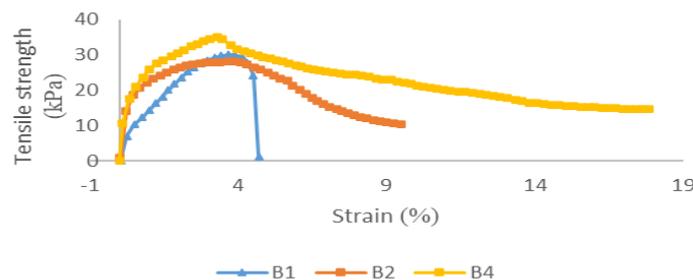
3.1. Split Tensile Strength Test Results of Soft Clay Reinforced with Coconut Coir Fibers at Various NaOH Concentrations

The following figures (Figures 3.1 to 3.5) illustrate the relationship between strain and tensile strength for soil–coconut coir fiber specimens treated with varying concentrations of NaOH, ranging from 0% to 20%. Each graph demonstrates how the tensile strength of the soil–fiber mixture evolves as the specimen is subjected to increasing strain until failure occurs. These visualizations are critical for understanding the effect of NaOH treatment on the mechanical behavior of the reinforced soil. By comparing the peak tensile strength and corresponding strain across different NaOH concentrations, the figures provide insights into the optimal fiber treatment for enhancing soil reinforcement performance.



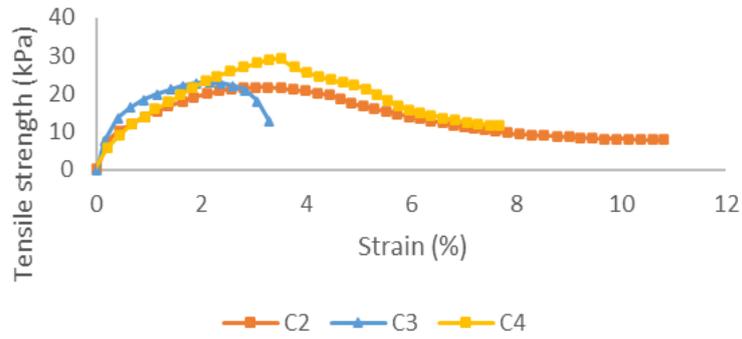
Source: Laboratory test results

Fig 3.1. Relationship between strain and tensile strength of the specimen with 0% NaOH concentration



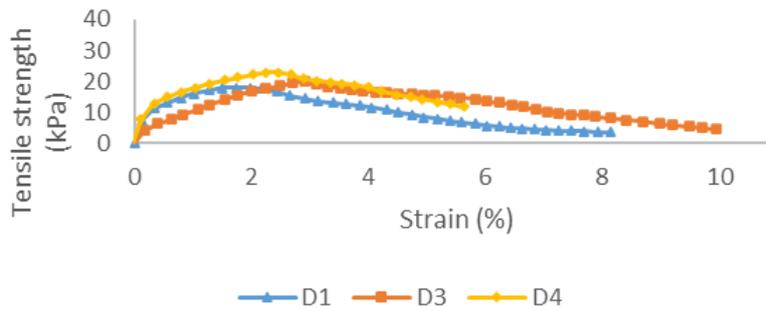
Source: Laboratory test results

Fig 3.2. Relationship between strain and tensile strength of the specimen with 5% NaOH concentration



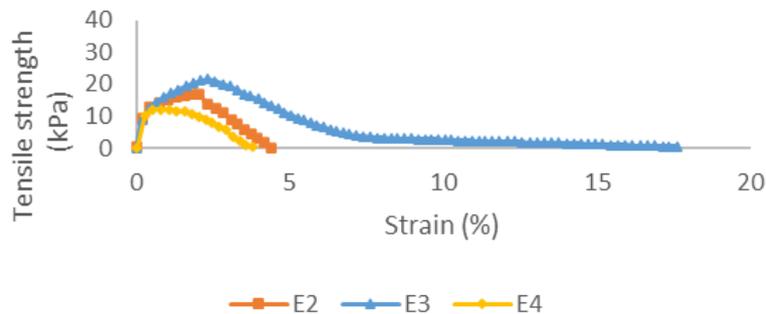
Source: Laboratory test results

Fig 3.3. Relationship between strain and tensile strength of the specimen with 10% NaOH concentration



