ISSN: 2447-3359

REVISTA DE GEOCIÊNCIAS DO NORDESTE

Northeast Geosciences Journal

v. 10, nº 2 (2024)

https://doi.org/10.21680/2447-3359.2024v10n2ID36735

Hydromechanical Behavior and Crack Formation Process in Expansive Soil Reinforced with Green Coconut Fibers

Comportamento hidromecânico e processo de formação de fissuras em solo expansivo reforçado com fibras de coco verde.

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Abstract: Green coconut fibers discarded in unsuitable locations become environmental liabilities. In this research, the feasibility of reusing coconut fibers as reinforcement in expansive soil in Paulista/PE is investigated through laboratory experiments, in a sample of compacted soil and in mixtures with coconut fibers in weight proportions of 0.25%; 0.50%; 1.00% and 2.00%. Tests were carried out on: granulometry, consistency limits, compression, expansion tension, hydraulic conductivity and analysis of crack formation due to drying. The potential for expansion, with the addition of fibers, there is a reduction in the soil expansion tension from 101.7 kPa for natural soil to 25.8 kPa for soil with 1% coconut fiber, a reduction of 74.63%. The tensile strength due to diametral compression increases 42% when adding 2% fiber to the natural soil. In relation to simple compression, it showed an increase in maximum tension of 57.49%. Hydraulic conductivity does not change, values do not exceed permeability (10^{-9} m/s). The crack intensity factor (CIF) decreases as the fiber content increases. The insertion of green coconut fibers into the expansive soil improves all investigated geotechnical characteristics of the expansive soil.

Keywords: Hydromechanical Behavior; Crack Formation; Expansive Soil.

Resumo: As fibras de coco verde descartadas em locais não adequados tornam-se passivo ambiental. Nesta pesquisa, a viabilidade de reutilizar fibras de coco como reforço, em solo expansivo de Paulista/PE, é investigada através de experimentos laboratoriais, em amostra do solo compactado e em misturas com fibras de coco nas proporções em peso de 0,25%; 0,50%; 1,00% e 2,00%. Foram realizados os ensaios de: granulometria, limites de consistências, compressão, tensão de expansão, condutividade hidráulica e de análise de formação de fissuras por secagem. O potencial de expansão, com o acréscimo de fibras, há redução na tensão de expansão do solo de 101,7 kPa do solo natural para 25,8 kPa para o solo com 1% de fibra de coco, uma redução de 74,63%. A resistência à tração por compressão diametral cresce 42% ao se adicionar 2% de fibra ao solo natural. Em relação à compressão simples, apresentou aumento na tensão máxima de 57,49%. A condutividade hidráulica não se altera, os valores não excedem a permeabilidade de (10^{-9} m/s). O fator de intensidade da fissura (CIF) diminui à medida que o teor de fibras aumenta. A inserção de fibras de coco verde ao solo expansivo melhora todas as características geotécnicas investigadas do solo expansivo.

Palavras-chave: Comportamento Hidromecânico; Formação de Fissuras; Solo Expansivo.

Received: 26/06/2024; Accepted: 26/08/2024; Published: 13/10/2024.

1. Introduction

Unsaturated soils are common in nature and are found in most geotechnical infrastructures, including earth slopes, pavements, embankments, earth dams, irrigation canals, and sometimes natural or compacted expansive soils subject to water content (suction). Climate plays a significant role in the behavior of unsaturated soil. For example, during the dry season with low precipitation, the soil exhibits lower water content levels, potentially leading to desiccation and high suction, which can affect the soil's strength. Conversely, during rainy periods, increased rainfall and soil water content reduce suction and, consequently, soil strength.

In expansive soils, characteristic cracks or fissures are observed in the field during dry seasons, while during rainy seasons, expansion may occur. According to Zhang *et al.* (2020), expansive soils, composed of highly hydrophilic materials such as montmorillonite and illite, are sensitive to changes in suction. As demonstrated by Ng *et al*. (2003), climate can significantly impact the hydromechanical behavior of expansive soils, potentially causing severe damage to structures built on them. Nelson *et al*. (1992) reported that, in a typical year in the United States, expansive soils can cause greater financial losses to homeowners than earthquakes, floods, tornadoes, and hurricanes combined. Driscoll *et al.* (2000) observed that the estimated average annual cost for expansive soil-related claims in the insurance sector, according to the British Insurance Association, exceeds 400 million pounds.

On the other hand, the high consumption of green coconut, valued for its nutrition, mineral content, and taste among Brazilians, generates a substantial environmental problem due to the significant volume and weight of coconut husks. Brazil, responsible for nearly 5% of global coconut production, is the fourth largest producer. It is essential that sustainability be discussed in all areas and fields of knowledge, aiming to include more sustainable processes, materials, and methodologies, thus reducing consumption and promoting the reuse of waste generated in these processes. In this context, Misra *et al.* (2011), stated that geotechnical engineering should not be excluded from this discussion and must seek more sustainable methods and technologies due to its fundamental importance in civil construction projects.

