

Reinforcing effect of recycled polypropylene fibers on a clayey lateritic soil in different compaction degrees

Natalia de Souza Correia^{1#} , Sabrina Andrade Rocha² 

Article

Keywords

Soil improvement
Soil-fiber properties
Lateritic soil
Direct shear test
Compaction degree

Abstract

The present research investigates the reinforcing effect of recycled polypropylene (R-PP) fibers on a compacted clayey lateritic soil in different compaction degrees. R-PP fibers of 12 mm length were mixed with the soil in the contents of 0.1 and 0.25% of soil dry weight. Unconfined compression strength tests (UCS), direct shear tests and indirect tensile strength (ITS) tests were conducted. Fibers addition showed no significant alterations in the optimum compaction parameters. The study evidenced increases in UCS, changing the soil behavior from a brittle failure to a ductile failure, while fiber contribution was most effective for 0.25% R-PP fibers content and 95% compaction degree. The use of fibers improved the shear stress-strain behavior of the composites and soils compacted at different degrees of compaction showed similar shear behavior, which is coherent to the soil water retention curves (SWRC) results. Significant increases in the tensile behavior of soil-mixtures for both fiber contents used were observed, and fibers increase was more significant than increase in soil degree of compaction. The stretching of the fibers and fibers orientation at the sheared interface in direct shear tests and the fiber “bridge” effect in ITS tests could be observed.

1. Introduction

Fiber reinforcement remains a viable soil improvement technique that has been the focus of a growing number of investigations due to a wide range of applications and combinations for use in geotechnical works. The technique of soil mechanical stabilization with fibers can be used in retaining structures, subgrade and subbases pavement layers, slope stability, soft soil embankments, soil hydraulic conductivity control, erosion improvement, piping prevention (Shukla, 2017; Tang et al., 2007; Ziegler et al., 1998) and shrinkage cracks mitigation (Ehrlich et al., 2019). According to Hou et al. (2020), as the global community is turning to a more sustainable way of development, engineers are encouraged to use stabilization technologies that can replace or minimize the use of traditional cement and other curing agents.

In general, research has shown that the fibers randomly distributed in the soil matrix have the advantage of intercepting the potential zone of rupture, and by fibers tensile strength mobilization, improve the soil stress-strain behavior, making the mixture more ductile (Consoli et al., 2012; Li & Zornberg, 2013; Shukla, 2017; Yetimoglu & Salbas, 2003; Zornberg, 2002). However, the investigation of the effect of short fibers

on the tensile strength of soils has not been taken extensively (Chebbi et al., 2020).

As regards soil-fiber applications, studies using fine or clayey soils have been less explored than sand-fiber studies in the literature, although widely available in many places and with equal potential for application in geotechnical practice. According to Freilich et al. (2010), there is a need for advancing studies in clayey soil-fibers due to the greater complexity related to fiber interaction mechanism in cohesive soils. The behavior of soils reinforced with polypropylene fibers has also been widely studied (Anagnostopoulos et al., 2013; Cai et al., 2006; Mirzababaei et al., 2017; Plé & Lê, 2012; Tang et al., 2007).

A study presented by Zaimoglu & Yetimoglu (2012) showed the UCS effects of a fine-grained soil reinforced with randomly distributed polypropylene fibers (12 mm length). Results demonstrated a trend of UCS values increasing due to fiber content increase in the soil mix and revealed increases up to 85% in the UCS results when 0.75% fiber content was used. Tang et al. (2007) evaluated the behavior of a clayey soil reinforced with different contents of polypropylene fibers (12 mm length) through direct shear tests. Results revealed

[#]Corresponding author. E-mail address: ncorreia@ufscar.br

¹Universidade Federal de São Carlos, Departamento de Engenharia Civil, São Carlos, SP, Brasil.

²Universidade Federal de São Carlos, Programa de Pós graduação em Engenharia Civil, São Carlos, SP, Brasil.

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that soil shear strength parameters increased with increasing fiber contents. Wang et al. (2017) investigated the strength behaviors of expansive soil-fibers by direct shear test and triaxial compression tests and found that the fibers enhanced shear strength and deviator stress-strain behavior, reducing the post peak strength loss.

The tensile strength of cohesive soil is an important mechanical parameter that controls tensile cracks initiation and propagation characteristics (Tang et al., 2016). Several types of tests are available to investigate soil tensile behavior and although direct tensile tests of soil are more reliable and more precise than indirect tensile tests, they are difficult to perform (Chebbi et al., 2020; Li et al., 2014; Nahlawi et al., 2004). Divya et al. (2014) studied the fiber content and fiber length effect on tensile-strain characteristics and crack formation, in a silty soil mixed with polyester fibers showing that soil-fiber mixtures were able to withstand more deformation and subsequently higher stresses at failure. Ehrlich et al. (2019) observed that the addition of fibers to the soil increases soil tensile strength and delays the crack opening process. Tang et al. (2016) states that few studies have been conducted to investigate the effect of fiber reinforcements on soil tensile properties and the effects of compaction conditions were rarely examined.

This study aims at investigating the effect of recycled polypropylene (R-PP) fibers on a compacted clayey lateritic soil in different degrees of compaction. R-PP fibers (12 mm length) were mixed with natural soil in the contents of 0.1 and 0.25%, aiming soil improvement. Mechanical tests, such as UCS, direct shear and tensile strength tests were conducted to quantify the fibers contribution to soil properties.

