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Shear strength behavior of clayey soil reinforced with polypropylene fibers under drained and undrained conditions

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ABSTRACT: The use of fiber reinforcement has been recognized as a viable soil improvement technique in numerous fill-type geotechnical applications. However, fewer studies on the use of fiber reinforcement in clayey soil have been reported compared to those in sandy soils despite equal potential for application in practice. The fundamental mechanisms controlling shear strength and deformability behavior of clay-fiber mixtures have still not been well established, nor the constraints that may affect their performance of shearing under different drainage conditions. This study aims to understand the behavior of a clay soil mixed with polypropylene fibers using results from drained and undrained triaxial compression tests, and to provide necessary calibration data for a shear strength prediction model. In drained tests, shear strength increased with fiber inclusion

for a given mean effective stress, represented by an increase in apparent cohesion. In the undrained tests, the shear strength was not affected by pore water pressure generation. Results from the drained and undrained tests indicate that the fiber content had a greater influence on the apparent cohesion than on the friction angle. Drainage affected improvement in the shear strength of fiber-reinforced soils, with similar improvement in the drained and undrained tests for higher confining stresses.

KEYWORDS: Polypropylene fibers; Clayey soil; Fiber reinforcement model, Triaxial compression; Drainage.

1. Introduction

Fiber reinforcement is an established approach to improve the shear strength and ductility of the stress-strain response of soils. In particular, the use of fiber reinforcement to permit the use of poorly draining, locally-available soils has gained increased attention and acceptance (Abou Diab et al. 2018; Hejazi et al. 2012; Sadek et al. 2010). Examples of applications where fiber-reinforced soils have been used in geotechnical engineering include retaining structures, stabilization of subgrade and subbases, improvement in soil bearing capacity, slope stability, soft soil embankments, controlling soil hydraulic conductivity, erosion improvement, piping prevention and mitigation of shrinkage cracks (Ehrlich et al. 2019; Shukla 2017; Tang et al. 2007; Ziegler et al. 1998).

Several authors have investigated the behavior of fiber-reinforced sands and found that inclusions of fibers improve the mechanical response of soils by mobilizing the tensile strength of fibers intersecting shear failure planes in the soil, resulting in a greater shear strength and an improvement in soil ductility (Gray 1986; Santoni et al., 2001; Consoli et al., 2002; Velloso et al., 2010; Sotomayor and Casagrande 2018; Louzada et al. 2019).

Fewer studies have investigated clay-fiber mixtures despite equal potential for application in geotechnical practice. The limited number of studies on fiber-reinforced clays have not yet established the fundamental mechanisms involving the behavior of clayey-fiber mixtures or the conditions that may affect their performance (Anagnostopoulos et al. 2013). In particular, only a few studies have focused on the shear strength of soil-fiber mixtures under undrained conditions, with most of these studies indicating that further research is necessary on this topic (e.g., Freilich et al. 2010; Li and Zornberg 2013; Mirzababaei et al. 2018).

Feuerhemel (2000) studied the inclusion of PP fibers (lengths of 12 and 36 mm and mixture of 0.50% fibers by volume) in a clayey soil using consolidated drained (CD) triaxial compression tests. Results showed a continuously increasing stress-strain curve with high ductility. Inclusion of fibers was found to increase the apparent cohesion by 3 times (fiber length of 12 mm) to 5 times (fiber length of 36 mm), while the friction angle was unaffected. Trindade et al. (2006) also evaluated the inclusion of PP fibers (20 mm and 0.25%) in a clayey soil using CD triaxial tests and showed that fibers reduced soil compressibility, while the friction angle remained unchanged, and the apparent cohesion increased by up to 70%.

