Drained and undrained shear behavior of a clayey soil reinforced with recycled polypropylene fibers

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ABSTRACT

The use of soil-fiber has been recognized as a viable technique of soil improvement in numerous geotechnical applications. However, existing research has not yet established the fundamental mechanisms controlling the behavior of clay-fiber mixtures and the constraints that may affect their performance. On the other hand, there is a growing increase in the development of methodologies for predicting soil-fiber behavior, as well as the use of soil-mixture constitutive models. In this context, the present work aims to contribute to the understanding of shear strength and deformability behavior of a clay soil reinforced with recycled polypropylene (R-PP) short fibers under drained and undrained triaxial tests. In terms of effective stresses, in drained condition, results showed that the fibers caused an increase in soil cohesion, remaining the angle of friction practically unaffected. In undrained condition, the contribution of fibers on friction angle increase was more significant than cohesion increase. Drainage during shearing have favored soil-fiber shear strength. All fiber-soil specimens presented “bulging” behavior after shearing. The interaction mechanisms between the soil and fibers, and consequently the shear strength of the composite, were not influenced by the drainage condition or by the development of pore water pressures during shearing.

1. INTRODUCTION

Environmental challenges have stimulated researchers to find techniques to improve the quality of geotechnical materials (Luwalaga, 2015). In this aspect, the use of soil-fiber, especially with local soils and alternative fibers, has been recognized as a viable technique of soil improvement in numerous geotechnical engineering applications. Regarding polymers, one of the growing commodities in the world, their use has increased in numerous applications, such as fibers for soil or concrete reinforcement. Polypropylene (PP), extensively used in packaging, is a very common type of polymer also used to product fibers. However, because of the short lifetime of PP packaging, the majority of these thermoplastics end up as waste in landfills. In this context, the polypropylene waste can be recycled and used for different products with "virgin-like" quality. Yin et al. (2016) states that recycled plastic fibers have started attracting attention around the world, and that the adoption of recycled plastic fibres has not yet been seen due to limited research focusing on their durability, performance and mechanical properties.

Corroborating to a sustainable world, the 2030 Agenda for Sustainable Development (United Nations, 2015) sets out in its objectives a substantial reduction in waste generation and the ideal of sustainable cities and buildings through the use of local materials for engineering works. In this aspect, the use of soil-fiber, especially with local soils, can be used in a diversity of applications, such as retaining structures, stabilization of subgrade and subbases, improvement in soil bearing capacity, soft soil embankments, controlling soil hydraulic conductivity, erosion improvement, piping prevention and shrinkage cracks mitigating (Ziegler et al. 1998; Tang et al. 2007; Shukla et al, 2017; Erlich et al., 2019). Consoli et al. (2002) carried out one of the first experiments on recycled polyethylene (PET) fibers derived from plastic wastes in the reinforcement of natural and artificially cemented sand, showing that the plastic waste improved soil mechanical response. In general, research has shown that fibers randomly distributed in the soil matrix have advantages such as intercepting the potential failure zone, by mobilizing fiber tensile strength and soil more ductility.

Regarding clayey soil-fiber mixtures, studies report changes in compression and shear strength behavior, deformability, failure mode, volumetric variation and initial stiffness. Due to the greater complexity related to fiber interaction mechanism in cohesive soils and the behavior of this soil under drained and undrained conditions, there is a need for additional evaluations (Freilich et al; 2010). Ma et al. (2018) states that tension of fiber strengthens the bond among clay particles, which enhances the shear strength of clay. In fact, research has not yet established the fundamental mechanisms that control the behavior of clayey-fiber mixtures or the conditions that may affect their performance (Anagnostopoulos et al. 2014). Özkul and Baykal (2007) suggest that most studies have focused on short-term strength behavior and that the strength and deformation behavior of clayey-fiber soils under saturated and drained loading conditions has not been widely studied. According to Li et al. (2013), the effects of drainage and pore water pressures on the effective strength of the fiber-clay mixtures are of interest.

