

Analysis of the Physical-Mechanical Behavior of Clayey Sand Soil Improved with Coir Fiber

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Abstract. The objective of this paper is to analyze the mechanical behavior of a clayey sand soil with added green coir fiber at 0.25%, 0.5%, 0.75%, and 1% by dry weight, through a series of laboratory tests that physically and mechanically characterize the samples in order to evaluate possible changes in the soil properties. Unconfined compression and indirect tensile tests were carried out. The addition of fibers to the soil resulted in a considerable increase in the strength of the composites. Unconfined compression strength for the soil and fiber mixtures was highest with 0.5% fiber content (50.8% higher than the soil without fibers), and the tensile strength was highest for 0.75% fiber content (85.4% increase). These results will hopefully encourage the use of vegetable fibers, specifically coir fiber, as an alternative material for use in civil engineering projects.

Keywords: alternative materials, coir fiber, indirect tensile test, reinforced soil, unconfined compression test.

1. Introduction

The usage of soil as a building material is common in civil engineering. However, some soils in their natural state have low strength. This characteristic intensifies when anthropogenic factors arise, such as the removal of vegetation cover, erosion, changes in drainage conditions, and disorganized human occupation, which occurs frequently in peripheral regions of large cities. This can exacerbate various socio-environmental problems, such as neighborhoods with poor infrastructure, residences located in high-risk areas, and degradation of natural systems (Souza, 2014), a common situation on the periphery of many Brazilian metropolises.

Awareness of the problem, and knowledge of the lack of strength capacity of some soils, makes it necessary to strengthen the soil by altering its properties to create a material capable of responding to the needs of the task (Cristelo, 2001).

Hejazi *et al.* (2011) cite soil improvement as “a procedure in which natural or synthetic additives are used to improve soil properties”, and typify this process in three different ways, as shown in Fig. 1. This paper deals with improvement through the addition of fibrous material.

The incorporation of fiber into fragile materials can provide various benefits, such as increased capacity to absorb energy before rupture, increased load capacity and unconfined compressive strength, and improved mechanical characteristics (Cabala, 2007).

The use of vegetable fibers in geotechnics has been studied with more emphasis in recent years, due to the demand for alternative materials and the need to dispose of

agricultural production waste. In order to substitute the use of synthetic materials with organic materials, however, studies are necessary to obtain conclusions and parameters on the viability of the use of these materials. The main objective of this paper is therefore to analyze the physical-mechanical behavior of composites of soil and coir fiber that can be used for soil stabilization projects.

1.1 Coir fiber

For Civil Engineering, vegetable fibers can have a number of applications, such as paving layers, retaining walls, temporary works, slope protection, foundations, and earthquake structures, among others (Kalita *et al.*, 2016). They have advantages over more conventional soil reinforcement materials, such as glass or carbon, but they also have certain disadvantages, as shown in Table 1.

Ali (2011) studied coir fiber and concluded that it is one of the most ductile vegetable fibers and capable of withstanding stress 4 to 6 times greater than other vegetable fibers. Table 2 shows the chemical composition of coir fiber according to various researchers. Coir fiber has a lower percentage of cellulose than other vegetable fibers, such as sisal and jute, between 33% and 43%, reaching 68.9% in some cases, according to Agopyan *et al.* (2005) and Asatutjarit *et al.* (2007). The hemicellulose content (0.15-31.1%) has the advantage of being low, since this material is attacked by microorganisms (Noguera *et al.*, 2000, apud Bolanões, 2013).

On the other hand, the amount of lignin is high, 20% to 40% (Passos, 2005), about two to four times more than jute and sisal fibers, providing compressive strength to cel-

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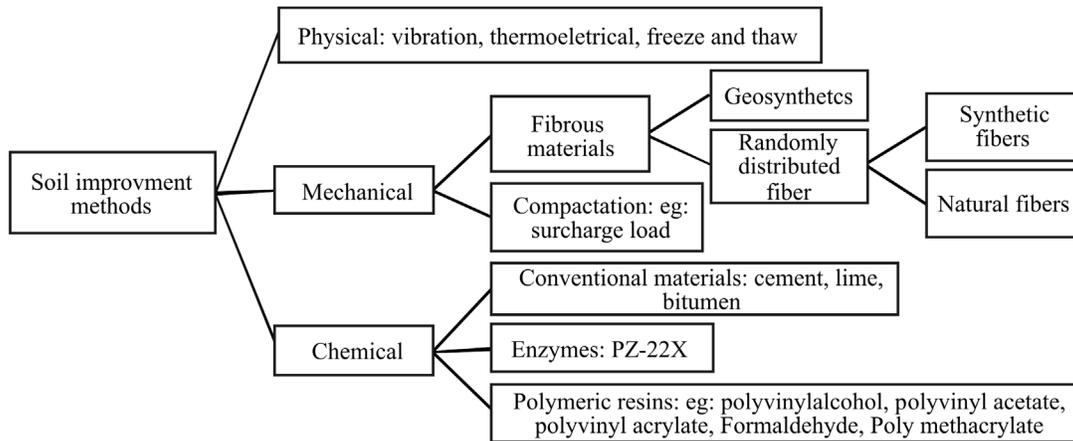


Figure 1 - Soil improvement methods. Source: Hejazi *et al.* (2011).