Freilich et al. (2010) observed that the effective shear strength parameters of soil-PP fibers from consolidated undrained (CU) triaxial compression tests were greater than from drained conditions, evidencing that the effective strength of the mixture may significantly decrease with time and drainage. Li (2005) noted that competing factors may arise in the fiber-soil interaction mechanism in clays, such as volume change tendency of soil and strain rate. Li (2005) also noted that the pore water pressure values at the fiber-soil interfaces within a specimen may differ from the pore water pressure measured at the ends of a clay specimens in a triaxial test. Özkul and Baykal (2007) also conducted CU and CD triaxial tests with 25 mm tire fibers in a clayey soil and found that the apparent cohesion values of the fiber-clay from CD triaxial tests were lower than those from CU triaxial tests. However, the friction angles from the tests with different drainage conditions were the same. Louzada et al. (2019) evaluated the mechanical behavior of a clayey soil mixed with PET flakes using CD triaxial tests and observed that an increasing flake content improved the interaction with soil particles, with an increasing trend in improvement with increasing effective confining stress.

Murray et al. (2000) found that adding 1% PP virgin polypropylene fibers to sandy silty soil in CU triaxial tests led to an increase in the undrained shear strength with a more ductile post-peak response. Khatri et al. (2016) also carried out a series of CU triaxial tests on fiber-reinforced clay and reported improved undrained shear strength with the increase in coir fiber content from 0.4% to 1.6%. Mirzababaei et al. (2017) evaluated the inclusion of recycled carpet fibers in a clayey soil using CU triaxial tests. The fiber content of 3% presented higher shear strength at the initial mean effective stress of 50 kPa when compared to the soil with 5% fiber. According to Mirzababaei et al. (2017), an increase in fiber content at a low initial effective consolidation stress may have an adverse effect on the strength of the reinforced soil by affecting soil grain interaction. Suffri et al. (2019) evaluated a clayey soil with coir fiber contents of 0.5 to 2.0% using CU triaxial tests and found that the inclusion of fibers increased the undrained shear strength. Mirzababaei et al. (2020) evaluated the reorientation of fibers in miniature fiber-reinforcement clay samples during unconsolidated undrained (UU) triaxial tests using computed tomography (CT) imaging. The results indicate that compaction induces an anisotropic distribution, and that fibers accumulated in the lower part of the specimens, with most fibers aligning in the horizontal direction. Palat et al. (2019) conducted CU triaxial tests in fiber-clay soils and emphasize that no conclusion could be made on the development of pore water pressure by the inclusion of fibers, and that more tests are necessary.

Jamei et al. (2013) developed an analytical method for predicting the undrained shear strength of fiber-clays for short-term stability analyses. The model of Jamei et al. (2013) is an extension of the model of Michalowski and Zhao (1996) for fiber-reinforced sands, and was developed to predict the principal stresses at failure for clayey soil-fibers mixtures as a function of volumetric fiber content, length, diameter, apparent cohesion and friction angle of the clay, and interface shear strength parameters. However, information on the interface shear strength parameters has been still an issue in quantifying the effectiveness of fiber-clay shear strength predictions using this model. To address the issues raised in the literature review, this study aims to understand the behavior of a clayey soil mixed with recycled polypropylene fibers using results from drained and undrained triaxial compression tests. The model of Jamei et al. (2013) was then used to capture the variations in undrained shear strength of fiber-reinforced clays with different relevant variables for this soil and for the clays investigated in the other studies mentioned in this section.

2. Experimental Program

2.1. Materials

The soil used in this research was obtained from the city of Santa Gertrudes, Sao Paulo - Brazil and is representative of residual soils that cover a large area of this territory. The clayey soil has a clay fraction of 50%, a silt fraction of 14%, and a sand fraction of 36% (ASTM D7928-17). According to an X-ray diffraction analysis (ASTM D4452-14), the clay fraction in the soil has predominant clay minerals of kaolinite, illite and hematite, while the silt and sand fraction is primarily quartz. The specific gravity of solids was found to be 2.9 (ASTM D854-14). The fines fraction of the clayey soil has a liquid limit of 51, a plastic limit of 29, and a plasticity index of 22 (ASTM D4318), so it classifies as a CH clay according to the Unified Soil Classification Scheme (ASTM D2487-17). Short discrete recycled polypropylene (PP) fibers were used as the reinforcements in this study. The PP-fibers have an average diameter (d_f) of 18 micrometers, a specific gravity (G_f) of 0.9, an average length (L_f) of 12 mm, zero water absorption, and a breaking tensile strength of 610 MPa.

