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Research Article
Analysis of the Hydromechanical Behavior and Crack Formation Process in Expansive Soil Reinforced with Green Coconut Fibers

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Abstract
Background and Objective: Coconut fibers, a byproduct derived from the coconut compound production process, can become waste as they are traditionally disposed of in improper locations, leading to pollution of beaches and cities in opposition to local laws, making them an environmental liability. In this study, the feasibility of reusing coconut fibers as reinforcement in expansive soil in Paulista, Pernambuco, was investigated through laboratory experiments. **Materials and Methods:** Samples of compacted soil and its mixtures with coconut fibers in weight proportions of 0.25, 0.50, 1.00 and 2.00% were tested. The following tests were conducted: Particle size analysis, consistency limits, compression, free swell, swell pressure, hydraulic conductivity and analysis of crack formation and propagation during drying. Classical statistical knowledge, descriptive parameters are used for initial knowledge of the data, was applied to statistical interference through analysis of variance for one and two factors, simple linear regression and multivariate analysis on principal components using Excel software. **Results:** With the addition of coconut fibers, there is a reduction in the soil's swell pressure from 101.7 kPa for natural soil to 25.8 kPa for soil with 1% coconut fiber, a reduction of 74.63%. Tensile strength by diametral compression increases by 42% when adding 2% of fiber to natural soil. Regarding simple compression, shows a maximum stress increase of 57.49%. The hydraulic conductivity does not change significantly with the addition of fiber and did not exceed a permeability of (10^{-9} m/sec). The crack intensity factor (CIF) decreases as the fiber content increases. **Conclusion:** The inclusion of coconut fibers modifies the wide cracks that occur in natural soil into narrower cracks. The addition of green coconut fibers to expansive soil in Paulista improves all the geotechnical characteristics investigated in the expansive soil.

Key words: Expansive soil, hydromechanical behavior, fiber reinforcement, expansion, crack test, crack formation process

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Unsaturated soils are common in nature and are found in most geotechnical infrastructure, including earth slopes, pavement, landfills, earth dams, irrigation channels and sometimes natural or compacted expansive soils subject to moisture variation (suction). Climate plays a significant role in unsaturated soil behavior. For instance, during the dry season with low precipitation, the soil has lower moisture levels, potentially leading to desiccation and high suction, which can affect the soil's strength. In contrast, during rainy periods, there is an increase in rainfall and soil moisture, reducing suction and, consequently, soil strength.

In expansive soils, characteristic cracks or fissures are observed in the field during dry seasons, while during rainy seasons, there may be swelling. Geotechnical engineering structures built on soils with volumetric instability can face serious issues when moisture levels change. Expansive soils, composed of highly hydrophilic materials like montmorillonite and illite, are sensitive to changes in suction[1].

As demonstrated by Ng *et al.*[2] climate can significantly impact the hydro-mechanical behavior of expansive soils, potentially causing severe damage to structures built on them. Nelson and Miller[3] reported that, in a typical year in the United States, expansive soils can cause greater financial losses to property owners than earthquakes, floods, tornadoes and hurricanes combined. The American Society of Civil Engineers estimates that one in every four houses experiences some damage from expansive soils. Driscoll and Crilly[4] noted that the estimated average annual cost to the British Insurance Association for expansive soil-related claims in the insurance industry exceeds 400 million pounds. In Brazil, specific data on costs related to damage caused by these soils are not available.

On another note, the high consumption of green coconuts, prized for their nutrition, mineral content and taste among Brazilians, generates a substantial environmental issue due to the significant volume and weight of coconut husks. Brazil, responsible for nearly 5% of global coconut production, ranks as the fourth-largest producer. It is essential that sustainability be discussed in all areas and activities of knowledge, seeking to include more sustainable processes, materials and methodologies, thereby reducing consumption and the reuse of waste generated in the processes. According to Roque *et al.*[5], geotechnical engineering should not be excluded from this debate and should seek more sustainable ways and technologies, due to its primary importance in a civil construction project.

In an effort to find an alternative to mitigate the problems of expansive soils in geotechnical engineering and also provide a solution for the use of green coconut fibers, reducing an environmental liability, this research aims to investigate the hydromechanical behavior of expansive soils in the municipality of Paulista, PE, reinforced with green coconut fibers. The overall objective of this research was to investigate the hydromechanical behavior of an expansive soil from Paulista/PE reinforced with green coconut fiber and to analyze the feasibility of incorporating green coconut fiber with an emphasis on the performance of these mixtures regarding crack formation and propagation due to drying.

