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Strength Performance of Nonwoven Coir Geotextiles as an Alternative Material for Slope Stabilization

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Featured Application: This research paper promotes green engineering in slope stabilization. The results of this study can serve as a reference in understanding the strength performance of natural fiber geotextile, specifically coir geotextile, as an alternative material for slope stabilization.

Abstract: Slope stability is one of the crucial factors to consider in every civil engineering project. One widely used method to stabilize slope is the use of polymeric products called geosynthetics. Natural fiber geosynthetics used for geotechnical applications have attracted attention because of their environmental and economic benefits. Coir fibers made into nonwoven geotextiles are utilized in this study as an alternative material for slope stabilization. One drawback of coir fiber geotextiles is their low tensile strength and limited life span due to their susceptibility to environmental factors. This study was conducted to evaluate the effect of mercerization and bleaching treatment on the strength performance of nonwoven coir geotextiles after exposure to conditions simulating biological and chemical degradation. Microscopic images of treated coir geotextiles show the removal of surface impurities that altered the physical components in the fiber. The grab tensile strength results prove that the mercerized coir geotextiles are suitable for field conditions and groundwater exposure. The untreated coir geotextiles showed superior puncture resistance relative to the chemically treated geotextiles. The chemical treatments improved the tensile strength; however, they weakened the puncture resistance of the coir geotextile due to the decrease in thickness. A slope stability simulation conducted using Rocscience Slide2 version 9.017 software proved that coir geotextiles can effectively reinforce slopes, with strength performance almost comparable to that of synthetic geotextiles.

Keywords: slope protection; natural fiber geosynthetics; coir geotextile; mercerization; bleaching treatment; puncture resistance; grab tensile strength; slope stability analysis

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1. Introduction

Slope stability is one of the crucial factors to consider in every civil engineering project. A slight movement of the slope can cause a significant impact on the stability of the structure, leading to catastrophic effects on people, infrastructure, and the environment. Therefore, it is essential to ensure that slope failure is prevented. Numerous developments and understandings of soil mechanical principles concerning soil properties have been formulated to better understand the behavior and stability of slopes [1]. An efficient method for slope failure risk calculation based on element failure probability was developed by Peng et al. [2] that engineers can use as a practical reference for reinforcement design and risk assessment of slopes. Research on the determination of failure load at different slope angles was conducted to formulate an analytical model that can predict the failure load [3]. An assessment tool was developed to determine whether a slope is susceptible to failure,

considering the soil strength parameters and some relevant triggering mechanisms for rapid assessment and to mitigate slope failure [4].

Numerous slope stability methods have been proposed and utilized to alleviate the devastating effects of slope instability. Kazmi et al. [5] stated that geometrical methods, drainage methods, retaining structures, and internal slope reinforcement are some techniques that can be employed as remedial techniques for slopes. Internal slope reinforcement involves the use of rock bolts, anchors, micro piles, soil nailing, and geosynthetics. Geosynthetics are engineering materials used to improve the stability and performance of soil-related civil engineering projects. Synthetic polymers from crude petroleum oils are used to make geosynthetics, although some comprise fiberglass, plant fibers, and bitumen. Geosynthetics is a generic name for planar products made of polymeric materials in contact with soil or rock. Geosynthetic types include geogrids, geomembranes, geotextiles, geonets, geocomposites, geopipes, and geofoams [6]. Geosynthetics are also combined with other materials to produce geocomposites. Combining geosynthetics with materials commonly considered waste, such as waste tires, recycled construction and demolition waste, and plastic bottles, was proven beneficial to the environment and viewed as sustainable [7]. Geosynthetics are widely used in the construction industry due to their numerous applications in engineering. The most common use for geosynthetics is slopes and revetments. Soil masses in sloping areas can be stabilized by applying layers of geotextile or geogrids within a soil mass to provide internal reinforcement, protecting the slope from shear failure [8].

Geotextiles are one of the most common and popular types of geosynthetics used in construction. Geotextiles are manufactured using synthetic or natural fibers; likewise, their design, form, size, and composition differ depending on the field use and application [9]. Additionally, geotextiles are used as tensile reinforcement to stabilize slopes [10]; they are placed perpendicular to a slope section, showing potential sliding surfaces. The shear strength of the slope also increases when geotextiles are used, as they reduce the pore water pressure. Geotextiles made from natural fibers are considered temporary engineering materials due to their biodegradable characteristics. Natural fiber geosynthetics have lower strength than petroleum-based geosynthetics. However, natural fiber geosynthetics have certain benefits, such as recyclability, biodegradability, and availability [11]. Rawal mentioned that natural fibers offer numerous desirable properties, such as high modulus of strength, low breaking extension, and low creep levels during use [12]. Noting that tensile strength is one of the essential properties of woven geotextiles, natural fibers show the highest potential for geotextiles. Synthetic fibers as geotextiles dominate the market, but using natural fibers should not be disregarded, since it offers environmental and economic benefits.

Geotextiles made from natural fibers have attracted the interest of several researchers to enhance their strength performance, bringing it in line with that of synthetic fibers [13–16]. Natural geotextiles are made from a variety of plant fibers. Some examples of plant fibers used to make geotextiles are coconut, jute, water hyacinth, palm, pineapple, and abaca. The main components of natural fibers that determine their physical properties are cellulose, hemicellulose, and lignin [14]. Among these fiber compositions, lignin and cellulose are the two components that determine the service life and durability of the fibers [13]. Coconut fiber contains 7.56% hemicellulose, 42.90% cellulose, and 41.28% lignin [17]. The high polysaccharide content (hemicellulose and cellulose) of natural fibers such as coir makes them highly hydrophilic. The hydrophilicity of fibers negatively affects their adhesion to hydrophobic materials, which can weaken and degrade the resulting composite [18]. Fibers also change their size due to moisture content, which can be avoided by removing moisture from fibers before applying them to any composite product [19].

Previous studies have focused on the application of natural fibers in the creation of natural fiber geotextiles for various purposes. Celis [20] studied the application of pineapple leaf fibers as the main material for geotextiles. The study showed that the utilization of pineapple leaf fibers is viable, since the tests showed that its properties are comparable to those of commercially available abaca geotextile. Furthermore, it was identified in the

study that even though pineapple geotextile is thinner than abaca geotextile, the former can sustain higher tensile stresses than the latter. Decano [21] focused on the utilization of corn stalk geotextile nets for erosion mitigation. The experiments yielded positive results. The corn stalk geotextile nets that were developed were most effective in soil mitigation at 30° and 60° slopes. Candelaria et al. [22] focused on measuring the sediment yield in coconut fiber geotextile (coco mat)-reinforced slopes. The experimentation involved the use of three different coco mat designs. The first was a stitched fiber coco mat, while the other two were woven geotextiles with different mesh sizes. The results of the study showed that coco mats were effective in containing soil erosion, especially when the nonwoven type was used. The nonwoven coco-mat-reinforced slope yielded the least amount of sediment due to runoff.

The advantages and disadvantages of a natural geotextile vary depending on how long it is utilized. A natural geotextile's biodegradability can be seen as an advantage for short-term reinforcements because it helps vegetation, but it can also be seen as a disadvantage in the long run because its life span is only about 2 to 5 years, whereas a synthetic geotextile's life span is over 10 years but can cause environmental harm. This knowledge enables researchers to pinpoint the sources of biodegradability and devise strategies to improve those necessary properties. Although weaknesses are present in natural fibers, they can be alleviated or improved by utilizing different fiber modification techniques through treatments.

