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Influence of coconut fiber on the microstructural, mechanical and hydraulic behavior of unsaturated compacted soil

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Article

Keywords
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Compacted soil
Mercury intrusion porosimetry
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Tensile strength

Abstract

This study aimed to evaluate the influence of the addition of coconut (coir) fibers on the microstructural, hydraulic and mechanical behavior of an unsaturated compacted soil. Specimens were molded and compacted, forming composites with 0%, 0.1%, 0.5% and 1% fiber in relation to their dry mass. The characterization of pores from the soil and fiber soil mixtures was performed by the Mercury Intrusion Porosimetry tests. Suction values were obtained through the filter paper method and soil water retention curves were adjusted with the Durner model due to the bimodal behavior. Tensile strength values were obtained from the indirect tensile strength test (Brazilian tensile test) for specimens with different suction values. It was found that the increase in fiber content in the material lead to a non-linear increase in macropores, which affected both the hydraulic and mechanical behavior of the soil. Furthermore, the shape of the soil water retention curve was preserved, but there were changes in the values of first and second air entry and residual suction. The tensile strength was negatively influenced, reaching a reduction of about 30% in the situation with higher fiber content. However, for higher levels, the behavior of the soil changed from brittle to ductile, increasing the supported deformations.

1. Introduction

During the development of engineering projects, a typical situation is to come across soils that, in the zone of interest, do not have adequate behavior. The most traditional way to solve this problem is to reallocate the soil, removing what is considered inadequate and replacing it with one with better properties, brought from elsewhere. This procedure, however, can lead to a substantial additional cost.

To ensure that the soil has ideal conditions and guarantees its proper performance, another frequently used solution is to implement procedures for improvements or stabilization by modifying its mechanical properties using chemical substances and/or physical mechanisms.

The addition of fibers to the soil is a type of stabilization approach. Studies such as that by Toledo Filho et al. (1999) demonstrates that fibers can change the mechanical behavior of the compound material, increasing its tensile strength and altering its permeability and ductility.

Savastano Júnior & Pimentel (2000) identified higher energy absorption by the fiber-reinforced soil, which remained with its pieces banded together even after rupture, and Motta (2018) studied the shear strength of soil reinforced with natural fibers, including coconut fiber (coir fiber). This author verified gains in tension after the peak of resistance, indicating that the material tolerated greater deformations. Cabala (2007) obtained similar results. Consoli et al. (2005) reported a constant increase in strength with increasing axial deformation, characterizing an elastoplastic stiffening behavior.

When comparing natural and synthetic fibers, it is acknowledged that the first option is less environmentally harmful, since its origin is not linked to the use of non-renewable resources. However, the behavior of natural fibers in fiber-reinforced soil is influenced not only by physical-mechanical properties but also by biochemical properties (Gowthaman et al., 2018). Among these natural fibers, coconut fibers are an example of natural waste that have several promising applications but are usually disposed of in landfills.

Brazil's coconut production is close to 1.6 billion units per year (Brainer, 2021). Each one of them generates about one kilogram of natural waste, taking 10 to 15 years to biodegrade and also contributing to the further proliferation of tropical diseases. In areas that grow coconut trees, most of which are coastal, this type of byproduct alone can account for almost 70% of all solid waste deposited in landfills.

Due to its wide availability, coconut fiber has been studied as an element to constitute composite materials. According to Gowthaman et al. (2018), limited researchers have focused on the application of coir fibers in the field

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of Geotechnical Engineering because this material, when exposed to a chemical environment, undergoes significant strength reduction. Lekha et al. (2015) and Yadav & Tiwari (2016) reported that the behavior of reinforced soil depends not only on the optimum quantity of coconut fiber but also on the quality of treated coconut fiber.

Anggraini (2016) and Gowthaman et al. (2018) presented a review on the use of natural fibers, including coconut fibers, where most of the reported studies is related to coir fiber with another additive in the fiber-reinforced soil system. By adding a mixture of these fibers with cement to soil, Raj et al. (2017) achieved improvements in the residual strength of the compound. Danso & Manu (2020) remarked that soil-cement mortar stabilized with lime and coconut fibers have better resistance against water absorption and good resistance against erosion. In addition, Oliveira Junior et al. (2018) and Gusmão & Jucá (2021) also perceived enhancement of shear strength in the new material.

Since Brazil is a tropical country, the occurrence of unsaturated residual soils is usual, and its properties are more complex than those specified in classic Soil Mechanics.

According to Fredlund & Rahardjo (1993), unsaturated soil consists of four phases: solid, composed of soil grains; liquid, formed by water and possible mineral salts dissolved in it; gaseous, composed of air; and the air-water interface, also called the contractile membrane.

