

Geotechnical Behavior and Soil-Fiber Interaction of Clayey Soil Mixed with Randomly Dispersed Coconut Fibers

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Abstract. This study aims to experimentally analyze the influence of the addition of different amounts of short coconut fibers on the geotechnical properties of tropical clay soil. Samples with 0, 0.5, 1, and 2 wt% of fiber in regard to the dry weight of soil were analyzed. Compaction, direct shear, compressibility, hydraulic conductivity, scanning electron microscopy (SEM), and energy dispersive spectroscopy (EDS) tests were performed on samples. The best results for the direct shear test were presented by the sample with 1 wt% of fiber. For the compressibility, the results improved proportionally to the added content of coconut fiber. Samples with less than 1 wt% did not show any significant changes in the hydraulic conductivity test; the hydraulic conductivity remained of the order of magnitude of 10^{-7} cm/s. The SEM and EDS analyses revealed the existence of bonds between the particles of clay and coconut fibers surface. The geotechnical behavior of the mixes with 0.5 and 1 wt% was improved because of this bond between the matrix and reinforcement phase.

Keywords: clayey soil-coconut fiber bond, compressibility, hydraulic conductivity, reinforced soil, shear strength.

1. Introduction

Clay soils have many applications in geotechnical engineering projects, most of them concerning their low hydraulic conductivity coefficient. For instance, they are vastly used for building contaminant barriers and landfill layers. Furthermore, for these types of practical applications, besides the hydraulic conductivity, the material should also present proper mechanical properties and low compressibility. These aspects are important and should not be neglected because the material is subjected to certain loads that may break it apart. Moreover, highly compressible materials can deform exaggeratedly, which may compromise the integrity of a compacted layer.

Gathering materials that combine all these crucial characteristics is the biggest challenge because of certain limitations, such as the lifespan of deposits or distance between deposits and application sites. Therefore, it is necessary to resort to different alternatives, such as the development of new materials that are both sustainable and possess similar or even better characteristics than conventional materials.

Geotechnical materials can be developed by reinforcing soil with short and randomly spread fibrous materials (Kumar & Sharma, 2018). This technique has proven its efficiency, especially with regard to the mechanical behavior of the resulting material. Many studies reported that the inclusion of fibers in a soil matrix, primarily with fine grains, raises the shear resistance of the material (Donato *et al.*, 2004; Babu & Vasudevan, 2008; Maliakal & Thiyyak-

kandi, 2013; Mohamed, 2013). However, better understanding of how this technique can affect other geotechnical properties of the soil-fiber compound is required.

The performance of a soil-fiber mixture depends not only on the individual properties of the constituents, but also on the compatibility between the fibers and soil. The interface between reinforcement and matrix constitutes the contact area of the elements in the blend and is essential for the transmission of mechanical tensions from the matrix to the reinforcement (Tang *et al.*, 2010). Therefore, the bond between fibers and soil is indispensable for improving the properties of the composite. According to Donato *et al.* (2004), clay soil matrices have reasonable bonding to fiber surfaces because of the format, size, and load distribution of the clay minerals. Rosário *et al.* (2011) found that vegetal fibers present predominantly polar surface energy, making them suitable for reinforcing matrices with polar electrostatic nature.

In Brazil, fibrous residues coming from green coconut (*Cocos nucifera*) are in the spotlight because of the great production and volume of discarded material. Approximately 85% of coconut weight, which is averagely 1.5 kg, is contained in its shell (Corradini *et al.*, 2009), which is constituted of a voluminous fibrous material with low degradation rate. Generally, these residues are inadequately discarded, causing environmental pollution, reducing the lifespan of landfills, and hosting microorganisms, which can transmit diseases. Actually, the recovery of waste to raise the useful life of landfills and to reduce negative environmental impacts is one of the main issues that

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several researchers have been trying to solve. Therefore, using the discarded coconut shells as reinforcement for soils can contribute to minimize some of these issues.

This study aims to experimentally analyze the best proportion of compacted clay soil and coconut fiber mixtures for applying it as a geotechnical material. Therefore, it is necessary to understand the effects of addition of different contents of randomly spread short coconut fibers in clay soil on the compaction, shear strength, and compressibility in different flooding conditions, as well as on the hydraulic conductivity. In addition, the elemental composition and structure of the interface formed between soil and fiber at the microscopic scale were investigated.

2. Materials and Experimental Program

2.1. Materials

The soil used was brought from the deposit of Barreiras, located in the Metropolitan Region of Recife (MRR), Pernambuco, Brazil. The soil was dried in the air and then disintegrated in the laboratory. The physical properties of the soil are listed in Table 1, and its chemical composition is presented in Table 2. All the data were obtained experimentally in laboratory.

Coconut fibers were acquired already processed by a productive community in Brazil. Currently, the technology used to benefit the residues of coconut bark and to obtain coconut fibers involves using machinery. The technological process is performed in the following steps. First, the equipment crushes whole barks or cuts through a roll of fixed knives that crush the mesocarp. Second, the crushed material is conveyed to a horizontal rotary press, which removes excess moisture from the material; at the end of this step, disaggregated fiber with liquid extract of the bark of the green coconut are obtained. 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,

Table 1 - Clayey soil physical properties.

Soil properties	Value
Particle density (g/cm^3)	2.618
Liquid limit (%)	49
Plastic limit (%)	31
Plasticity index (%)	18
USCS classification	CL
Boulder (%)	1
Sand (%)	37
Silt (%)	22
Clay (%)	40
Activity index	0.45

Table 2 - Clayey soil chemical composition.

Compound	Value
pH	5.7
Ca (cmol/dm^3)	0.7
Mg (cmol/dm^3)	0.4
Al (cmol/dm^3)	0.9
K (cmol/dm^3)	0.2
Na (cmol/dm^3)	0.5
P (cmol/dm^3)	0.01
C.O. (g/kg)	2.62
M.O. (g/kg)	4.09
N (g/kg)	0.2
Relation C/N	13.1
Fe (g/kg)	0.04

short fibers were used, because they do not have as much applicability as long fibers.

Chemical composition and some physical and mechanical properties of the fibers are presented in Table 3. All the data were obtained experimentally in the laboratory using the methods described by Satyanarayana *et al.* (2007).

2.2. Sample preparation

Compounds with 0, 0.5, 1.0, and 2.0 wt% of coconut fiber in relation to the dry weight of clay soil were studied. These values were chosen in accordance with the experiments documented in academic papers related to reinforcing soils with fibers (Prabakar and Sridhar, 2002; Mohamed, 2013); another reason was evaluation of the effect of doubled percentages of coconut fiber mass in the mixtures.

Table 3 - Physical and mechanical properties and chemical compounds of the coconut fibers.