In this study, we utilized a nonwoven natural geotextile from coconut fibers called coir geotextile as soil reinforcement for slopes. Coir geotextiles can be either woven or nonwoven. The difference between nonwoven and woven geotextiles is the manner of fabrication of the coir [23]. In a nonwoven geotextile, the fibers are mechanically intertwined by pressing the coconut fibers. On the other hand, in woven geotextiles, the fibers are intertwined with a weaving process. These two types of geotextiles offer different benefits depending on the properties being evaluated. According to Koerner [23] and based on common observations of geotextile performance, nonwoven geotextiles tend to be more permeable, be better separators, and be more flexible than woven geotextiles. In woven geotextiles, the mechanical strength, durability, and effectiveness for erosion control are enhanced compared with nonwoven geotextiles. Despite the enhancement in properties, woven geotextiles tend to be less flexible and offer less filtration than nonwoven geotextiles. In this research, we used nonwoven geotextiles because they are cheaper and faster to produce, making them suitable for limited-life geotextiles made from coir. Moreover, nonwoven geotextiles present biaxial tensile properties [24] ideal for slope reinforcement.

Most previous studies on coir geotextiles have focused on their performance for soil erosion control. This study on coir geotextiles was conducted to observe their performance when utilized as soil reinforcement for slope stabilization. Since coir is made from natural fibers, it is expected to have lower mechanical strength and shortcomings relative to synthetic fibers when it comes to durability due to degradation. Accordingly, we explored the mechanical performance of coir geotextiles under various chemical treatments and exposures to evaluate the viability of the product when used as an alternative material for slope reinforcement.

The present study focused on addressing the weaknesses of coir geotextiles and improving their mechanical properties in slope stability applications by applying two treatment methods: alkaline treatment, i.e., mercerization, and alkaline peroxide treatment, i.e., bleaching. Since geotextiles are commonly placed on slopes or in contact with the ground, they are exposed to numerous factors that affect their strength and durability. In this study, we also aimed to evaluate the strength performance of coir geotextiles when exposed to environmental conditions such as field and groundwater exposure. Additionally, the effectiveness of coir geotextiles in slope stability applications was verified through slope stability analysis simulations using Rocscience-Slide2 software.

The findings of this study can help to identify the most suitable treatment method to improve the strength of coir geotextiles exposed to environmental conditions leading

to biological and chemical degradation. It is expected that this study can contribute to enhancing the performance of coir geotextiles, making them a viable alternative to synthetic geotextiles. Coir fibers are considered waste material in the agricultural sector. Coconut fiber is one of the most famous forms of waste from coconut production [25]. The world produces around 30 million tons of coconuts, mostly coming from tropical countries in South America or Southeast Asia. Coconuts are abundant in the Philippines, and according to Pogosa et al. [26], the Philippines uses 14.69 billion coconuts per year for different purposes; however, when coconut fiber is extracted, around 9 billion husks from these coconuts are left out or burnt in the field. As such, using coir geotextiles to solve geotechnical engineering problems can be regarded as a sustainable solution to address the waste management problem of the agricultural industry, in addition to reducing the cost of slope stabilization methods. The use of natural fiber geotextiles conforms to green concepts in engineering, promoting environmental benefits.

2. Materials and Methods

2.1. Treatment Method

2.1.1. Alkaline Treatment: Mercerization Method

Coir geotextiles were thoroughly washed with clean tap water (Figure 1) and allowed to air dry for two days before being subjected to chemical treatment. The alkaline treatment or mercerization process was performed by soaking the coir geotextiles in five-percent sodium hydroxide for four hours. A four-hour soaking time was chosen because it resulted in the greatest increase in the strength of the natural fiber, as demonstrated in the study by Ray et al. [27]. The coir geotextiles were rinsed with water until the pH level reached seven (7). The samples were air-dried at room temperature for two (2) days.



Figure 1. Washing of coir geotextiles in preparation for treatment.

2.1.2. Alkaline Peroxide Treatment: Bleaching Method

The coir geotextiles were cut into smaller dimensions and soaked in sodium hydroxide solution (NaOH) with a five-percent volume of hydrogen peroxide. The geotextiles were then subjected to heat for 90 min at a temperature of 70 °C to 90 °C [28]. The pH level of the solution was maintained at 11. After treatment, the samples were washed with clean water until a pH level of seven (7) was achieved. The coir geotextiles were then air-dried at room temperature for two days.

2.2. Exposure Method

2.2.1. Exposure to Field Conditions

The coir geotextiles were placed in a container, sandwiched between damp soil with a thickness of approximately 40 mm in order to simulate the effect of field conditions or biological degradation. A schematic diagram of the setup is shown in Figure 2. An ultraviolet (UV) lamp was placed above the container to simulate the effect of the sun in the field. This simulation of the sun, alongside the damp soil, was intended to encourage microorganisms to thrive within the setup. The UV lamp was continuously operated for 16 h to keep the surroundings warm and dry. Untreated, mercerized, and bleached coir geotextiles were subjected to the field exposure condition for 8 weeks.

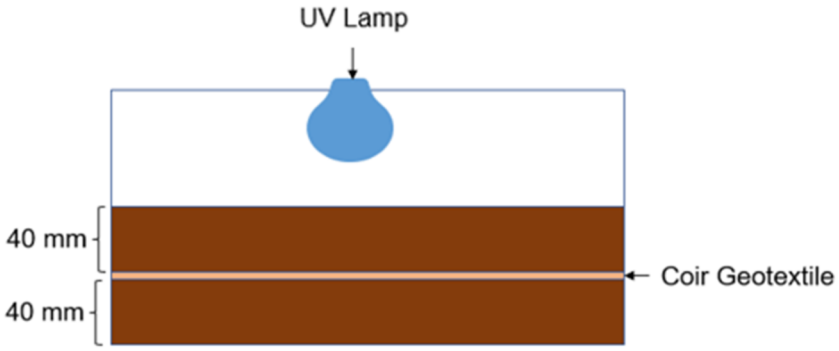


Figure 2. Schematic diagram of exposure to field conditions.

2.2.2. Exposure to Groundwater

The effect of groundwater intrusion was simulated to investigate the impact of chemical degradation on the coir geotextiles, following a similar process as that described in the study by Kalipcilar et al. [29]. An aqueous solution containing one-percent sodium sulfate was prepared to simulate groundwater intrusion. A solution of 5000 g of water to 50 g of sodium sulfate was prepared and poured incrementally into the setup wherein the coir geotextile was embedded within a container of soil. The water level of the solution was maintained higher than the topmost soil layer to keep the soil fully saturated and the samples well-exposed to the solution. This setup was maintained for 8 weeks for the untreated, mercerized, and bleached geotextiles. Figure 3 shows a schematic diagram of exposure to groundwater.