Source: Laboratory test results

Fig 3.4. Relationship between strain and tensile strength on the test specimen with 15% NaOH concentration



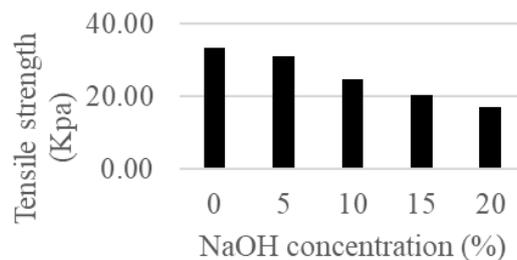
Source: Laboratory test results

Fig 3.5. Relationship Between Strain and Tensile Strength of Specimens with 20% NaOH Concentration

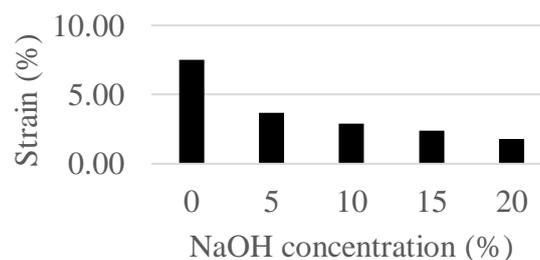
Based on the stress–strain graphs for all NaOH concentration variations (0%, 5%, 10%, 15%, and 20%), all specimens exhibit a relatively similar pattern. The tensile strength increases with increasing strain until it reaches a peak value, after which it decreases beyond a certain strain level. For the 0% NaOH variation, the maximum tensile strength reached 37.47 kPa, which is the highest value among all variations. At 5% NaOH concentration, the maximum tensile strength was 35.02 kPa, while at 10% it reached 33.57 kPa. Furthermore, at 15% NaOH concentration, the maximum tensile strength decreased to 22.94 kPa, and at 20% NaOH concentration, the lowest value was recorded at 21.66 kPa. 3.2. Effect of NaOH Concentration in Coconut Coir Fiber Soaking on Soil Tensile Strength and Strain. From the laboratory splitting tensile strength test results presented in the stress–strain relationship graphs for various NaOH concentrations (Figures 3.1 to 3.5), the peak stress value causing the specimen to split into two parts can be identified. This peak stress represents the tensile strength of the mixture. The tensile strength and maximum strain values for each specimen variation are presented in Table 3.1 and Figure 3.6 below.

Table 3.1. Tensile Strength and Strain Values of Test Specimens

No.	Benda Uji	Kadar NaOH	Regangan Max	Rata-rata Regangan Max	Kuat tarik (kPa)	Rata-rata Kuat tarik (kPa)
1	A1	0%	8,686	7,50	37,46	33,48
2	A2		7,314		37,59	
3	A3		6,486		25,38	
4	B1	5%	3,8	3,67	30,15	31,13
5	B2		3,8		28,23	
6	B3		3,4		35,01	
7	C1	10%	3,086	2,90	21,69	24,64
8	C2		2,086		23,01	
9	C3		3,514		29,23	
10	D1	15%	1,829	2,39	17,96	20,35
11	D2		2,914		20,16	
12	D3		2,429		22,93	
13	E1	20%	2,057	1,79	16,97	16,95
14	E2		2,4		21,66	
15	E3		0,914		12,23	



Source: Laboratory test results

Fig 3.6. Relationship between NaOH concentration and the splitting tensile strength of the specimens