In unsaturated soils, the difference between the pressure exerted by air and that exerted by water on the contractile membrane corresponds to the matric suction (Fredlund & Rahardjo, 1993). Lu & Likos (2004) defined that suction consists of quantifying the thermodynamic potential of water in the soil pores in relation to the free water potential.

Oliveira (2004) mentions that with the decrease in water content and consequent increase in matric suction, the soil's strength increases. This happens because seasonality causes variations of soil moisture, thus interfering with suction (Fredlund & Rahardjo,1993) and superficial tension.

Unfortunately, usually, the variation of suction is not considered in geotechnical engineering projects, which tend to focus only on the past situation of the soil (Carvalho & Gitirana Junior, 2021). That practice can lead to incorrect decisions regarding resistance parameters. Fredlund (2021) asserts that considering in-situ suctions as temporary is a misconception that should be disregarded.

Considering the aforementioned circumstances and combining the necessity to make use of more sustainable resources and the pertinence of understanding the behavior of unsaturated soils, this study seeks to test the feasibility of incorporating coconut fibers in artificial slopes. For this purpose, the analysis was made based on the evaluation of the effect of additions of different amounts of fiber on the microstructural, hydraulic and mechanical behavior of an unsaturated compacted soil. The assessment was made based on the results of mercury porosimetry tests, soil water retention curves and tensile strength curves (Brazilian tensile tests).

2. Materials and methods

2.1 Materials

The soil used in the tests is characterized by a silty texture and high plasticity, as observed in Table 1.

Fiber produced by a company of gardening artifacts was employed. Performing the cut in a standardized manner and separating the fiber wefts would lead to an unapproachable procedure in means of reproducibility in actual field applications. Thus, it was opted to use fiber cuts with undefined sizes and only restraint that the fragments were smaller than the diameter of the specimen (50 mm). According to Anggraini (2016) the effective length ranged is about 10-50 mm.

The method proposed by Maher & Gray (1990), which reports that random insertion of the fibers does not create specific planes of weakness, was applied in this study.

The evaluated fiber additions were: 0%: corresponds to the soil in its natural composition (without fibers); 0.1% in relation to the dry mass of the soil: amount chosen in order to verify whether a small addition of fiber would already have an effect on soil properties; 1%: the literature (Festugato, 2008; Sachetti, 2012; Anggraini, 2016) indicates that values above this lead to mechanical limitations related to the homogenization with soil and water, which can interfere with the results of the experiments; 0.5%: intermediate value between the lowest and highest contents.

2.2 Preparation of the fiber soil mixture and molding of the specimens

The soil, acquired in the form of deformed samples, was crumbled and air-dried. The fiber was manually untangled, weighed, cut and hand mixed with the soil. There was an adversity in obtaining a homogeneous mixture: the fiber tended to form agglomerations that had to be undone by untangling the threads (except the 0.1% mixture).

Table 1. Physical characterization results and average index properties.

Gravel (%)	*Sand (%)*	*Silt (%)*	*Clay (%)*	*LL (%)*	*PL (%)*	*PI (%)*	*USCS*	*Gs*
2.1	40.7	44.8	12.4	58	45	12	MH	2.74

Number of replicates: 3.

Legend: see List of Symbols.

The air-dried soil was passed through sieve number 4 and mixed with distilled water to the target moisture content. The soil was then sealed in bags and stored for at least 1 day to allow moisture equalization. The samples were compacted with the maximum specific dry mass for the Standard Proctor effort of 14.4 kN/m^3, corresponding to an optimum water content of 16%.

For molding the specimens, cylindrical PVC ring-shaped molds with 20 mm of height and 50mm of diameter were used. The fiber soil system was compressed into three layers using a plain compaction apparatus that applied pressure simulating trampling over the entire cross-sectional area of the specimen. In order to evaluate the effect of fiber insertion on the microstructural, hydraulic and mechanical characteristics of the fiber soil composites, the fibers were inserted into the soil after moisture equalization and mixed manually before compaction. It is noteworthy that the fibers replaced part of the dry soil mass, maintaining the same compaction parameters, in terms of specific dry mass and gravimetric water content.

For each fiber addition analyzed (0%; 0.1%; 0.5% and 1%), at least 10 samples were molded with the mentioned characteristics, with a variation of 14.4 ± 0.3 kN/m^3 for the specific dry mass and 16 ± 0.9% for the gravimetric water content.

The hydraulic and mechanical behaviors were evaluated using the soil water retention curve and the tensile strength variation curve as a function of matric suction. For this purpose, the specimens were subjected to a drying path, in which they underwent a capillary saturation process for 3 days and then placed to air dry so that each sample reached a certain water content value (between 2% and 34%).