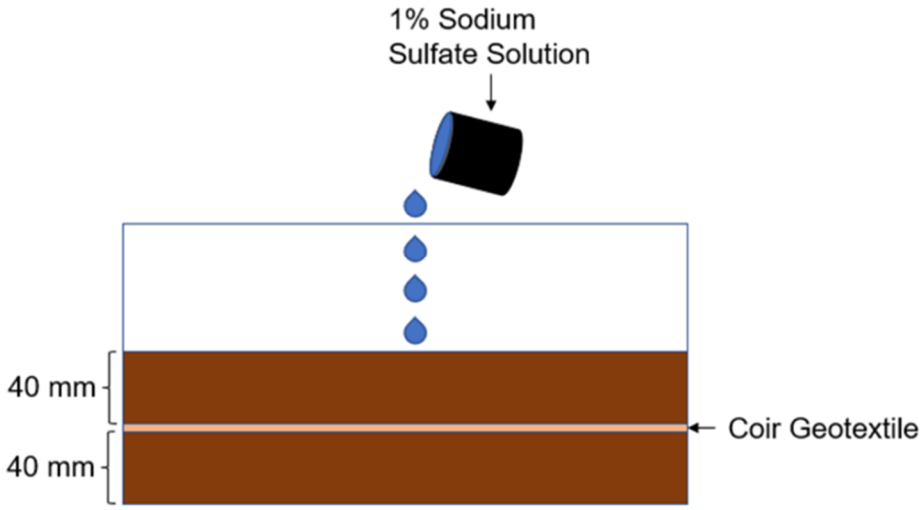
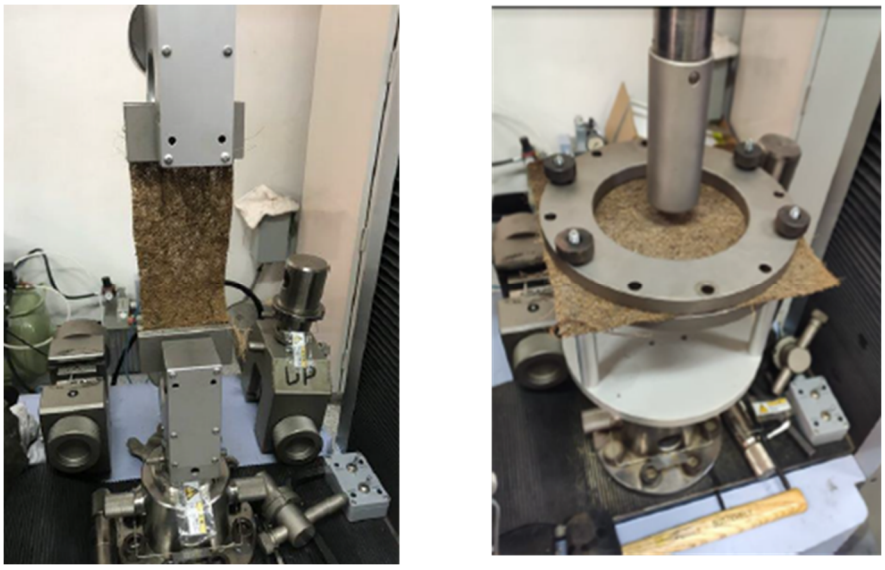


Figure 3. Schematic diagram of exposure to groundwater.

2.3. Tests Methods for the Mechanical Properties of Coir Geotextile

The following tests were used to identify the different mechanical properties of the specimens: the grab-breaking test, following ASTM D4632, and the CBR puncture test, following ASTM D6241. These tests were performed on all untreated and treated geotextiles after subjecting them to exposure conditions. The actual tests are shown in Figure 4.



(**a**) (**b**)

Figure 4. Test methods used to determine the mechanical properties of nonwoven coir geotextiles. (**a**) Grab-breaking test. (**b**) CBR puncture test.

Samples with dimensions of 200 mm by 100 mm were used for the grab-breaking test, while the machine clamps were set to be 75 mm apart. The whole width of the sample was clamped from end to end to obtain more accurate tensile load results. The setup allowed for the incorporation of the varying thicknesses of treated specimens in the analysis of grab-breaking strength.

For the CBR puncture test, the specimens were secured to the machine by inserting four rods (two on each side) that were fastened by a screw cap. The machine speed for the 50 mm diameter flat puncture rod was set to 50 mm/min.

2.4. Slope Stability Simulation Using Rocscience Software Program

The slope stability simulation was conducted using limit equilibrium analysis with Rocscience Slide2 software, a two-dimensional slope stability program that evaluates the factor of safety or failure probabilities within a given slope geometry. The base slope form, external loading, groundwater, and reinforcements can be modeled for different cases in simulations and analyses. The software program analyzes slopes by determining the stability of slip surfaces using various methods. In this study, we considered the Bishop Simplified, GLE/Morgenstern-Price, Janbu Simplified, and Spencer methods of slope stability analysis in the calculation of the factor of safety of the slope [1]. Since the main purpose of the simulation was to compare the performance of synthetic geotextiles to that of coir geotextiles as quantified in terms of the factor safety of the slope, a fictitious slope geometry (as shown in Figure 5) was created and used for the analysis. A slope angle of 45 degrees was considered in the slope geometry, as this was considered a steep slope [30]. The fictitious slope has a base of 80 m and a maximum height of 40 m.

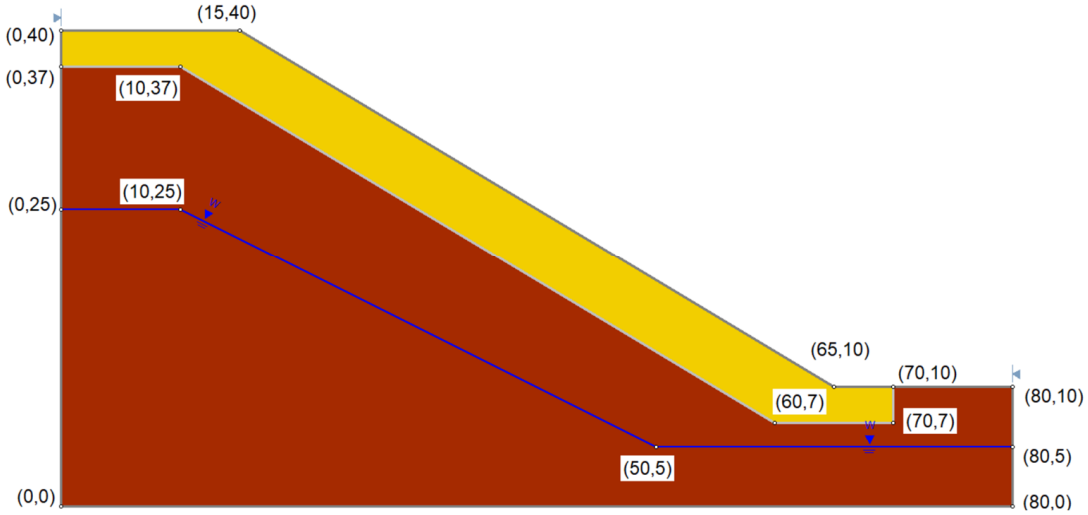


Figure 5. The geometry of the slope used for the slope stability analysis with Rocscience Slide2.

The retained soil of the slope, colored in red, was set to be silty sand, and the backfill or the reinforced soil is colored in orange. The groundwater table is represented by the blue line from the left to right of the slope geometry. The properties of the soil used in the analysis are shown in Table 1. All the soil parameters are assumed values and were set constant in all cases for slope stability simulations.

Table 1. Soil properties used for the slope stability analysis.

Property	Soil	
	Silty Sand	**Backfill**
Unit Weight (kN/m^3)	18	16
Strength Type	Mohr-Coulomb	Mohr-Coulomb
Cohesion (kPa)	22	2
Angle of Friction (°)	35	35

With the grab-breaking strength of each type of geotextile identified, the reduction factors listed in Table 2 were then applied to attain the allowable tensile strength used in the analysis. The thickness of the synthetic geotextile was the same as that of the nonwoven coir geotextiles in order to assess the effect of the different treatments on the nonwoven coir geotextiles in the stability of the slope. All the grab-breaking strength values were multiplied by 3 mm, the original thickness of all samples before treatment so that the strength was expressed as load per unit width. As for the nonwoven synthetic geotextile, a sample with the nearest ultimate tensile strength to that of the nonwoven coir geotextile was considered.