2.2. Specimen Preparation

A fiber content of 0.25% was selected for the experiments in this study as it is representative of soil mixtures evaluated in other studies (Feuerharmel 2000; Li and Zornberg 2005; Özkul and Baykal 2007; Freilich et al., 2010; Rowland Otoko 2014; Diambra and Ibraim 2014; Mirzababaei et al. 2017). Greater fiber contents were evaluated, but issues with homogenization occurred, so only a single fiber content was investigated in this study to demonstrate the impacts of drainage conditions on the shear strength of fiber reinforced soils. Before mixing the fibers, the soil was homogenized to different initial gravimetric water contents. Then, PP fibers were randomly distributed in the soil matrix and a mechanical mixer was used to reach a homogenous distribution of fibers in the soil. To obtain the target compaction parameters for the soil-fiber mixture, standard Proctor compaction tests were conducted on the soil with and without fiber reinforcements according to ASTM D698-12e2. Prior to compaction, prepared mixtures were preserved in sealed bags for a minimum of 24 hours for moisture homogenization. The standard Proctor compaction curves for the clay with and without fiber reinforcements are shown in Figure 1. Although there are slight differences, it can be assumed that the presence of fibers does not significantly alter the compaction curve for the soil, and the compaction curve for the unreinforced soil was used as the reference for specimen preparation. Results of other studies show similar compaction curves for soils with and without fiber reinforcement (Kumar and Singh 2008; Mirzababaei et al. 2013; Gelder and Fowmes 2016).

2.3. Triaxial Test Procedures

In order to investigate the shear strength behavior of soil-fiber mixtures, triaxial consolidated-drained (CD) and consolidated-undrained (CU) tests were performed on the soil-fiber mixtures according to ASTM D7181-20 and ASTM D4767-20, respectively. The 50 mm-diameter specimens were statically compacted to a height of 100 mm to reach as relative compaction of 95% at the optimum gravimetric water content of the unreinforced soil. The specimens were saturated using water percolation and backpressure, and a minimum B-parameter of 0.9 (Skempton 1954) was reached in each test. Subsequently, specimens were consolidated mean effective stresses of 50, 100, 200, and 300 kPa, which are within the range of stresses investigated in previous studies (e.g., Freilich et al., 2010; Mirzababaei et al., 2017; Özkul and Baykal, 2007). The shearing rate was set to be 0.01 mm/min in the CD triaxial tests and 0.15 mm/min in the CU triaxial tests.

3. Test Results

3.1. Triaxial Test Results

Deviator stress-axial strain and volumetric strain-axial strain curves for specimens with fiber contents of 0 and 0.25% from isotropic CD triaxial compression tests are shown in Figure 2. As expected, an increase in shear strength and an increase in contraction are observed with increasing mean effective stresses for both materials. After a fiber-clay mixture undergoes plastic deformation, the resistance of the fibers is mobilized, and hardening is observed. For the higher mean effective stresses, the fiber-clay mixtures showed a hardening behavior and did not exhibit a clear peak shear strength. This behavior was also observed by Feuerhemel (2000). Regarding the volumetric strain-axial strain response, the clay-fiber mixtures showed greater contraction than the clay with no fiber reinforcement. Greater contraction during shearing of fiber-reinforced soils compared with unreinforced soils was also observed by Abou Diab et al. (2018) and Louzada et al. (2019). In addition, all specimens exhibited bulging behavior after shearing, which, according to Özkul and Baykal (2007) and Ekinci and Ferreira (2012), is a typical behavior of fiber-clay samples. As observed in the study of Abou Diab et al. (2018) and herein, the addition of fiber reinforcements reduced the degree of bulging and resulted in a uniform deformation along the length of the specimens.