Table 1 - Advantages and disadvantages of the use of plant fiber for geotechnics.

Advantages	Disadvantages
Ecological and renewable;	Fibers degrade after being stored for a long time;
Low cost (or low cost by volume);	High moisture absorption (hygroscopicity);
Fully biodegradable;	Low strength to moisture;
Non-toxic;	Low thermal stability;
Easy to handle, low density, and light weight;	Weak adhesion in its natural state to numerous matrices;
Non-abrasive during processing and use;	Need for chemical, mechanical or thermal treatments to be used as reinforcement for cementitious composites.
Good insulation against heat and noise;	
Acceptable specific strength properties;	

Source: Bolaños (2013).

ular tissue and fibers. According to Babu & Vasudevan (2007), coir fiber is much more advantageous in certain applications, such as erosion control, or improvement of slope performance, due to the high lignin content.

It is also important to know the physical and mechanical properties of coir fiber, in order to better understand how it will behave in composites (Bledzeki & Gassan, 1999). Table 3 shows the physical and mechanical properties of coir fiber, as determined by several authors (Ali,

2011). The properties shown may differ among the studies cited, as the fibers may come from different origins, and may be tested using different methods and under different humidity conditions (Faruk *et al.*, 2012).

2. Materials and Methods

The soil was collected from the Alto do Reservatório hillside, located in Recife, Pernambuco. It is an area considered to have a high risk of slope instability (Meira *et al.*,

Table 2 - Coir fiber chemical composition.

Hemi-cellulose (%)	Cellulose (%)	Lignin (%)	Reference
-	43	45	Satyanarayana <i>et al.</i> (1990)
31.1	33.2	20.5	Ramakrishna <i>et al.</i> (2005)
15-28	35-60	20 - 48	Agopyan <i>et al.</i> (2005)
16.8	68.9	32.1	Asasutjarit <i>et al.</i> (2007)
0.15-0.25	36-43	41 - 45	Corradini <i>et al.</i> (2006)
0.25	43.4	45.8	Shankar <i>et al.</i> (2012)
0.15-0.25	32-35	40-45	Faruk <i>et al.</i> (2012)

Table 3 - Physical and mechanical properties of coir fiber.

Diameter (mm)	Length (mm)	Tensile strength (MPa)	Elongation (%)	Young's modulus (GPa)	Density (kN/m ³)	Reference
0.10-0.40	50-252	100 - 130	10-26	19-26	14.5-28	Aggarwal (1992)
0.11-0.53	-	108-252	13.3	2.5-4.5	10.0	Toledo <i>et al.</i> (2005)
0.1-0.4	-	174	10-25	16-26	-	Reis (2006)
-	-	500	-	-	11.5	Rao & Rao (2007)
0.27	50	142± 36	24± 10	2.0	-	Li <i>et al.</i> (2007)
0.13-0.23	-	100 - 250	-	3.0	-	Tomczak (2010)
-	-	175	30	4-6	12	Faruk <i>et al.</i> (2012)
-	-	220	15-25	6	12.5	Mohammed <i>et al.</i> (2015)

2006) and is susceptible to erosion. Coir fibers were supplied by an agricultural machinery company. They were cut to a length of 20 mm, a value based on previous studies (Babu *et al.*, 2008; Bolaños, 2013; Chaple & Dhattrak, 2013; Maliakal & Thiyyakkandi, 2013; Kar *et al.*, 2014; Aguilar, 2015). Following this, mixtures were prepared with proportions of 0.25%, 0.5%, 0.75%, and 1% with respect to the dry soil weight. These amounts were chosen based on previous studies (Bolaños, 2013; Chaple & Dhattrak, 2013; Maliakal & Thiyyakkandi, 2013; Singh & Mittal, 2014; Tiwari & Mahiyar, 2014; Aguilar, 2015; Anggraini *et al.*, 2015; Ayninola & Oladotun, 2016; Kalita *et al.*, 2016; Subramani & Udayakumar, 2016).

The following tests were carried out: Particle-size distribution (ABNT NBR 7181, 2016a), Consistency limits (ABNT NBR 7180, 2016b; ABNT NBR 6459, 2016c), Specific gravity (ABNT NBR 6508, 1984), and Proctor compaction (ABNT NBR 7182, 2016d). Four samples were produced (Fig. 2a) using static compaction method in a cylindrical mold (50 mm diameter x 100 mm height) for carrying out the mechanical tests: unconfined compressive strength (UCS) (ABNT NBR 12770, 1992) at a fixed strain rate of 0.5 mm/min (Fig. 2b) and tensile strength by diametral compression, or indirect tensile strength (ITS) (ABNT NBR 7222/2011) only, done at a strain rate of 0.25 mm/min (Fig. 2c).