Feuerhemel (2000) also studied the inclusion of PP fibers (12 and 36 mm and 0.50%) in a clayey soil using triaxial consolidated drained (CD) tests. Results showed continuous growth of soil-fiber strength, even at strains levels of 28%. Fibers have increased cohesion up to 3 times (12 mm) and 5 times (36 mm), while angle of friction was practically unaffected. Trindade et al. (2004) also evaluated the inclusion of PP fibers (20 mm and 0.25%) in a clayey soil using triaxial consolidated drained (CD) tests. The fibers addition reduced soil compressibility and soil friction angle remained unchanged, while cohesion increased up to 70%. Freilich et al. (2010) showed failure envelopes determined from CU triaxial tests indicating an increase in the effective shear strength of the soil with the PP fibers. Results from CD triaxial tests indicated that the strength of the fiber-clay was lower for long term-fully drained conditions, providing evidence that the effective strength of the mixture may significantly decrease with time and drainage. Özkul and Baykal (2007) also conducted CU and CD tests with 25 mm tire fiber-clay. Results are in agreement with Freilich et al. (2010) where strength of the fiber-clay from CD triaxial was lower than in CU tests. Friction angle remained unchanged in both drainage conditions.

Khatri et al. (2017) also carried out a series of undrained triaxial tests on fiber-reinforced clay with 0.4% to 1.6% coir fiber and reported improved shear strength with the increase in fiber content. Mirzababaei et al. (2017) analyzed the inclusion of recycled carpet fibers in a clayey soil using triaxial consolidated drained (CU) tests. The fiber content of 3% presented higher shear strength at the initial effective stress of 50 kPa when compared to the soil with 5% fiber. However, at lower initial effective consolidation stresses, Mirzababaei et al. (2017) suggests that fiber cannot stretch effectively and may slip during the shear and indicate up to 5% carpet waste fiber to optimally improve the shear strength behavior of clays. Louzada et al. (2019) evaluate the mechanical behavior of a clayey soil mixed with PET flakes using consolidated drained triaxial tests and concluded that flakes content improved the interaction between the particles of PET and soil, causing an enrichment on soil cohesion and friction angle, while the influence of the confining stress was evidenced.

Najjar et al. (2013) states that the growing interest in understanding the behavior of fiber reinforced soils indicates that this technology remains a viable option that could be used in the future in a wide range of geotechnical applications. In this context, the present study aims to contribute to the understanding of shear strength and deformability behavior of a clayey lateritic soil with the inclusion of 0.25% recycled polypropylene (R-PP) short fibers under drained and undrained triaxial tests. Ultimate tensile strength tests were conducted on recycled polypropylene to confirm polypropylene quality.

2. MATERIALS AND METHODS

2.1 Soil

A lateritic clayey soil was chosen in this research since it represents a typical soil that covers a large area in Brazilian territory. Lateritic clayey soils present high shear strength and low compressibility, which makes them excellent materials when compared to conventional clays (Bueno et al. 2006). The clayey soil was collected in Santa Gertrudes, Sao Paulo, Brazil. Basic soil properties are presented in Table 1 and soil particle distribution curve is shown in Figure 1, according to ASTM D 7928. Maximum dry density and optimum moisture content of soil was obtained based on standard Proctor tests (ASTM D 698).

Table 1. Characteristics of tested soil.

Characteristics	Clayey soil	Specification
Soil classification (USCS)	CH	ASTM D 2487
Percent sand (%)	36	ASTM D 7928
Percent fines (<0.074 mm) (%)	64	
Specific gravity, G_s	2.99	ASTM D 854
Maximum dry unit weight (kN/m^3)	16.9	ASTM D 698
Optimum water content (%)	24.0	
Liquid limit (%)	51	ASTM D 4318
Plasticity limit (%)	20	
Plasticity Index (%)	21	