2.3 Mercury porosimetry test

The characterization of pores from the soil and fiber soil mixtures was performed by Mercury Intrusion Porosimetry (MIP) tests. This technique allows discerning the different pore diameters and their distribution in the analyzed material. For this purpose, the Poresizer 9320 equipment from Micromeritics Instrument Corporation was used, capable of inspecting pores up to 6×10^{-6} mm in diameter at an applied pressure of 212 MPa.

According to Romero & Simms (2008), in the MIP technique an absolute pressure P is applied to a non-wetting liquid (mercury) in order to enter the empty pores. Assuming the pores in soil to be cylindrical, the relationship between the intrusion pressure P and the pore radius r is $P = -2\,\gamma \cos \Theta / r$, where γ is the mercury surface tension (0.480 N/m at 20 °C) and Θ is the contact angle (140°) (Wang et al., 2020).

To carry through this experiment, as shown in Figure 1, a specimen from each mixture investigated was selected. They were cut to ensure the size specifications to fit the equipment – approximately 16 mm in diameter and 25 mm in height. For each pressure application stage, the volume of mercury injected into the pores of the sample was determined.

As porosimetry is based on capillarity laws that govern the intrusion of a fluid, it is possible to correlate the MIP results with the soil water retention curve (SWRC) results (Décourt et al., 2022). The phenomenon of water desorption that occurs in the drying SWRC curve can be associated with the expulsion of air from the pores by mercury injection. In this context, the results obtained by MIP tests were compared to the SWRC tests, for the soil and the fiber soil samples (Aung et al., 2001; Sun & Cui, 2020; Décourt et al., 2022).

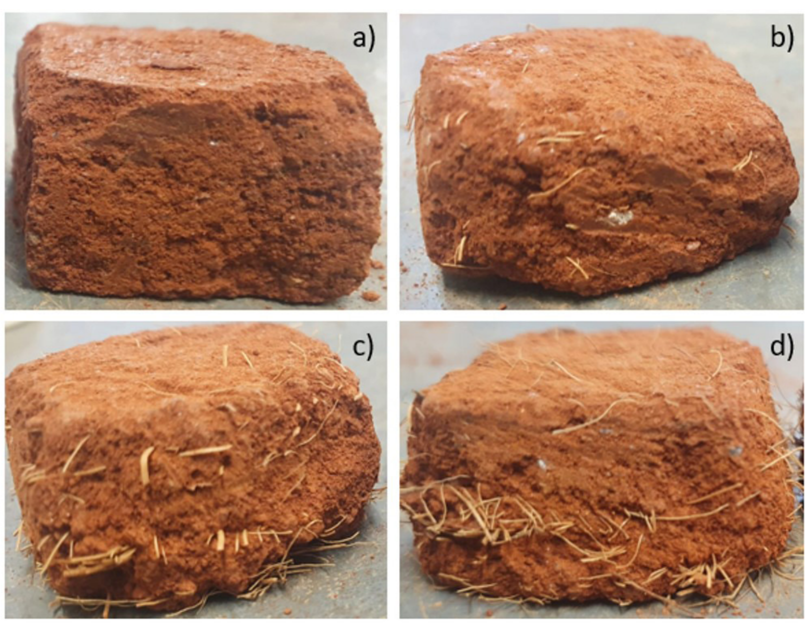

Figure 1. MIP tests samples. (a) 0% fiber; (b) 0,1% fiber; (c) 0,5% fiber; (d) 1% fiber.

2.4 Soil water retention curve

Following the specifications from ASTM (2017), a Whatman™ 42 filter paper was put in direct contact with the analyzed soils both at the top and bottom of the specimens, which were then wrapped and placed inside a thermal box. They were then kept in this arrangement for at least 7 days in order to allow enough time to transfer moisture from the fiber soil to the filter paper.

After this period, the moisture content of the filter paper was determined (Marinho & Oliveira, 2006). Each paper disc was individually inserted into a weighing scale (Sartorius Analytical Balance BL 210 S, with the readability of 0.0001g and weighing capacity of 210g), and its mass variation was registered for predetermined times (10; 20; 30; 40; 50; 60; 90 and 120 s). With these values, the mass at time zero for both wet and dry conditions was estimated through exponential correlation.

As the studied soil presents a bimodal behavior (referring to the entrance of air in the macro and micropores), the obtained curves were adjusted by the method of Durner (1994), as shown in Equation 1, based on the simple model of van Genuchten (1980). The necessary coefficients for the application of the model were obtained using the SWRC Fit software and the values of the first and second air entry and the first and second residual suction were obtained through graphs.

$$S_e = \sum_{i}^{k} w_i \left[\frac{1}{1+\left(\alpha_i h\right)^{n_i}} \right]^{m_i} \tag{1}$$

Where k is the number of subsystems, w_i are weighting factors with $0 < w_i < 1$ and $\Sigma w_i = 1$, h is the pressure head and α_i, m_i, n_i are water retention parameters.