Kar e Pradhan (2011) studied the unconfined compressive strength and direct shear strength of a clayey soil located in Burla, India, mixed with coconut fibers and polypropylene fibers. The fiber contents used were 0.2%, 0.4%, 0.6%, 0.8%, and 1%. For the unconfined compression test, the best results were obtained with 0.6% fiber, achieving an unconfined compressive strength of approximately 160 kPa, with this strength decreasing to 140 kPa at 0.8% fiber content. Narani, *et al*. (2019) studied the hydromechanical behavior of an expansive clayey soil located in Tehran, Iran, mixed with nylon fibers in proportions of 0.1%, 2%, 3%, and 4%. They observed an increase in strength and a decrease in expansion potential with the addition of fibers up to a percentage of 3%. They also noted that with the increase in fiber content, there was an increase in the optimum water content content and a decrease in the maximum dry unit weight of the mixtures on the Proctor curve. Chaduvula *et al* (2016) They conducted drying tests on clay from Nanded, India, reinforced with synthetic PET fibers in proportions of 0%, 0.25%, 0.50%, and 0.75%. The unreinforced soil exhibited uniform, long, and thick cracks, while the reinforced soil showed fewer cracks of smaller area, with the appearance of cracks being delayed. In an attempt to find an alternative to mitigate the problems of expansive soils in Geotechnical Engineering and to provide a solution for the use of green coconut fibers, thereby reducing environmental liability, this research aims to investigate the hydromechanical behavior of expansive soils in the municipality of Paulista, PE, Brazil, reinforced with green coconut fibers. The general 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 such material, with an emphasis on the performance of these mixtures regarding crack formation and propagation.

2. Methodology

The deformed samples of expansive clay soil come from Brazil, specifically from the municipality of Paulista in the state of Pernambuco, collected at the Wastewater Treatment Station of the Sanitation Company in the state of Pernambuco (COMPESA). The coconut fibers were obtained in processed form from a company based in Fortaleza, CE, Brazil. Currently, the technology used to process coconut husk waste and extract coconut fibers involves the use of machines. The pressed material is then classified; long fibers are separated from short fibers and powder using a screening device with fixed helical hammers and a perforated sheet. In this study, short fibers were used as they are less applicable compared to long fibers. All data were experimentally obtained in the laboratory using the methods described by Abbaspour *et al.* (2019). Table 1 presents the physical characterization of the soil and fibers.

Table 1 – Physical characterization of the soil and fibers.

Physical Indices and Geotechnical Classification	Soil	Green coconut fiber
Maximum dry unit weight (kN/m³)	16.04	
Optimum water content (%)	21.30	
Water absorption (%)	-	414.00
Particle density (kN/m³)	26.70	12.60
(%) Gravel	0	
(%) Sand	31	
(%) Silt	31	
(%) Clay	38	
Liquid limit (%)	52	
Plastic limit (%)	21	
Plasticity index (%)	31	
Activity index	0.76	
AASHTO classification	A-7-6	
USCS classification	CH	
Tensile Stress (MPa)	-	239.71
Young's modulus (GPa)	-	2.16

Source: Faustino (2022).

2.1 Experimental Program

The methodological procedures in the geotechnical investigation program of an expansive soil in the municipality of Paulista/PE, Brazil, are presented, with the aim of obtaining the physical, rheological, and hydromechanical characterization of the natural soil and its mixtures with green coconut fibers (soil-0.25% Fiber, soil-0.5% Fiber, soil-1% Fiber, and soil-2% Fiber). The program was divided into 4 stages.

The first stage involves the preparation of the soil and fibers used in the research, as well as the physical characterization of these materials through laboratory tests, following the standards of the Brazilian Association of Technical Standards (ABNT, 2016a, 2016b, 2016c, 2016d, 2016e) and the American Society for Testing and Materials ASTM (2021).

In the second stage, the percentages of green coconut fibers were defined. The proportions used are 0.25%, 0.50%, 1.00%, and 2.00%. The fiber diameter is 0.3 mm (ranging between 0.27 and 0.50 mm), and its length is 20 mm (ranging between 10 and 30 mm), meeting the recommendations of Abbaspour *et al*., (2019), Kodicherla *et al*., (2019) e Mandeep *et al*., (2020). The mixing process began with the addition of 50% of the total volume of distilled water to the soil to achieve the desired water content for the mixture. The adhesion induced in the soil by this amount of water facilitates the random distribution of the fibers (Abbaspour *et al*., 2019), subsequently, the designated amount of fibers (0.25%, 0.5%, 1.00%, 2.00%) was added along with the remaining amount of water. The mixture was homogenized until there was a visual uniformity of the soil with the fibers. The mixtures were kept in impermeable and airtight plastic bags for 48 hours to ensure uniform water content in the mixture.

In the third stage, hydraulic and mechanical tests were conducted on the natural soil and the mixtures compacted to their respective optimum water content and maximum dry unit weight. The permeability coefficient was assessed according to the ABNT NBR 14545/2000 standard using a flexible-wall permeameter (Tri-flex 2) with samples of 127 mm height and 100 mm diameter. The saturation of the specimens was carried out by backpressure, applied in stages, starting at 50 kPa and increasing to 200 kPa over a duration of 6 hours. After saturation, a consolidating confining stress of 220 kPa was applied, maintaining a stress of 200 kPa at the base of the sample and reducing the pressure at the top of the sample to 50 kPa, creating a hydraulic gradient of 150 kPa for vertical and upward water percolation through the samples.

The swell potencial tests and expansion stress tests followed the recommendations of the standard D 4546 (ASTM, 2021). The unconfined compression tests and the diametral compression tensile tests were conducted according to the standards NBR 12770 (ABNT, 2011) and NBR 7222 (ABNT, 2011). Figure 1 shows details of the permeability, swell potencial, unconfined compression, and diametral compression tensile tests.

Figure 1 – Hydromechanical Tests: a) Permeability test ; b) Swell potencial test; c) Unconfined compression test e d) Diametral compression tensile tests.
Source: Authors (2024).