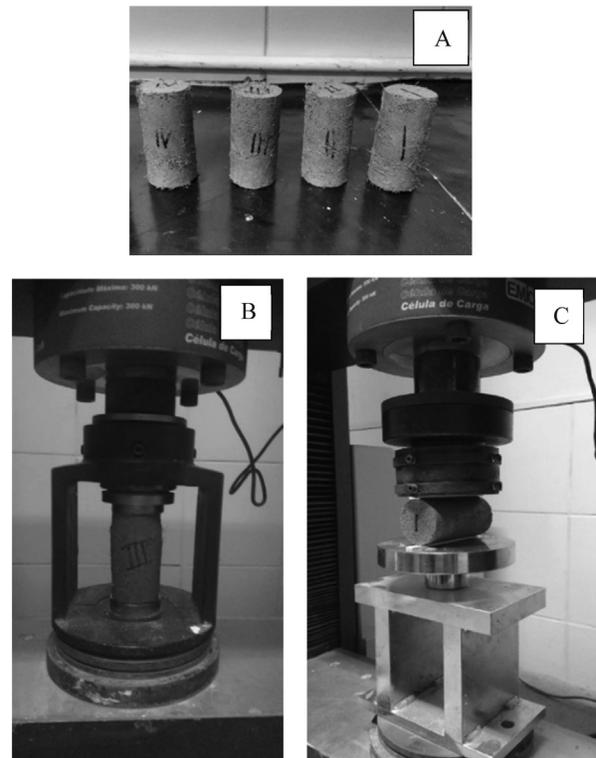

Figure 2 - (a) Samples; (b) Unconfined compression test; (c) Indirect tensile test.

Table 4 - Results of physical soil characterization and mixture tests.

Sample	Specific gravity	Liquid limit (%)	Plastic limit (%)	Plasticity index (%)	Optimum moisture content (%)	Maximum dry density (kN/m ³)	USCS	TRB
Soil	2.63	44	23	21	15.3	17.55	SC	A-7-6
S+0.25%	2.63	43	30	13	16.5	17.50	SM	A-7-5
S+0.5%	2.63	44	30	14	16.5	17.42	SM	A-7-5
S+0.75%	2.62	41	27	14	16.3	17.29	SM	A-7-6
S+1%	2.63	43	31	12	16.8	17.35	SM	A-7-6

An important feature to be analyzed when including fibers in soil mixtures is the form in which rupture occurs when the test is performed. Visual analysis of the increase

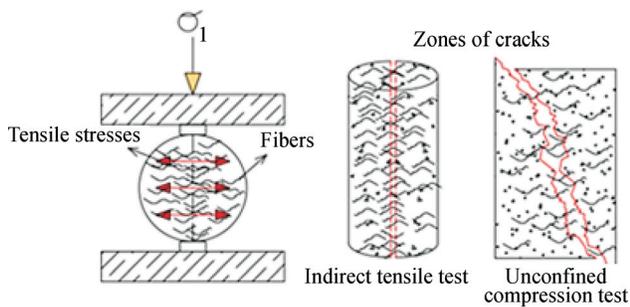


Figure 3 - Arrangement of the fibers in the rupture zones of the unconfined compression and indirect tensile tests. Source: Guedes *et al.*, 2016.

in fibrous ductility is interesting, and was used by other authors like Feuerharmel (2000) and Festugato (2008), considering that this characteristic tends to increase with the addition of fibers. The rupture patterns were analyzed in order to understand how the fibers acted as an improvement material. Figure 3 shows the probable ruptures that may occur (Guedes *et al.*, 2016).

3. Results and Discussion

Physical and mechanical characterization of soil and mixtures are presented and discussed.

3.1. Physical characterization

Figure 4 shows the particle size distribution curves for the soil and mixtures, and Table 4 presents the results of the specific gravity, consistency limit, and compaction test,