2. Experimental programme

2.1 Materials and samples preparation

A lateritic soil was investigated in this research since it represents typical soils that cover a large area in the Brazilian territory and are found in many places in the world. In this research, the soil used was taken from the city of Santa Gertrudes, Sao Paulo, Brazil, and consists of a clay of high plasticity (CH) according to Unified Soil Classification System (SUCS) in (ASTM, 2017a). Although SUCS classifies this soil as a high plasticity clay, it presents a significant percentage of fine sand. In terms of predominant clay minerals, the clay fraction has Kaolinite, Illite, Gibbsite and Hematite (ASTM, 2014a). According to MCT method of soil classification, this lateritic fine-grained soil is classified as LG' (Nogami & Villibor, 1991). The soil sample was characterized according to: specific gravity test (ASTM, 2014b), particle size analysis (ASTM, 2017b), Proctor test (ASTM, 2012) and Atterberg limits tests (ASTM, 2017c). The properties of the soil are presented in Table 1 and particle size distribution curve of the soil is shown in Figure 1.

The technique of filter paper was used to determine the soil water retention curves (SWRC), standardized by (ASTM, 2016a). Soil samples were compacted at optimum water content and in two conditions of compaction degree:

95% and 98%. The SWRC were constructed by the drying process. The SWRC of the lateritic clay soils are presented in Figure 2. The curves were adjusted by the equation of Fredlund & Xing (1994), depicted in Equation 1. The curve adjustment parameters are shown in Table 2.

The clayey soil presents SWRC with unimodal behaviors in both degrees of compaction, which is coherent with the granulometric distribution of this soil. Results showed a great variation of suction pressures over a small range of soil water contents, due to the greater retention capacity of the soil. SWRC with similar behavior to the soil used in this research were obtained by Feuerharmel et al. (2006) and Portelinha & Zornberg (2017) for compacted fine lateritic soils.

$$w(\Psi) = w_r \cdot (w_s - w_r) \cdot \left(w_1 \cdot \left[\frac{I}{I + (\alpha_1 \cdot \Psi)^{n_1}} \right]^{m_1} + (I - w_1) \cdot \left[\frac{I}{I + (\alpha_2 \cdot \Psi)^{n_2}} \right]^{m_2} \right) \quad (1)$$

where: Ψ is the suction (kPa); w is the moisture content (g/g or m³/m³), w_s is the saturated moisture content of the soil; w_r is the residual moisture content of the soil; α , n , m (kPa) are curve fitting parameters.

Regarding different degrees of compaction, the SWRC behavior is coherent with expected results since the more pores in the compacted soil, the further the curve rises and the more it flattens (Figure 2). For the same level of moisture content, the soil compacted at 98% degree of compaction showed a lower level of suction in comparison to 95%.

Polypropylene (PP) fibers were used as the reinforcements in this study. The R-PP fibers have 18 micrometers in diameter, 0.9 g/cm³ of specific mass and 12 mm length, zero water absorption. The fibers are made of recycled polypropylene (R-PP). The characterization of the fibers by fiber filament was not done in this research. According to fiber's manufacturer, the breaking tensile strength of the PP fibers is 610 MPa.

Table 1. Physical properties of the CH soil.

Property Value	Symbol	Value
Soil classification (USCS)	CH	-
Percent sand (%)	-	36
Percent fines (<0.074 mm) (%)	-	64
Specific gravity	G_s	2.9
Maximum dry unit weight (kN/m ³)	$\rho_{d(max)}$	16.7
Optimum water content (%)	w_{opt}	24.5
Liquid limit	LL	51
Plasticity limit	PL	29
Plasticity index	PI	22

Table 2. Fitting parameters of SWRC.

Fredlund & Xing (1994) parameters - CH soil (drying)					
θ_s	θ_r	a_f	n_f	m_f	R^2
(m ³ /m ³)	(m ³ /m ³)	(kPa)	-	-	-
0.452	0.000001648	8192.8	0.98629	2.8702	0.985
0.432	0.000006693	4147.9	0.97284	2.8707	0.987

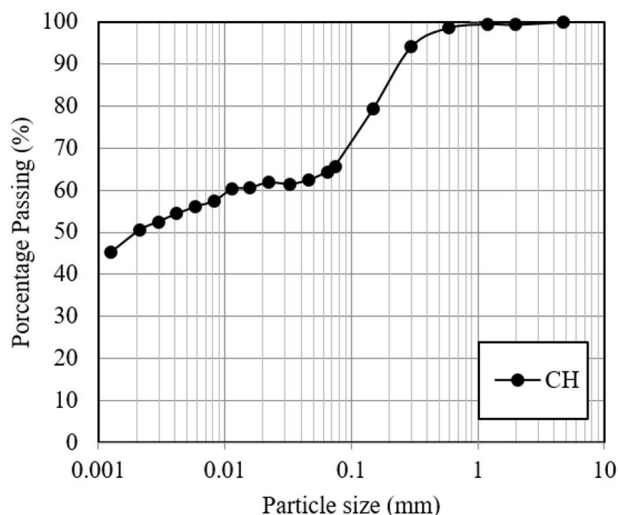


Figure 1. Particle size distribution of the CH soil.