Source: Laboratory test results

Fig 3.7. Relationship between NaOH concentration and the strain values

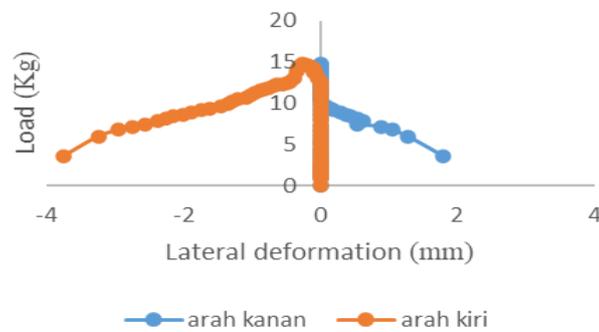
From Figure 3.6, it is evident that the specimen reinforced with untreated coconut coir fibers (0% NaOH) exhibited the highest average splitting tensile strength, reaching 33.48 kPa. In contrast, the specimen treated with the highest NaOH concentration (20%) recorded the lowest tensile strength, with an average value of 16.95 kPa. This indicates that the absence of NaOH treatment provided the most favorable condition for maximizing the tensile strength of the soft clay–coir fiber mixture. A similar trend is observed in the strain behavior of the specimens. As shown in Figure 3.7, the highest average strain was obtained in the 0% NaOH specimen, measuring 7.5%, whereas the specimen with 20% NaOH exhibited the lowest average strain of 1.79%. These results collectively suggest that NaOH treatment, under the conditions applied in this study, does not enhance the tensile or deformational performance of the clay–fiber composite. Based on the

results presented in Table 3.1, it can be concluded that soaking coconut coir fibers in NaOH for three hours does not significantly improve the mechanical properties of soft clay. The superior tensile performance of the 0% NaOH specimens compared to treated fibers suggests that both the concentration of NaOH and the soaking duration critically influence the structural integrity of the fibers and, consequently, the composite mixture.

Excessive alkali exposure can negatively affect the fibers. Rokbi et al. (2011) reported that overexposure to alkali solutions may weaken or damage natural fibers. Specifically, the flexural and tensile properties of fiber composites decrease due to the reduction of lignin, which is responsible for binding cellulose fibrils together. As lignin diminishes beyond an optimal alkali concentration, the fiber’s tensile capacity is reduced, resulting in lower composite strength. Similarly, Arsyad (2016) emphasized that alkali treatment serves to clean the fiber surface by removing waxy coatings, lignin, hemicellulose, and other impurities, thereby improving the bonding between fibers and the soil matrix. While this treatment can enhance interfacial adhesion and potentially increase tensile strength, prolonged or excessive exposure to NaOH may degrade cellulose, the primary structural component of the fibers. This degradation compromises the fibers’ load-bearing capacity and diminishes the overall performance of the fiber–soil composite. Consequently, in this study, NaOH-treated fibers did not yield higher tensile strength or strain values, highlighting that untreated fibers (0% NaOH) are more effective in reinforcing soft clay under the tested conditions. These findings underscore the importance of optimizing chemical treatment parameters, as inappropriate concentrations or durations of NaOH immersion can lead to deterioration rather than improvement of fiber-reinforced soil composites. Future investigations may focus on varying soaking durations or employing alternative chemical treatments to balance surface roughening and fiber integrity, ensuring both optimal bonding and structural performance in soil reinforcement applications.

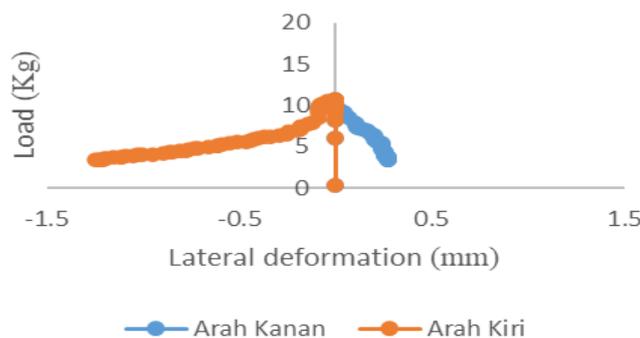
3.2. Effect of NaOH-Soaked Coconut Coir Fibers on Lateral Deformation of Soft Clay Mixtures

The lateral deformation values were obtained using dial gauge readings and are presented in the form of load–lateral deformation graphs, as shown in Figures 3.8 through 3.12.