MATERIALS AND METHODS

Study area: The deformed samples of clayey expansive soil come from Brazil, State of Pernambuco, Municipality of Paulista. The search location is located at sewage treatment plant of the Sanitation Company of the State of Pernambuco (COMPESA). Coconut fibers were obtained in a processed form from a company based in Fortaleza/CE, Brazil. The soil and fibers were collected in 2022 in January, the tests were carried out in the same year in June and July. Currently, the technology employed to process coconut husk residues and extract coconut fibers involves the use of machinery. Finally, the pressed material is classified; namely, long fibers are separated from short fibers and powder in a sorting apparatus, which uses fixed helical hammers and a perforated sheet. In this study, short fibers were used, because they do not have as much applicability as long fibers. All the data were obtained experimentally in the laboratory using the methods described by Narani *et al.*[6]. Figure 1 demonstrated the gradation curve of the local soil and Table 1 presents the soil engineering and physical properties.

Table 1: Soil engineering and physical properties

Soil properties	Value
Particle density (g/cm^3)	2.67
Liquid limit (%)	52.56
Plastic limit (%)	21.81
Plasticity index (%)	30.75
USCS classification	CH
AASHTO	A-7-6
Boulder (%)	0
Sand (%)	31
Silt (%)	31
Clay (%)	38
Activity index	0.76
Maximum dry unit weight (kN/m^3)	16.04
Optimum moisture content (%)	21.3

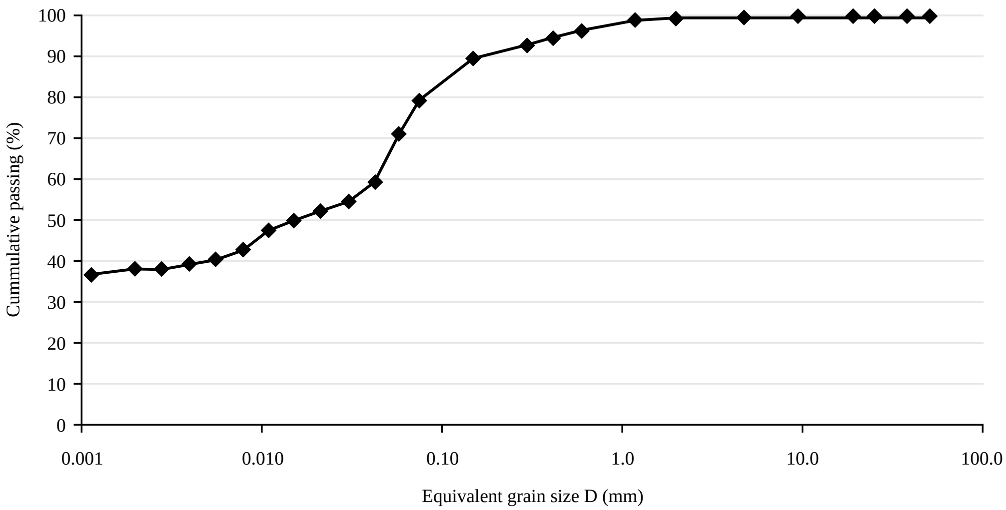

Fig. 1: Gradation curve of the local soil

Methodology: In this section, the investigated the methodological procedure employed in the geotechnical investigation program of an expansive soil in the municipality of Paulista, PE, was presented, to obtain the physical, rheological and hydromechanical characterization of the natural soil and its mixtures with coconut fibers (soil-0.25% fiber, soil-0.5% fiber, soil-1% fiber and soil-2% fiber). The research program was divided into 5 stages. The first one involves the preparation of the soil and the fibers used in the research, as well as the physical characterization of these materials through tests conducted in the laboratory, following the ABNT and ASTM standards[7]. The second phase focused on selecting the percentages of fibers to be incorporated into the soil, based on the studies by Narani *et al.*[6], Kodicherla and Nandyala[8] and Basson and Ayothiraman[9]. This phase also includes the preparation of the defined mixtures and the characterization of the formed composites. In the third stage, hydraulic and mechanical are carried out on the natural soil and the investigated mixtures. The fourth stage involves evaluating the influence of fibers on cracking dynamics and expansivity, as well as conducting an optical microscopic analysis of the soil and mixtures. A Hirox digital microscope (KH-7700) with 100x magnification was used to analyze the soil-fiber interaction after compaction. In the fifth and final stage, the analysis and interpretation of the results from the laboratory tests are conducted and compared with the existing literature. Coconut fibers had an average diameter of 0.27 mm, in a range of 0.19 and 0.31 mm. Its average length was 20 mm, in a range between 12 and 28 mm. The humidity hygroscopic average found was 23.02% while the maximum absorption in 48 hrs submerged was 414%. The maximum dry specific weight found was 12.6 kN/m^3.