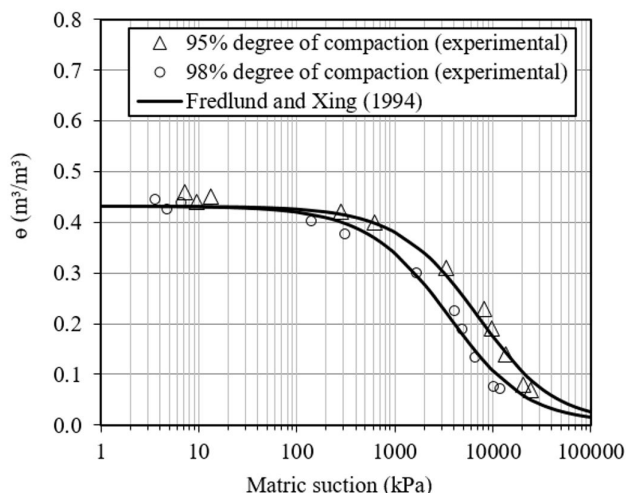


Figure 2. Soil water retention curves of the CH soil in different compaction degrees.

R-PP Fibers were randomly inserted into the soil mass in 0.1% and 0.25% of soil dry weight and were distributed (homogenously) and mixed with the soil. A manual mixer was used to facilitate mixing process. Figure 3 presents soil-fibers mixing process for 0.1% fiber content. Similar fiber contents were found in several studies (Diambra & Ibraim, 2014; Feuerharmel, 2000; Freilich et al., 2010; Li & Zornberg, 2005; Mirzababaei et al., 2017; Özkul & Baykal, 2007; Rowland Otoko, 2014). Soil-fiber mixtures were preserved in air-proof bags for a minimum of 24 hours for moisture homogenization.

2.2 Methods

In order to investigate soil improvement due to fibers inclusion, UCS tests were conducted with following ASTM 2166 (ASTM, 2016b) with samples compacted at the optimum compaction parameters for each soil condition. Natural and fiber-reinforced samples were compacted 95% and 98% compaction degrees. Tests were conducted in triplicates with maximum coefficient of variation of 15%.

For the same conditions of optimum compaction parameters and degrees of compaction, direct shear tests (drained condition) were conducted following ASTM D3080 (ASTM, 2011) on compacted natural soil and R-PP soil mixtures. The test was conducted on shear box of 100 x 100 x 25 mm. Samples were consolidated under vertical stresses of 50, 100 and 200 kPa prior to shearing, and testing loading rate was 0.5 mm/min. Loads and displacements at axial and horizontal directions were recorded automatically by a computer-controlled data collection system. Data of shear stresses as a function of horizontal displacement were recorded up to a total displacement of 15 mm to observe post-failure behaviors.

Brazilian tensile strength method for measuring tensile strength of compacted soils was conducted according to ASTM D3967 (ASTM, 2016c) to quantify the effect of fiber contents on the indirect tensile behavior of the clayey soil.

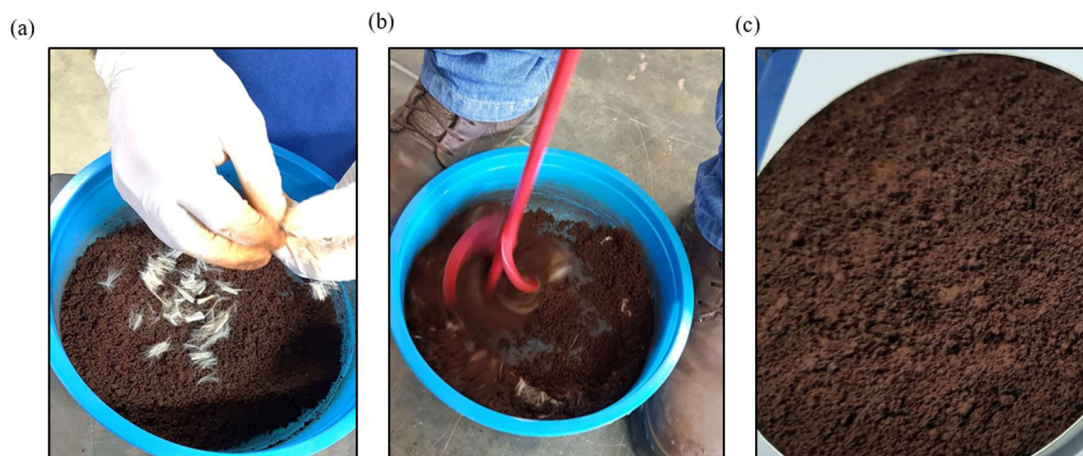


Figure 3. Soil-fiber mixing process: (a) fibers addition; (b) soil mixing process; (c) homogenized soil-fiber mix.

Tests were conducted using samples compacted at 95% and 98% degrees of compaction, in triplicate, and with maximum coefficient of variation of 15%.

3. Results and discussion

3.1 Behavior of R-PP fibers on soil compaction properties

Figure 4 presents the compaction curves of CH soil mixtures with 0.1% and 0.25% fiber content, compared to respective natural soils. Maximum dry unit weight values did not change with fiber inclusion in the clayey soil, while the optimum water content values slightly increased. Results of no significant alterations in the compaction curves of soil-fiber mixtures were evidenced by others studies (Gelder &

Fowmes, 2016; Kumar & Singh, 2008; Marçal et al., 2020; Mirzababaei et al., 2013).