2.5 Indirect tensile strength test – Brazilian tensile test

After determining the soil suction by the filter paper method, all samples underwent the splitting tensile strength test, standardized by ASTM (2016). To the accomplishment of this analysis, a load at a speed of 0.9 mm.min^{-1} was applied. For the samples without fiber and with the lowest addition (0.1%), the test was completed when the load ring indicated a constant or maximum reached value, which was monitored alongside the tracking of the tensile crack. In samples with higher fiber content (0.5% and 1%), the cracks were not as noticeable and the values in the load ring did not stabilize. Thus, an interval of 11 minutes from the start of loading was set as a stopping criterion to end the experiment.

The application of a compressive load on the specimen generates a state of tensile stress, to which the strength value can be provided by applying Equation 2, proposed by Krishnayya & Einsenstein (1974).

$$\sigma_t = \frac{2 \times P}{\pi \times d \times h_s} \tag{2}$$

Where P is the maximum vertical load applied in the test; d is the diameter of the sample and h_s, is its height.

3. Analysis and results

3.1 Microstructural behavior of the fiber soil mixture

Figure 2 displays the results obtained from the MIP tests. It can be observed that the microstructural behavior, in general, was consistent for all the evaluated samples. The achieved curves show a bimodal behavior of the materials, both in the natural and reinforced soil samples, with groups of micro and macropores.

Based on BS ISO (2009) and what was assumed by Décourt et al. (2022), the micropores are related to the clay fraction (φ < 0.2μm), mesopores to the silt fraction (0.2 < φ < 6μm) and macropores to the sand fraction (φ > 6μm). Accordingly, when quantifying the curve obtained from each sample, it can be observed in all cases that the highest percentage of pores is located in the micropore zone, followed by the macropore zone.

Regarding the addition of fibers, there is an increase in macropores and a consequent decrease in micropores as the fiber content increases. This development is not presented linearly, as it can be observed that the biggest behavior change occurred in the samples with 0.1% and 0.5% of fiber. Table 2 shows the values for each case studied.

Also, based on the results presented in Table 2, it is possible to compare the total porosity of the samples measured by the MIP tests with the average porosity determined by the physical properties of the soil. It can be inferred that the increase in soil macro and mesoporosity increases the porosity obtained by the mercury intrusion porosimetry tests, which improves the befitting with the average physical porosity index of the samples (47.1%). For samples with 1% fiber, the difference between the mentioned data is 6%. This fact, also observed in Romero et al. (1999) and Décourt et al. (2022), may be associated with isolated and/or occluded micropores, which are not filled with mercury during the test.

3.2 Hydraulic behavior of the fiber soil system

The retention curves for the natural and fiber soils (Figure 3) depict a bimodal behavior which, as already demonstrated by Figure 2, relates to the air entry into both the macro and micropores of the soil.

Although the curves correspond to samples compacted with the same average of dry specific mass and gravimetric water content, they differ from each other, among other aspects, in the shape conceived by the fitting method.

Table 2. Micro, meso, macro and total porosity indexes from MIP tests.

Samples	Micropores (%)	Mesopores (%)	Macropores (%)	MIP
	ϕ < 0.2mm	0.2mm <ϕ< 6mm	Φ >6mm	Porosity (%)
0%	62.2	3.5	34.4	38.0
0.1%	63.9	3.6	32.4	37.9
0.5%	57.0	3.7	39.3	39.5
1%	56.3	4.1	39.6	41.1

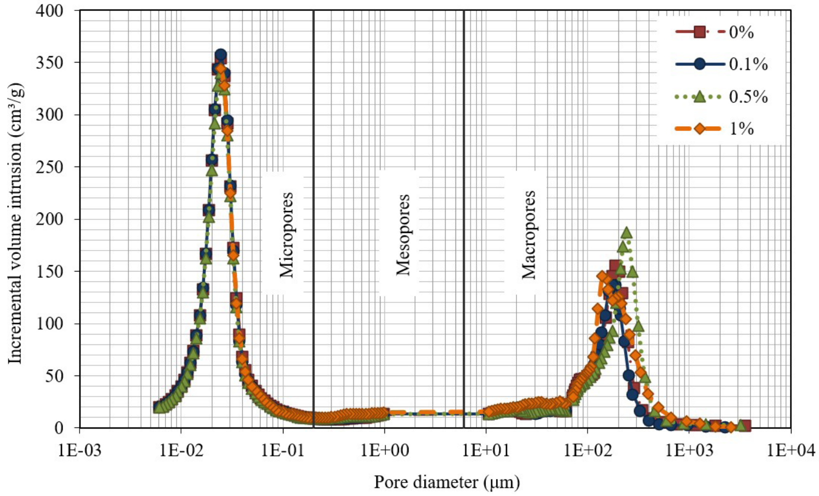

Figure 2. Porosimetry tests results for all samples tested.