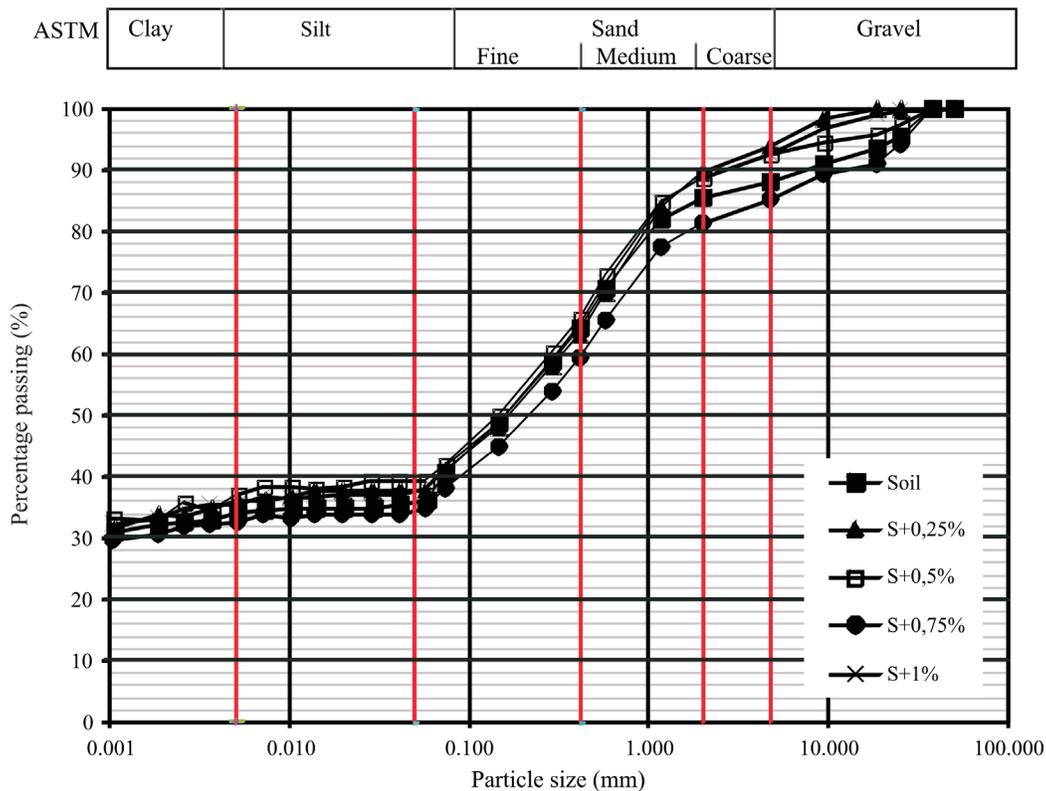


Figure 4 - Grain size distribution curves.

including Unified Soil Classification System (USCS) and Transportation Research Board (TRB) classifications.

The soil is a clayey sand, and the mixtures are silty sand. The insertion of the fibers decreased the plasticity index. The introduction of the fibers contributed to a slight decrease in the maximum dry density of the mixtures, because the fibers are lighter than the soil, while the increase of the optimum moisture values can be explained by the moisture absorption capacity of the fibers.

The same trend was observed by other authors, such as Chaple & Dhattrak (2013), who saw the maximum dry density decrease from 17.30 kN/m³ for the soil to 16.60 kN/m³ for the 1% coir fiber mixture. For all mixtures, the optimum moisture increased from 18.10% for the soil to 20.76% for the 1% coir fiber mixture. Soundara & Kumar (2015) obtained maximum dry densities of 19.80 kN/m³ for soil and 17.20 kN/m³ for 1.5% coir fiber, and optimum moisture of 6.50% for soil and 19% for 1.5% coir fiber.

3.2. Mechanical characterization

The results of the unconfined compressive strength and indirect tensile strength tests are presented and discussed.

3.2.1. Unconfined compression strength tests

Table 5 presents the unconfined compression strength results obtained from the samples, along with other important parameters. The values of simple compressive strength, for both the soil and the mixtures, had low dispersion (coefficient of variation less than 15%) and low modulus of elasticity, except for S+1%, which had medium dispersion of 22.9% (value between 15% and 30%) (Ferreira, 2018). The unconfined compressive strength increased with the insertion of coir fiber, reaching the highest value for the 0.5% fiber mixture. This effect may be caused by an interaction between the soil and fiber, indicating a possible optimum fiber content with the best soil-particle entanglement. For the higher fiber values of 0.75% and 1%, there was a small decrease in strength.

Similar behavior was obtained by Kar & Pradhan (2011) in soils of similar granulometry with 15-mm length fibers, where soil strength increased with 0.6% coir content. Chegenizadeh & Nikraz (2012 used 20-mm length fi-

bers, and found soil strength increased with 1.0% coir. Kar *et al.* (2014) performed this investigation in a clay-sand soil with 20 mm fibers and found that the best content was 0.8%, providing a 57% increase in UCS.

Stress-strain curves are shown in Fig. 5. The curves for the soil show a peak in strength, typical of friable material, reaching its maximum between 3 and 3.5% strain, following which, a decrease occurs for all applied stresses (Fig. 5a). For the mixtures, no strength peak was observed, but instead a hardening plastic behavior, characterizing a material more ductile than soil. There is a continuous increase in strength with higher deformations (Figs. 5b to 5d). Kar *et al.* (2014), and Subramani & Udayakumar (2016) obtained similar observations.

The increasing fiber addition was observed to turn the composite into a less rigid material, due to the fact that fiber is a more flexible material than soil (Fig. 5). The values for the rupture strain at this percentages increase with increasing fiber content; showing a tendency for the mixtures to be more ductile than soil. Therefore, the soil curve showed a behavior characteristic of a more rigid material, with a deformation peak and fragile rupture. With the inclusion of the fiber, this characteristic changes, indicating a less rigid and more ductile material.

Figure 6 shows 95% confidence intervals for the unconfined compressive strength test results. The S+ 0.5% and S+ 0.75% mixtures obtained the best results, considering that the S+ 0.25% and S+ 1% samples did not present statistically significant differences from the soil.

The results presented in this paper also point to a tendency of increase and decrease of strengths related to the elasticity modulus, reaffirming that it decreases with the insertion of fiber (Fig. 7), except for the 0.25% mixture, which showed a slight increase.

When the improved soil is subjected to an external load, the fibers become active, increasing the interconnection between the soil particles. This increases the strength of the composite. However, studies indicate that the addition of fibers beyond the ideal amount could actually reduce the effectiveness of this strength improvement, as the fibers would interact with each other, rather than with the soil (Sivakumar & Vassudevan, 2008; Anggraini, 2016).

Table 5 - Unconfined compression strength values.