Table 2. Reduction factors applied to geotextiles [23,31].

	Reduction Factor	
	Coir Geotextile	**Synthetic Geotextile**
Creep	2	1.6
Installation	1.2	1.1
Deterioration	1.4	1.1
Factor of Safety	1.5	1.3

A summary of the procedures is presented in Figure 6. The geotextiles were subjected to the treatment processes. One set of geotextiles was subjected to mercerization treatment, another set of geotextiles underwent treatment by bleaching, and one set was not subjected to any treatment, serving as control specimens. After the treatment process, each group of treated geotextiles and the untreated group underwent exposure, namely no exposure, field condition simulation, and groundwater exposure. After eight weeks of exposure, the geotextiles were tested for their mechanical properties by grab-breaking test and CBR puncture test. The data obtained from the tests were used in the simulations of slope stability analysis using Rocscience Slide2 software to assess the performance of coir geotextiles as soil reinforcement in comparison to commercially available geosynthetic geotextiles.

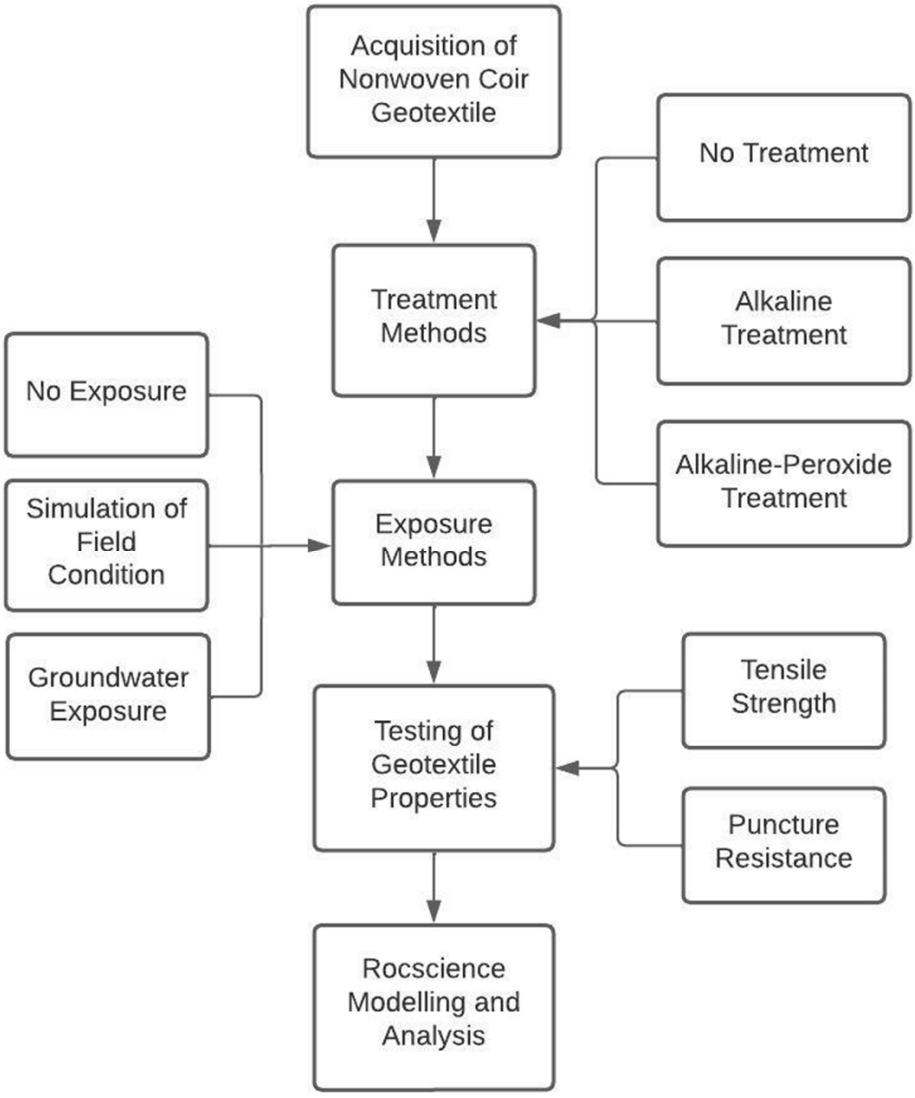


Figure 6. Summary of procedures.

3. Results and Discussion

3.1. Effect of Treatment Processes on the Physical and Microfabric Structure of Nonwoven Coir Geotextiles

Before treatment, the nonwoven coir geotextiles had a dull brown color with three (3) mm thickness. Physical changes, such as the color and thickness of the nonwoven coir geotextiles, were observed after the mercerization and bleaching treatment processes. Figure 7 shows that the mercerized nonwoven coir geotextile has a more vibrant yet lighter color than that of the untreated nonwoven coir geotextile. On the other hand, the bleached nonwoven coir geotextile presents a very light color compared to both the untreated and

the mercerized samples. The hydrogen peroxide in the solution caused the discoloration of the bleached geotextile [32]. When dissociated within an alkaline medium, hydrogen peroxide produces perhydroxyl ions, which make the color of the fibers lighter [28].

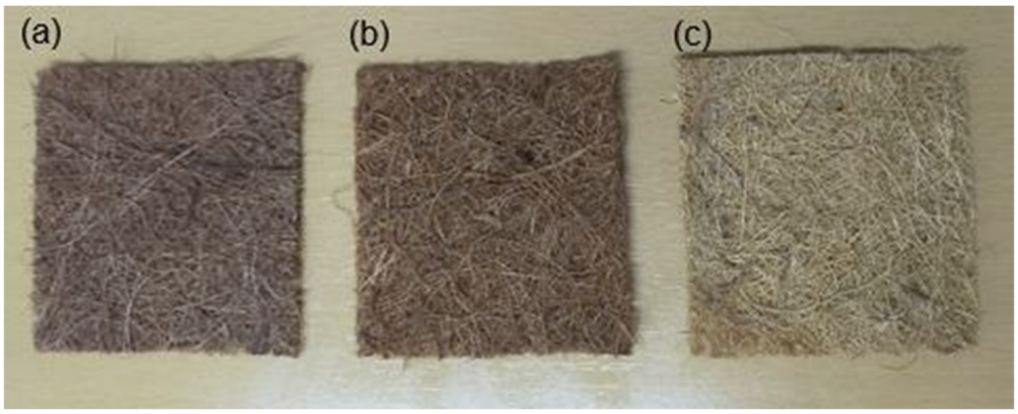


Figure 7. Nonwoven coir geotextiles: (**a**) untreated; (**b**) after mercerization treatment; (**c**) after bleaching treatment.