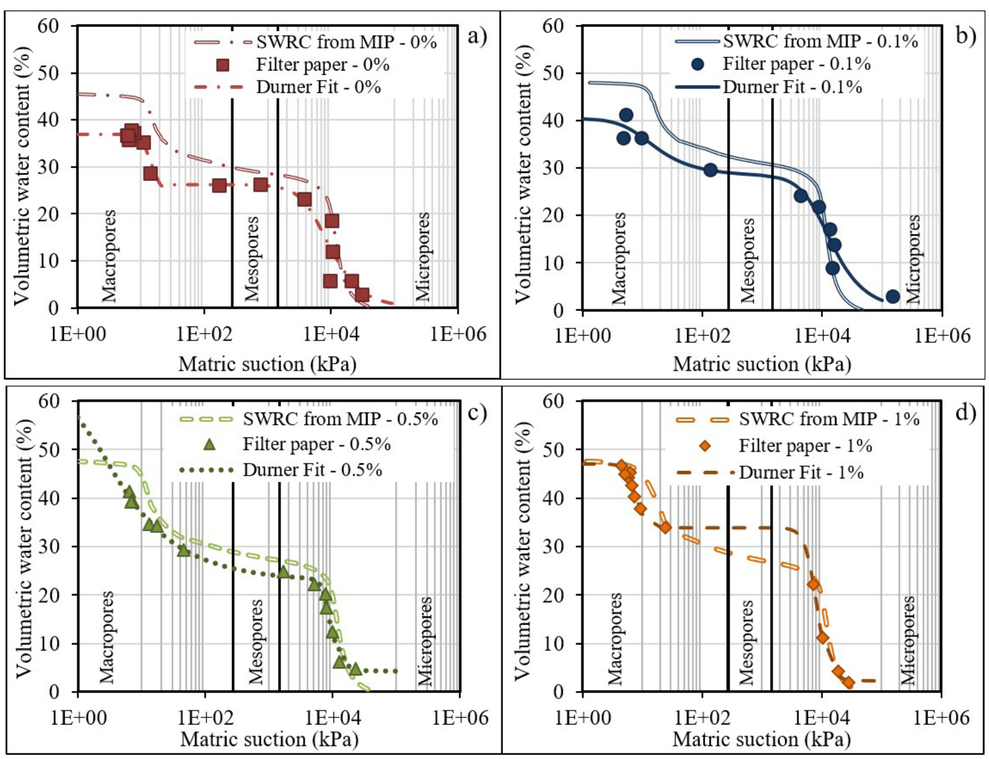

Figure 3. Soil water retention curves and correlation between the filter paper method and MIP tests. (a) Soil without the addition of fiber; (b) Fiber soil with 0.1% fiber; (c) Fiber soil with 0.5% fiber; (d) Fiber soil with 1% fiber.

Compared to the soil in its natural conditions, the level of the saturated zone decreased in the three analyzed fiber soils, thus demanding less energy to drain water from the macropores and conceding the entrance of air. In Figure 3c, the level of the saturated zone is reduced, making it difficult to detect the first air entry. This may have occurred due to curve fitting, as there are not enough data for low suction values with 0.5% fiber addition.

There was also variation in the value of the second air entry amidst the analyzed soils. For the natural soil, the value was 2900 kPa, while in soils with 0.1%, 0.5% and 1% fiber additions, second air entry of 4000 kPa, 6700 kPa and 5900 kPa were determined, respectively. This result implies that the addition of coconut fiber postpones the moment when the air starts to fill the micropores of the soil.

The difference between the curves can also be observed in the residual zone, which was shifted to the right side, suggesting that the stage in which desaturation occurs was more expressive in fiber-reinforced soils.

Furthermore, Figure 3 shows, for all types of samples analyzed, the correlation between the data obtained from the filter paper tests and the retention curve derived from the MIP tests. It can be observed, in general, that the filter paper data were better fitted on the desaturation zone, after the second air entry. This deviation at the beginning of the curve was also encountered by several other authors (Aung et al., 2001; Mendes & Marinho, 2020; Décourt et al., 2022), but no widely accepted explanation justifies this difference.

Nevertheless, it is worth noting that, for systems with 0.5% and 1% fiber additions (Figure 3c and Figure 3d), a better fit between the two methodologies is established, covering the entire range from macro to micropores. This condition may be related to the further infiltration of pores during mercury injection.

3.3 Mechanical behavior of the fiber soil system

From the suction values obtained with the filter paper test and with the data from the tensile strength test, the curves in Figure 4 were plotted. In all four situations, the soil presented a tensile strength curve with a similar format to that obtained by Benessiuti et al. (2010) for this same soil. As observed, the strength value increases slowly in the first section, which corresponds to the lowest suction values, and is proceeded by considerable gains until reaching a peak, from which the tensile strength begins to decrease.