	Average UCS (kPa)	Strength increase (%)	Variation coefficient (%)	Average elasticity modulus (MPa)	Variation coefficient (%)	Average rupture strain (%)
Soil	421.4± 22.4	-	5.3	17.2± 2.1	11.9	3.3
S+0.25%	513.3± 37.7	21,8	7,3	20.3± 1.9	9.3	4.5
S+0.5%	635.4± 84.6	50,8	13.3	16.6± 0.6	3.5	6
S+0.75%	553.9± 26.6	31.5	4.8	11.9± 0.6	5.1	6
S+1%	546.1± 40.9	29.6	7.5	6.3± 1.4	22.9	6.4

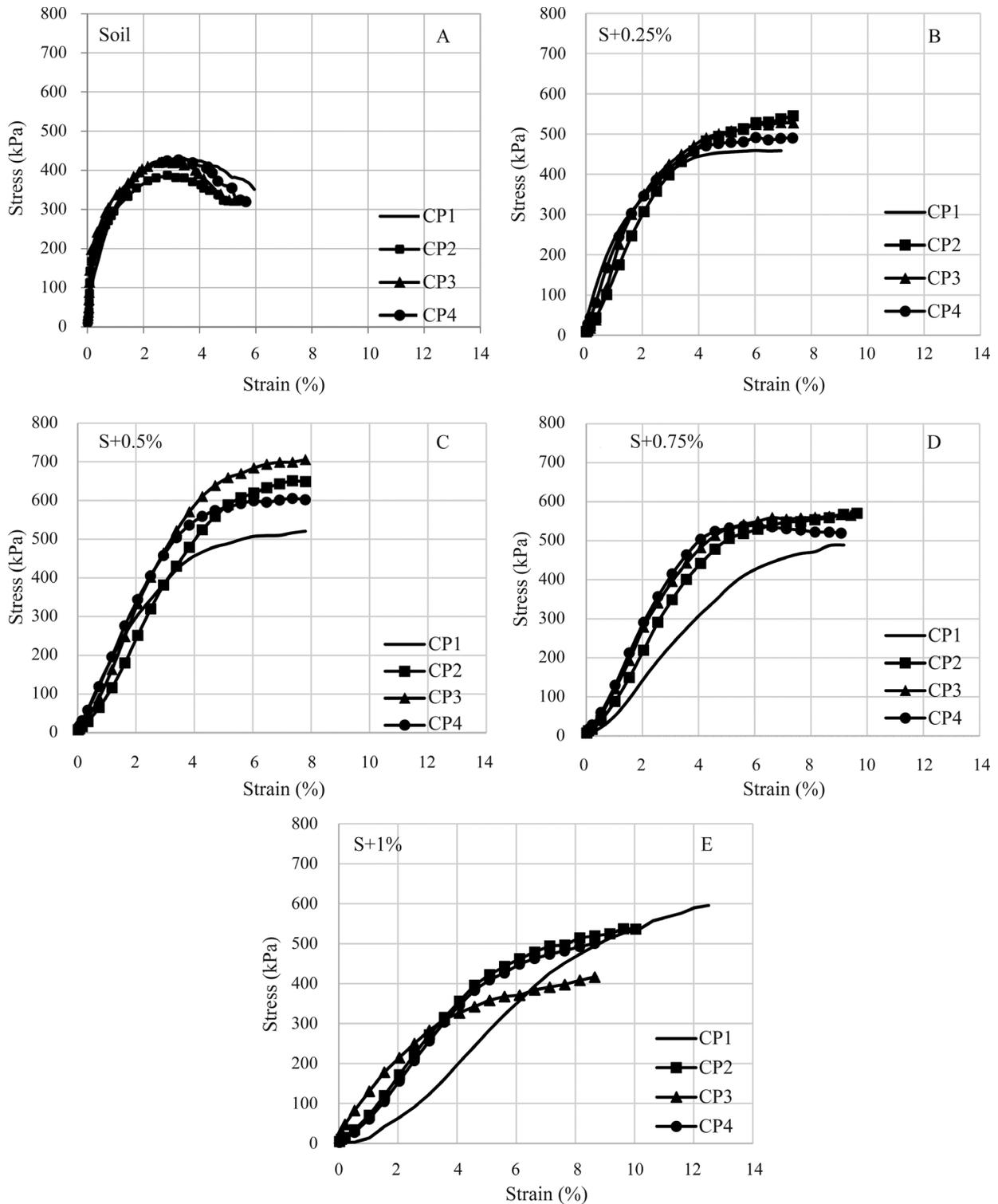


Figure 5 - Unconfined stress-strain curves for soil and mixtures.

Regarding the rupture pattern, as the fiber content increases, visible external ruptures occurred less frequently. Figure 8 shows the specimens following the test for the soil, S+0.5%, and S+1% mixtures. The S+0.5% mixture had the highest strength, but the S+1% sample was more ductile,

with fewer apparent ruptures distributed throughout the test body.