Properties/compounds	Value
Density (g/cm^3)	1.27
Average diameter (μm)	250
Average length (mm)	22
Tensile strength (MPa)	110
Young's modulus (MPa)	2550
Chemicals	
α - Cellulose (%)	42.51
Hemicellulose (%)	15.36
Lignin (%)	41.02
Ashes (%)	2.65
Extracts (%)	3.32

The mixtures were prepared on a metallic tray, where the fibers were randomly added in small portions to the soil. Then, the mixtures were revolved using a spatula for homogenizing the material. These processes were repeated until all the fiber content was incorporated into the matrix. After that, cylindrical samples with a diameter of 10 cm and height of 12.7 cm were molded with respect to the compaction in their respective dry densities and optimum moisture content, corresponding to the values obtained in the Proctor Compaction Test, which uses the Proctor Compaction Energy, as stated by the NBR 7182 Standard (ABNT, 1988).

2.3. Experimental program

2.3.1. Shear strength test

The shear strength parameters for different composites were obtained through the direct shear test following the ASTM D3080 standard (ASTM, 2004). The samples were molded from the compacted specimens in the dry unit weight and optimum moisture content corresponding to each mixture. The tests were performed using vertical normal stresses of 50, 100, and 200 kPa. The horizontal displacement rate used in the test was 0.483 mm/min. When the stress-horizontal displacement curve did not show well-defined peak values, the shear stress peak or maximum value was adopted as the rupture point, which makes possible to obtain the shear strength, cohesion (c), and friction angle (ϕ) parameters.

The tests were conducted under non-flooded and flooded conditions. In the non-flooded condition, the samples were sheared immediately after molding. In the flooded condition, the samples were inserted into the test equipment, and water was added until the box holder was completely filled; then, the setup was left for 24 h, before the flooded test was carried.

2.3.2. Compressibility test

The compressibility parameters for different mixtures were obtained using a fixed ring-type oedometer cell with drainage at the top and bottom of a sample, as the NBR 12007 standard procedures suggest (ABNT, 1990). The samples were molded from the compacted specimens using metal rings with area of 40 cm² and height of 2 cm. The test was performed using one-dimensional compression press.

The test was performed under non-flooded and flooded conditions. For the flooded condition, water was injected into the samples at the base of the cell immediately after applying a 10-kPa load. Samples were loaded in stages of 10, 20, 40, 80, 160, 320, 640, and 1280 kPa, and the loads were held for 24 h in both scenarios. After applying the loads, the height variation of the samples was measured with strain gauges with a sensitivity of 0.01 mm at 6 s, 15 s, 30 s, 1 min, 2 min, 4 min, 8 min, 15 min, 30 min, 1 h, 2 h, 4 h, 8 h, and 24 h. After the maximum load was reached, it was discharged in stages of 640, 160, 40, and 10 kPa. Then,

the curves of the logarithm of the applied stress vs. void ratio were plotted, and the compressibility parameters were obtained using these plots.

2.3.3. Hydraulic conductivity test

The hydraulic conductivity tests were performed for different mixtures according to the procedures established in ASTM D5084-10 (ASTM, 2010). The hydraulic conductivity was measured using a flexible wall permeameter on samples with dimensions of 12.5 cm in height and 10.0 cm in diameter. The samples were compacted with the optimum moisture content and dry unit weight corresponding to each mixture. A hydraulic gradient of 100 kPa was used to generate water percolation in the samples; then, the flow measurements were taken. Systems composed of porous stone and filter paper were used at the top and bottom of the samples to prevent loss of sample particles during water percolation. At the end of the tests, the samples were exhumed for analysis of their internal integrity. The tests were repeated until three values were obtained with $\pm 10\%$ difference from each other (minimum of three and maximum of five replicates for each sample). The coefficient of saturated hydraulic conductivity of the samples was defined as the average of flow measurements.

2.3.4. Soil-fiber interface analysis

Scanning electron microscopy (SEM) analysis was performed on the surfaces of the fibers present on the shear rupture plane of the samples with different coconut fiber contents. This analysis was carried out to evaluate the microstructural interaction between the matrix and reinforcement and to understand the influence of the interface between the different phases of the blend on the geotechnical performance of the reinforced soil.

The used samples were subjected to metallization vacuum of 10⁻⁵ bar in the Department of Fundamental Chemistry of the Federal University of Pernambuco; then, they were analyzed with a scanning electron microscope belonging to the Laboratory of the Mechanical Engineering Department of the same institution. In addition to microscopic analysis, elemental microanalysis of the soil-fiber contact zone of the samples was performed on the same equipment using the X-ray energy dispersion spectroscopy (EDS) technique. This analysis aimed to characterize the interfacial chemical composition of different mixtures.

3. Results and Discussion

3.1. Compaction characteristics

The compaction curves of pure soil and mixtures are shown in Fig. 1. It should be noted that the addition of fibers reduced the dry unit weight and increased the optimum moisture content. It suggests that the increase of the fiber content resulted in blends with larger porosity.

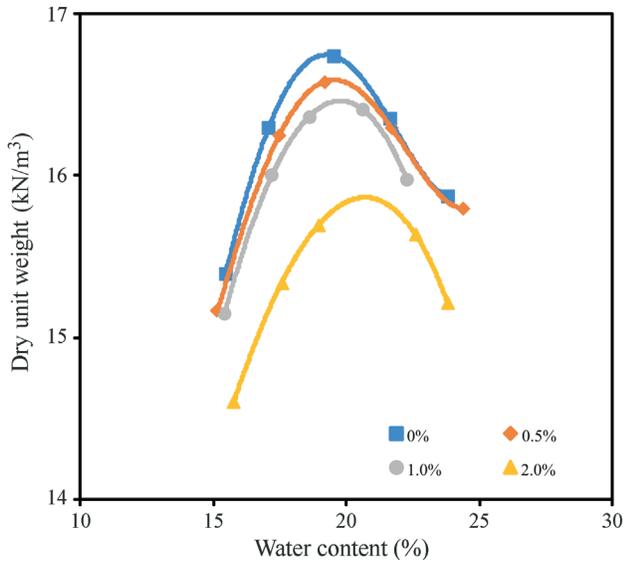


Figure 1 - Compaction curves of natural soil and soil-fiber mixtures.

The compaction parameters, maximum dry unit weight, and optimum moisture content for pure soil and different mixtures are presented in Table 4. The optimum moisture content of natural soil was 19.2%. However, the optimum moisture content of soil-fiber mixtures varied between 19.4% (mixture with 0.5 wt% of fiber) and 20.5% (mixture with 2 wt% of fiber), which is 0.2% and 1.3% more than the value of water content obtained for the natural soil, respectively. The maximum dry unit weight value for the natural soil was 16.80 kN/m³. For the mixtures, the maximum dry unit weight varied between 16.60 kN/m³ (mixture with 0.5 wt% of fiber) and 15.84 kN/m³ (mixture with 2 wt% of fiber), which is 0.2 and 0.96 kN/m³ less than the value obtained for the natural soil, respectively. Prabakar & Sridhar (2002) observed similar reduction of the maximum dry unit weight and increase of the optimum moisture content with increasing fiber content in the mixture by evaluating the addition of up to 1 wt% of randomly distributed sisal short fibers in a clay soil classified as CL by USCS from Bhopal in India. Mohamed (2013) also verified the reduction of maximum dry unit weight with the increase of the fiber content by evaluating the random inclusion of up to 1.5 wt% of hay fibers in clay soil, which

Table 4 - Compaction parameters of natural soil and soil-fiber mixtures.