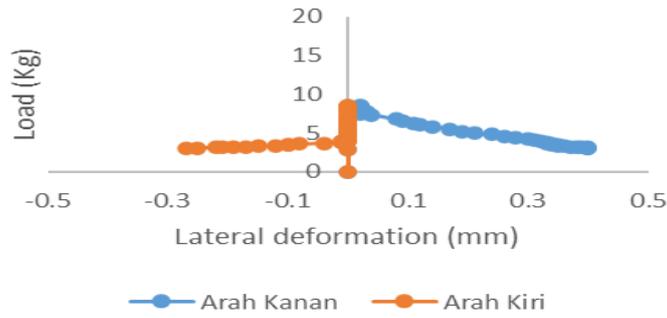
Source: Laboratory test results

Fig 3.8. Lateral deformation of the specimen with 0% NaOH



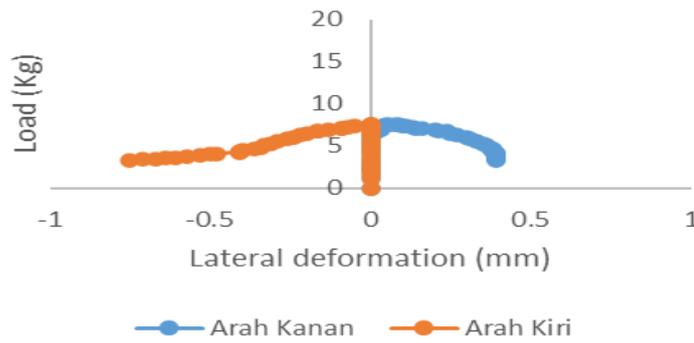
Source: Laboratory test results

Fig 3.9. Lateral deformation of the specimen with 5% NaOH



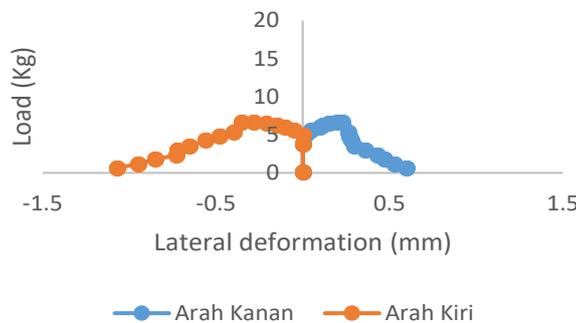
Source: Laboratory test results

Fig 3.10. Lateral deformation of the specimen with 10% NaOH



Source: Laboratory test results

Fig 3.11. Lateral deformation of the specimen with 15% NaOH



Source: Laboratory test results

Fig 3.12. Lateral deformation of the specimen with 20% NaOH

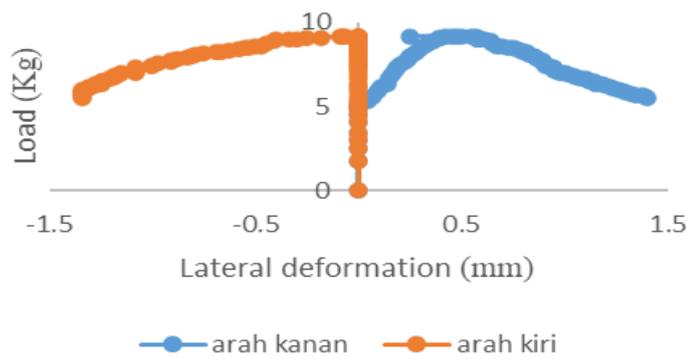
Based on the dial gauge readings, it was observed that the soft clay mixture reinforced with 0% NaOH exhibited the highest lateral deformation among all tested specimens. The specimen with 0% NaOH also sustained higher vertical loads compared to mixtures with higher NaOH concentrations, indicating that the load-bearing capacity of the untreated fiber–soil composite was superior to that of the chemically treated variants. This finding aligns with the results reported by Fitriyana and Rochim (2017), who noted that lateral strain increases with higher vertical stress, whereas lower vertical stress results in correspondingly smaller lateral strain. In the present study, the untreated 0% NaOH specimen experienced greater vertical loads than the NaOH-treated specimens, which consequently led to larger lateral deformation values. This trend confirms that the deformation response is closely related to the applied load: higher loads induce greater lateral movement within the soil–fiber composite. Similarly, Patria (2010) reported that increasing applied load can result in more pronounced slipping or shear between the soil matrix and the reinforcement material.