The relationships between the secant elastic modulus with axial strain and between the principal effective stress ratio (σ_1'/σ_3') and the axial strain for clayey soils with and without reinforcement are shown in Figures 3a and 3b, respectively. A greater modulus is observed for the reinforced soil in comparison with the unreinforced soil, especially for lower mean effective stresses. The ratios in Figure 3b indicate that the efficiency of the fibers does not seem to increase with the increase of the confining stresses, which is expected since it improves the soil-fiber interaction. There is potentially a fiber breakage effect for the higher mean effective stress levels. Mirzababaei et al. (2020) found that the improvement in shear strength of fiber-reinforcement clay decreased with confining stress for this reason. The fiber-clay specimens in the drained tests exhibited "bulging" behavior after reaching the maximum deviator stress, and the unreinforced clay specimens exhibited partial development of a shear plane. Xu et al. (2018) also observed bulging failure in the CU tests with localized bulging in the middle of the specimens. Mirzababaei et al. (2020) noted that bulging may occur in different vertical locations of the specimen if fibers are not uniformly distributed.

The stress paths for mixtures with 0% and 0.25% fiber contents are shown in Figure 4 in p' – q space, where q is ($\sigma_1 - \sigma_3$) and p' is ($\sigma'_1 + 2\sigma'_3$)/3. The failure criteria adopted is the value of deviator stress at 20% of axial strain. In the drained triaxial tests, the shear strength increased with fiber inclusion for a given mean effective stress, represented by an increase in apparent cohesion. Similar behavior was observed by Trindade et al. (2006) in a study with the inclusion of 0.25% PP fibers (20 mm) in a clayey soil using CD triaxial tests. Ma et al. (2018) states that tension of fiber strengthens the bond among clay particles, which enhances the shear strength of clay.

The results from the CU triaxial tests are shown in Figure 5. Different from the CD triaxial tests, clear initial peak values in the deviator stress-axial strain curves are observed in Figures 5a and 5b. Although the initial peak value for the mixtures with 0.25% fiber content is similar or lower than the unreinforced clay, the mixtures with 0.25% fiber content show a hardening effect with continued straining. As the pore water pressures in Figures 5c and 5d show monotonically increasing trends that do not depend on the presence of fibers, the hardening effects in Figures 5a and 5b can be attributed to the fibers. A greater amount of hardening was observed for the mixtures with a fiber content of 0.25% with increasing initial mean effective stress. Similar to the results of Mirzababaei et al. (2020), higher undrained shear strengths were observed for reinforced specimens at all confining stresses.

The excess pore water pressures were consistently positive during the undrained triaxial tests (Fig. 5c and 5d) consistent with the trend of volume contraction observed in the drained triaxial tests. As observed in the study of Xu et al. (2018) and herein, the induced pore water pressures increased steadily with axial strain and approached an asymptotic value. In general, the fibers did not influence the generation of pore water pressures during undrained shearing. However, as the increase in pore water pressures led to a decrease in mean effective stress, this contributed to the greater improvement in deviator stress with axial strain for the tests performed at higher mean effective stresses.

Relationships between the secant modulus with axial strain and between the principal effective stress ratio (σ_1'/σ_3') and the axial strain for clayey soils with fiber contents of 0 and 0.25% are shown in Figure 6a and 6b, respectively. The results in Figure 6a show that there was no significant increase in the secant modulus with the inclusion of fibers, while the results in Figure 6b indicate that the presence of fibers led to an improvement in shear strength for higher confining stresses at consolidation.

Fig. 7 presents the stress paths and effective shear strength parameters (defined using the maximum principal stress different failure criterion) for the clayey soil with fiber contents of 0 and 0.25% from the CU triaxial tests. The effective stress paths are consistent with the expected behavior of normally consolidated tropical soils (Futai et al., 2004; Louzada et al., 2019). Similar to the CD triaxial test results, the presence of fibers had a greater influence on the values of apparent cohesion than on the friction angle. Also similar to the results from the CD triaxial tests, the effective shear strength of the fiber-soil specimens was higher than the unreinforced specimens. In both drainage conditions, an increase in apparent cohesion was observed without a significant effect on the friction angle. The shape of the effective stress paths of unreinforced and fiber-reinforced specimens reflect an increase in pore pressure with increasing strain. Different from the CD triaxial tests, the effect of the fibers on the soil strength increases as the effective confining pressure at consolidation increases. In other words, the tests at higher initial values of p’ experienced a greater change in pore water pressure, which led to less interaction between the clay and fibers and a lower amount of improvement. These results emphasize the importance of considering the clay-specific evolution in volume change with strain in CD triaxial tests and pore water pressure generation with strain in CU triaxial tests. The results presented herein are in agreement with the results obtained from literature (Murray et al., 2000; Li, 2005; Özkul and Baykal, 2007; Freilich et al., 2010; Khatri et al., 2016). Freilich et al. (2010) also observed greater shear strengths from CU triaxial tests on fiber reinforced soils than from CD triaxial tests.