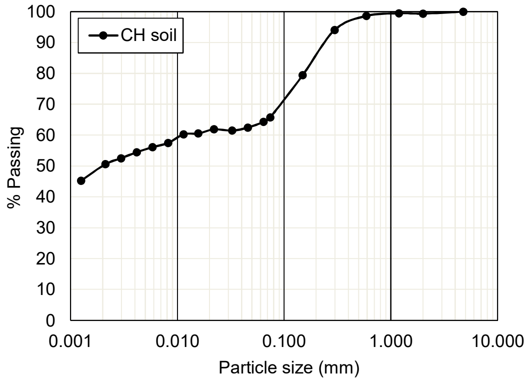
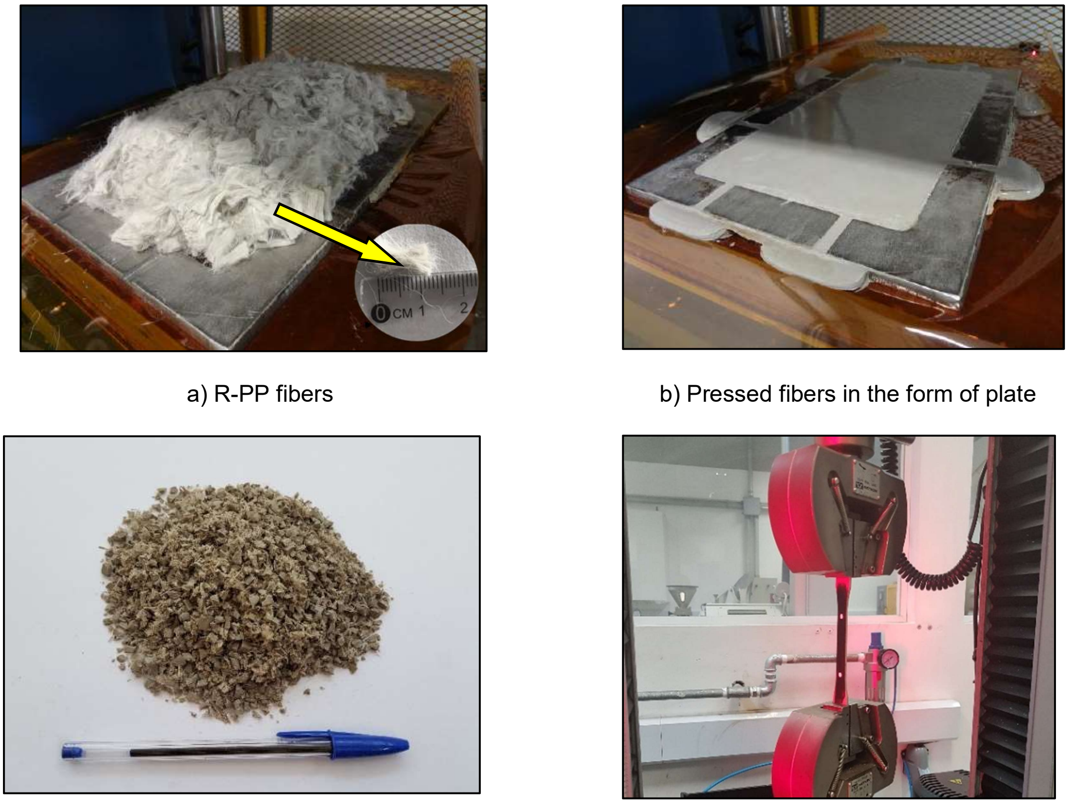


Figure 1. Injection molding process.

2.2 R-PP Fibers

The fibers used in this research are made of recycled polypropylene. Fibers are 18 micrometers in diameter, 0.9 g/cm^3 density and 12 mm length. In order to evaluated que quality of recycled polypropylene, ultimate tensile strength tests were conducted according to ASTM D 638. To obtain the injected specimens, it was necessary to agglomerate and press the fibers (Figure 2a) so that they could form a plate (Figure 2b). This molding process was performed only to obtain recycled polypropylene strength parameters. The characterization of the fibers by fiber filament (Fig. 2a) was not done in this research.



a) R-PP fibers

b) Pressed fibers in the form of plate

c) Raw material granules

d) Injected test specimens during test

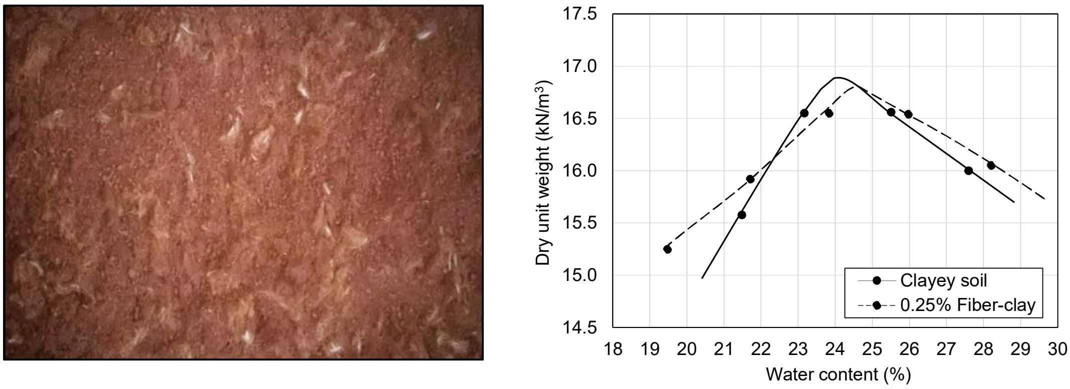
Figure 2. Fiber pressing for injection molding process and tensile strenght tests of recycled polypropylene.