In the context of this study, the larger lateral deformation observed in the 0% NaOH mixture suggests that the untreated coir fibers maintained stronger interfacial bonding and better energy absorption

capacity, allowing the composite to accommodate higher loads before failure. These results imply that the addition of NaOH-treated fibers does not necessarily enhance the lateral deformation performance of soft clay. In fact, excessive chemical treatment may reduce fiber integrity, leading to decreased load transfer efficiency between the fibers and the soil. Consequently, both the ultimate lateral deformation and the load-bearing capacity of the composite decrease with increasing NaOH concentration. Therefore, under the tested conditions, untreated fibers provided the most effective reinforcement, sustaining higher vertical loads and exhibiting greater lateral deformation prior to failure.

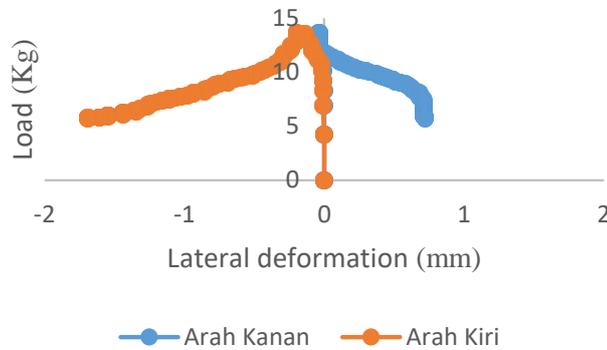
3.1. Effect of NaOH Variation on the Lateral Deformation of Soil–Fiber Mixtures under 3 MPa Stress.

This subsection analyzes the lateral deformation of the soil–fiber mixture specimens subjected to a load of 3 MPa. The presented graphs illustrate the relationship between the applied load and lateral deformation, allowing observation of the material’s deformation behavior during testing.