A comparison of the percent improvement in peak deviator stress as a function of the confining stress at failure ($\sigma'_{3,f}$) from this study (CU and CD triaxial tests) with those from the literature involving other soils and types and percentages of fibers is shown in Figure 8. For the CU triaxial tests, the confining stress at failure was the same for the unreinforced and reinforced soils except for the specimens tested at the highest initial confining stress of 300 kPa, in which case the average confining stress at failure for the reinforced and unreinforced specimens was used to create this plot. The results in this figure show that drainage affected the improvement in the shear strength of fiber-reinforced soils, with similar improvement in the drained and undrained tests for higher confining stresses. A diminishing improvement with increasing confining stress at failure was observed in both the drained and undrained tests, which was also observed by Freilich et al. (2010). Studies on fiber reinforced sands indicate that extension and pullout of the reinforcements may become more difficult at higher confining stresses, potentially leading to fiber breakage (Li 2005; Attom and Al-Tamimi 2010; Hamidi and Hooresfand 2013; Najjar et al. 2013). Results of Palat et al. (2019) and Mirzababaei et al. (2018) show no clear trend on the effect of confining stresses on the improvement in the undrained shear strength of fiber-reinforced clayey soils.

3.2. Predictive Model for Undrained Shear Strength of Fiber-Reinforced Clay

The model of Jamei et al. (2013) was developed to capture the undrained shear strength (or principal stress difference) of fiber reinforced clay sheared under axisymmetric loading conditions. The model predicts the major principal stress at failure (σ_1) for the known minor principal stress at failure (σ_3), as follows:

$$\sigma_1\left(1 + D.\chi_f.tan\delta_i\right) - \sigma_3\left(-2K - D.\chi_f.tan\delta_i\right) + \chi_f.c_i(I_1 + K.I_2) - B = 0 \qquad (1)$$

where the parameters are defined as: $\chi_f = \eta_f.\frac{d_f.L_f^2.N_v}{2}$, $N_v = \frac{\frac{\chi_{F,v}}{100}}{\pi\left(\frac{d_f}{2}\right)^2 L_f\left(1+\frac{\chi_{F,v}}{100}\right)}$, $\chi_{F,v} = \frac{\eta_f.\gamma_d}{(1+\eta_f).G_f.\gamma_w}$, $K_p = tan^2(45 + \frac{\phi}{2})$, $K = -0.5K_p$, $K_a = tan^2\left(45 - \frac{\phi}{2}\right)$, $\Psi_o = arctan\left(\sqrt{2K_a}\right)$, $H = -c.cot\,(\phi)$, $B = H\left(1 - K_p\right)$, $I_1 = \frac{cos^3\,(\Psi_o)}{3}$, $I_2 = \frac{3.cos^3\,(\Psi_o) - cos^3\,(\Psi_o)}{3}$, $I_1" = \frac{2.cos^5\,(\Psi_o)}{5} - \frac{cos^3\,(\Psi_o)}{3}$, $I_2" = cos^3\,(\Psi_o) - cos\,(\Psi_o) - \frac{2.cos^3\,(\Psi0)}{5} - \frac{cos^3\,(\Psi0)}{3}$, $A' = (I''_1 + K.I''_2)$, $D = (I_1 + K.I_2 - A')$, δ_i = $C_i.tan(\phi)$, c_i = $C_i.c$, η_f = gravimetric fiber content, d_f = equivalent fiber diameter, L_f = fiber length, $\chi_{F,v}$ = volumetric fiber content; N_v = number of fibers per unit volume, γ_d= dry unit weight of the clay, G_f = specific gravity of the fibers, γ_w= unit weight of the water and ϕ= effective shear strength parameter of natural clay and c_i and δ_i= apparent cohesion and friction angle components of interface soil-fiber strength (defined by Jamei et al. 2013).