Statistical analysis: The statistical analysis was the classical statistical knowledge, descriptive parameters are used for initial knowledge of the data, was applied to statistical interference through analysis of variance for one and two factors, simple linear regression, multivariate analysis on principal components using excel software.

RESULTS AND DISCUSSION

The values of the consistency limits and plasticity index of the natural soil and soil-fiber were presented in Table 1. The addition of coconut fiber to the soil in Paulista, PE did not significantly alter the soil's true density and particle size distribution compared to the behavior of the mixtures observed by Menezes *et al.*[10]. Both the soil and the soil-fiber mixtures exhibit high plasticity (IP>15%). The liquid limit (LL) increases from 52.56% (soil) to 69.40% (soil-2% fiber) and the plastic limit (LP) also increases from 21.81% (soil) to 27.63% (soil-2% fiber). As LL increases more than LP, the plasticity index increases from 30.75% (soil) to 41.77% (soil-2% fiber), as shown in Fig. 2. Similar results were found by Narani *et al.*[6] and Basson and Ayothiraman[9], when analyzing the behavior of an expansive clay from India reinforced with coconut fiber.

For mixtures of soil with coconut fiber (Fig. 2a), the apparent specific weight dryness decreases with increasing fiber percentage and optimal soil moisture increases with the addition of fibers (Fig. 2b). This could be a result of the fiber coconut is a light material and substitute for the soil, which caused the reduction of mix densities studied by Kodicherla and Nandyala[8]. As the increase in percentage of coconut fibers, there is an increase in the optimum moisture content of the mixture, which may be based on the adsorption of water by fibers described by Shukla[11].