Figure 8 shows a comparison of the thickness of the coir geotextiles under different treatments. After treatment, the thickness of the coir geotextiles was reduced, with the bleached geotextile being the thinnest. Measurement of thickness using a Vernier caliper showed that the thickness of the untreated, mercerized, and bleached geotextiles was 3 mm, 2 mm, and 1.5 mm, respectively. One of the main causes of the reduction in thickness of the treated geotextiles was the detachment of some fibers during the treatment processes. The treatment processes caused the thinning of the samples owing to the reduction in the hemicellulose and lignin contents of the fibers. During the bleaching process, the hydrogen peroxide removed the lignin and hemicellulose surface impurities of the fibers. Similarly, mercerization makes the surface of fibers rougher and influences the extraction of lignin and hemicellulosic compounds from the fiber.

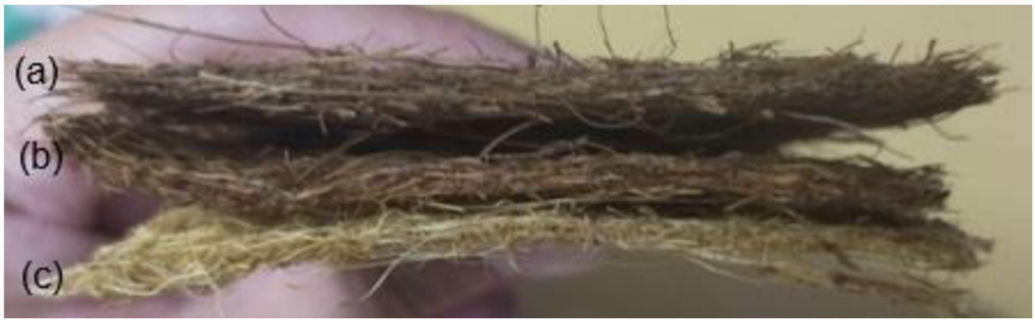
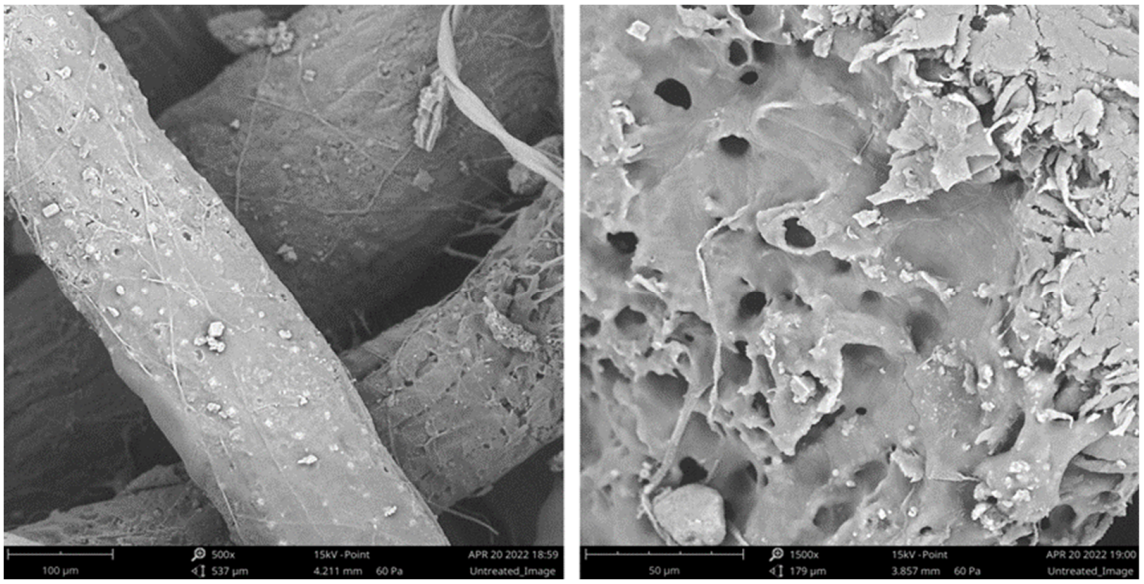


Figure 8. Nonwoven coir geotextiles showing the thickness: (**a**) untreated; (**b**) mercerized; (**c**) bleached.

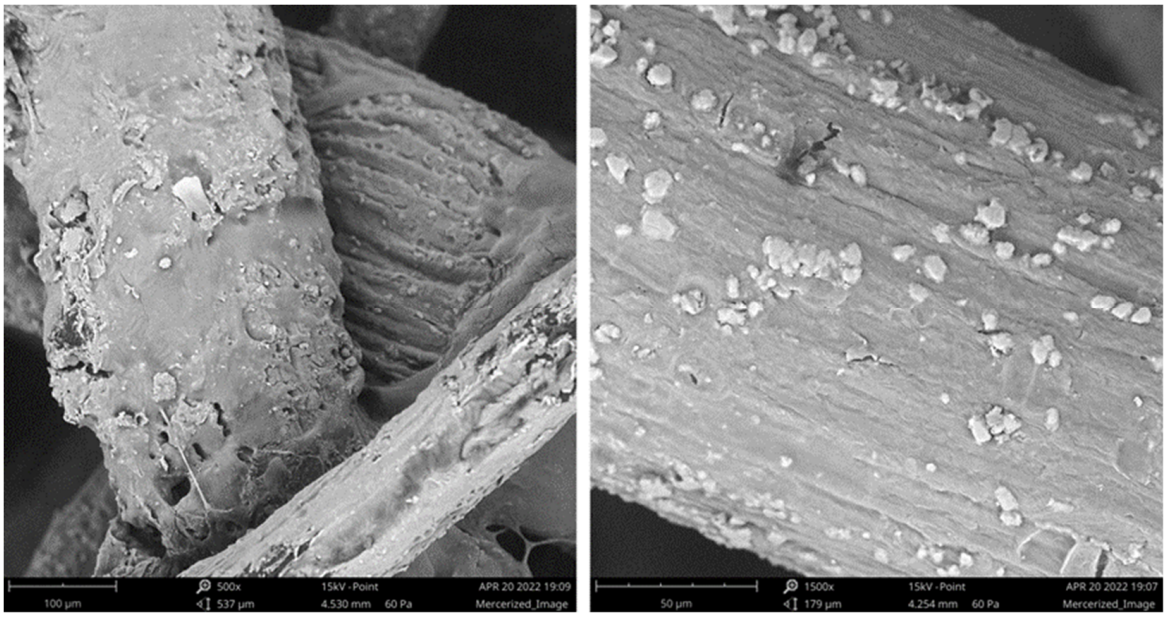
The surface morphology of the nonwoven coir geotextiles was investigated using a scanning electron microscope (SEM). Figure 9 shows the SEM micrographs of untreated nonwoven coir geotextiles with magnifications of 500× and 1500×. These micrographs show that impurities are prevalent across the surfaces of the fiber. Extensive cracking along the surface can also be detected in these micrographs at higher magnification (Figure 9b). Asasutjarit et al. [33] reported similar properties of untreated coir fiber, with the layer of the coir fiber covered with surface impurities.



(**a**) (**b**)

Figure 9. Micrographs of untreated nonwoven coir geotextiles. (**a**) at 500× magnification. (**b**) at 1500× magnification.