The plates were then granulated to obtain a suitable particle size material to feed the injector (Figure 2c). From the granules, type I specimens were molded by injection, according to ASTM D 638, and submited to tensile strength test (Figure 2d). Tensile strength tests were conducted at the Materials Characterization & Development Center (CCDM) at UFSCar. According to the results, the R-PP material showed average ultimate tensile strength of 31.2 MPa, 164% of elongation at break and tensile modulus of 1.74 GPa, which is in the range of virgin PP mechanical properties.

3. RESULTS AND DISCUSSION

3.1 Compaction tests

R-PP Fibers were randomly inserted into the soil mass in 0.25% of soil dry weight and were homogenously distributed and mixed with the soil. Figure 3a show aspects of R-PP fibers mixed with clayey soil. Considering the importance of compaction parameters for each soil mixture in geotechnical application, Standard Proctor tests were conducted (ASTM D698) for natural and fiber-soil mixture. Results of optimum parameters were used to compact specimens for triaxial tests. Figure 3b shows alterations on soil compaction curves obtained after 0.25% R-PP fibers addition. It is observed in Figure 3 that the behavior of Maximum dry unit weight of natural clayey soil did not significantly altered with fibers inclusion. Optimum moisture content (OMC) increased from 24% to 24.5% with R-PP fibers addition.