Bolaños (2013) and Maliakal & Thiyyakkandi (2013) verified similar behavior for fiber contents of 0.75%, 1%, and 1.5%. Kar & Pradhan (2011) also found a similar result

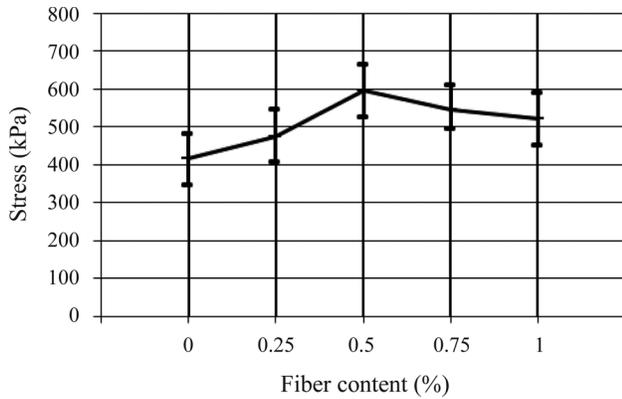


Figure 6 - Variation of unconfined compressive strength and 95% confidence intervals for the unconfined compressive strength test.

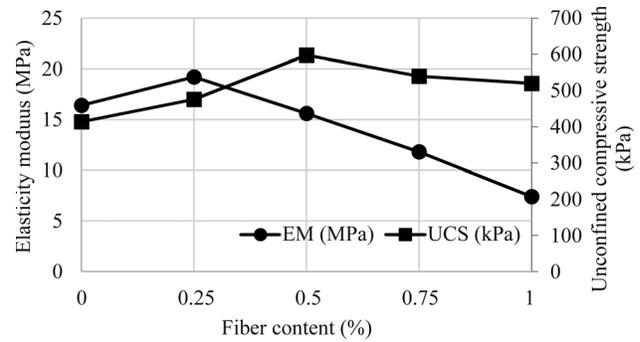


Figure 7 - Unconfined compressive strength and its relation to elasticity modulus.

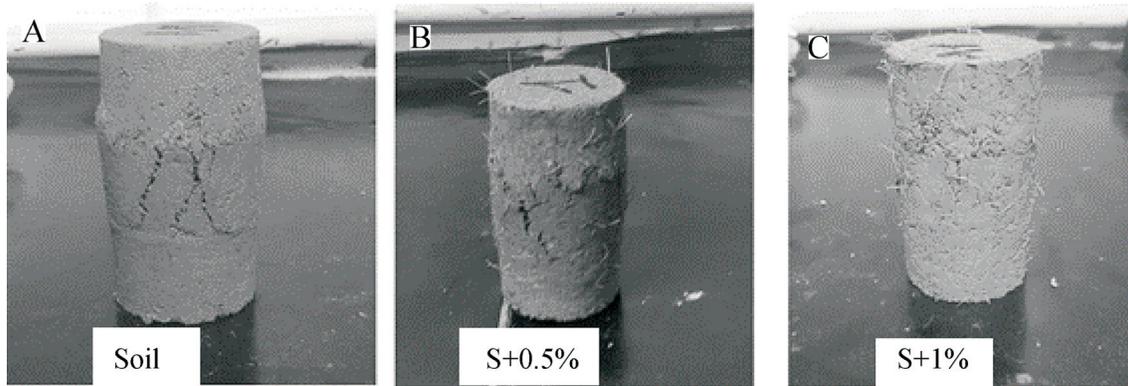


Figure 8 - Rupture patterns found in soil, S+0.5%, and S+1%.

for 0.4% fiber content, but with 15 mm fibers in clayey soil. Sebastian *et al.* (2011) found the best results with 0.8% of 20 mm fibers in a clay soil.

3.2.2. Indirect tensile strength test

Table 6 shows ITS test results, along with other parameters for the analyses. The values of tensile strength under diametral compression for both the soil and the mixtures, had low dispersion (coefficient of variation lower than 15%), except for the S+0.5% mixture, which had medium dispersion of 18.95% (value between 15% and 30%) (Ferreira, 2018).

The indirect tensile strength increased with the insertion of coir fibers, reaching the highest value for 0.75% fiber content. This effect may be due to interaction between soil and fiber, indicating that there is an optimum fiber content for the best soil-particle entanglement. Above the optimum fiber content value, the excess fibers in the mixture reduce the interaction between the materials. For 1% content, there was a small decrease in strength.

With the decrease in modulus of elasticity values and increase in rupture strain values, the tendency of the mixtures to become more ductile than the soil was identified. The stress-strain curves are shown in Fig. 9. The soil was found to

Table 6 - Indirect tensile strength values.

	Average ITS (kPa)	Strength increase (%)	Variation coefficient (%)	Average stiffness modulus (MPa)	Variation coefficient (%)	Average rupture strain (%)
Soil	20.5± 1.9	-	9.3	1.2± 0.1	9.9	1.4
S+0.25%	19.2± 1.9	-6.4	9.9	2.6± 0.2	7.9	3.5
S+0.5%	31.5± 5.9	53.7	18.9	2.3± 0.05	2.1	5
S+0.75%	38± 5.7	85.4	15.0	2.9± 0.7	24.9	8
S+1%	26.3± 3.5	28	13.3	1± 0.1	8.2	9.8

have low indirect tensile strength, where there is a peak, generally between 1 and 1.5% deformation, at which the soil completely ruptured across its longitudinal section. (Fig. 9a).