Fiber content (%)	Optimum moisture content (%)	Maximum dry unit weight (kN/m ³)
0	19.2	16.80
0.5	19.4	16.60
1	19.6	16.43
2	20.5	15.84

agrees with the results obtained in this work. Meanwhile, reduction of the optimum moisture content of the mixtures with up to 1 wt% of fiber and increase of the optimal moisture content of the mixtures with up to 1.5 wt% of fiber were observed.

3.2. Shear strength

The shear stress-horizontal displacement curves obtained for natural and reinforced soils with different fiber contents (0.5, 1, and 2 wt%) in non-flooded and flooded conditions at normal stresses of 50, 100, and 200 kPa are shown in Figs. 2, 3, and 4, respectively.

The inclusion of coconut fibers in clay soil in both flood conditions increased the peak strength at all the adopted normal stress levels. The increase in peak strength was more pronounced for mixtures with 0.5 and 1 wt% of the fiber content. Furthermore, it is noted that for the higher levels of normal stress (Figs. 3 and 4), the peak strength

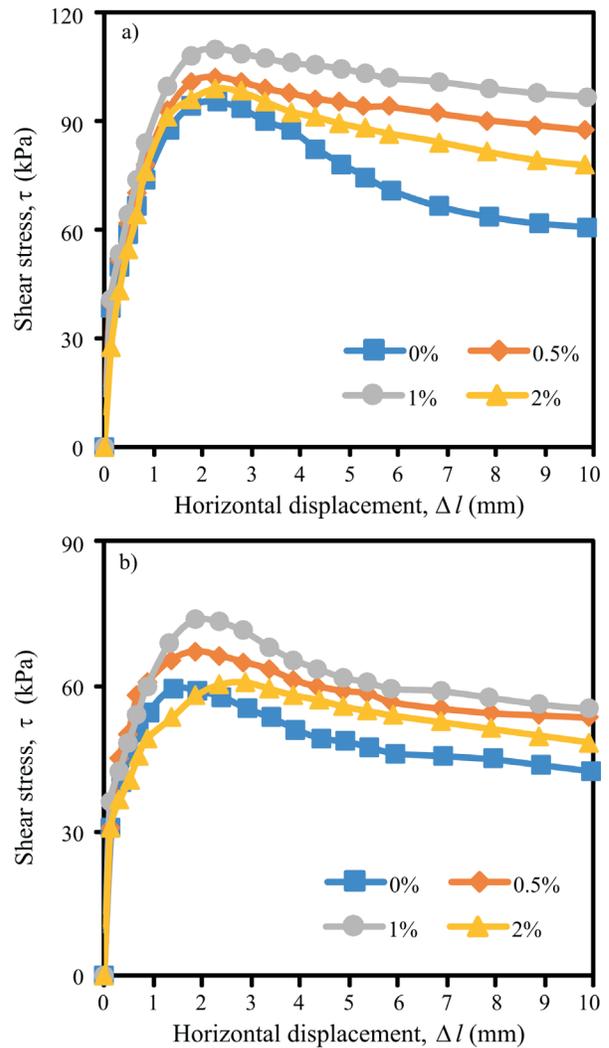


Figure 2 - Shear stress-horizontal displacement curves of natural soil and soil-fiber mixtures for normal stress of 50 kPa in non-flooded (a) and flooded (b) conditions.

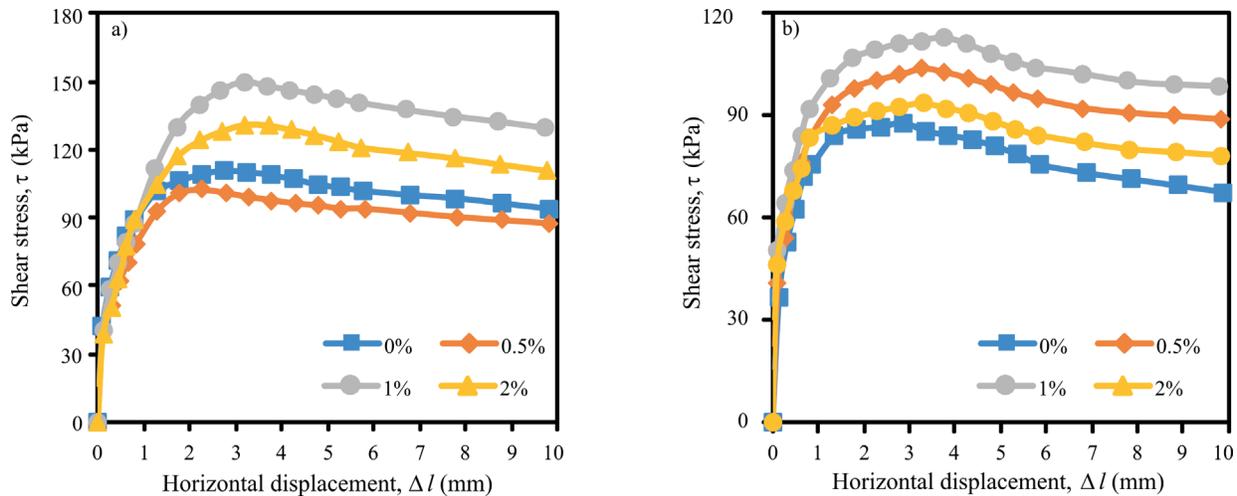


Figure 3 - Shear stress-horizontal displacement responses of natural soil and soil-fiber mixtures for normal stress of 100 kPa in non-flooded (a) and flooded (b) conditions.