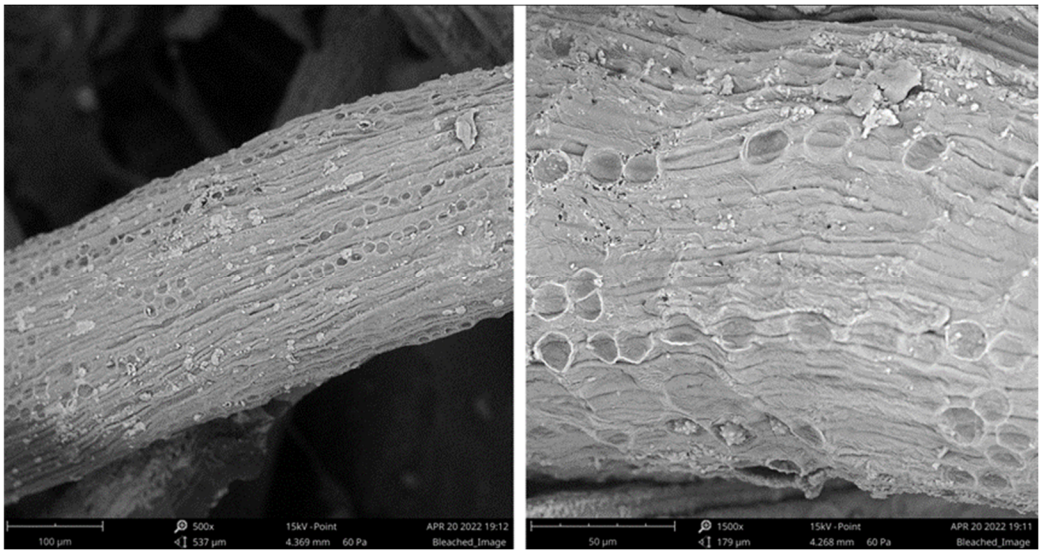
Micrographs of the mercerized nonwoven coir geotextile are shown in Figure 10. After the mercerization treatment, the micrographs revealed small cracks on the surface of the coir fiber and the removal of surface contaminants; however, minimal impurities remained on the surface of the coir fiber. Alkali treatment or mercerization treatment removes the binding materials from the fiber bundles. The alkaline solution (NaOH) dissolved the surface lignin, resulting in a twofold impact [34]. In a study by Rout et al. [35], residues of the impurities in the form of globular protrusions, which are fatty deposits known as tyloses, remained on the fiber surface after the removal of the surface contaminants through alkali treatment.



(**a**) (**b**)

Figure 10. Micrographs of mercerized nonwoven coir geotextiles. (**a**) at 500× magnification. (**b**) at 1500× magnification.

Micrographs of the bleached-treated nonwoven coir geotextile are shown in Figure 11. Similar to the mercerized specimen, the impurities on the surface of the coir fiber were reduced. However, the bleached sample shows a smoother and clean fiber surface compared to the mercerized and untreated specimens. Moreover, after the bleaching treatment, the surface of the coir fiber contained a large number of regularly placed pores or holes. In a study by Carvalho et al. [36], the fatty deposits or impurities that were buried inside the surfaces of the untreated fiber were eliminated, resulting in empty spaces on the coir fiber surface, producing a rough surface with globular markings.



(**a**) (**b**)

Figure 11. Micrographs of bleached nonwoven coir geotextiles. (**a**) at 500× magnification. (**b**) at 1500× magnification.

Energy-dispersive X-ray (EDX) results are summarized in Table 3, indicating that the elemental composition of a nonwoven coir geotextile is carbon (C), oxygen (O), silicon (Si), and calcium (Ca). Sgriccia et al. [37] stated that the oxygen-to-carbon ratio (O/C) of cellulose, hemicellulose, and pectin equals 0.83, whereas lignin has an oxygen-to-carbon ratio of 0.35. Moreover, Brigida et al. [38] studied the effect of chemical treatments on the properties of green coconut fiber; the O/C of the treated fibers in the study resulted in a value less than the O/C of cellulose, hemicellulose, and pectin reported in the research by Sgriccia et al. [37]. They concluded that the surface of the green coconut fiber contains a significant proportion of waxes. Likewise, an increase in the value of O/C of the treated fibers indicates that the chemical treatments reduced the proportion of waxes on the surface.

Table 3. Elemental weight percentage of the untreated and treated nonwoven coir geotextiles.

Element	Weight Percentage of Composition (%)		
	Untreated	Mercerized	Bleached
C	54.49	22.32	30.47
O	34.51	36.03	53.19
Si	1.33	0.73	0.43
Ca	0.5	5.72	4.32
O/C ratio	0.63	1.61	1.75

The value of O/C, as shown in Table 3 for untreated, mercerized, and bleached samples, is equal to 0.63, 1.61, and 1.75, respectively. The O/C value of the untreated sample is less

than 0.83, and the O/C value for hemicellulose, cellulose, and pectin, indicates that there are significant lignin and wax contents on the surface of the coir fiber. Furthermore, the O/C values for the treated samples are higher than the 0.83 O/C value reported in the study by Sgriccia et al. [37]. This signifies that the chemical treatments (mercerization and bleaching) are effective in reducing waxes and impurities on the fiber surface.

3.2. Effect of Treatment Processes on the Grab-Breaking Strength of Nonwoven Coir Geotextiles

The average grab-breaking strength of the treated and untreated coir geotextiles under different exposure conditions is shown in Table 4 and presented in Figure 12. In an unexposed condition, the bleached specimen showed the most significant improvement, with an increase of 41.77% in tensile strength, followed by the mercerized sample, with an increase of 9.97% in comparison to the untreated samples. These results are in agreement with the findings of Pathirana [39] and Then et al. [32], who showed that subjecting natural fibers to mercerization and bleaching benefits the mechanical properties of coir and, therefore, those of the resulting geotextile. The mercerization of natural fibers assists in extracting lignin and hemicellulosic compounds [40], which leads to improved mechanical properties of the fibers. Similar to mercerization, bleaching reduces the hemicellulose and lignin in natural fibers, resulting in an increase in fiber/matrix adhesion. The process eliminates surface impurities of the fibers, as shown in the SEM micrographs (Figure 11), in which the bleached coir geotextile looks smoother compared to the mercerized coir geotextile. Bleached coir geotextiles have a higher tensile strength than mercerized coir geotextiles, as a study by Zhang et al. [41] proved that lower lignin contents result in higher tensile strength. In a controlled environment without exposure, the improvements brought about by the treatment of nonwoven coir geotextiles are notable, especially the bleaching treatment.

Table 4. Average Grab-breaking strength of untreated and treated nonwoven coir geotextiles.

Treatment	Grab-Breaking Strength (KPa)		
	Exposure Conditions		
	Without Exposure	Exposure to Field Condition	Exposure to Groundwater
Untreated	994.17	1451.11	1157.78
Mercerized	1093.33	1769.58	2272.08
Bleached	1409.44	1555.00	1612.22

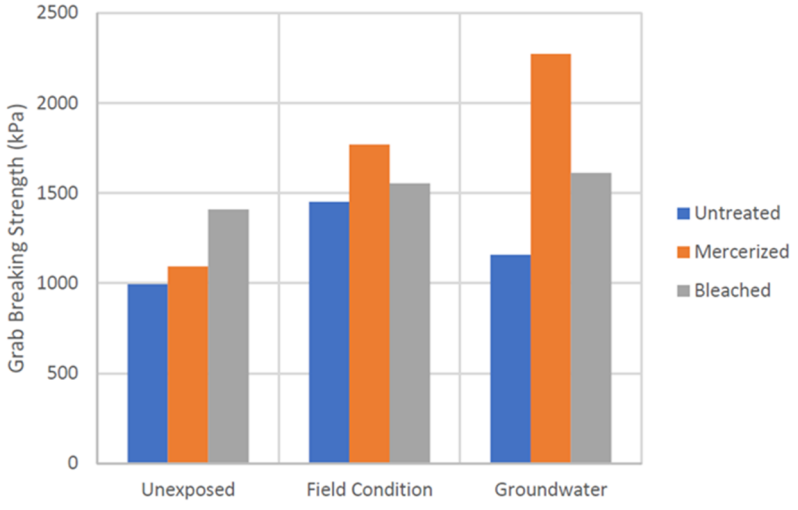


Figure 12. Average grab-breaking strength of treated and untreated coir geotextiles under different exposure conditions.