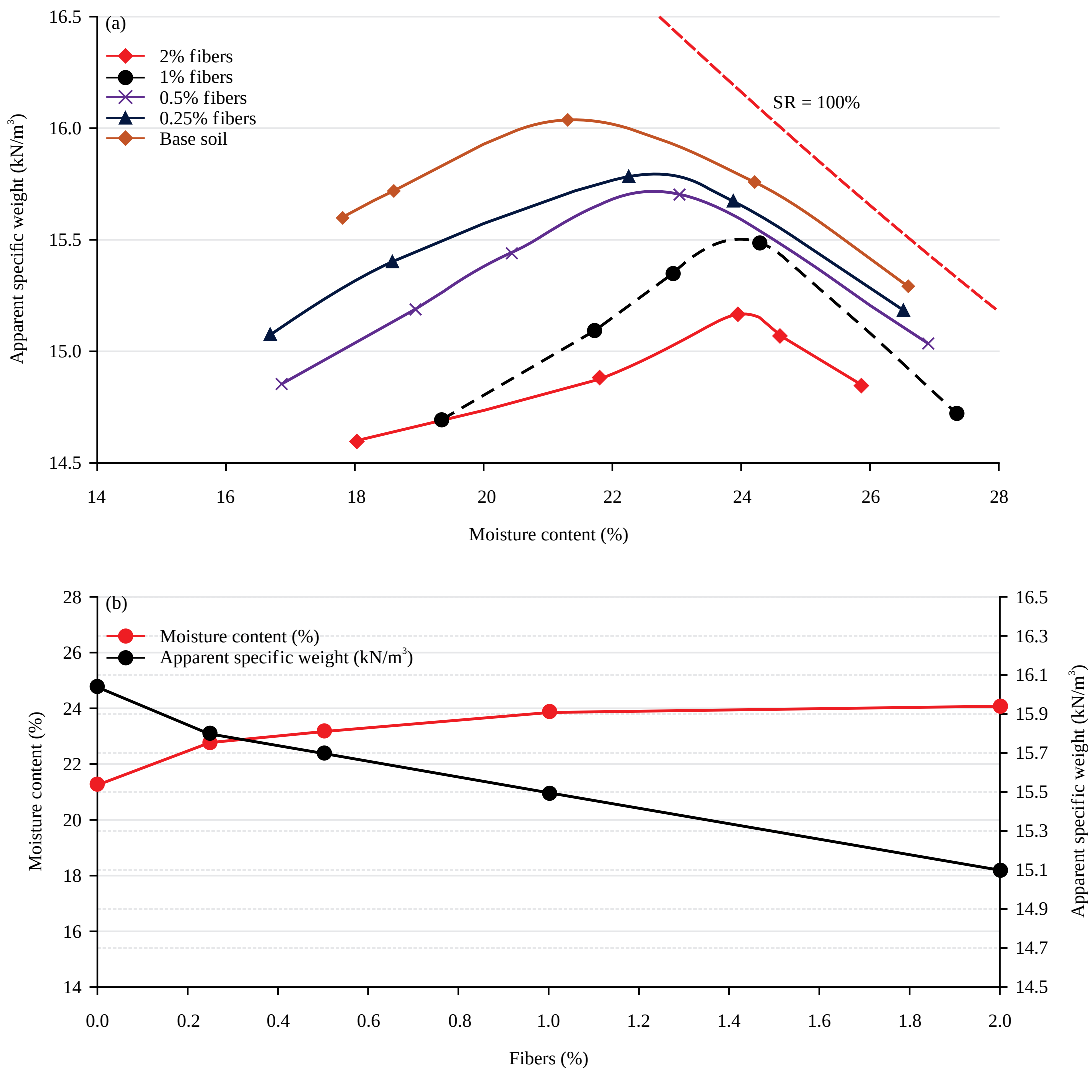

Fig. 2(a-b): Soil compaction test, (a) Apparent specific weight dryness and (b) Moisture content versus fiber percentage

The natural soil had a hydraulic conductivity coefficient of 2.64×10^{-8} cm/sec. It is noticeable that mixtures with 0.25, 0.5, 1 and 2% of coconut fibers showed hydraulic conductivity coefficients similar to that of the natural soil, approximately 3.45×10^{-8}, 2.76×10^{-8}, 2.99×10^{-8} and 2.62×10^{-8} cm/sec, respectively. Thus, fiber content did not significantly affect hydraulic conductivity; however, it is important to note that even though coconut fiber is a material that is difficult to biodegrade, tests should be carried out to assess the behavior of hydraulic conductivity and other properties over time.

The tensile strength by diametral compression increases with the insertion of fibers from the green coconut (Fig. 3), with an increase of 6.20% for a fiber content of 0.25 and 19.03% for a 0.5% fiber content, 32.05% for a 1% content, reaching a higher value with 2% fiber-41.93% higher than the natural soil. The fibers increase peak strength and induces strain hardening behavior in the mix by controlling and mitigating stress through stress transfer through the cracks for fibers, which share efforts in traction requests.

Figure 4 shows that the expansion potential was restricted by the reinforcement with coconut fiber. The expansion potential is reduced by 4.91, 22.09, 38.39 and 46.42% for fiber contents of 0.25, 0.5, 1 and 2%, respectively, compared to the natural soil. These trends have been reported by other researchers and are often attributed to the soil-fiber interaction. This effect was reduced at extremely high fiber contents, as observed by Fazli and Rodrigue[12] and Babu and Vasudevan[13]. A fiber content of 2% can be considered the level at which the expansion potential is most significantly reduced.