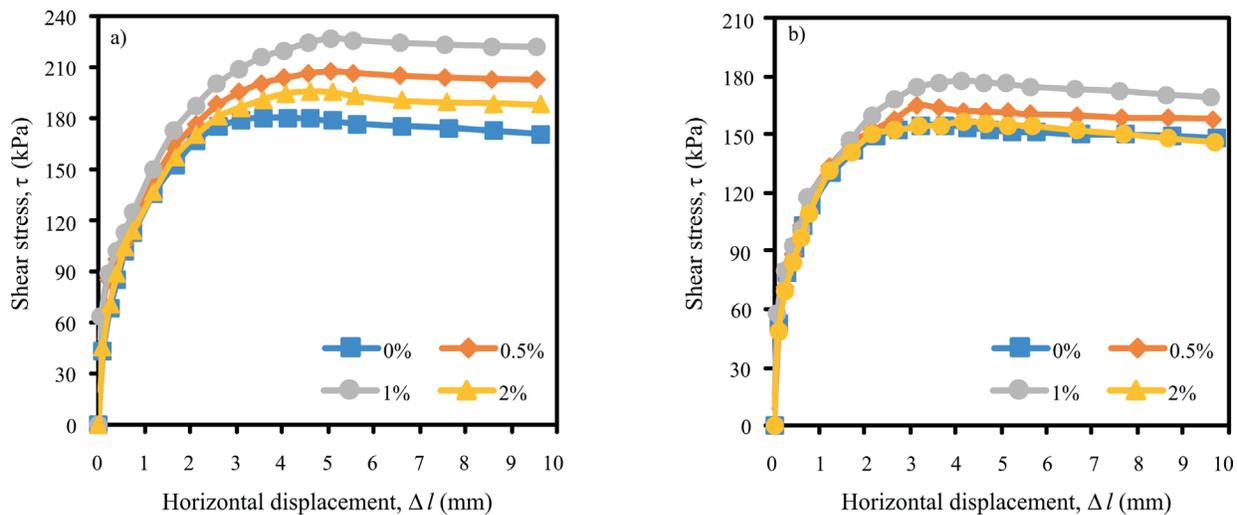


Figure 4 - Shear stress-horizontal displacement responses of natural soil and soil-fiber mixtures for normal stress of 200 kPa in non-flooded (a) and flooded (b) conditions.

gains were more evident. It was also found that with the addition of fiber and increase of the applied normal stress, there was a reduction of the post-peak strength drop. This effect was also more pronounced in the mixtures with 0.5 and 1 wt% of reinforcement. The rise of the peak strength and the decline of the post-peak drop in fiber-reinforced soils were also observed in other matrices reinforced with different types of fiber (Consoli *et al.*, 2007; Maliakal & Thyyakkandi, 2013; Mohamed, 2013; Onyejekwe & Ghattaora, 2014; Tang *et al.*, 2016).

Natural soil is fragile at the breakpoint for low levels of normal stress (Fig. 2). However, this behavior is reduced as the normal stress levels increase (Figs. 3 and 4). The reinforced mixtures with different levels of coconut fibers showed less fragile rupture behavior, which agrees with the results obtained by Tang *et al.* (2016). It occurred because

the inclusion of fibers increased the ductility and toughness of the material, especially for the 0.5 and 1 wt% contents; in these cases, the area below the shear stress vs. horizontal deformation curve is higher compared with the material with 2 wt% of fiber. In addition, there is a certain similarity between the shear stress-horizontal displacement curves of natural soil and different mixtures at levels up to 1 mm of horizontal deformation in all flood conditions and levels of normal stress adopted in the test. This suggests that regardless of the flood condition, certain deformation of the matrix is required for the fiber reinforcement to take a noticeable effect. Presumably, from this point, the matrix-reinforcement assembly contributes simultaneously to the shear strength of the soil-fiber composite. As a result, the increase in shear strength observed in the curves of the mixtures occurs.

The obtained results enabled the analysis of how the addition of fibrous material influenced the shear strength parameters of the soil. Using the Mohr-Coulomb linear criterion the cohesion (c) and friction angle (ϕ) parameters of each sample were obtained, as shown in Table 5.

In general, it can be seen that in both test conditions, the inclusion of coconut fibers influenced more on the cohesion intercept than on the friction angle. The natural soil had the cohesion and friction angle of 60.4 kPa and 30.5° (non-flooded) and 25.9 kPa and 32.7° (flood condition), respectively. Among the mixtures, the 1-wt% content of coconut fibers provided the highest shear strength parameter values, namely, 81.2 kPa cohesion and 32.7° friction angle in the non-flooded condition and 41.3 kPa cohesion and 34.6° friction angle in the flooded condition. Thus, the 34.4% cohesion increase and 7.5% angle of friction increase were observed in the non-flooded condition, and 59.5% cohesion increase and 5.8% angle of friction increase were observed in the flooded condition compared with natural soil.

The blend with 0.5 wt% of coconut fibers presented intermediate values of the shear strength parameters with approximately 76.4 kPa cohesion and 31.3° friction angle for the non-flooded condition and 36.7 kPa cohesion and 32.9° friction angle for the flooded condition. Compared with natural soil, there were 26.5% increase in the cohesion and 2.6% increase in the angle of friction for the non-flooded condition, and 41.7% increase in the cohesion and 0.6% increase in the angle of friction for the flooded condition.

The mixture with 2 wt% of coconut fiber presented the lowest values of the shear strength parameters with approximately 71.3 kPa cohesion and 30.1° friction angle for the non-flooded condition and 29.3 kPa cohesion and 32.7° friction angle for the flooded condition. Compared with natural soil, there were 18.0% increase in the cohesion and 1.3% reduction in the angle of friction for the non-flooded condition and 13.1% increase in the cohesion and unchanged angle of friction for the flooded condition.

Therefore, the optimum ratio between clay soil and short coconut fibers was found to be 1 wt% of reinforcement material for the shear strength test. Presumably, the mixtures with up to 1 wt% of coconut fiber content can be

used as a geotechnical material for construction systems that are usually made up of compacted clay soils, such as base layers and landfill covers. However, it is important to verify the variability of the shear strength parameters and mechanical performance over time, even though coconut fibers show low degradation rates.

According to Donato *et al.* (2004), the increase in shear strength of reinforced soils is more significant in clay materials, because there is a greater probability of matrix-reinforcement adhesion due to the greater amount of contact points between the fibers and soil particles. In this sense, the mixtures with 0.5 and 1 wt% of coconut fibers probably presented more contact between fibers and clay particles. Meanwhile, in the mixture with 2 wt% of fibrous material more fiber-fiber contacts may occur, compromising matrix-fiber adhesion and generating greater probability of sliding. This can explain why the mixtures with 0.5 and 1 wt% of the reinforcement material showed better mechanical performances, cohesion, and friction angle values than the 2-wt% coconut fiber blend.

Comparing these results with other studies that used fibers to reinforce matrices of compacted clay soils classified as CL by the Unified Soil Classification System, it was noticed that the coconut fiber reinforcement showed a higher proportion of optimal mixture. For example, Prabakar & Sridhar (2002) analyzed clay mixtures and sisal fibers and obtained better shear strength parameters using 0.75 wt% of fibrous material. The content of 1 wt% presented lower performance than the other contents analyzed by the authors. Coconut fibers have higher lignin content than sisal fibers (Satyanarayana *et al.*, 2007); therefore, coconut fibers present greater flexibility. It is likely that because of this feature, coconut fibers accommodate more elements in the matrix without compromising matrix-reinforcement adhesion.