No strength peak was observed for the mixture samples S+0.25% and some of sample S+0.5% (Figs. 9b and

9c). Samples S+0.75% and S+1% showed no strength peak, however strength increased along the specific deformation, demonstrating the plastic behavior of the composite.

The soil indirect tensile strength is very low, and the insertion of fiber generated an improvement, especially for

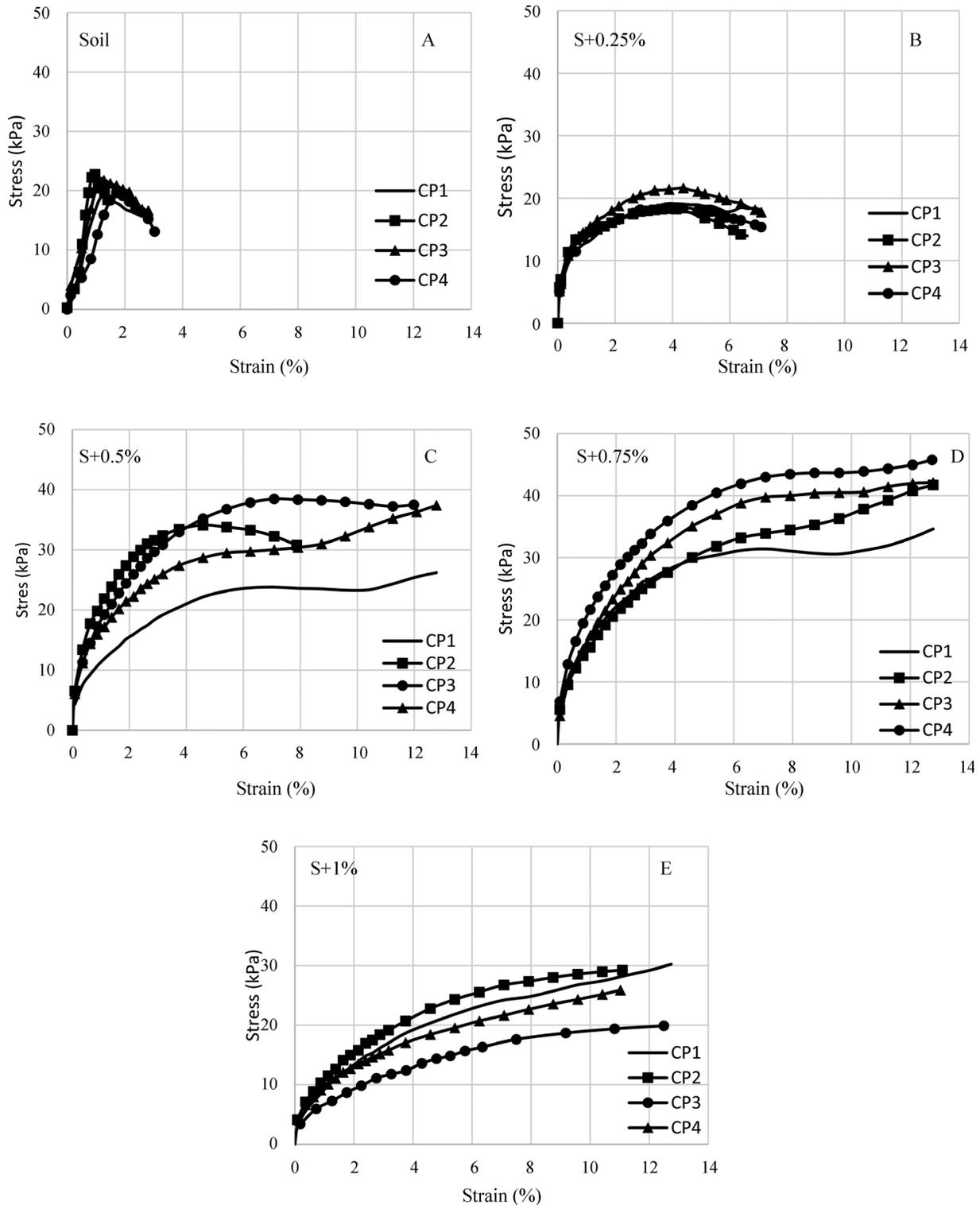


Figure 9 - Indirect tensile stress-strain curves.

the 0.75% content mixture, which provided the best inter-connection between the soil particles. For the 1% content mixture, there was a slight decrease in strength compared to the 0.75% content mixture. Figure 10 shows the 95% confidence intervals for the indirect tensile strength values. The S+0.75% mixture obtained the best results, considering that the S+0.25%, S+0.5%, and S+1% samples did not have a statistically significant difference in relation to the soil.