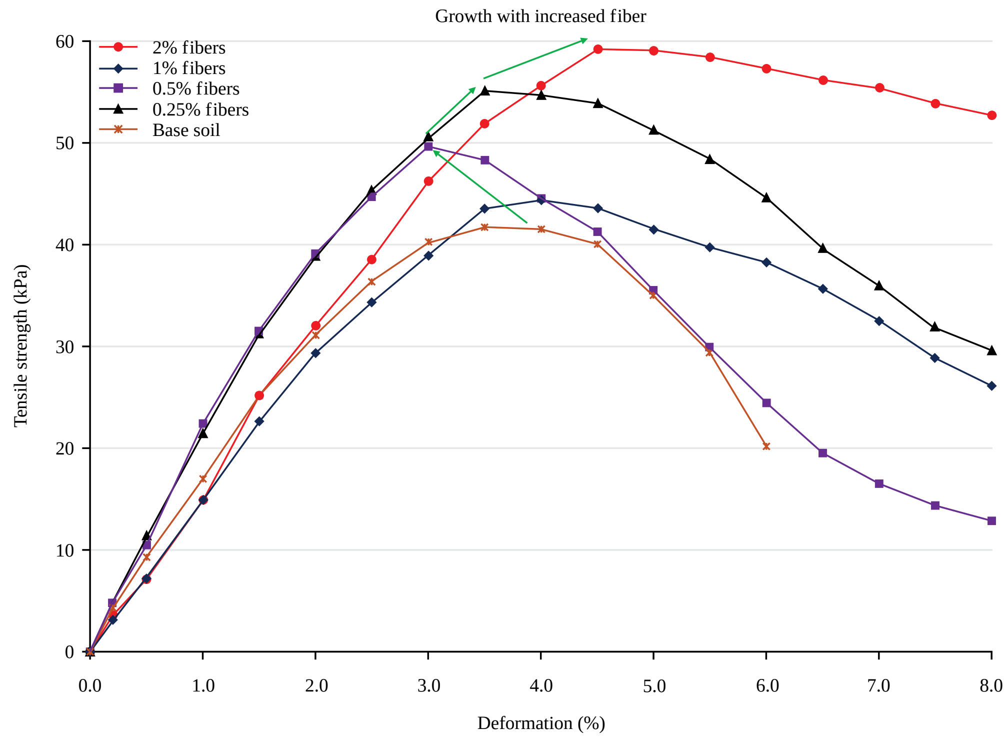

Fig. 3: Tensile strength versus deformation

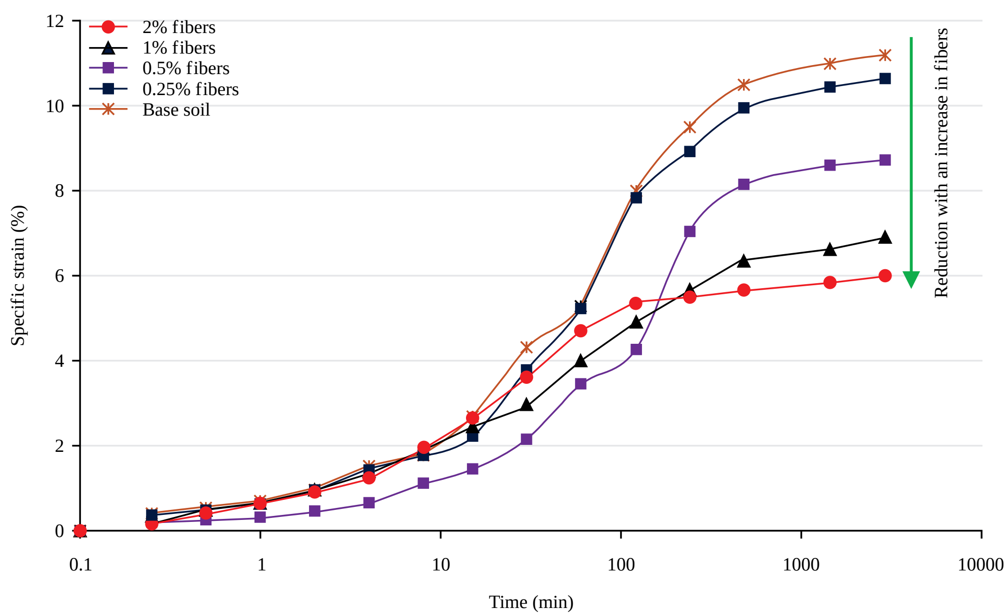

Fig. 4: Results of 'free' expansion tests

Figure 5a shows a microscopic optical device with a 100x magnification that was used to analyze the soil-fiber interaction after compaction, presents the matrix, interface and fibers and Fig. 5b shows the interaction soil-fiber after compaction for a soil+1% fiber, then a public domain image processing program (ImageJ) was employed to obtain detailed information on the cracking mechanics of the soil sample. The photos were obtained via a webcam to monitor the crack formation process, images were obtained by using a Logitech C922 PRO STREAM Full HD webcam connected to a notebook.

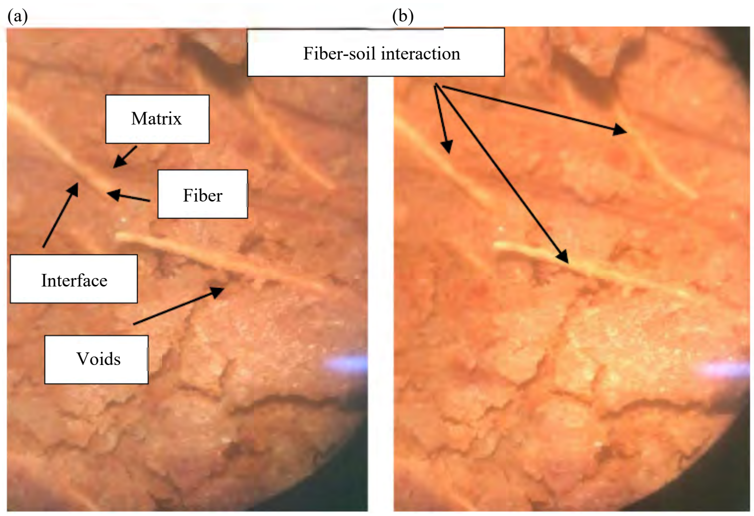

Fig. 5(a-b): Fiber-soil interaction, (a) Fibers, interface and voids and (b) Fiber-soil interaction after compaction for a soil+1% fiber