Tang *et al.* (2007) evaluated the mixtures of clay soil and polypropylene fibers and found that the best mechanical performance and shear strength parameters were obtained with 0.25-wt% fiber content. Vegetable fibers have higher porosity than synthetic fibers, which favors higher mechanical adhesion because of the penetration of the matrix into the pores of the fibers. In addition, unlike synthetic fibers, plant fibers are polar in nature, which favors adhesion by electrostatic attraction between the matrix and reinforcing elements. This may have contributed to higher optimum coconut fiber content than the analyzed clay matrix.

3.3. Compressibility

The vertical stress vs. void ratio plots obtained for natural soil and mixtures with different fiber contents for the non-flooded and flooded conditions are shown in Fig. 5.

The addition of fiber in the clay soil matrix in both flood conditions increased the slope of the virgin compression line; the highest slope was observed for the mixture

Table 5 - Shear parameters of the natural soil and soil-fiber mixtures in the non-flooded and flooded conditions.

Fiber content (%wt)	Non-flooded			Flooded		
	c (kPa)	ϕ (°)	R^2	c (kPa)	ϕ (°)	R^2
0	60.4	30.5	0.9729	25.9	32.7	0.9989
0.5	76.4	31.3	0.9879	36.7	32.9	0.9981
1	81.2	32.7	0.9934	41.3	34.6	0.9977
2	71.3	30.1	0.9989	29.3	32.7	0.9989

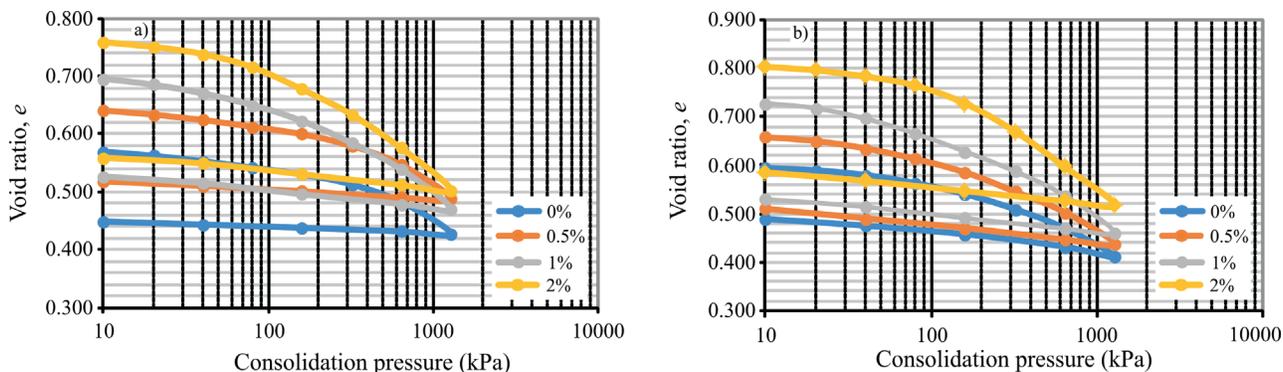


Figure 5 - Consolidation curves of natural soil and soil-fiber mixtures in the non-flooded (a) and flooded (b) conditions.

with 2-wt% content of fibrous material. This suggests that the addition of fibers increased the compressibility of the mixtures. A directly proportional relationship between fiber content and compressibility was observed; namely, the higher the fiber content was, the greater the slope of the virgin compression line became. Morandini & Schneider (2017) evaluated the influence of polypropylene fibers on matrices of lateritic soil and bentonite clay and observed similar behavior. These results may be related to the fact that the addition of fibers reduces the density of the material, which was verified by the compaction parameters, providing an increment in the initial void ratio of the soil and consequently increasing the compressibility of the composite.

The addition of fibers also increased the volumetric variation between the initial and final void ratios of the samples. The vertical tension vs. void ratio curves of the natural soil and mixture with 0.5 wt% of coconut fiber have similar shapes with more evident stiffness drop from the vertical tension of 300 and 200 kPa in the non-flooded condition (Fig. 5a). The curves of the mixtures with 1 and 2 wt% of coconut fiber exhibited different shapes from the others, with a stiffness drop more evident from 80 kPa tension (Fig. 5a). This suggests that the addition of fibers increases the virgin compression portion and reduces the vertical stress over the densification compared with natural soil. It is verifiable that the increase of the volumetric variation with the addition of fiber, when comparing the initial and final indicators of sample void ratio, was more significant in the flooded condition. The vertical stress vs. soil void ratio curves in the flooded condition show more evident stiffness drop from the 100 kPa point of vertical stress (Fig. 5b). In the cases of mixtures with 0.5, 1, and 2 wt% of coconut fiber, the stiffness drops are evident from the vertical tension of 20 kPa (Fig. 5b). This suggests that besides the addition of fiber, the flood condition also contributes to increasing the portion of virgin compression and reduction of the vertical tension over densification compared with natural soil.

The compression index (C_c) and decompression index (C_s) obtained through the curves of Fig. 6 are presented

in Table 6. They were obtained by the relationship between the differences of the initial and final logs and the initial and final void ratio values. The inclusion of coconut fibers increased the compression and decompression indices of the clay matrix; these gains were more significant for the decompression index in both flood conditions.

The compression index increased with the increase of the fiber content of the mixtures; it took the values of 0.182, 0.196, 0.228, and 0.241 for the coconut fiber contents of 0, 0.5, 1, and 2 wt%, respectively, for the non-flooded condition. In the flooded condition, the obtained values of C_c were 0.195, 0.218, 0.256, and 0.261 for the fiber contents of 0, 0.5, 1, and 2 wt%, respectively.

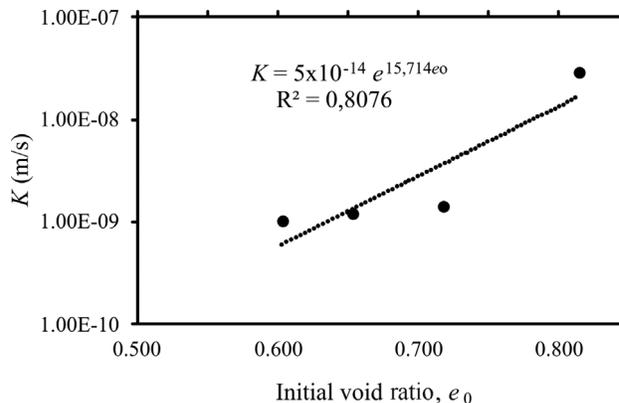


Figure 6 - K_{water} vs. initial void ratio of natural soil and soil-fiber mixtures.

Table 6 - Compressibility parameters of natural soil and soil-fiber mixtures in the non-flooded and flooded conditions.