3.2 Influence of R-PP fibers on soil unconfined compression strength

The axial stress-strain curves from UCS tests of natural soil and R-PP fibers reinforced mixtures are shown in Figure 5 for the different soil compaction degrees. Analyzing the stress-strain curves of the natural soil and soil-fiber mixtures, it is observed that for the natural soil there was a significant reduction in resistance after the rupture of the specimen. On the other hand, mixtures of 0.10% soil-fiber and 0.25% soil-fiber showed increases in strength with increase in strains, changing the soil behavior from a brittle failure to a ductile failure. This result is consistent with that presented in previous studies, carried out in clayey soil, using different types of fibers (Marçal et al., 2020; Tang et al., 2007; Tran et al., 2018). Figure 6 shows typical photographs after tests for samples compacted at 95% compaction degree of compaction.

Figure 7 compares UCS results for the different degrees of compaction as function of R-PP fiber content in the clayey soil. For both cases, UCS increased with increasing degree of compaction. However, for 95% degree of compaction, the contribution of 0.1% and 0.25% of R-PP fibers to increase UCS of soil was more significant than the results presented at 98% degree of compaction. This analysis evidenced that the fiber contribution was most effective for 95% degree of compaction, showing that fiber content increase was most significant than compaction degree increase.

The increases obtained in UCS due to the inclusion of fibers are consistent with previous results from the literature that evaluated PP fibers, e.g., (Kumar & Singh, 2008; Santoni et al., 2002; C. Tang et al., 2007; Zaimoglu & Yetimoglu, 2012). Tang et al. (2007) states that this increase in UCS results might be related to the fibers bridging effect,

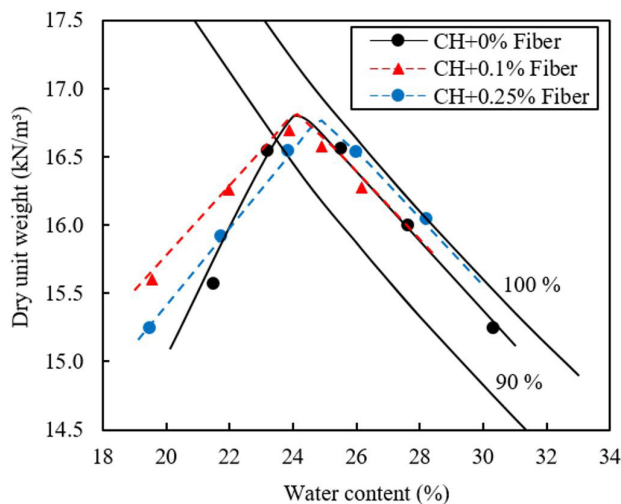


Figure 4. Proctor compaction curves natural soil and R-PP fiber mixtures.

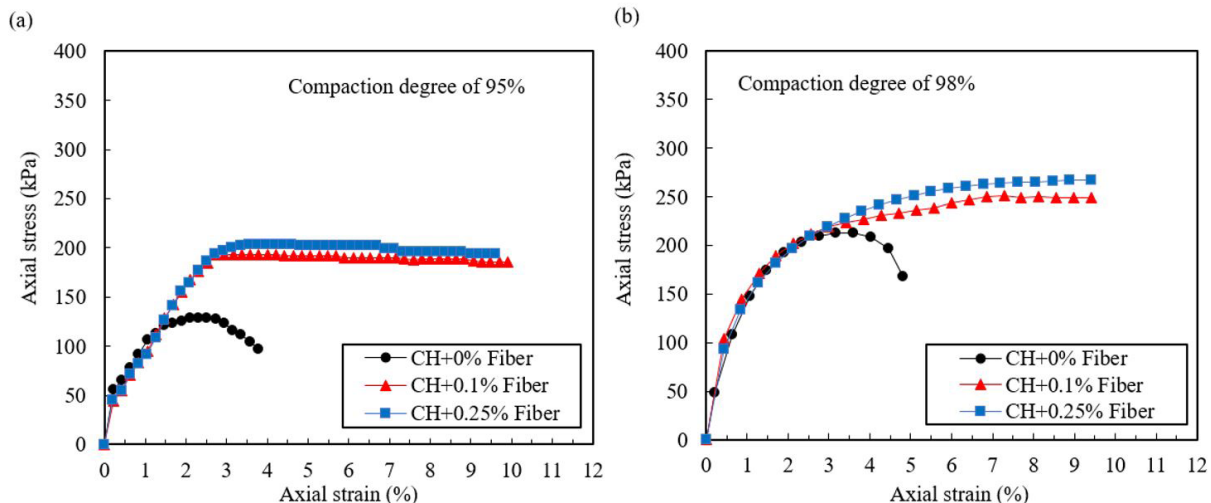


Figure 5. Axial stress-strain results of natural soil and R-PP fiber mixtures: (a) 95% degree of compaction; (b) 98% degree of compaction.