In the fourth stage, the influence of the addition of green coconut fibers on the crack propagation process in the expansive soil and its mixtures is assessed. The apparatus and methodology proposed by Ferreira *et al.* (2020) are used. The assembled apparatus is capable of monitoring the ambient temperature, relative humidity of the environment, and the water content variation of the sample subjected to drying and wetting cycles, as shown in Figure 2. Soil and mixture samples were homogenized to achieve uniform water content equilibrium at 1.1 times the value of the Liquid Limit, compacted into Petri dishes with a diameter of 150 mm and a height of 15 mm with the aid of a plastic tamper, which was used to spread the soil in the mold and remove air bubbles. The plate-soil/mixture assembly was placed on a scale with a capacity of 2,000 g and a sensitivity of 0.01 g. This procedure allowed for real-time weight measurements of the assembly, thereby enabling the calculation of the soil water content at any given moment. Incandescent lamps and the laboratory air conditioner were turned on before the start of molding (approximately 2 hours before the actual testing) in order to stabilize the initial ambient temperature. The entire assembly is housed inside a Medium Density Fiberboard (MDF) cabinet to ensure partial isolation from the environment and to prevent external interference such as improper handling. To monitor the crack formation process, images were captured using webcam Logitech C922 PRO STREAM Full HD connected to a notebook.

Using the free software Auto Screenshot Capture, it was possible to control the automatic image capture at a predetermined interval of 10 minutes. Image analysis was conducted using the ImageJ.exe software, which allowed for comparisons between the crack patterns of the tested samples, determining the time of appearance of the first cracks in each 2D image, and calculating the geometric indices: a) o Crack Intensity Factor – CIF, this corresponds to the intensity of cracking in a sample, measured by the ratio between the surface area that has cracked at any given time and the surface area of the sample in its initial state.; b) The crack width is calculated as the shortest distance from a stochastic point on one edge to the opposite boundary of a crack segment.; c) o comprimento total de fissura é calculado, contando o número total de pixels branco após a imagem ter sido esqueletizada; d) The total crack length is calculated by counting the total number of white pixels after the image has been skeletonized. The number of crack segments, defined as the elements between two adjacent intersections, are considered as a crack segment, according to Tang *et al.* (2019).

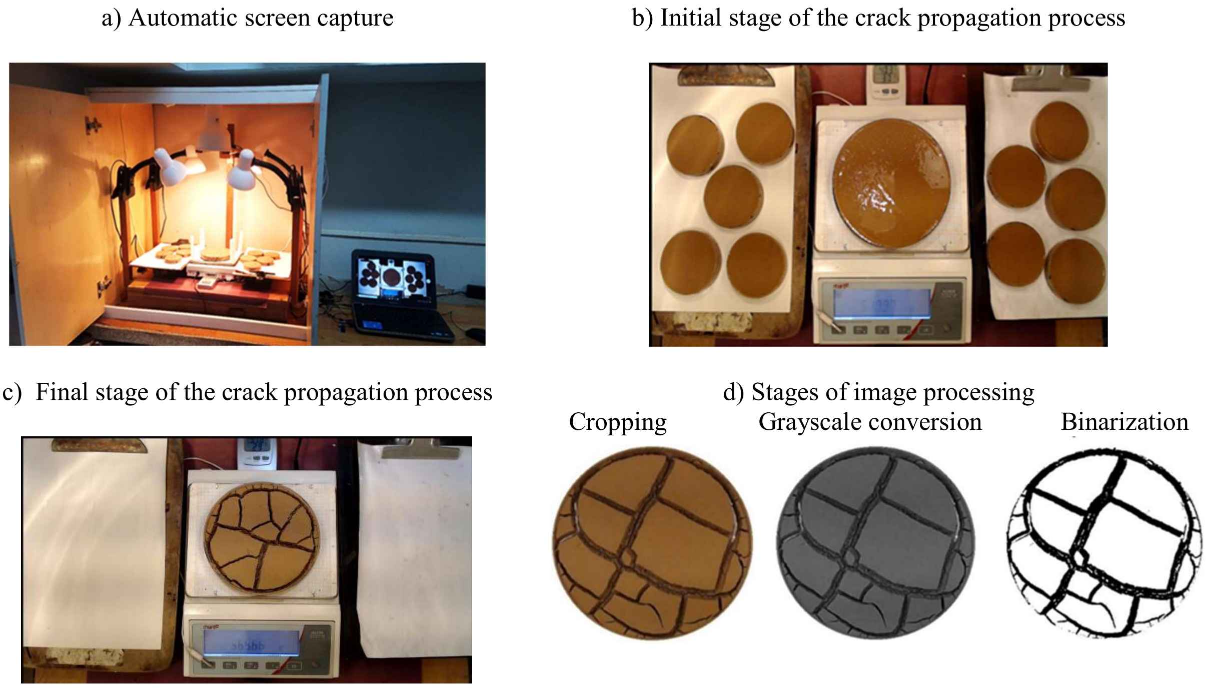


Figure 2 – Monitoring the process of crack formation and propagation due to drying.
Source: Authors (2024).