Fiber content (%wt)	Non-flooded		Flooded	
	C_c	C_s	C_c	C_s
0	0.182	0.009	0.195	0.029
0.5	0.196	0.016	0.218	0.033
1	0.228	0.032	0.256	0.039
2	0.241	0.031	0.261	0.035

It was found that in the mixture with 0.5 wt% of coconut fibers the compression index increased by 8% and 12% for the non-flooded and flooded conditions, respectively. For the mixture with 1 wt% of coconut fibers, the compression index increased by approximately 25% in the non-flooded condition and 31% in the flooded condition. In the mixture with 2 wt% of coconut fibers, the observed gains in the compression index were 32% in the non-flooded condition and 34% in the flooded condition. Thus, depending on the applied stress level, ratio between the materials, and flooding condition, the addition of coconut fibers in the clay soil can provide approximately 30% more deformation by primary compression.

As for the decompression index, the values obtained in the non-flooded condition were 0.009 for the natural soil, 0.016 for the blend with 0.5 wt% of fiber, 0.032 for 1 wt% of fiber, and 0.030 for 2 wt% of fiber. In the flooded condition, these values were 0.029, 0.033, 0.039, and 0.035 for contents of 0, 0.5, 1, and 2 wt% of coconut fiber, respectively. This indicates that fibers increase the potential for soil expansion due to stress relief. In the non-flooded condition, the decompression index increased by approximately 78%, 256%, and 94% for the blends with 0.5, 1, and 2 wt% of coconut fibers, respectively, compared with natural soil. In the flooded condition, the decompression index increased by 14%, 34%, and 6% for the mixtures with 0.5, 1, and 2 wt% of coconut fibers, respectively. The content of 1 wt% of coconut fibers showed major influence on the potential of deformation by tension relief, especially in the non-flooded condition. Therefore, for the compressibility, the optimal ratio between clay soils and randomly distributed short coconut fibers was not found. This open question may become a limitation of the application of these mixtures as geotechnical materials.

3.4. Hydraulic conductivity

The results of the saturated hydraulic conductivity tests of natural soil and mixtures with different levels of coconut fibers are presented in Table 7.

Natural soil had a coefficient of hydraulic conductivity of 1.01×10^{-9} m/s, which is practically similar to that of the mixtures with 0.5 and 1 wt% of coconut fibers with approximately 1.20×10^{-9} m/s (approximately 19% more than natural soil) and 1.43×10^{-9} m/s (approximately 42% more than natural soil), respectively. Meanwhile, the mixture with 2 wt% of coconut fibers showed the coefficient of hydraulic conductivity of 2.87×10^{-8} m/s (approximately 2742% more than natural soil), which is higher by an order of magnitude than the coefficient of hydraulic conductivity of natural soil. These results agree with Miller & Rifai (2004), who evaluated mixtures of clay soil (classified as CL) and polypropylene fibers and observed changes of the order of magnitude of hydraulic conductivity of the mixture with 1 wt% of fiber content.

Table 7 - Initial void ratio and hydraulic conductivity of natural soil and soil-fiber mixtures.

Fiber content (%)	e_0	K_{water} (m/s)	Variation from the natural soil (%)
0	0.603	1.01×10^{-9}	-
0.5	0.653	1.20×10^{-9}	19
1	0.718	1.43×10^{-9}	42
2	0.814	2.87×10^{-8}	2742

It is believed that for the 2-wt% coconut fiber blend, the reason for the hydraulic conductivity increase is similar to that affecting the mechanical performance of this blend, namely, the loss of soil-fiber adhesion. The amount of fiber in this blend increases the fiber-fiber contacts, which creates macropores and increases the hydraulic conductivity. Figure 6 shows the behavior of hydraulic conductivity as a function of the initial void ratio of natural soil and soil-fiber mixtures. It is possible to observe that the hydraulic conductivity increases with the increase of the initial void ratio. This suggests that the structure of a material has significant influence on the hydraulic conductivity and may be responsible for the results obtained for the hydraulic conductivity of the soil-fiber mixtures.

According to the hydraulic conductivity results, mixtures with up to 1 wt% of coconut fiber can be used as a geotechnical material of construction systems, considering that the coconut fiber in these proportions does not significantly influence the hydraulic conductivity compared with natural soil. According to USEPA (2007), the final landfill cover layer must have a hydraulic conductivity lower than the bottom layer or be less than 10^{-7} m/s. According to this criterion, for example, even the 2-wt% fiber blend can be considered as a suitable material for cover layers of landfills. However, as previously reported, it is important to note that although coconut fibers possess low degradation rate, tests must be carried out to verify the behavior of hydraulic conductivity over time to verify its adequate application in mixtures as a geotechnical material.

3.5. Soil-fiber interface analysis

The micrographs made for the mixtures with different coconut fiber content are presented in Fig. 7. In general, no ruptured fibers were observed, indicating that the elements adequately supported the adopted stress levels. Such a behavior was also observed by Anagnostopoulos *et al.* (2013) when analyzing micrographs of clayey soil (CL) and polypropylene fiber mixtures.

Clay particles agglomerate around fibers, providing embedding in the matrix. This inlay is most evident in blends with 0.5 and 1 wt% of fiber (Figs 7a, 7b, and 7c). This behavior favors the transmission of mechanical stresses from the matrix to the fibers, resulting in the improve-