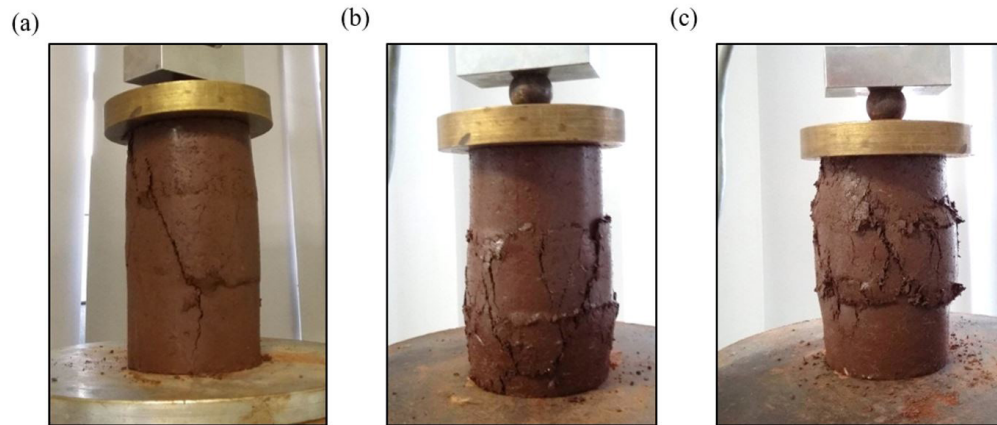


Figure 6. Samples compacted at 95% degree after failure for: (a) natural soil; (b) 0.1% fiber content; (c) 0.25% fiber content.

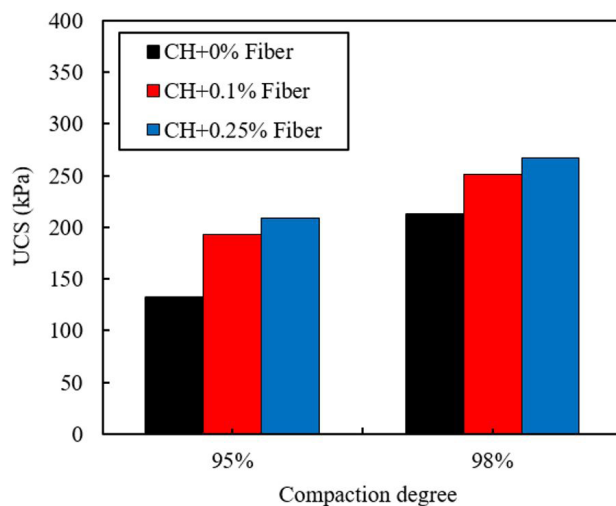


Figure 7. UCS results for both degrees of compaction as function of R-PP fiber content in the clayey soil.

which can efficiently prevent the further development of failure planes and deformations of the soil.

3.3 Influence of R-PP fibers on soil shear strength

Direct shear tests were conducted considering each combination of soil and R-PP fibers and degree of compaction. Results of shear stress-displacement curves are presented in Figure 8. For both degrees of compaction, the inclusion of fibers improved the shear stress-strain behavior of the composite for all the normal stresses analyzed. Results of shear stress for 0.25% fiber content was superior to 0.1% fiber content addition, showing the improvement of soil shear properties due to fiber reinforcement in both degrees of compaction. For 95% degree of compaction (Figure 8a), initial stiffness of the soil increased with R-PP fibers addition, for all normal stresses analyzed, indicating superior fibers mobilization. Still in Figure 8, it is important to highlight that, regarding substantially more ductile behavior for soil-

fibers compacted 98% compaction degree in comparison to untreated soil, this may be a prejudice rather than a benefit depending on the desired behavior for the soil.

Figure 9 presents typical photographs after direct shear tests for samples with 0.25% fiber content and 95% degree of compaction. The stretching of the fibers and fibers orientation at the sheared interface can be visualized. Darvishi & Erken (2018) and Kumar & Singh (2008) highlights the mechanism of fibers stretching in the soil matrix during the shearing process. According to Kong et al. (2019), the extension of fibers is due to the rearrangement and microstructure disturbance during shearing provides an important contribution to the strength increase.

Figure 10 shows the shear strength envelopes of CH soil and R-PP fiber-reinforced soils for 95% and 98% degrees of compaction. Results are presented considering values of peak shear strength. Higher shear strength was evidenced in 0.1% and 0.25% soil-fiber mixes for 95% degrees of compaction, where the contribution was more attributed to apparent cohesion than friction. Regarding SWRC data (Figure 2), the soil compacted at 95% degree of compaction presented superior suction than the soil compacted at 98% degree of compaction, which approximates soil shear behaviors. On the other hand, for 98% degrees of compaction, the contribution was more attributed to friction angle. For Shao et al. (2014) and Yetimoglu & Salbas (2003), the increase in the friction angle is most probably associated with mobilization of friction between fibers and the soil particles. It is important to highlight that lateritic soils present good shear strength behavior when unsaturated, as observed by the high soil friction angle.

Figure 11 presents the improvement in soil shear strength properties for all analyzed cases. As observed in UCS tests, results of shear stress for 0.25% fiber content addition was superior to 0.1% fiber content, showing improvement in soil properties due to fiber reinforcement in both degrees of compaction. That means that the number of fibers in the shear plane is a very important parameter (Marçal et al., 2020). In