a) Fiber-soil mixture

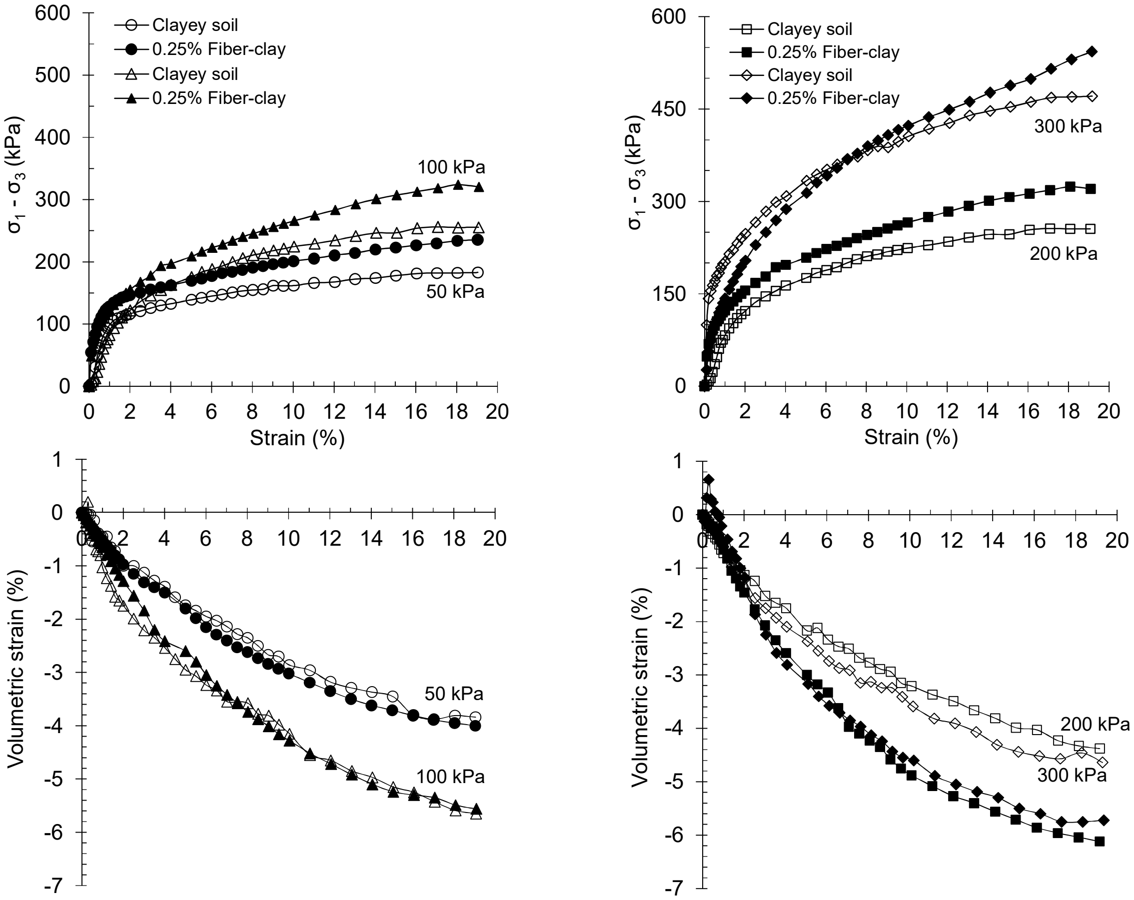
b) Compaction curves

Figure 3. Fiber-soil mixture and compaction curves.

3.2 Triaxial tests

In order to investigate strength parameters, triaxial consolidated-drained (CD) and consolidated-undrained (CU) tests were carried out on the clayey soil and fiber-soil mixture, respectively according to ASTM D7181 and ASTM D4767. Specimens were compacted with 50 mm of diameter and 100 mm of height with 95% compaction degree. During the tests, samples were saturated using backpressure and water percolation, which was guaranteed by Skempton's parameter B of 0.9 (Skempton, 1954). Triaxial test speed was obtained from consolidation tests. The shear velocity used for all samples was 0.15 mm/min. As regards confining pressures, researches in the literature with fiber-soil studies indicates 50 to 400 kPa (Özkul and Baykal, 2007; Freilich et al.; 2010; Mirzababaei et al., 2017). In this research, for both triaxial tests, confining pressures of 50 kPa, 100 kPa, 200 kPa and 300 kPa were used.

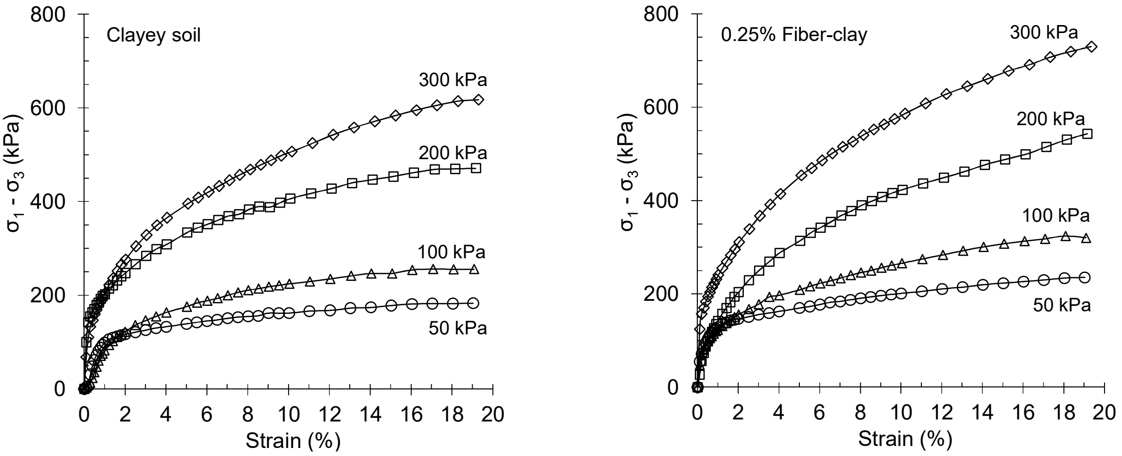
Figure 4 shows stress-strain–volumetric curves of natural clayey soil and 0.25% fiber-soil mixture in isotropical drained compression tests (CD). In general, an increase in the diference of principal stresses was oberved with increasing confining pressure during tests. Regarding volumetric strains, both soils presented reducing volumes during shearing, a tpycal behavior of normally consolidated clays. For the volumetric strain, The natural and the fiber-soil mixture remained with almost the same changes in the volume contraction throughout the triaxial (CD) test, expect for 200 kPa and 300 kPa, where fibers shower greater compressibility than natural soil. To better highlight the changes provided by the inclusion of fibers, Figure 5 presents comparative results of stress-strain curves for natural and fiber-soil mixture. For 0.25% soil-fiber tests, it is found that after the soil undergoes plastic deformation, the fibers act more significantly resulting in an increase in the drained shear strength compared to the natural soil. For the higher confining stress (300 kPa), soil-fiber mixture did not present peak shear strenght and remaining supporting higher loads. These behavior was also observed in the studies of Feuerhemel (2000) and Diab et al. (2018). In addition, all specimens presented “bulging” behavior after shearing, which, accordin to Özkul and Baykal (2007) and Ekinci and Ferreira (2012) is typical of fiber-clay samples.