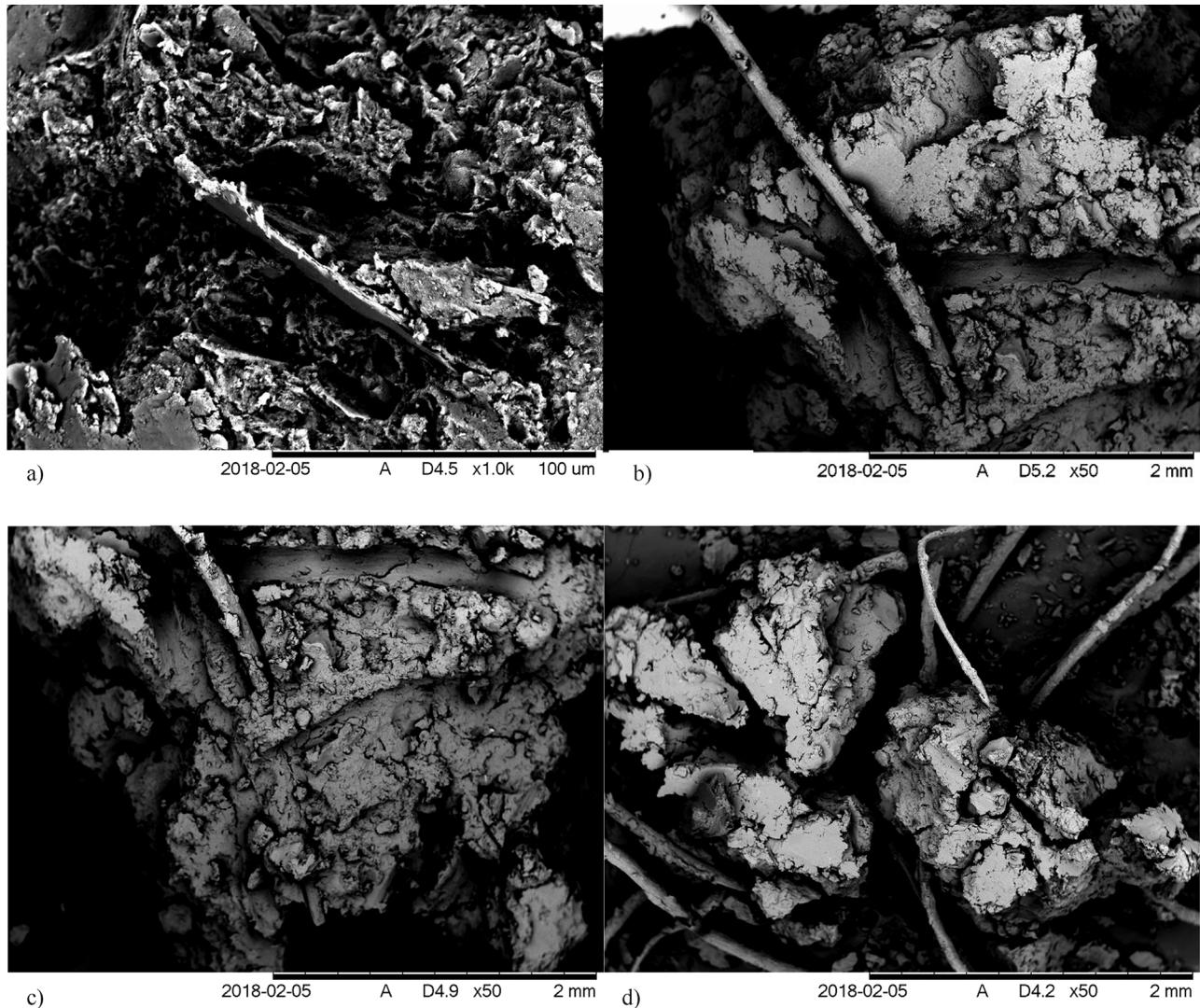


Figure 7 - SEM images of the blends with different percentages of coconut fiber: a) 1000 \times magnification of the mixture with 0.5 wt% of fibers; b) 50 \times magnification of the mixture with 0.5 wt% of fibers; c) 50 \times magnification of the mixture with 1 wt% of fibers; and d) 50 \times magnification of the mixture with 2 wt% of fibers.

ment of the shear strength of the soil-fiber assembly. In addition, it leads to the formation of the structure, which provides lower compression indices and hydraulic conductivity compared with the 2-wt% mix. Although the distribution of coconut fibers was random, in Fig. 7d, it can be seen that there may be a tendency for agglomeration of fibers in the 2-wt% blend, causing reduced interaction between soil and fibers. It, in turn, increases the fiber-fiber contacts, which compromise matrix adhesion to the reinforcement. Moreover, it can possibly create fragile points with greater compressibility, which can generate a rough surface with many localized settlements in layers compacted with these proportions.

Through the images shown in Fig. 8, it was established that the clay particles remained adherent to the surface of the fibrous material after shearing the samples. It

indicates that there is strong interfacial bonding owing to good compatibility between the matrix and reinforcement.

Some of the possible mechanisms for adhesion of the particles to the fiber surface are the mechanical adhesion and adhesion by electrostatic attraction between matrix and fiber. The mechanical adhesion occurs in the consolidation stage of the shear test. Because of the applied normal stress, local plastic deformations occur in the fiber creating cavities filled by the matrix, which provide an anchorage on the fiber surface (Tang *et al.*, 2007, Tang *et al.*, 2010). Moreover, during the compacting process of the blends, smaller particles are pressed to penetrate the pores of the fiber causing mechanical adhesion (Moraci & Gioffre, 2006; Anagnostopoulos *et al.*, 2013). The electrostatic attraction occurs because vegetal fibers usually possess polar surface energy. If the matrix has nonpolar nature, there will be little

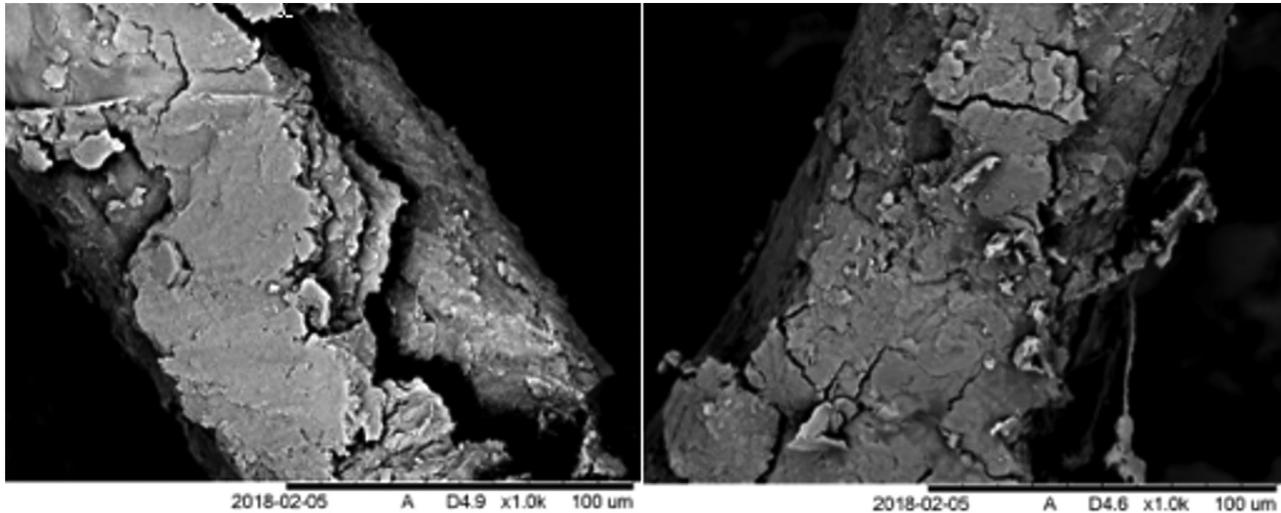


Figure 8 - Images of clay soil adherent to the surface of expanded fibers in 1000 \times .

electrostatic adhesion to the fiber surface. Conversely, if the composite matrix is polar, adhesion will occur because of the electrostatic attraction between the materials.

Clay soils are formed by various minerals, whose type and quantity influence the electrical nature of the material. Clay particles are constituted by thin lamellae that are generally negatively charged at the surface and positively at the edges, favoring the occurrence of electrostatic interactions (Macedo *et al.*, 2008). In this sense, the charge distribution in the clay particles and polar surface energy of the fibers should favor the electrostatic adhesion between the clay soil matrix and the coconut fiber surface.