The grab-breaking strength of the geotextiles subjected to field conditions showed a different trend than the unexposed scenario. In this condition, the mercerized specimen showed the most significant improvement in tensile strength, with an increase of 21.94%, while the bleached sample exhibited an increase of 7.15% in comparison to the untreated sample. As mentioned with respect to the unexposed condition, the bleached coir geotextile is expected to provide the most considerable tensile strength due to its lower lignin content. Still, the mercerized coir geotextile showed the highest tensile strength for the field condition simulation. Lower lignin contents mean that the geotextile can produce greater tensile strength. However, lower lignin contents also mean that the cell walls of the fibers become less stiff, which allows more degradation to occur [42]. With less lignin content in the bleached specimens, they became prone to a faster degradation rate, allowing the mercerized samples to hold out longer when placed under field conditions.

According to the grab-breaking strength of the coir geotextiles under groundwater exposure, the mercerized specimen exhibited the greatest improvement in tensile strength, with an increase of 96.24%, followed by the bleached sample, with an increase of 39.25% in comparison with the untreated specimen. As stated, fibers with less lignin content are expected to have higher tensile strength but less resistance against degradation. Therefore, the amount of lignin in the geotextile contributes to the greater tensile strength of the mercerized specimen relative to the bleached specimen.

3.3. Effect of Treatment Processes on CBR Puncture Resistance of Nonwoven Coir Geotextile Components

The average values of the ultimate CBR puncture resistance of nonwoven geotextiles subjected to different exposure conditions are shown in Table 5 and Figure 13. The strongest geotextile in terms of puncture resistance is the untreated nonwoven coir geotextile. In contrast, the mercerized and bleached geotextiles have less puncture resistance, decreasing by 42% and 52.86%, respectively. The trend shows that the CBR puncture resistance decreases as the nonwoven geotextile becomes thinner. This result is also supported by Askari et al., whose work shows that thinner, nonwoven polypropylene geotextiles also have less CBR puncture resistance [43].

Table 5. Average CBR puncture resistance of untreated and treated nonwoven coir geotextiles.

Treatment	CBR Puncture Load (N)		
	Exposure Conditions		
	Without Exposure	Exposure to Field Condition	Exposure to Groundwater
Untreated	1064.42	849.25	1144.50
Mercerized	617.33	764.25	704.00
Bleached	501.75	446.67	817.92

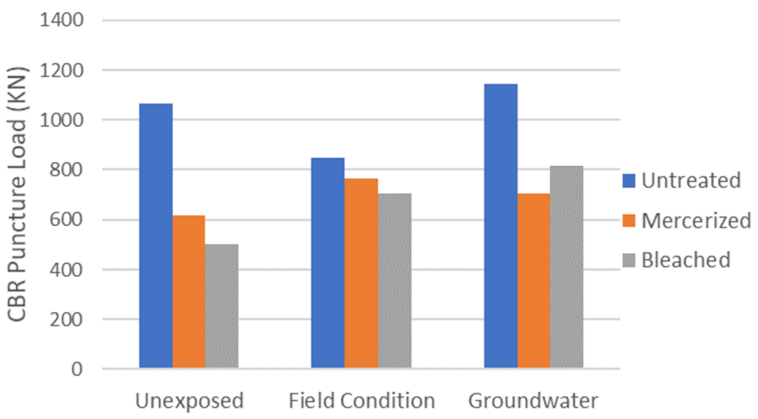


Figure 13. Average CBR puncture resistance of treated and untreated coir geotextiles under different exposure conditions.

Similar to the CBR puncture resistance trend of the geotextiles under unexposed conditions, the untreated nonwoven geotextile exhibited the strongest CBR puncture resistance under field condition simulation. The mercerized and bleached specimens also showed a weaker CBR puncture resistance, with decreases of 10.01% and 47.4%, respectively. Similarly, the trend also shows that increased thickness results in increased CBR puncture resistance.

Like the values of CBR puncture resistance reported for unexposed and field-exposed specimens, a similar trend was observed in that the untreated nonwoven coir geotextile had the highest value as compared to the mercerized and bleached coir geotextiles. As mentioned earlier, this was due to the treatments causing a reduction in thickness, which, in turn, caused a reduction in strength. This reduction in thickness was caused by the removal of the hemicellulose and lignin contents of the fibers making up the nonwoven coir geotextiles as a result of the treatments. The treatment processes also caused fibers to disintegrate.

3.4. Slope Application of Nonwoven Coir Geotextile Simulated Using Rocscience—Slide2 Program

The Slide2 program of Rocscience was used in this study to evaluate the performance of geotextiles used as soil reinforcement to stabilize slopes. The performance of the geotextiles was assessed according to the resulting safety factor when the material type and on-center spacing were altered. The primary objective of the analysis was to evaluate the performance of the coir geotextiles compared to commercially available synthetic geotextiles. The application of the Slide2 software program enabled the determination of whether coir geotextiles are a viable alternative to synthetic geotextiles.

The slope geometry and soil properties used in the simulation are stated in Section 2.4. The analysis was first performed for the slope without reinforcement, and an initial factor of safety of 1.307 was attained with Bishop's simplified procedure. This factor of safety can be said to be stable for a slope but not for an embankment; therefore, additional support for the ground is required to achieve a factor of safety of 1.5, which was deemed safe for dams [44]. A target value of 1.5 for the safety factor was considered so that the designed slope reaches a satisfactory safety value for most sloped structures.

To properly assess the performance of the coir geotextiles, two types of analysis were applied. The first set of simulations was performed under the same conditions as the commercially available synthetic geotextiles. The constant value of spacing was obtained through a repetitive simulation using different spacing values until a factor of safety of 1.5 was obtained for the slope reinforced with synthetic geotextile. The spacing obtained from repetitive simulations to achieve a factor of safety of 1.5 for the slope reinforced with synthetic geotextile was set as constant and used throughout the simulations for all nonwoven coir geotextile samples. With a constant spacing applied in the simulations, the factor of safety values of each coir geotextile sample was assessed.

Table 6 shows the resulting factor of safety of the coir geotextiles when using the spacing obtained from the synthetic geotextile to achieve a 1.5 factor of safety. The lengths of all the geotextiles used were set at a constant value of ten (10) meters. The nonwoven coir geotextiles were set at a constant thickness of three (3) millimeters. The allowable tensile strength was obtained from the grab-breaking strength test after the application of reduction factors. The thickness of the synthetic geotextile was 0.9 mm which has a strength nearest to the strength of the natural geotextile As demonstrated by the results, the mercerized coir geotextile subjected to groundwater exposure had the highest factor of safety. In comparing the safety factor of the strongest coir geotextile to that of the synthetic geotextile, it can be observed that with the same spacing, the safety factor showed a decrease of around 4.53% but still showed an improvement as compared to the unreinforced slope. This indicates that with a proper treatment method, the strength of coir geotextiles can increase and improve the stability of slopes with an effect almost comparable with that of synthetic geotextiles.