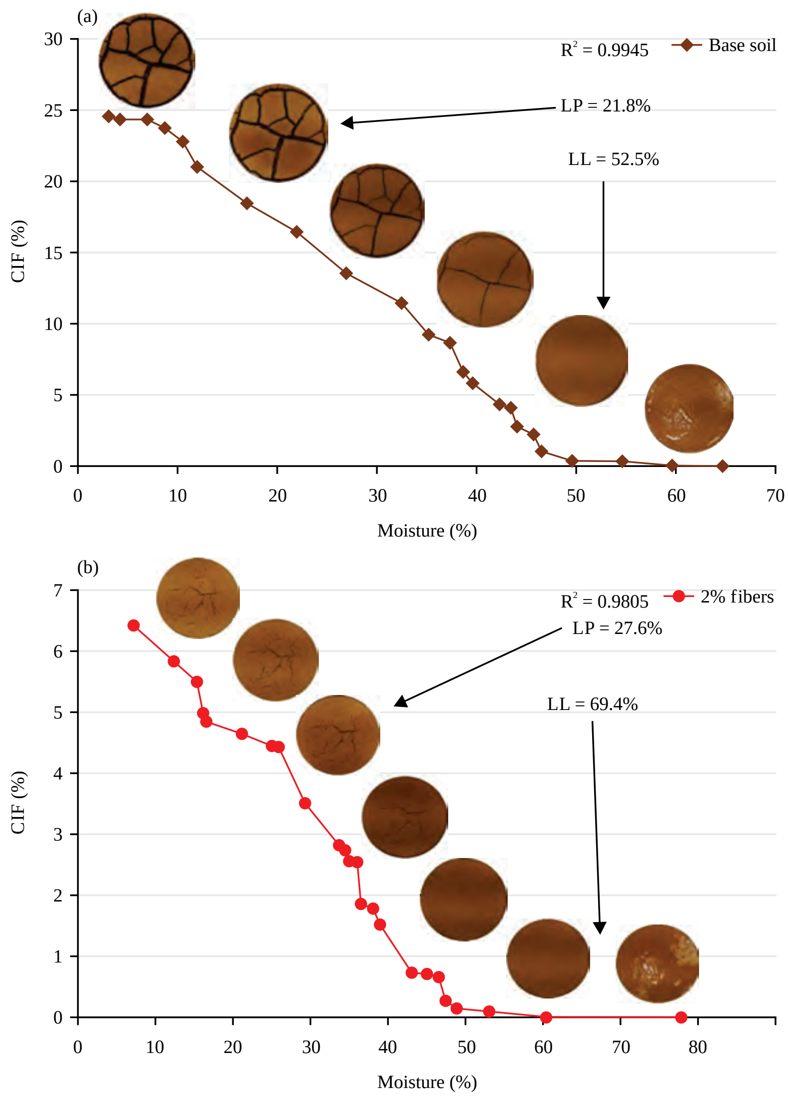

Fig. 6(a-b): Curve CIF versus moisture, (a) Curve CIF vs moisture natural soil and (b) Curve CIF vs moisture soil+2% fiber