In the fourth stage, tests were also conducted to determine the water retention curve of the soil and mixtures. Smaller plates were placed inside the apparatus, but outside the scale, to measure suction. The total suction of the soil and mixtures was measured using the filter paper technique during the crack formation process, following the guidelines established in the ASTM D5298 standard (ASTM, 2010). The aim was to evaluate the influence of the addition of coconut fibers on the water retention of the studied soil. The water retention curve was constructed through the drying of samples and filter paper, using Whatman No. 42. Starting from the saturated condition, the samples were dried in the crack formation apparatus. Every 5% decrease in gravimetric water content, the smaller plates were removed, and filter papers were placed in direct contact with the samples to determine the corresponding matric suction of the water content in the sample. After this stage, the samples with the filter papers were wrapped in layers of plastic film (PVC) and aluminum foil. A water content equilibration period of 7 days for the sample-paper assembly was adopted. During this period, the samples were kept in a polystyrene box. Subsequently, the filter papers and part of the wet soil were weighed and placed in capsules and dried in an oven at 100°C for 24 hours. Then, they were weighed on a scale with a sensitivity of 0.001 g to determine the equilibrium water content content of the soil and mixtures.

3. Results

The influence of the addition of green coconut fibers on the hydromechanical behavior and crack formation process of expansive soil in the municipality of Paulista-PE is analyzed here.

3.1 Influence of adding green coconut fibers on the hydromechanical behavior of the soil

The addition of green coconut fiber in proportions of 0.25%, 0.50%, 1.00%, and 2.00% to the expansive soil of Paulista/PE, Brazil does not significantly alter the real density and grain size distribution. A similar observation was found by Menezes *et al.* (2019). 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 the LL increases more than the LP, the plasticity index rises from 30.75% (soil) to 41.77% (soil-2% fiber), as shown in Table 2. Similar results were found by Abbaspour *et al.* (2019) and Mandeep *et al.* (2019), when analyzing the behavior of an expansive clay from India, reinforced with coconut fiber.

Table 2 – Values of liquid limits, plasticity limits, and plasticity indices of the soil with fiber contentes.

Fiber Content (%)	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index (%)	Variation of Plasticity Indices (%)
Base Soil	52.56	21.81	30.75	-
Soil+0.25%Fibers	58.7	25.11	33.59	2.84
Soil+0.5%Fibers	59	24.94	34.06	3.31
Soil+1%Fibers	64.5	25.92	38.58	7.83
Soil+2%Fibers	69.4	27.63	41.77	11.02

Source: Authors (2024).

The maximum dry bulk density decreases with the increase in fiber percentage. This may be due to the coconut fiber being a light material and a substitute for the soil, which leads to a reduction in the mixture's densities, according to Kodicherla *et al.* (2019). As the percentage of coconut fibers increases, there is an increase in the optimum water content of the mixture, which may be due to the water adsorption by the fibers, Shukla *et al.* (2017), Figure 3.

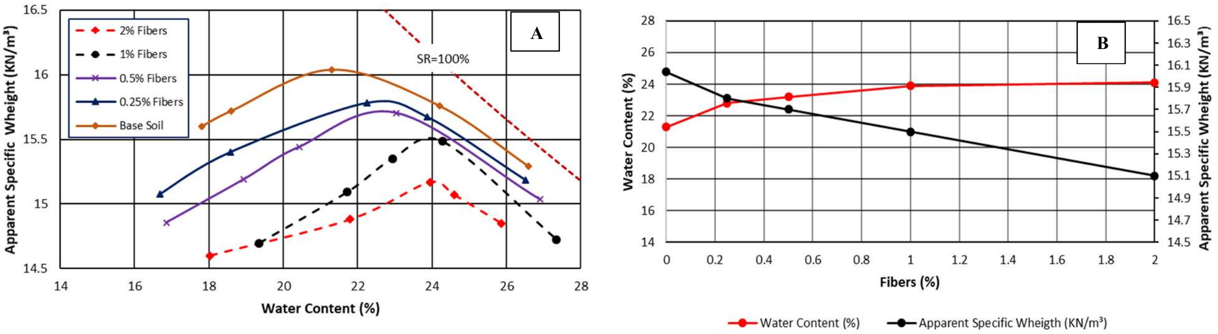


Figure 3 – Compaction curves of Natural Soil and dry Coconut Fiber-Soil mixtures with fiber content. a) Compaction curves; b) Variation of water content and apparent specific weight.
Source: Authors (2024).

The natural soil has a permeability coefficient of 2.64 x 10^{-10} m/s. It is noticeable that mixtures with 0.25%, 0.5%, 1%, and 2% of coconut fibers showed permeability coefficient values similar to those of the natural soil: 3.45 x 10^{-10} cm/s, 2.76 x 10^{-10} m/s, 2.99 x 10^{-10} m/s, and 2.62 x 10^{-10} m/s, respectively. Thus, the fiber content did not significantly affect permeability.

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 natural soil. Such trends have been reported by other researchers and are often attributed to the soil-fiber interaction. This effect was reduced with extremely high fiber contents, as observed by Narani *et al*. (2019). A fiber content of 2% can be considered the level at which the expansion potential is most significantly reduced.

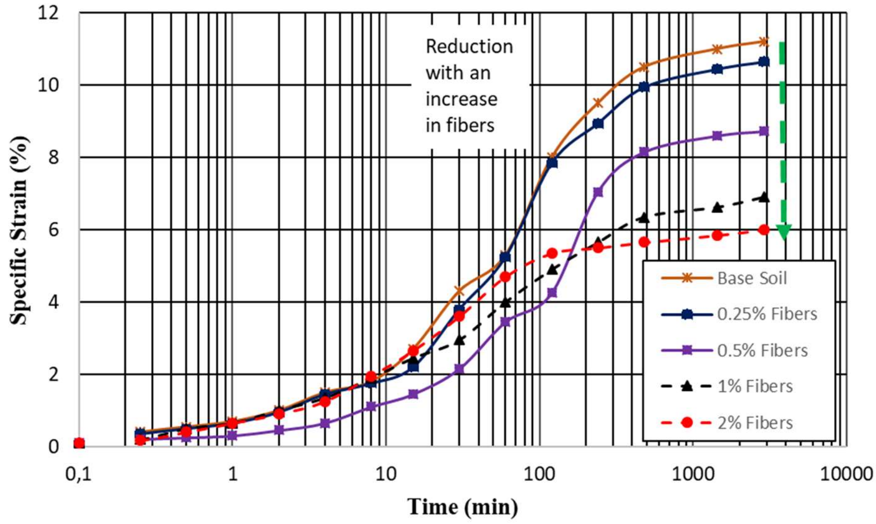


Figure 4 – Results of 'free' expansion tests.
Source: Authors (2024).