a) CD tests (50 and 100 kPa)

b) CD tests (200 and 300 kPa)

Figure 4. Stress-strain–volumetric curves of clayey soil and fiber-soil mixture in CD tests.

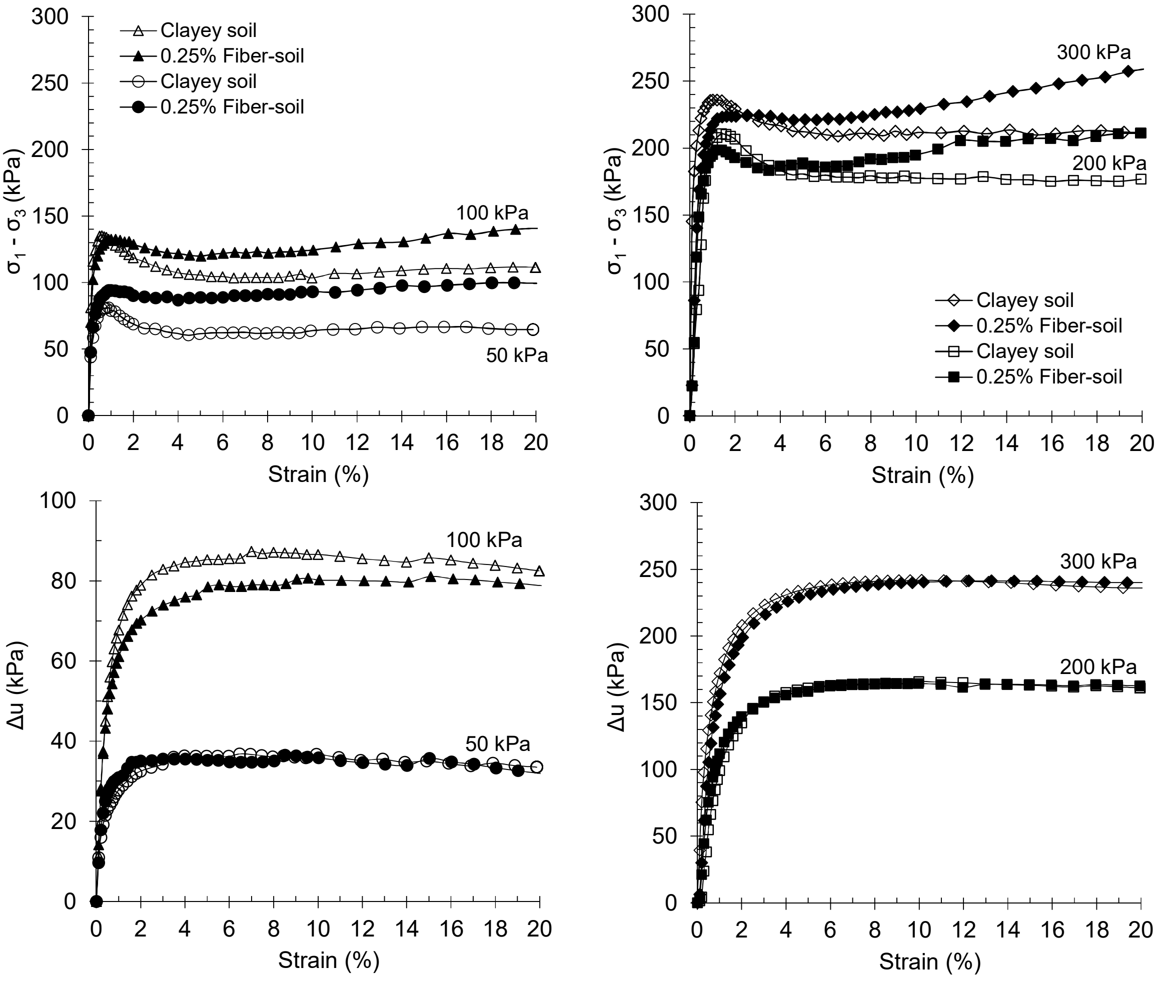


a) Clayey soil

b) 0.25% Fiber-soil

Figure 5. Comparison of stress-strain curves of clayey soil afiber-clay mixture in CD tests.

Figure 6 presents stress-strain–excess porewater pressure curves of natural clayey soil and 0.25% fiber-soil mixture in isotropical undrained compression tests (CU). The strength of fiber-soil mixture superior than strength