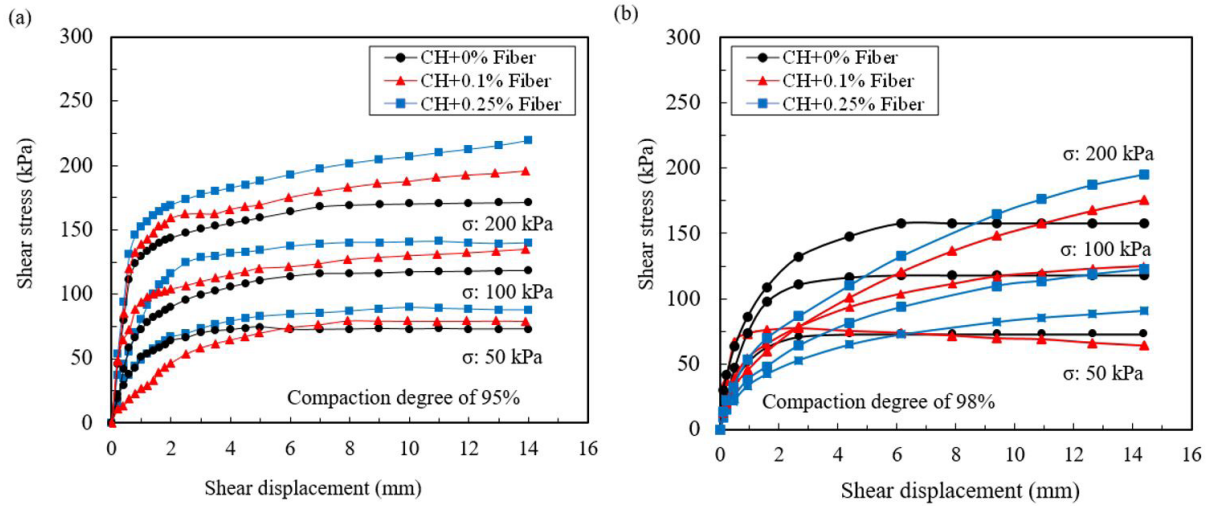


Figure 8. Shear stress-displacement curves of natural soil and R-PP fiber mixtures: (a) 95% degree of compaction; (b) 98% degree of compaction.

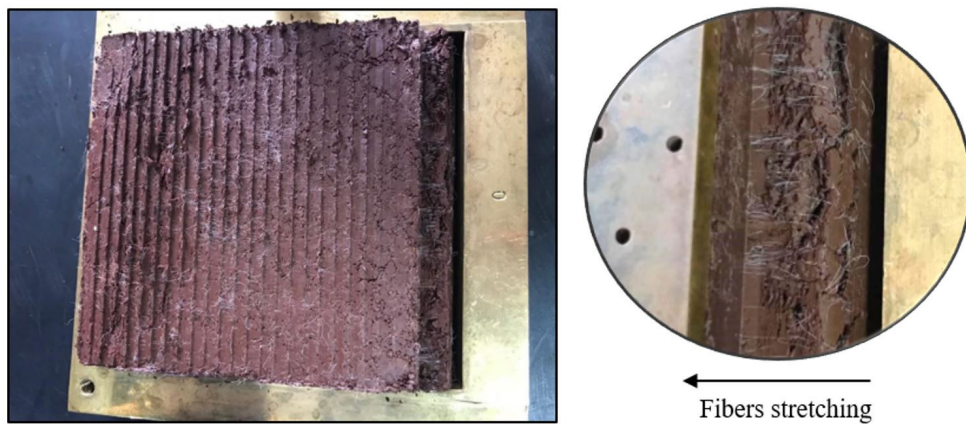


Figure 9. Stretching of the fibers during shearing.

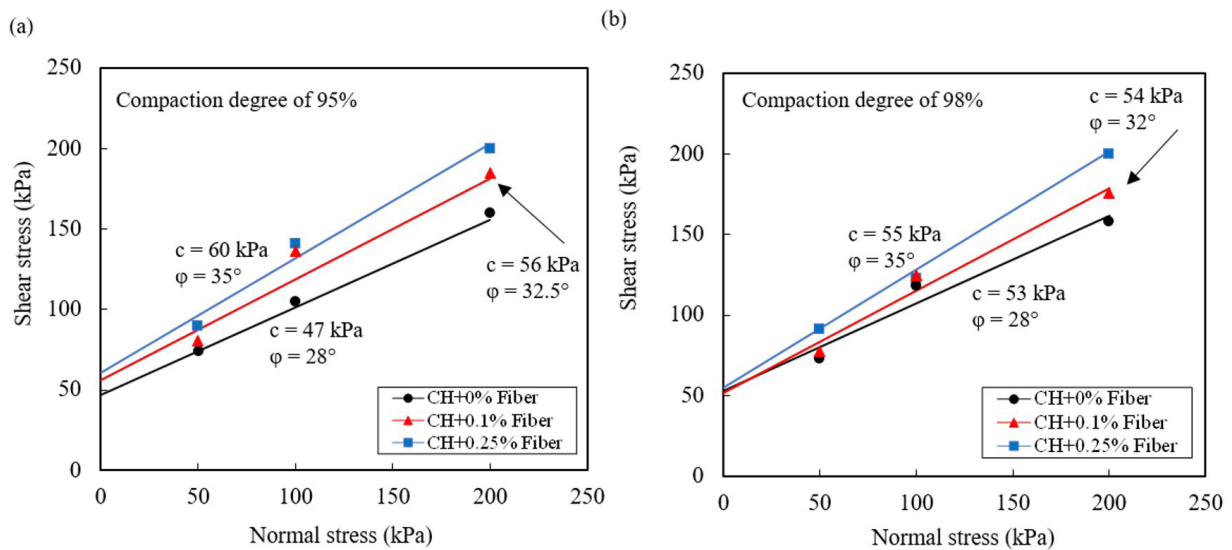


Figure 10. Shear strength envelopes of natural soil and R-PP fiber mixtures: (a) 95% degree of compaction; (b) 98% degree of compaction.