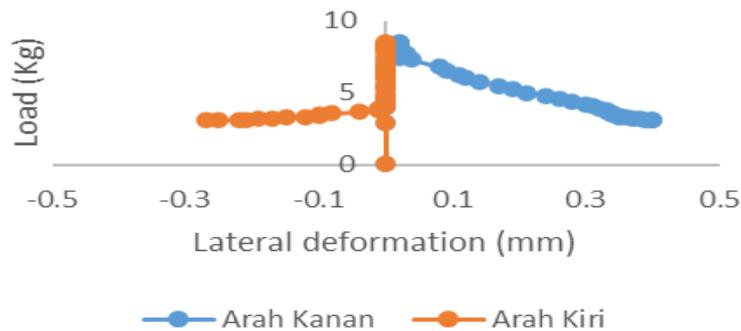
Source: Laboratory test results

Fig 3.13. Lateral deformation of the specimen with 0% NaOH under 3 MPa stress



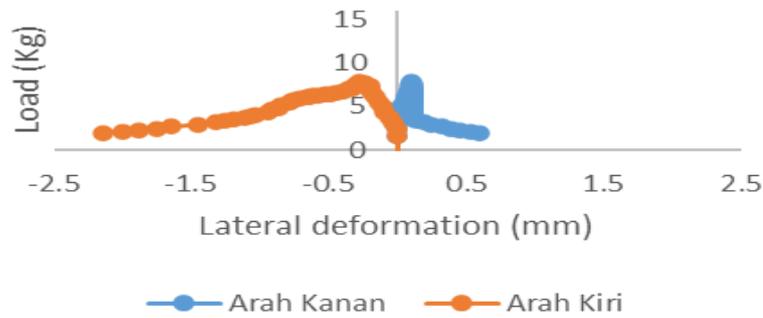
Source: Laboratory test results

Fig 3.14. Lateral deformation of the specimen with 5% NaOH under 3 MPa stress



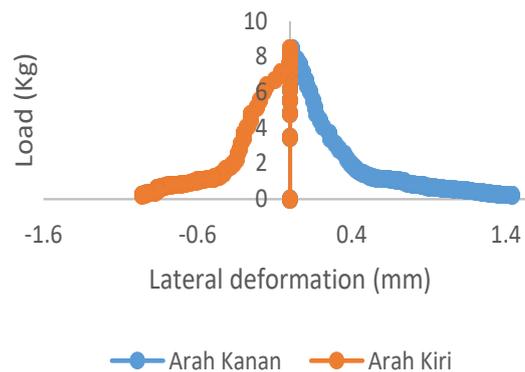
Source: Laboratory test results

Fig 3.15. Lateral deformation of the specimen with 10% NaOH under 3 MPa stress



Source: Laboratory test results

Fig 3.16. Lateral deformation of the specimen with 15% NaOH under 3 MPa stress



Source: Laboratory test results

Fig 3.17. Lateral deformation of the specimen with 20% NaOH under 3 MPa stress

Based on the dial gauge readings presented in Figures 3.13 to 3.17, it was observed that, under identical applied stress, the soft clay mixture reinforced with 5% NaOH-treated coconut coir fibers exhibited the highest lateral deformation. This outcome is primarily attributed to the fact that the maximum load sustained among all tested specimens was recorded for the 5% NaOH mixture, reaching 13.74 kg. This maximum load exceeded that of the specimen with untreated fibers (0% NaOH), indicating that, under these conditions, the soil–fiber composite with 5% NaOH treatment demonstrated greater load-bearing capacity and structural strength compared to the untreated mixture. The higher lateral deformation observed in this specimen suggests a more effective distribution of stress and a higher tolerance to applied loads, which reflects an improved mechanical interaction between the coir fibers and the clay matrix. The findings align with the observations of Fitriyana and Rochim (2017), who reported that lateral strain in soil increases with higher vertical pressures and decreases under lower pressures.

In the context of this study, the specimen with 5% NaOH fibers experienced a higher applied load than the 0% NaOH specimen, resulting in increased lateral deformation. This behavior suggests that the treated fibers contribute to better stress transfer within the soil matrix, thereby enhancing the composite's capacity to resist external loads. Similarly, Patria (2010) noted that increased applied loads can lead to greater shear interactions between soil and reinforcement, resulting in higher lateral strains. In this study, the elevated lateral deformation for the 5% NaOH mixture can be interpreted as a combination of enhanced load distribution and partial fiber-matrix slip, which may improve the overall energy absorption of the soil composite during stress application. However, it is important to note that increasing the NaOH concentration beyond 5% does not continue to improve lateral deformation or load-bearing performance. Specimens with higher NaOH concentrations (10%, 15%, and 20%) exhibited progressively lower maximum loads and reduced lateral deformation, indicating that excessive alkali treatment may compromise fiber integrity.

As discussed by Rokbi et al. (2011), excessive alkali concentrations can weaken or damage natural fibers, reducing their contribution to the composite's mechanical properties. Arsyad (2016) also emphasized that prolonged alkali treatment can degrade cellulose, the primary structural component of coconut coir

fibers, leading to diminished load transfer and reduced deformation capacity. In summary, the results suggest that a moderate NaOH treatment of 5% enhances the load-bearing performance of soft clay–coir fiber mixtures, as reflected in both higher maximum load and increased lateral deformation. This indicates an optimum treatment level for balancing fiber reinforcement effectiveness and structural integrity, while higher NaOH concentrations may lead to fiber degradation and diminished composite performance.

IV. CONCLUSION

Based on the results of this study, it can be concluded that soaking coconut coir fibers in a NaOH solution for 3 hours did not enhance the splitting tensile strength of the soft clay–fiber mixture. Among the tested variations, the optimum NaOH concentration was 0% (untreated fibers), which produced the highest average splitting tensile strength of 33.48 kPa. In contrast, increasing NaOH concentrations from 5% to 20% resulted in a gradual reduction in tensile strength, with the lowest average value recorded at 20%. Similarly, the highest maximum strain value, 7.50%, was observed in specimens reinforced with untreated fibers, while higher NaOH concentrations led to lower strain capacity. The results indicate that excessive alkali treatment may weaken the fiber structure, potentially due to degradation of essential components such as cellulose, thereby reducing its reinforcing effectiveness within the soil matrix. In terms of lateral deformation, variations in NaOH concentration influenced the deformation behavior of the mixtures. Higher NaOH concentrations tended to reduce the load-bearing performance and alter deformation characteristics, likely due to fiber damage during treatment. Overall, untreated coconut coir fiber demonstrated the most effective performance for improving the tensile behavior of soft clay under the conditions investigated in this study.

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