Similar results were obtained by Anggraini *et al.* (2014), for a clayey soil stabilized with lime, in which the addition of 1% fiber content showed strength gains, while a higher fiber content (1.5% and 2%) had reduced gain; and by Anggraini *et al.* (2015), for a clayey soil with 0.5% coir

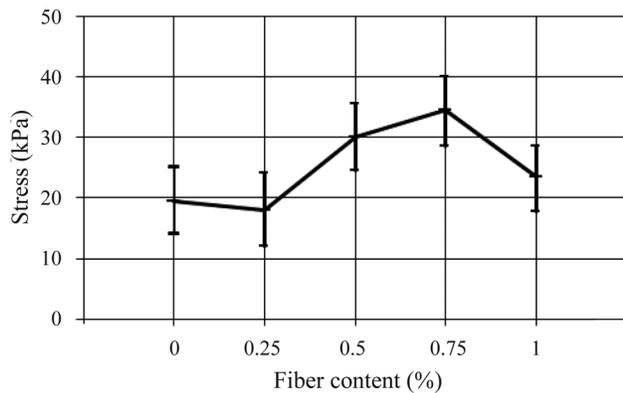


Figure 10 - Variation of indirect tensile strengths and 95% confidence intervals of indirect tensile strength.

fiber content, which decreased at higher content levels (1%, 1.5%, and 2%).

The ITS values were compared to the modulus of elasticity, reaffirming that it decreases as fiber content increases (Fig. 11). The stiffness modulus increases for the mixtures, making them more resistant materials than the soil, reaching the lowest value for 1% fiber content.

A definite vertical rupture plane, characteristic of a rigid material, is observed in the region where stress is applied (Fig. 12a). The specimens of sample S+0.75% (Fig. 12b) did not present a defined rupture plane, as the stress tended to dissipate to other regions of the specimen. Due to the presence of fibers, radial cracks also formed, but the soil remained cohesive.

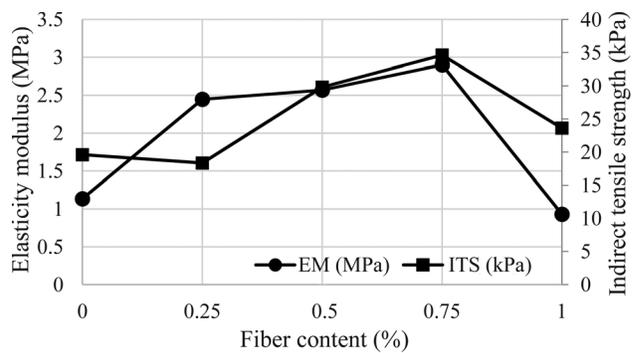


Figure 11 - Indirect tensile strength and its relationship with the elasticity modulus.

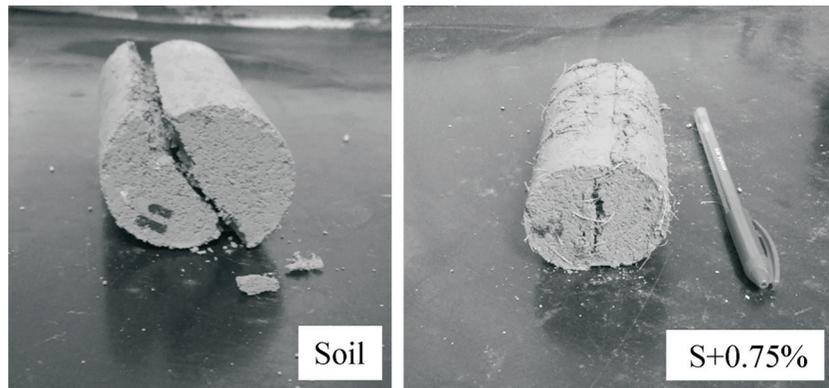


Figure 12 - Rupture pattern of the a) Soil and b) S+0.75% mixture after indirect tensile strength test.

Table 7 - Comparison between UCS and ITS values.

Mixture	Average strength (kPa)		Strength increase (%)		ITS/UCS (%)
	UCS	ITS	UCS	ITS	
Soil	421.4	20.5	-	-	4.8
S+0.25%	513.3	19.2	21.8	-6.4	3.7
S+0.5%	635.4	31.5	50.8	53.7	4.9
S+0.75%	553.9	38	31.5	85.4	6.8
S+1%	546.1	26.3	29.6	28	4.8

3.2.3. Unconfined compressive strength vs. indirect tensile strength

There is a general increase in strength when comparing the behavior of the average UCS and ITS values (Table 7). The UCS was highest at 0.5% fiber content, slightly decreasing for higher fiber contents, whereas the ITS showed little difference between the soil and S+0.25% mixture in numerical terms, although the test piece did not rupture or in half. There is a tendency for strength to increase up to 0.75% fiber, decreasing slightly at 1% content. ITS values were around 5% of the UCS values. Regardless of the content, the fibers contributed more to the ITS, providing an increase of around 40%, than to the UCS, whose average gain was 33%.

4. Conclusions

A comprehensive program of laboratory tests was performed to analyze the physical and mechanical properties of soil reinforced with coir fiber.

- The physical characteristics of the soil, such as specific gravity, optimum moisture content, and maximum dry density do not change significantly with the inclusion of coir fiber. The plasticity index decreased with the addition of fibers.
- Fibers in the soil matrix were verified to provided an increase in the unconfined compressive strength. The highest increases were reached at 0.5% coir fiber content, 50% greater than that of soil without fiber.
- The incorporation of fibers increased the indirect tensile strength. Higher increases were found with 0.75% coir fiber content, which was 85% higher than that untreated soil.
- The insertion of fibers made the soil a more ductile material, prone to reach higher strength with deformation.

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