Motta et al. (2015) found similar results for an undisturbed young residual micaceous soil from Rio de Janeiro, Brazil. The reason for the observed behavior is probably related to the formation of micro-cracks and the breakdown of the

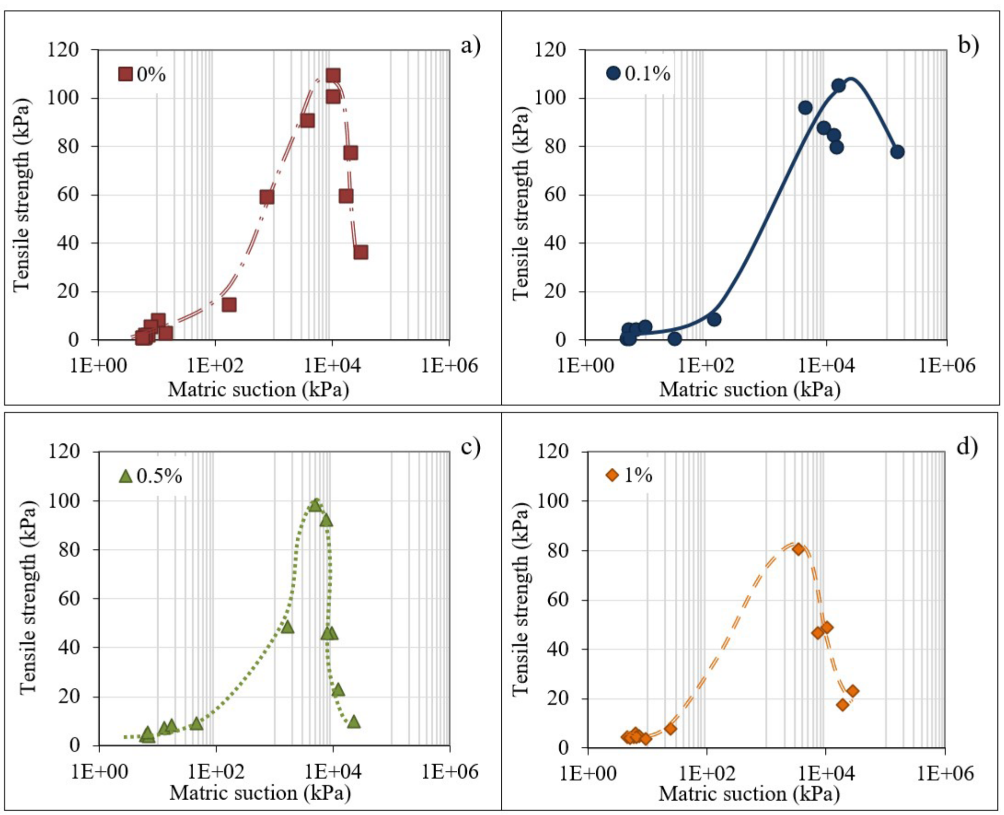

Figure 4. Tensile strength *versus* matric suction curves. (a) Soil without the addition of fiber; (b) Fiber soil with 0.1% fiber; (c) Fiber soil with 0.5% fiber; (d) Fiber soil with 1% fiber.

meniscus for higher suctions that act decreasing the tensile strength.

Bulolo et al. (2021) found two types of behavior for compacted samples of two residual soils from Singapore. For all the sample sets, drying of the soil specimens from the wet of optimum to the dry of optimum showed an increase in tensile strength. These values increase up to a certain limit and then generally become constant despite further drying. However, some data show a slight drop in tensile strength at extremely low water contents. The authors mentioned that after the air entry value (AEV), the water phase becomes increasingly discontinuous in the soil and the contribution of suction to the tensile strength becomes increasingly minimal.

Figures 5a and 5b exemplify the ruptured surfaces seen in fiber soils with lower fiber content. In some samples of the fiber soil systems with higher fiber content, it was possible to delineate the crack, as illustrated in Figure 5b, but not in the majority. Most of the specimens showed a large deformation, making it difficult to identify the failure.

This change in soil behavior from brittle to ductile is in agreement with the results obtained by Cabala (2007), who found that the elastic modulus of a soil-cement reinforced with coconut fiber varied inversely proportional to the amount of fiber content. Specifically, the bigger the fiber amount, the lower the rigidity of the material, which leads to an improvement in its ability to withstand deformations.

Although the visual identification of rupture was inadequate in these cases, the stopping criteria (calculated based on the speed and load applied by the equipment) is within that described in the literature for situations of large deformations, which guarantees that the sample actually failure and that its strength value was obtained correctly.