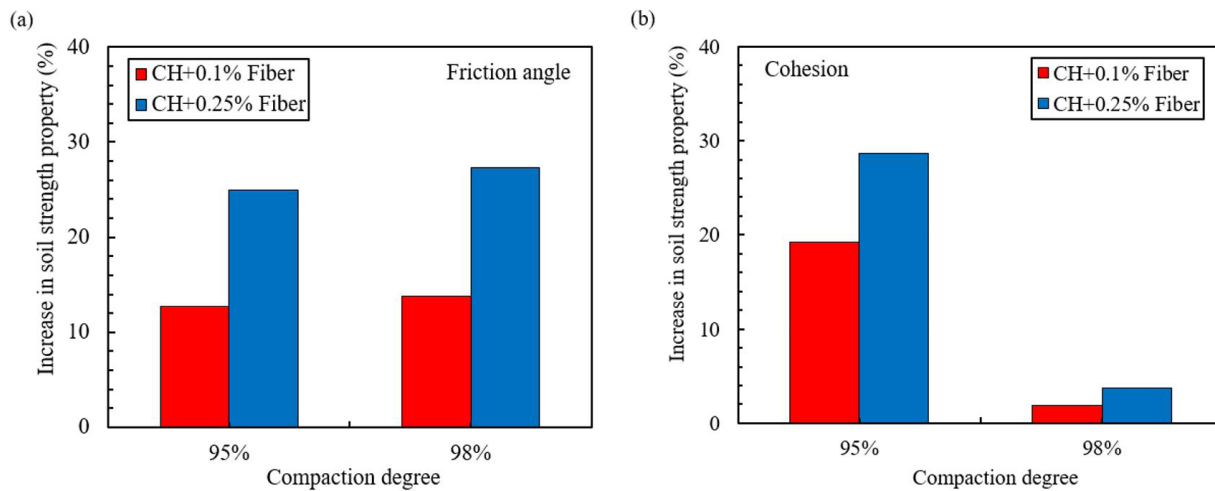


Figure 11. Results of improvement in soil shear strength properties for all analyzed cases: (a) friction angle; (b) cohesion.

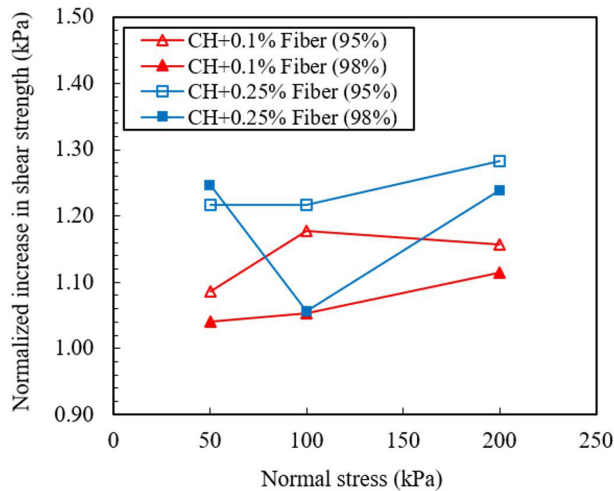


Figure 12. Normalized improvement in soil shear strength after R-PP fibers addition.

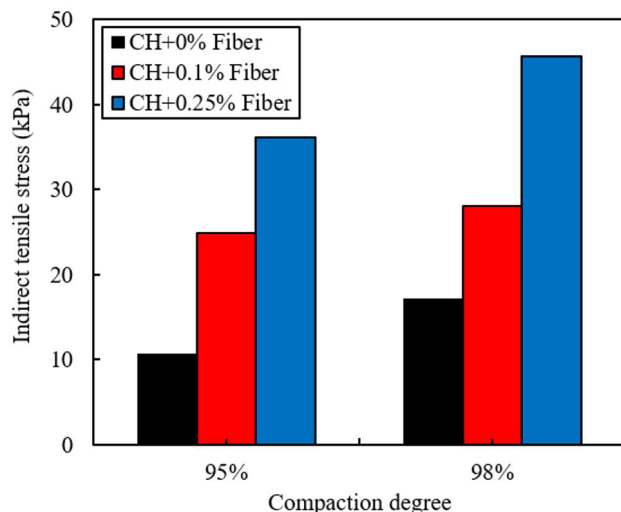


Figure 13. Indirect tensile stress results of natural soil and fiber-soil mixtures.

general, improvement in soil friction angle (Figure 11a) was most significant than improvement in soil apparent cohesion (Figure 11b). Figure 12 presents normalized improvement in shear strength of CH soil and R-PP fiber-reinforced soils for 95% and 98% degrees of compaction. Results showed a slight increase in shear stresses with increasing normal stresses for both compaction degrees and evidences improvement in soil strength after R-PP fibers addition.