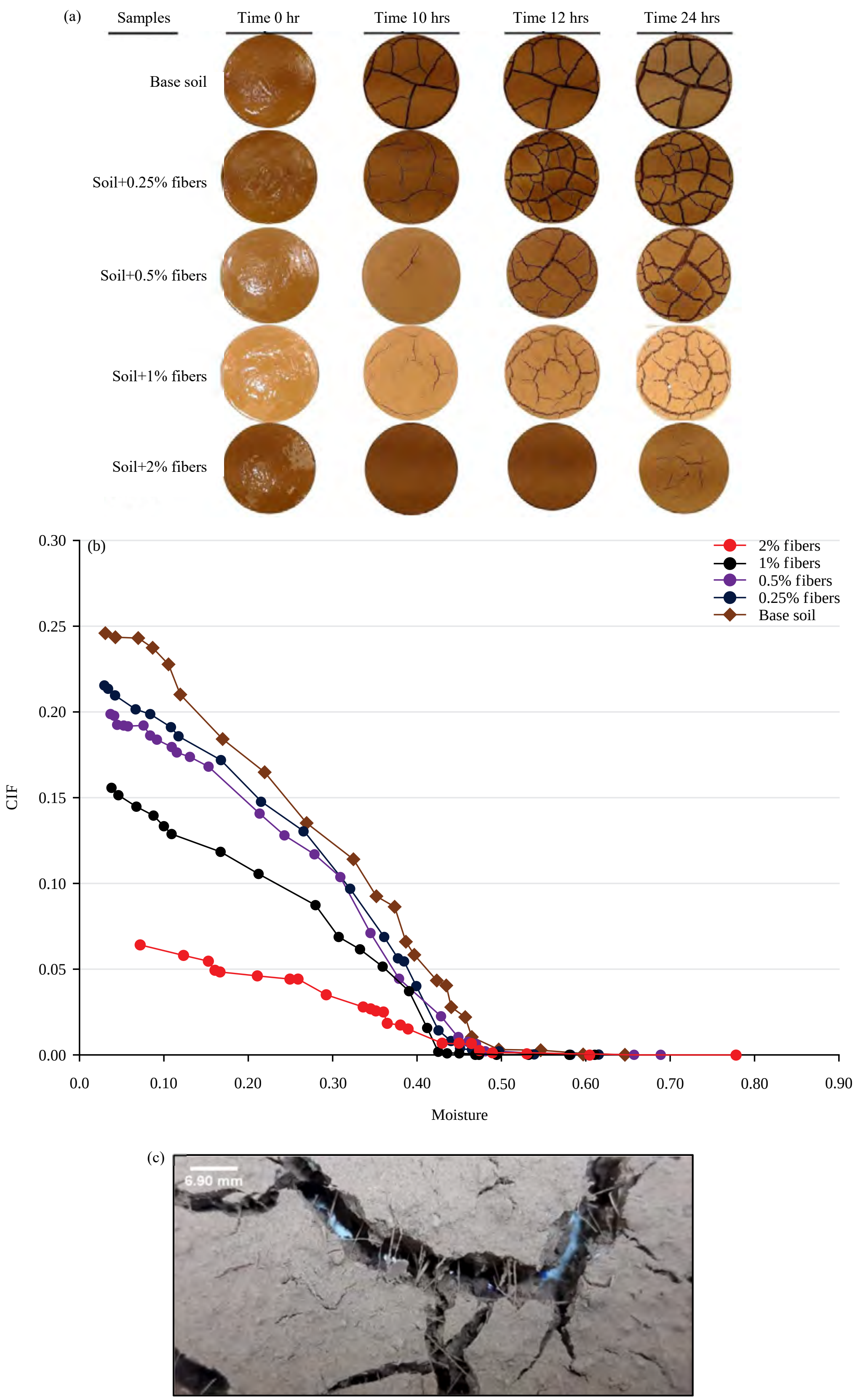

Fig. 7(a-c): Comparison of crack formation and propagation over time in soil and mixtures, (a) Soil, (b) CIF and (c) Microscopic optical