It is also worth noting that this occurrence did not interfere with acquiring the strength peaks, since this fact is associated with samples with lower suction values. The samples that showed the highest values of tensile strength presented a clear rupture surface, characterized by a brittle failure. Thus, it was possible to observe a change in the behavior of the fiber soil system as a function of matric suction.

When quantitatively evaluating the graphs, it is evidenced that: for the natural soil, the strength peak was 109 kPa, corresponding to the suction value of 10645 kPa; for the fiber soil with 0.1% fiber, the strength peak was 105 kPa for a suction of 16066 kPa; for the 0.5% fiber soil, the strength peak reached a value of 98 kPa for a suction of 5064 kPa; and for the fiber soil with 1% fiber, the strength peak was 80 kPa for a suction of 3469 kPa. Comparing the fiber soil with the soil without reinforcement, it was deduced that the fiber addition of 0.1% changed less significantly the behavior of the material, being characterized by a decrease in strength of approximately 4%. On the other hand, in the materials with 0.5% and 1% of fiber addition, the tensile strength decreased by approximately 10% and 26%, respectively. Furthermore, a decrease in suction values associated with strength peak values can be observed in the specimens with higher percentages of fiber.

In the literature, studies that evaluated the addition of coconut fiber as soil reinforcement address its effect on other types of strength without associating them with suction, hence it was not possible to effectively compare the results obtained. Cabala (2007) revealed that the flexural strength of the reinforced specimens was lower than that of the natural soil, maybe due to the lack of adhesion between the two phases present in the composite material.

Based on studies regarding natural fibers (Anggraini, 2016; Gowthaman et al., 2018), an improvement in the tensile strength of the analyzed material was expected. Nevertheless, it was noted that, for the evaluated components, the addition of fibers equal to or less than 0.1% of the dry mass did not lead to enhancement of the soil behavior regarding its ability to

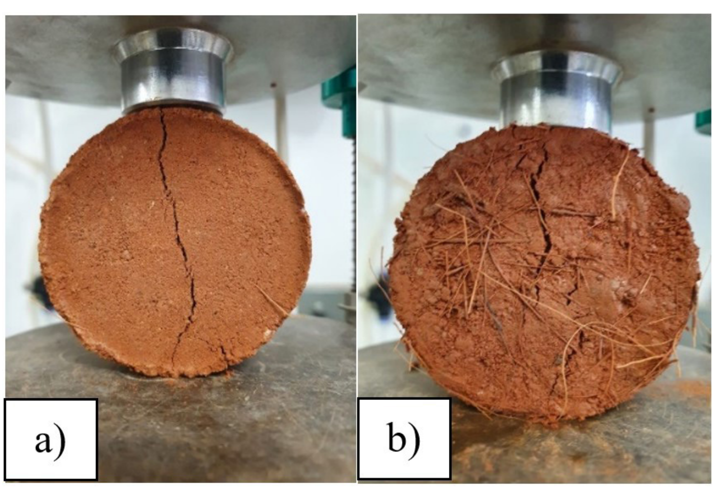

Figure 5. Rupture surfaces in samples subjected to the splitting tensile strength test. (a) Fiber soil with 0.1% fiber; (b) Fiber soil with 0.5% fiber.

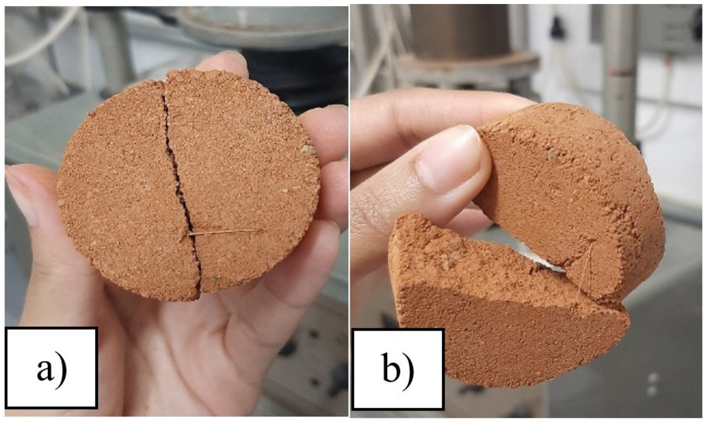

Figure 6. Rupture surfaces in the samples submitted to the diametral compression test. (a) Fiber crossing the rupture surface of the sample; (b) Fiber anchoring effect, keeping the two pieces of the ruptured sample together.

resist tensile stress. This divergence in results can be explained by the particularities of the materials, which differ in each study, and by the decisions made during the preparation and execution of the tests. The lack of standardization of fiber length and diameter and the specimen's structure could have been a source of interference. Moreover, it is worth mentioning that most of the studies is related to fiber-reinforced soil with another additive. This third element could be responsible for the benefits of coir fibers in geotechnical applications.