Table 3 presents the expansion pressure obtained by the constant volume method and for soil-fiber mixtures at 0.25%, 0.5%, 1%, and 2% percentages. The natural soil compacted at optimum water content and maximum dry apparent specific weight has a pressure of 101.70 kPa, and the addition of coconut fibers resulted in a gradual reduction of expansion pressure as the fiber content in the soil increased. For the studied percentages, it was not possible to completely eliminate the expansion pressure, but for the 1% coconut fiber content, the reduction was 74.63%, which may be manageable depending on the structural project to which the soil will be exposed. The expansion pressure values in natural soil compacted at optimum water content and maximum dry apparent specific weight indicate, according to the Jimenez Salas (1980) criterion, the possibility of severe damage. With the gradual addition of coconut fibers, there is a noticeable reduction in the tendency for cracking or damage to structures, ranging from Significant Cracks (0.25%), Minor Cracks (0.5%), to the possibility of no structural damage (1% and 2%).

Table 3 – Expansion pressure values by the constant volume method.

Fiber Conten	Expansion pressure (kPa)	Reduction (%)
Base Soil	101.70	-
Soil+0.25%Fibers	77.50	23.79
Soil+0.5%Fibers	53.33	47.56
Soil+1%Fibers	25.80	74.63
Soil+2%Fibers	26.60	73.85

Source: Authors (2024).

In Figure 5, it is observed that the failure pattern in the specimens and the unconfined compressive stress increase with the addition of green coconut fibers, with an increase of 5.33% for a fiber content of 0.25%, 39.79% for a fiber content of 0.5%, reaching the highest value with 1% fiber (54.21% higher than natural soil). The axial stress-strain curves for each investigated sample are presented in Figure 5. With the maximum stress and axial strain at failure, it is observed that the increasing addition of fibers tends to increase the modulus of elasticity, further increasing stiffness and exhibiting a more ductile failure, likely because the fiber is a more flexible material than the soil. The maximum stress energy (Eu) – Resilience Modulus, which is the strain energy per volume required to stress a material from an unloaded state to its yield stress limit, is represented by the blue arrows in Figure 5.

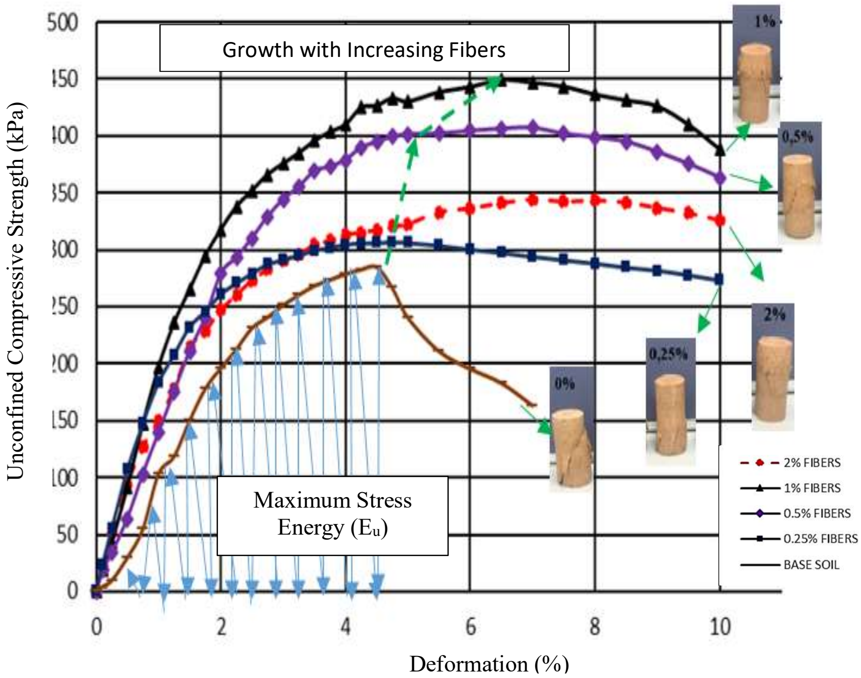


Figure 5 – Unconfined Compressive Strength of soil and mistures.
Source: Authors (2024).

The diametral compressive strength increases with the addition of green coconut fibers (Figure 6), with an increase of 6.20% for a fiber content of 0.25%, 19.03% for a fiber content of 0.5%, 32.05% for a fiber content of 1%, reaching the highest value with 2% fiber, 41.93% higher than natural soil. The fibers increase the maximum strength and induce a strain-hardening behavior in the mixture, controlling and mitigating stress by transferring stress through cracks to the fibers, which share the load in tensile stresses.