of natural soil, and the influence of fibers increases with confining pressures. For all the confining stresses, the stress-strain curves showed an increase in strength and a reduction after peak strength; however, this behavior was less significant in soil-fiber mixture than the reductions observed in the natural soil.

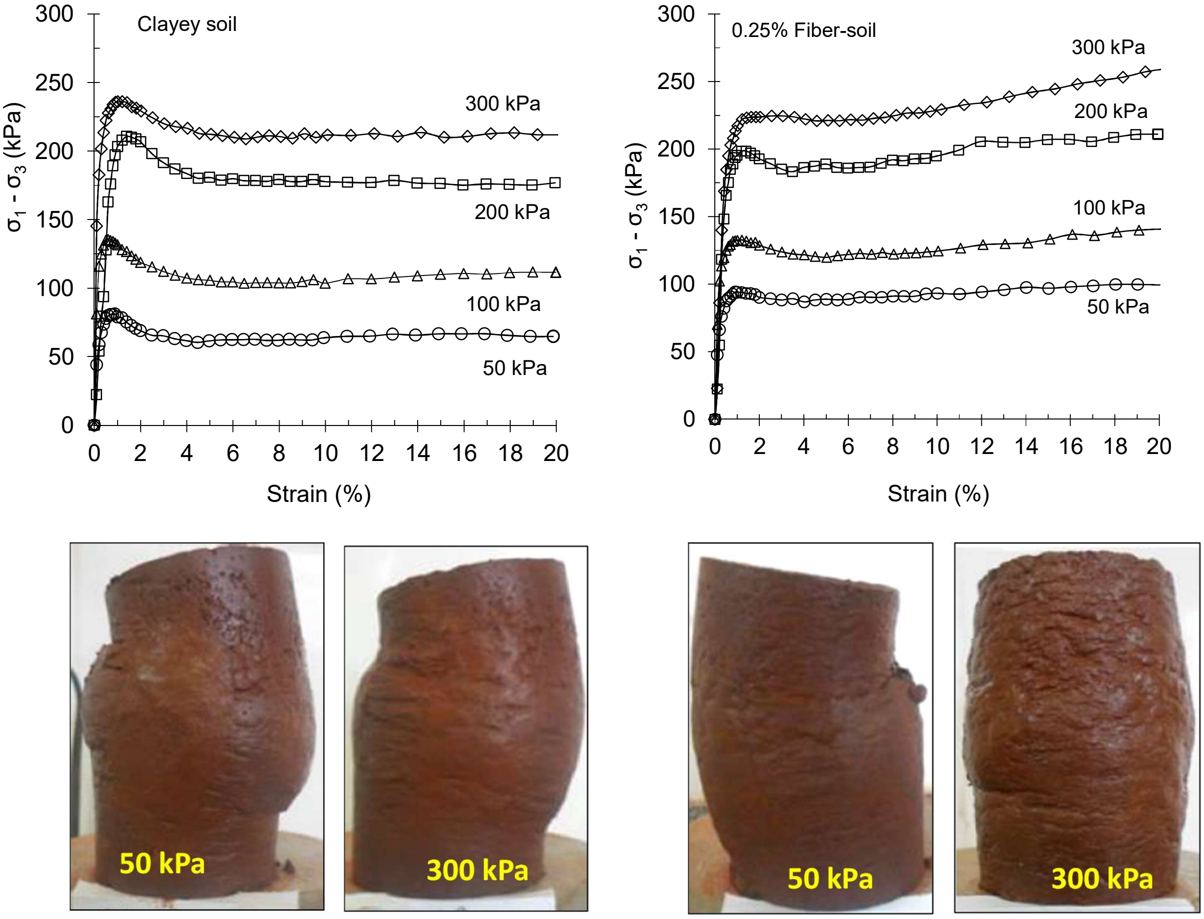


a) CU tests (50 and 100 kPa)

b) CU tests (200 and 300 kPa)

Figure 6. Stress-strain curves and excess porewater pressure-strain curves of clayey soil and fiber-soil mixture in CU tests.