3.4 Influence of R-PP fibers on indirect tensile behavior

Indirect tensile strength tests were conducted to quantify the effect of fiber content on the indirect tensile behavior of natural soil since it is an important mechanical parameter that controls the initiation and propagation characteristics of tensile cracks. Figure 13 presents the results of indirect tensile stress of natural clay and 0.1% and 0.25% fiber-soil samples compacted at 95% and 98% degrees of compaction. The tensile strength of the clayey soil increased with increase in fibers content and increased with increase in soil compaction degree. In terms of tensile behavior, the effect of fibers increase was more significant than the effect of compaction properties. Li et al. (2014) mentioned that the fibers share some tensile load for the soil matrix, since the movement of the fibers in the soil matrix is prevented by the interactions between the fibers and the soil matrix, causing greater resistance to the composite.

Figure 14 shows the failure mode of soil-fiber mixtures and fibers stretching details for 0.1% and 0.25% fibers addition. The fiber-reinforced specimens formed the fiber “bridges” reported by Tang et al. (2007). The “bridging” effect of fibers prevented the early development of traction cracks and, consequently, corroborated the more ductile behavior of the soil-fiber mixtures. Tang et al. (2016) states the post-failure tensile behavior is mainly conditioned by

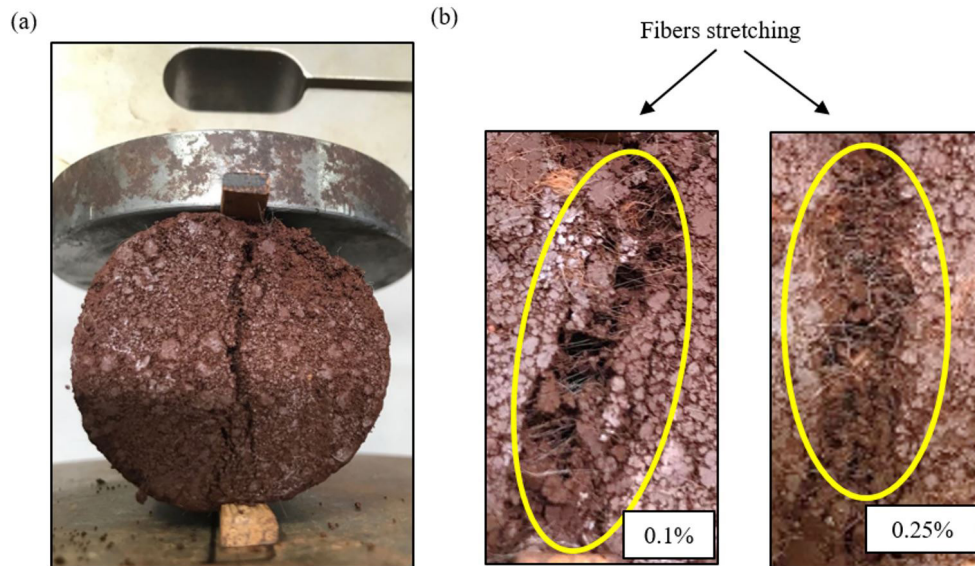


Figure 14. Failure mode of soil-fiber mixtures: (a) detail of rupture; (b) fibers stretching detail at 98% compaction degree.

the interfacial shear strength of the embedded fibers and the tensile strength of the fibers.

4. Conclusions

This study evaluated the reinforcing effect of recycled polypropylene fibers on a clayey lateritic soil compacted in different compaction degrees. The study involved UCS tests, direct shear tests and indirect tensile strength tests. Outcomes of the combinations of fiber contents and degrees of compaction were evaluated. The following conclusions can be drawn:

- The use of R-PP fibers as reinforcements in the clayey lateritic soil revealed an increase in UCS, changing the soil from a brittle behavior to a ductile failure in all evaluated cases. Fibers contribution was most effective for 95% compaction degree. Nevertheless, the increase in fiber content from 0.1 to 0.25% showed a significant effect on the UCS of clayey lateritic soil, being most effective than increasing soil degree of compaction;
- Direct shear tests results indicated that, for both degrees of compaction, the inclusion of R-PP fibers improved the shear stress-strain behavior of the composite with similar results. Higher shear strength was evidenced in 0.1% and 0.25% soil-fiber mixes for 95% degrees of compaction, where the contribution was more attributed to apparent cohesion than friction. Soil compacted at 95% degree of compaction presented superior suction than the soil compacted at 98% degree of compaction, which approximates soil shear behaviors;

- The tensile strength of the clayey soil increased with increase in fibers content and increased with increase in soil compaction degree. In terms of tensile behavior, the effect of fibers increase was more significant than the effect of compaction properties;
- The stretching of the fibers and fibers orientation at the sheared interface could be visualized, while the “bridging” effect of fibers could be observed in the tensile strength test.

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Declaration of interest

The authors declare no conflict of interest.

Author’s contributions

Natalia de Souza Correia: supervision, conceptualization, writing - original draft preparation, revision. Sabrina Andrade Rocha: investigation, data curation, validation.

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List of symbols

CH	High plasticity clay
m_f	curve fitting parameters
n_f	curve fitting parameters
θ_r	volumetric residual moisture content
θ_s	volumetric saturated moisture content
SWRC	Soil water retention curves
w	gravimetric moisture content
w_r	gravimetric residual moisture content
w_s	gravimetric saturated moisture content
α	curve fitting parameters
Ψ	suction
G_s	Specific gravity
$\rho_{d(\max)}$	Maximum dry unit weight (kN/m ³)
w_{ot}	Optimum water content (%)
LL	Liquid limit
PL	Plasticity limit
PI	Plasticity index