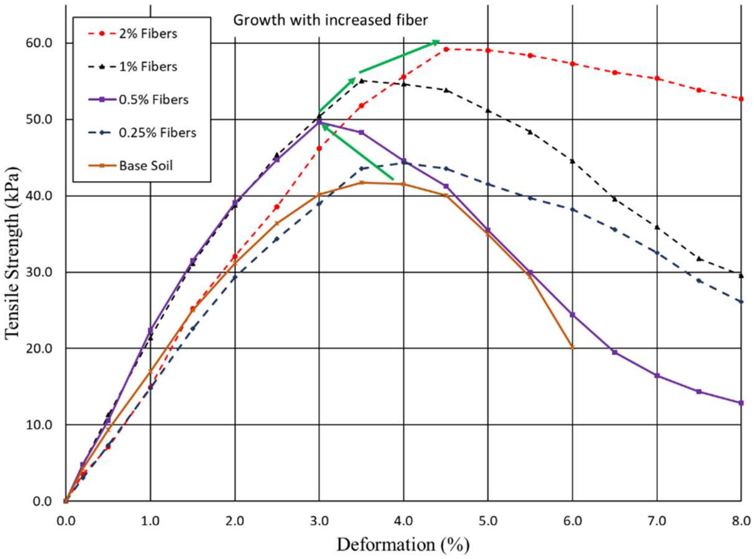
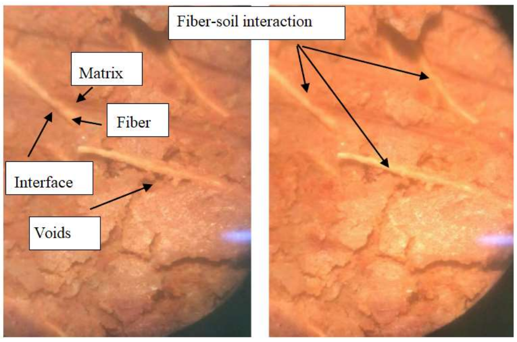


Figure 6 – Results of diametral compressive tensile strength for natural soil and different mixtures.
Source: Authors (2024).

The soil exhibits peak behavior, typical of brittle materials, with an increase in strength observed at 4.5% strain (Figure 6). After this deformation, there is a decrease in the applied stresses. For the mixtures, a plastic behavior with slight softening is observed. There was also an increase in the modulus of elasticity with the addition of fibers up to 1%. Similar observations were made by Kar *et al.* (2014) and Sarah *et al.* (2019).

Figure 7 shows images of the soil-fiber interaction after compaction for the soil+1% fiber mixture. The interaction was observed through an optical microscope with 100x magnification, which was used to analyze the soil-fiber interaction post-compaction. It is observed that the fibers were randomly distributed in the soil, with good physical interaction. It is also noted that, with shear cutting, the fibers shifted, leaving indentations.

a) Interaction after compaction for the soil+1% fiber mixture

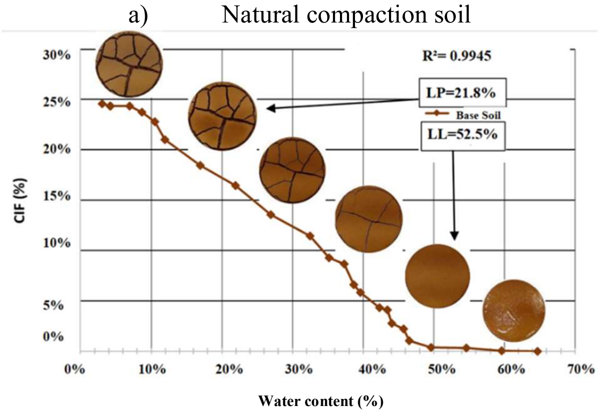


b) Soil Interaction in the Crack Formation Process

Figure 7 – Interaction Soil-fibers: a) after compaction for the soil+1% fiber mixture; b)In the Crack Formation Process. Source: Authors (2024).

3.2 Influence of Adding Green Coconut Fibers on the Formation and Propagation of Cracks Due to Drying

The process of crack formation due to drying starts within the sample along with soil contraction, radiating inward with greater intensity. The sequential pattern of cracks occurs simultaneously across the entire surface of the soil, leading to a subdivision of the initial area. The gradual loss of water content leads to the propagation of cracks in diverted directions, causing bifurcations at certain points. The shapes of the crack patterns at intersections are predominantly in the form of “X” or “Y,” forming geometric elements. Primary cracks and subsequent propagation from the center to the edges contribute to the development of the surface crack network, as shown in Figure 8. Images were selected to assess the evolution of cracks and the determination of CIF during the drying of the samples. All tests showed a color change from wet soil to dry soil color after drying at the end of the tests (through photographic analysis). No significant color change occurred in the early stages of drying, indicating that water content loss was uniform across the surface of the sample during the initial drying state.



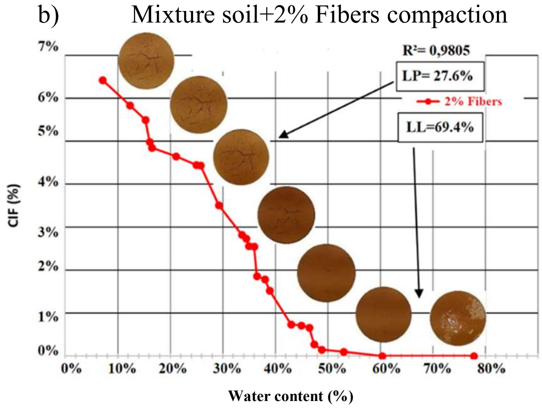


Figure 8 – Curve CIF versus water contente: a) Natural compaction soil; b)Mixture soil+2% Fibers compaction. Source: Authors (2024).