Figure 7 presents comparative results of stress-strain curves for natural and fiber-soil mixture. Fibers contributed to a better distribution of shear stresses on the composite, as also verified for the drained triaxial tests (Figure 4). After the reduction in peak strength, fiber-soil samples showed another increase in shear strengths troughout the tests. This greater interaction between soil particles and fiber causes the fibers to stretch and consequently, when initiating the failure phase, the fibers better contribute in the distribution of shear stresses. Also in Figure 7, fiber-soil specimens presented "bulging" behavior after shearing, as observed in drained tests, while natural specimens exbited partial development of a shear plane. Regarding excess porewater pressure developed during tests (Figure 6), in all cases, the values obtained were positive and then associated with a trend of volume contraction, as in triaxial drained tests. It can be concluded that the fibers restrict the dilatation of soil mixture during undrained shear, as observed by Consoli et al . (1998) and Freilich et al. (2010). The interaction mechanisms between the soil and fibers, and consequently the shear strength of the composite, were not influenced by the drainage condition or by the development of pore water pressures during shearing.



a) Clayey soil

b) 0.25% Fiber-soil

Figure 7. Comparison fo stress-strain curves of clayey soil afiber-clay mixture in CU tests.

Table 2 presents strength parameters of clayey soil and fiber-soil mixtures, obtained from Mohr stress circles envelopes in CD and CU tests. It is possible to verify that, in drainage condition, there was a greater influence of the fibers on the values of effective cohesion than on friction angles. The cohesive portion corresponds to the main contribution of the fibers, being responsible for the superior performance of these composites in drained condition. However, in undrained test, the contribution of fibers on friction angle increase was more significant (over 40%) than cohesion increase. The observations of this study show the possible soil improvement of additon recycled PP short fibers in a laterict clayey soil, contributing to sustainable practices in geotechnical engineering.

Table 2. Shear strength parameters of clayey soil and fiber-soil mixtures

Shear strength parameters	c' (kPa) CD	c' (kPa) CU	c (kPa) CU	ϕ' (°) CD	ϕ' (°) CU	ϕ (°) CU
Clayey soil	29.0	22.0	21.0	28.0	24.0	13.8
0.25% Fiber-soil	40.9	22.0	25.0	29.8	33.0	14.6

4. CONCLUSIONS

The present study aims to contribute to the understanding of shear strength and deformability behavior of a clay soil reinforced with recycled polypropylene (R-PP) short fibers under drained and undrained triaxial conditions. Samples were prepared at specified percentage of 0.25% of short fibers and were isotropically consolidated under confining pressures of 50, 100, 200 and 300 kPa. The conclusions drawn from the present study are as follows:

The experimental results of drained tests show that there was improvement in the shear strength of soil with inclusion of recycled PP fibers. Clayey and fiber-clay soils presented reducing volumes during shearing. It is found that after the soil undergoes plastic deformation, the fibers act more significantly resulting in an increase in the drained shear strength.

Undrained compression tests showed the strength of fiber-soil mixture superior than strength of natural soil, and that the is influence of fibers increases with confining pressures. Fiber-clay samples showed increase in shear strengths troughout the tests even after peak strengh. Fibers restricted the dilatation of soil mixture during undrained shear.

The interaction mechanisms between the soil and fibers, and consequently the shear strength of the composite, were not influenced by the drainage condition or by the development of pore water pressures during shearing. According to the results of strength parameters in drainage condition, there was a greater influence of the fibers on the values of effective cohesion than on friction angles. On the other hand, in undrained test, the contribution of fibers on friction angle increase was more significant than cohesion increase. Fiber-clay specimens presented “bulging” behavior after shearing in both drainage and undrainage conditions.

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