Table 6. Strength performance of coir geotextiles in terms of factor of safety when used as slope reinforcement.

Treatment–Exposure	Allowable Tensile Strength (KN/m)	Spacing (m)	Factor of Safety Determined by Bishop's Method
Untreated–Unexposed	0.58	0.300	1.362
Mercerized–Unexposed	0.64	0.300	1.367
Bleached–Unexposed	0.83	0.300	1.384
Untreated–Field Condition	0.85	0.300	1.386
Mercerized–Field Condition	1.04	0.300	1.402
Bleached–Field Condition	0.92	0.300	1.392
Untreated–Groundwater	0.68	0.300	1.371
Mercerized–Groundwater	1.34	0.300	1.432
Bleached–Groundwater	0.95	0.300	1.394
Synthetic Geotextile	1.98	0.300	1.500
No Reinforcement	---	---	1.307

Various analytical methods to calculate the safety factor result in different values. Figure 14 shows the trends of the factor of safety determined according to Bishop's simplified method, Janbu's simplified method, Spencer's method, and the Morgenstern–Price method. In all methods of calculating the factor of safety, a similar trend can be observed in all types of geotextiles: the strongest coir geotextile is the mercerized coir geotextile subjected to groundwater exposure.

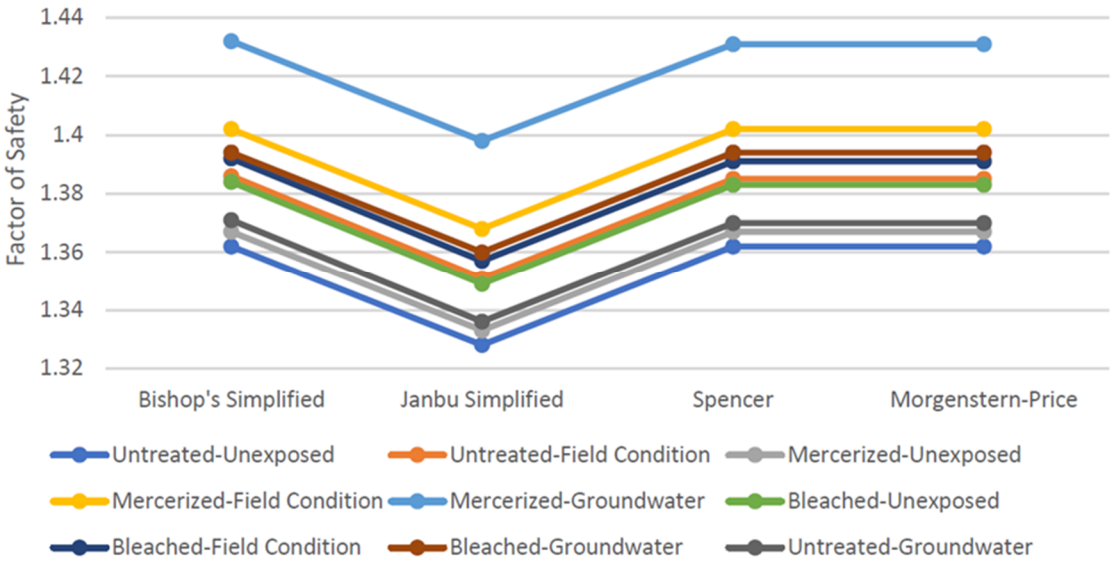


Figure 14. The factor of safety of coir geotextiles using various limit equilibrium methods.

The second set of simulations was performed to achieve a targeted safety factor by varying the spacing of the coir geotextiles until a safety factor of 1.5 was achieved. Table 7 presents the spacing and the number of geotextiles required for each specimen to achieve the targeted safety factor. The mercerized coir geotextile subjected to groundwater exposure showed the least required spacing fewest geotextiles to achieve a 1.5 factor of safety. Relative to the other coir geotextiles, the mercerized specimen exposed to groundwater only required 56 more layers and 0.102 m less spacing than the synthetic geotextile. This analysis shows

that some coir geotextiles can have strength comparable to that of the synthetic geotextile used in the model, especially for short-term applications.

Table 7. Summary of the requirements of coir geotextiles for slope reinforcement with a target factor of safety of 1.5.

Treatment–Exposure	Allowable Tensile Strength (KN/m)	Spacing (m)	Number of Geotextiles
Untreated–Unexposed	0.58	0.084	392
Mercerized–Unexposed	0.64	0.095	347
Bleached–Unexposed	0.83	0.120	275
Untreated–Field Condition	0.85	0.124	266
Mercerized–Field Condition	1.04	0.150	220
Bleached–Field Condition	0.92	0.133	248
Untreated–Groundwater	0.68	0.099	333
Mercerized–Groundwater	1.34	0.198	166
Bleached–Groundwater	0.95	0.140	235
Synthetic Geotextile	1.98	0.300	110
No Reinforcement	---	---	---

4. Conclusions

Mercerization and bleaching treatments applied to nonwoven coir geotextiles altered their physical properties. Mercerization made the color of the nonwoven coir geotextile lighter and more vibrant while bleaching made the color much lighter. As seen in the SEM micrographs, both treatments reduced the thickness of the coir geotextiles, since the impurities and some biological components such as surface wax, lignin, and hemicellulose were removed. On the other hand, the removal of such components caused an increase in their tensile strength.

Under the exposed conditions, mercerized coir geotextiles are better than bleached coir geotextiles because they are more resistant to the effects of degradation. Bleached coir geotextiles are better for unexposed conditions, but these conditions are unlikely to occur, as geotextiles are commonly placed in the field and can be exposed to numerous factors.

The grab-breaking test revealed that the treatments effectively increased the tensile strength of the coir geotextiles. Results from the unexposed condition show that the bleaching treatment resulted in the greatest tensile strength, followed by mercerization, in comparison to the untreated samples. Exposure to field and groundwater conditions also increased the grab-breaking strength of nonwoven coir geotextiles. For all treatments, the exposed condition showed a higher value of grab-breaking strength than the unexposed condition.

The CBR puncture test provided a different result from the grab-breaking test. For the unexposed, field condition, and groundwater exposure scenarios, the untreated specimens showed the most significant puncture resistance as compared to the treated samples. Removing surface impurities and biological components caused by the treatments led to a reduction in thickness, which decreased the puncture resistance of the nonwoven coir geotextiles.

The nonwoven coir geotextiles were incorporated into a slope stability model using Rockscience Slide2 version 9.017 software and were shown to improve the stability of the slopes. The amount of spacing between the geotextiles is an essential factor when it comes to soil reinforcement. With the same spacing conditions as the synthetic geotextile, all of the coir geotextiles used for reinforcement have a safety factor slightly lower than that obtained for the synthetic geotextile but still show an improvement as compared to the unreinforced slope. Nonwoven coir geotextiles have a comparable strength with that of some synthetic

geotextiles such as nonwoven geotextiles. Under short-term loading conditions, it can be concluded that coir geotextiles can be effective as slope reinforcement.

We recommend future studies of the real-life application of coir geotextiles as soil reinforcement for slopes to determine their onsite performance. Future studies can include the evaluation of the most well-suited construction methods when using coir geotextiles. To assess the viability of coir geotextiles as an alternative to geosynthetic materials in terms of economic aspects, a cost analysis can be conducted in comparison with commercially available geosynthetic geotextiles. The treatment processes and exposure methods used in this study can be adopted for woven coir geotextiles, and the results can be compared with those of nonwoven geotextiles.

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