The initial water content of the test with natural soil is 57.8% (corresponding to 1.1 times the liquid limit) and the void index is 1.51. The sequence of images in Figure 8a shows the appearance and evolution of cracks over approximately 28 hours of testing. This test showed the appearance of cracks directed from the edge to the center, due to soil contraction. Considering that the test lasted 28 hours, that the first cracks appeared at 7.1 hours and that after 24 hours of observation, basically no further crack development was observed, the cracking process lasted 9.3 hours. As soil water content decreased, contraction and propagation of secondary cracks occurred across the entire soil surface. In general, a secondary crack originates from a primary crack, showing a “T” or “Y” shape, similar to that found by Tang *et al.,* (2012) and Ferreira *et al*, 2020. The initial water content of the soil + 2% fiber mixture is 76.34% (corresponding to 1.1 times the liquid limit) and a void index of 1.51. The sequence of images in Figure 8b shows the appearance and evolution of cracks over approximately 30 hours of testing. This test showed the appearance of small cracks directed from the edge to the center, due to soil contraction. Considering that the test lasted 30 hours, that the first cracks appeared after 10 hours and that, after 24 hours of observation, there was practically no further development of cracks, the cracking process lasted 14 hours. As soil water content decreases, secondary cracks contract and propagate across the entire soil surface. In general, a secondary crack originates from a primary crack, showing a “Y” and “X” shape, but much smaller in relation to the previous mixtures. There was a large reduction in the CIF across the entire section in relation to the compacted natural soil (Figure 8b). The final CIF of the compacted natural soil is 24.3%, while the CIF of the soil reinforced with 2% fiber is 6.43%, representing a reduction of 73.53%. In Figures 16 and 17, in the CIF versus water content curve, a linear increase in the CIF can be observed with the loss of water content, from 48.84% to 7.13% water content, where the CIF has a tendency to stabilize. In unreinforced soil, primary cracks start at the surface, when the tensile strength limit of the soil is due to the attraction caused by traction, and due to the absence of any tensile reinforcement, extend throughout the depth, Sinals *et al*. (2016). This behavior can be observed in Figure 9, showing an increase in the cracked area with increasing sample suction.

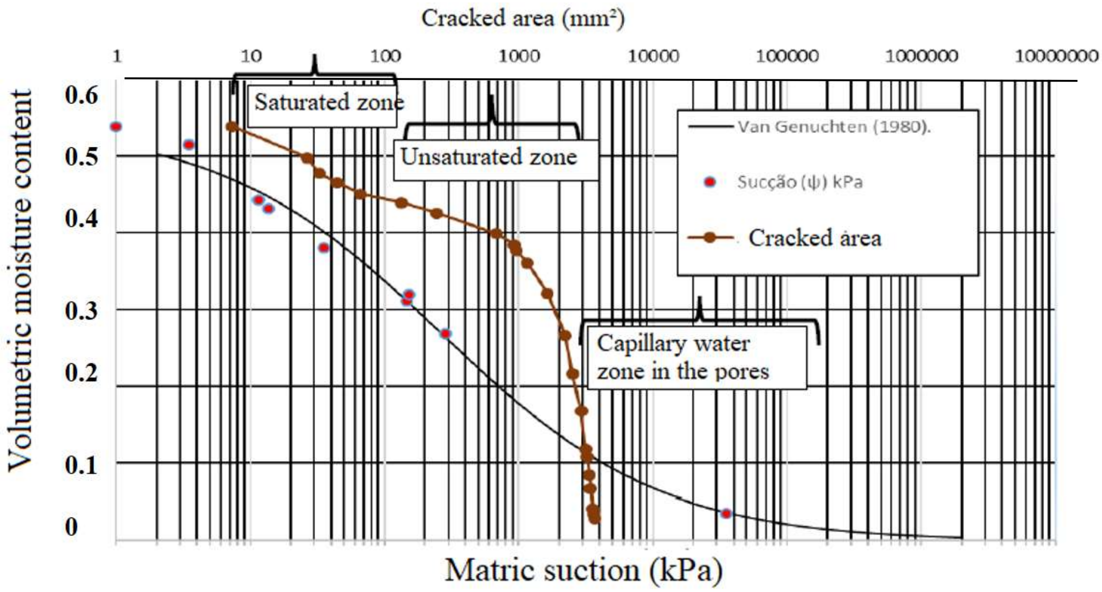


Figure 9 – Correlation between the cracked area and soil suction.
Source: Authors (2024).

Analyzing the images of the tests with samples of natural soil, Soil+0.25% Fiber, Soil+0.5% Fiber, Soil+1% Fiber and Soil+2% Fiber, it is observed that the cracks follow a different pattern for each percentage of coconut fiber added to the compacted soil (Figure 10). There is a significant reduction in the cracked area of the expansive clayey soil Paulista/PE with the increase in green coconut fibers, which shows the comparison between the natural soil and the reinforced soil, Figure 10.

4 Discussions

Laboratory tests were carried out to evaluate the cracking potential and hydromechanical behavior of an expansive soil from Paulista, Pernambuco, unreinforced and reinforced with varying proportions of green coconut fiber. The actual density of the mixture remained practically unchanged. A similar observation was found by Menezes *et al.* (2019). The addition of coconut fibers to the soil increases the LL more than the LP; similar results were found by Abbaspour *et al.* (2019) e Mandeep *et al.* (2019), when analyzing the behavior of an expansive clay from India reinforced with coconut fiber.

The hydraulic conductivity remained unchanged and is in the order of 10^{-10} m/s, both in the natural soil and in the mixtures, indicating that the increase in fiber content did not significantly alter the permeability. It is noted that the fine soil matrix surrounded the fibers, not creating preferential percolation paths. It is important to emphasize that, although coconut fiber is a material that is difficult to biodegrade, tests must be performed to evaluate the behavior of hydraulic conductivity and other properties over time.