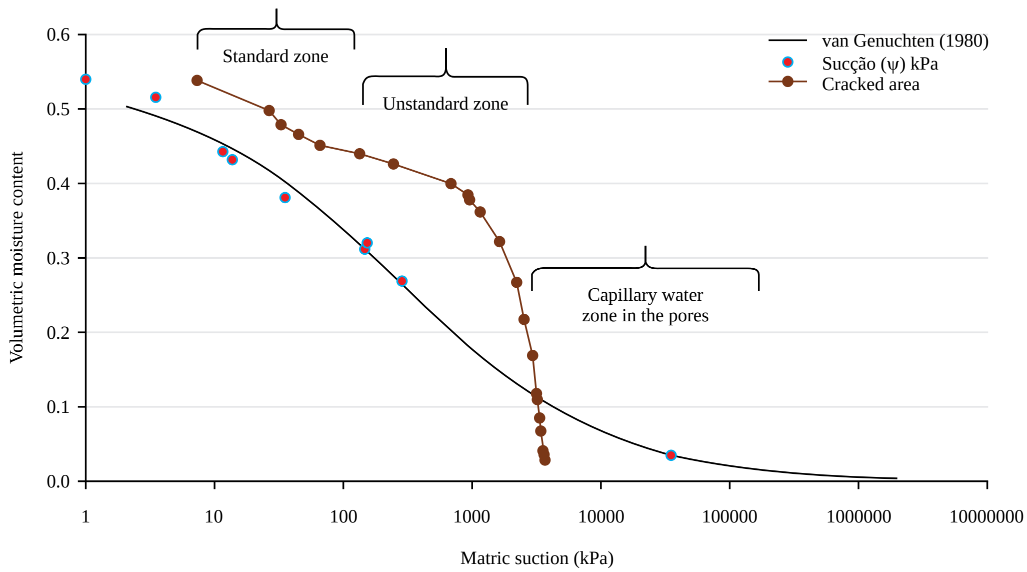

Fig. 8: Correlation between the cracked area and soil suction

Using the free Auto Screenshot Capture software, it was possible to control the capture automatic imaging for a predetermined time of 10 min, yielding various indices for characterizing the crack pattern: Total cracked area, CIF and CRR.

Images were selected to assess the evolution of cracks and the determination of CIF and other indices during the drying of the samples (Fig. 6a). It was observed that in all tests, there was a change in the color of the wet soil to the color of the soil after drying at the end of the tests (through the analysis of the photographs). No significant color change occurred in the early stages of drying. This indicated that moisture loss was uniform across the surface of the sample in the initial drying state. Analyzing the images from the tests with samples of natural soil, soil+0.25% fiber, soil+0.5% fiber, soil+1% fiber and soil+2% fiber, it was evident that the cracks follow a different pattern for each percentage of coconut fiber added to the soil (Fig. 6b).

It is observed that there was a significant reduction in the cracked area of the expansive clay soil from Paulista/PE with the increase of green coconut fibers. Figure 7a-c shows the comparison between the natural soil and the reinforced soil.

The soil that is not reinforced, primary cracks begin at the surface when the soil's tensile strength limit is reached due to drying-induced suction and because of the absence of any tensile reinforcement, they extend to the entire depth observed by Peron *et al.*[14], Costa *et al.*[15] and Signes *et al.*[16]. This behavior can be observed in Fig. 8, showing an increase in the cracked area with the rising suction of the sample.

Laboratory tests were conducted to assess the cracking potential and the hydromechanical behavior of an expansive soil from Paulista, Pernambuco, both unreinforced and reinforced with varying proportions of green coconut fiber. The real density of the mixture remained largely unchanged, hydraulic conductivity stayed below 10^{-9} m/sec and the physical properties of the soil were not significantly affected by the addition of the fiber. Soil expansion pressure decreased from 101.7 kPa in the natural soil to 25.8 kPa in the soil with 1% coconut fiber, representing a reduction of 74.63%. The tensile strength in the diametral compression test increased with increasing fiber content, with the best percentage being 2%, resulting in a 42% increase in tensile strength compared to the natural soil. Studies have shown that incorporating coconut fibers can significantly reduce the occurrence of cracks during the drying process. The crack intensity factor (CIF) decreases with increasing fiber content, reaching the greatest reduction at a 2% fiber level.

CONCLUSION

According to the aforementioned results, it can be inferred that green coconut fibers can be effectively used as reinforcing agents to improve the geotechnical characteristics of expansive soils. Fibers mixed with soil can be used as waterproof linings and covers in municipal solid waste landfills and their use as an improvement technique can reduce environmental liabilities. Therefore, it can be concluded that green coconut fibers are effective reinforcement agents for improving the geotechnical properties of expansive soils.

Below are some suggestions for future research, carry out the same tests with the same fiber content, but mixing with other environmental passives of similar particle size, carry out the same tests with the same fiber content, but of different lengths, carry out the same tests with higher fiber contents, carry out the same tests with other types of fibers and study the effect of coconut fibers for collapsible soils.

SIGNIFICANCE STATEMENT

It has been proven that the addition of coconut fiber can effectively reduce cracked areas during the drying process. The crack intensity factor (CIF) decreases as the fiber content increases, leading to a maximum reduction of non-fiber cracks of 2%. Due to the resistance to traction of the fibers, the fibers reduced the cracks keeping the sample intact with the 2% fiber reinforcement. Green coconut fibers provide the tensile strength needed in clayey soil, overcoming drying cracks, showing that the soil reinforced with green coconut fiber can be considered an efficient method to resist drying cracks. According to the results mentioned, green coconut fibers can be effectively employed as reinforcing agents to improve geotechnical characteristics of expansive soils and used as waterproof liners and covers in municipal solid waste landfills and its use as an improvement technique can reduce environmental liabilities.

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