In the case of fiber soil with a fiber addition of 1%, the main issue may have been the difficulty in homogenizing the material. As the fibers tended to cluster, it is a possibility that the samples had part of their volume filled only by fiber instead of soil.

Although the addition of coconut fibers did not result in an improvement in tensile strength, not preventing the soil from breaking, it was observed that, once broken, the fibers helped to keep the pieces together, working akin a sort of stapler (Figure 6).

3.4 Correlation between the microstructural, hydraulic and mechanical behaviors

By comparing microstructural and hydraulic behavior, from MIP tests and filter paper method (Figure 2 and Figure 3), for all cases concerning natural soil and fiber soil mixtures, two predominant groups of pores could be identified, located in the zone of macro and micropores, where the highest percentage of pores have diameters smaller than 0.2μm, related to the second air entry value zone. The increase in fiber content from 0.1% to 0.5% caused a greater increase in the soil macroporosity, a greater decrease in the soil microporosity and, consequently, a greater increase in the air entry value. From 0.5% to 1% fiber, the observed variations were smaller in terms of microstructural and hydraulic behaviors.

When comparing the retention curve acquired from the MIP tests with the results from the filter paper tests, better fits were observed in samples with higher fiber content, which consequently have a higher percentage of macropores. This fact implies that samples with porosity values estimated by MIP tests closer in comparison with the average physical porosity index comprise the best data concurrence.

By correlating the SWRC – obtained by the filter paper test – and the tensile strength graph (Figure 3 and Figure 4), it can be perceived, for the same amount of fiber, that for low suction values, the strength increases at a slow pace. From the first air entry, the property increases significantly until it reaches its peak and then decreases again. In all four analyzed cases, the point of maximum tensile strength is found near the second air entry.

For the natural soil and the fiber soil with 0.1% fiber, the peak is located practically in the center of the second desaturation segment, halfway to the residual phase; for the fiber soil with 0.5% and 1%, it is located just before the second air entry value.

According to Villar et al. (2007), this demeanor of tensile strength decrease after the second air entry is influenced due to the condition of continuous air in the sample. Benessiuti et al. (2010), Motta et al. (2015) and Bulolo et al. (2021) obtained similar results.

The addition of fibers equal to or less than 0.1% did not have a significant effect on tensile strength, decreasing it by 4%. However, the addition of a higher fiber amount (1%) reduced the strength by about 30%. It is assumed that the optimal point of material addition has been exceeded.

4. Conclusions and recommendations

The purpose of this study was to evaluate how the addition of coconut fibers would interfere on the microstructural, mechanical and hydraulic behavior of an unsaturated compacted soil, in order to test the feasibility of incorporating coconut fibers in artificial slopes.

The increase in fiber content in the material lead to a non-linear increase in macropores and a non-linear decrease in micropores, which affected both the hydraulic and mechanical behavior of the soil.

Regarding the hydraulic behavior, it was demonstrated that for all materials tested, the addition of fibers interfered with the SWRC format, modifying the values of the first and second air entry and residual suction. Such changes did not display a linear conduct with the increase in fiber content.

Regarding the mechanical behavior, it can be verified that the change in soil structure affected its tensile strength, where the addition of fibers decreased the tensile strength peak values. Despite the decrease in tensile strength, the samples with the highest fiber content evidently withstood greater deformations than the natural soil, implying that it had its rupture behavior transitioned from brittle to ductile, as expected. In this sense, the fibers operated similarly to vegetation roots on slopes, helping to avoid sudden ruptures that could result in greater damage.

Future research is necessary to understand the behavior of the fiber soil system including: a study of different types of homogenizations of the fiber soil system; analysis of the dimensions, size, diameter and orientation of the fiber; analysis of the effect of time and exposure to climatic conditions on the fibers.

Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the contents of the paper and there is no financial interest to report.

Authors' contributions

Fernanda Santos Gomes: conceptualization, data curation, visualization, writing – original draft. Mariana Ferreira Benessiuti Motta: conceptualization, data curation, methodology, supervision, validation, writing – original draft. George de Paula Bernardes: conceptualization, formal analysis, methodology, supervision, validation, writing – review & editing. Paulo Valladares Soares: validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols

d	Sample diameter
h	Pressure head
h_s	Sample height
k	Number of subsystems
m	Water retention parameter
n	Water retention parameter
w	Weighting factors
Gs	Specific gravity of grains
LL	Liquidity limit
MIP	Mercury intrusion porosimetry
P	Maximum vertical load applied
PI	Plasticity index
PL	Plasticity limit
PVC	Polyvinyl chloride
S_e	Effective saturation
SWRC	Soil water retention curve
USCS	Unified soil classification system
α	Water retention parameter
σ_t	Tensile strength

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