"Free" expansion and expansion stress decrease with the addition of green coconut fibers to values up to 2% of addition. The expansion stress values obtained by the constant volume method are high (101.70 kPa) for small and medium-sized buildings and for many geotechnical engineering infrastructure works, and can cause serious damage, according to the criteria of Jimenez Salas (1980). With the addition of coconut fibers to the soil, there is a reduction in the cracking process and structural damage is reduced, going from Major Cracks (0.25%), Small Cracks (0.5%) to the possibility of there being no damage to the structures (1% and 2%), according to the same criteria. The stress versus deformation curve in simple compression tests shows peak behavior, typical of friable material, with an increase in resistance being recorded when the deformation is 4.5%, Figure 5. After this deformation, there is a decrease in the applied stresses. For the mixtures, a plastic behavior is observed with small softening. There was also an increase in the modulus of elasticity with the increase in fibers up to 1%; similar behaviors were obtained by Kar, Pradhan and Naik (2014) and Sarah and Hussein (2019).

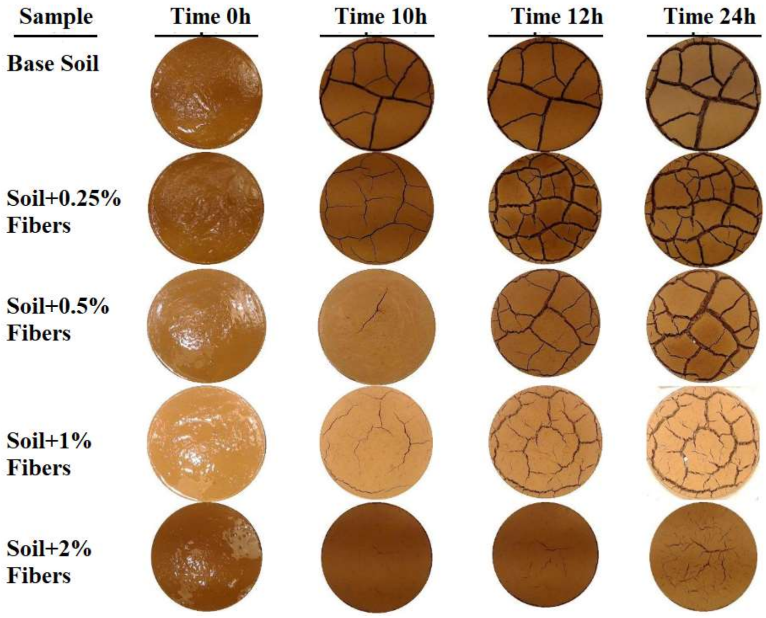


Figure 10 – Comparison of crack formation and propagation over time in soil and mixtures.
Source: Authors (2024).

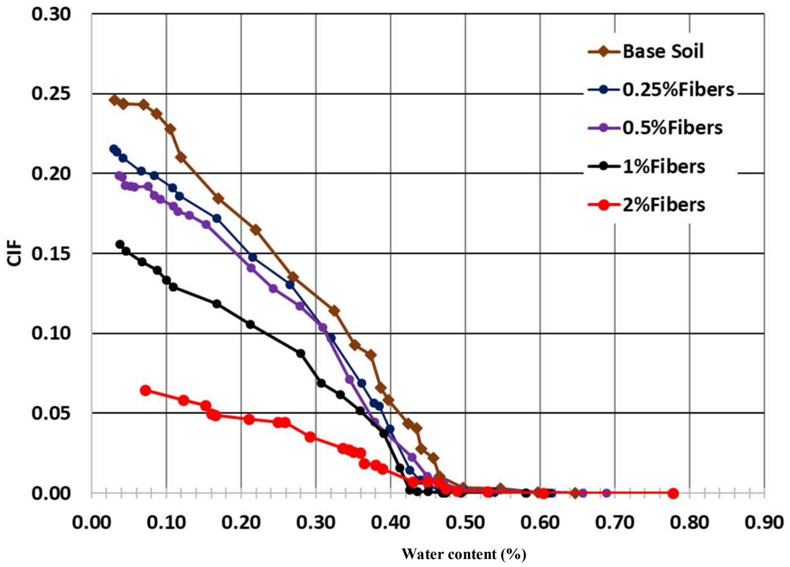


Figure 11 – Evolution of CIF versus Natural soil water content and soil+fiber mixtures.
Source: Authors (2024).

5 Conclusions

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 crack reduction of 2% in the soil-fiber mixture. Due to the tensile strength of the fibers, they reduced cracking, while keeping the sample intact with 2% fiber reinforcement. Green coconut fibers provide the necessary tensile strength in clayey soils, overcoming drying cracks, showing that 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 used as reinforcing agents to improve the geotechnical characteristics of expansive soils and used as impermeable linings and covers in urban solid waste landfills and their use, as an improvement technique, can reduce environmental liabilities.

According to the above-mentioned results, it can be inferred that green coconut fibers can be effectively used as reinforcing agents to improve the geotechnical characteristics of expansive soils and to reduce soil expansivity. Therefore, it can be concluded that green coconut fibers are effective reinforcing agents to improve the geotechnical properties of expansive soils.

Acknowledgements

The authors thank the Federal University of Pernambuco for helping them conduct experiments on their campus and Compesa for free access to the Janga Sewage Treatment Plant for sample collection and monitoring of field tests.

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