The elementary analysis performed in the soil-fiber interfacial zone for the mixtures with 0.5, 1, and 2 wt% of fiber is presented in Fig. 9. The mixtures with better soil-fiber adhesion (up to 1 wt% of fiber) showed similar contents of oxygen, carbon, aluminum, silicon, iron, nitrogen, and sulfur. The soil-fiber interface of the 0.5-wt% fiber blend had 37.9% oxygen, 18.8% carbon, 18.1% aluminum, 17.8% silicon, 4.2% iron, 1.8% nitrogen, and 1.3% sulfur (Fig. 9a). The soil-fiber interface of the 1-wt% fiber blend had 38.6% oxygen, 18.3% carbon, 18.9% aluminum, 17.7% silicon, 3.9% iron, 1.5% nitrogen, and 1.2% sulfur (Fig. 9b). Meanwhile, the mixture with 2 wt% of fiber in which the soil-fiber bond was reduced, had 32.9% oxygen, 49.7% carbon, 7.1% aluminum, 7.8% silicon, 1.6% iron, and 0.8% sulfur (Fig. 9c).

The clay minerals present in the soil are composed of hydrated Al, Fe, and Mg silicates with the crystalline structure in layers (Coelho *et al.*, 2007). Furthermore, Macedo *et al.* (2008) found that red clay soils, such as the one used in the mixtures, usually show a predominance of SiO_2 , Al_2O_3 , and Fe_2O_3 . Therefore, the higher values of oxygen, aluminum, silicon, and iron observed in the compounds with 0.5 and 1 wt% of fibers are associated with the higher amounts of clay minerals present at the soil-fiber interface of these

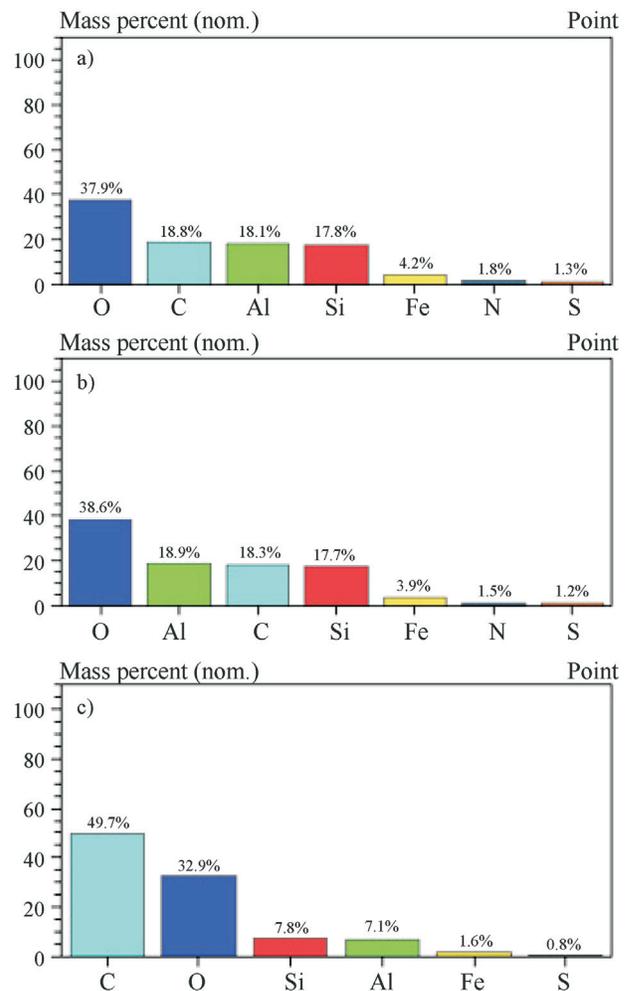


Figure 9 - Elemental analysis of the soil-fiber interface obtained by the EDS technique: a) mixture with 0.5 wt% of fiber; b) mixture with 1 wt% of fiber; and c) mixture with 2 wt% of fiber.

mixtures after the direct shear test of the samples. These results indicate that the clay particle content adhered in the interfacial zone with the coconut fiber was higher in the mixtures with up to 1 wt% of fiber, which confirms that the soil-fiber interaction in these mixtures is greater. Meanwhile, Corradini *et al.* (2009) reported that the cellulose chains of coconut fibers are polysaccharides formed of carbon, oxygen, and hydrogen. Therefore, the higher carbon content and lower oxygen, aluminum, silicon, and iron contents observed in the 2-wt% fiber blend are related to the higher vegetal tissue presence and lower presence of clay minerals in the soil-fiber interface of this mixture. This result indicates that in the 2-wt% fiber mixture, the amount of clay particles attached to the coconut fiber in the interfacial zone was lower because of the higher amount of fibers; it confirms that for this fiber content fiber-fiber contacts prevail, which compromises the matrix-reinforcement bond of the composite.

4. Conclusions

Based on the results obtained in this research, it can be concluded that the addition of different quantities of short coconut fibers randomly distributed in a clay soil matrix has significant influence on the compaction, shear strength, compressibility, and hydraulic conductivity. In particular, the following conclusions can be drawn:

1. The compaction test revealed that the optimum moisture content increases and the maximum dry unit weight reduces with the increase of the added fiber content;
2. The shear strength of the blends improved with content of up to 1 wt% of coconut fibers. In this range of content, there is a rise in the peak strength, reduction in the post-peak strength drop, and increment in the cohesion and friction angle parameters, regardless of the test flood condition;
3. The compressibility of the mixtures increased directly proportional to the coconut fiber content. The addition of coconut fiber has negatively affected the compressibility and therefore the addition of coconut fiber is not indicated as a geotechnical material. The main effects observed in the addition of coconut fibers to the soil were the increases of the compressibility curves slope, primary compression portion, and compression and decompression indices in both flood conditions.
4. Mixtures with less than 1 wt% of fiber did not show significant changes in hydraulic conductivity, which remained of the same order of magnitude of natural soil of 10^{-7} cm/s. However, for the mixtures with greater fiber content, the hydraulic conductivity sharply increased by approximately one order of magnitude.
5. SEM images indicate that clay particles adhere to the surface of coconut fibers, explaining the behavior observed in the geotechnical properties of the studied mixtures. The main effects of coconut fiber addition at a microscopic scale were the loss of adhesion verified

in the 2-wt% blend due to the tendency of localized fiber agglomeration.

6. EDS performed at the interfacial zone of the mixtures with 0.5 and 1 wt% of fiber suggested that there was a greater amount of aluminum and iron oxides from the clay minerals in the soil-fiber contact, confirming that there is greater matrix-reinforcement interaction for these mixing ratios. The analysis performed in the 2-wt% fiber blend indicated a reduction in the supply of clay minerals and greater amount of vegetal tissue, indicating the predominance of fiber contacts, which confirms the weakened matrix-reinforcement adhesion observed in this proportion.

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List of Symbols

- CL: clay of low compressibility
c: cohesion
 ϕ : friction angle
e: void ratio
C_c: compression index
C_s: decompression index
K_{water}: hydraulic conductivity
e₀: initial void ratio
O: oxygen
C: carbon
Al: aluminum
Si: silicon
Fe: iron
N: nitrogen
S: sulfur