After calculation of the major principal stress at failure, the undrained shear strength can be calculated as the difference (σ_1-σ_3). The parameters used in the Jamei et al. (2013) predictive model are summarized in Table 1. In this study, an interface coefficient (C_i) of 0.8 was used to be consistent with Zornberg (2002) and Abou Diab et al. (2016). The model requires the volumetric fiber content ($\chi_{F,v}$), which is equal to 0.48% for a gravimetric fiber content of 0.25%.

The undrained shear strength (i.e., the maximum principal stress difference) measured in the PP fiber-clay CU triaxial tests were compared with those calculated using the predictive model of Jamei et al. (2013) in Figure 9. Abou Diab et al. (2016) evaluated the predictive model of Jamei et al. (2013) using undrained triaxial tests of soil-fiber mixtures from the literature including those of Prabakar and Sridhar (2002), Plé and Lê (2012), Maheshwari et al. (2011), Jamei et al. (2013) and Wu et al. (2014), and these are also included in the comparison in Figure 9 along with the data from this study. It is important to highlight that a range of fiber types, contents and soils were used in this comparison. For lower confining stresses, the model of Jamei et al. (2013) has a good fit to the undrained shear strength data, while for higher confining stresses it tends to overestimate the undrained shear strength.

4. Conclusions

This study evaluated the behavior of a clay soil mixed with recycled polypropylene fibers using results from drained and undrained triaxial compression tests. 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 main conclusions drawn from the present study are as follows:

- The experimental results of consolidated-undrained triaxial compression tests show that there was improvement in the shear strength of soil with inclusion of recycled PP fibers. In the drained tests, shear strength increased with inclusion of recycled PP fibers for a given mean effective stress, represented by an increase in apparent cohesion. Unreinforced and fiber-clay mixtures remained with similar trend in volume contraction during shearing. It was found that fiber inclusions did not mobilized stresses at low levels of strains and contributions were found to occur as closer as the stress state at failure;

- The results from consolidated-undrained triaxial compression tests showed the strength of fiber-soil mixture superior to strength of natural soil, and that the influence of fibers increases with confining pressures. Fiber-clay samples showed increase in large displacement shear strength and fibers restricted the dilatation of soil mixture during undrained shear;
- Results from the drained and undrained triaxial tests indicate that the fiber content had a greater influence on the apparent cohesion than on the friction angle. Fiber-clay specimens presented “bulging” behavior after shearing in both drainage and undrained conditions. Drainage affected the improvement in the shear strength of fiber-reinforced soils, with similar improvement in the drained and undrained tests for higher confining stresses, and
- The predictive model of Jamei et al. (2013) was used to capture the undrained shear strength. Results were found to adequately predict the undrained shear strength of clay-fiber mixtures at low effective stresses but showed deviations at high effective stresses.

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FIGURES

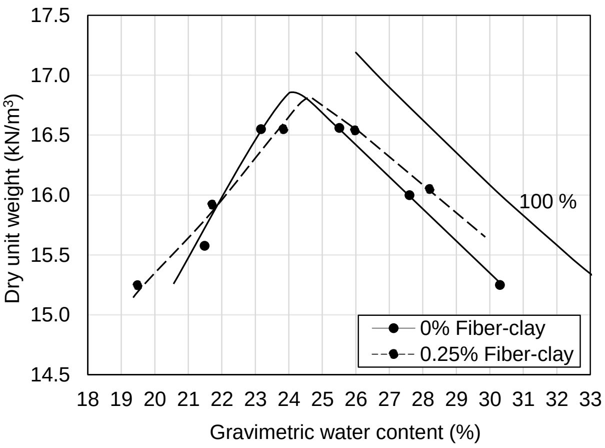


Fig. 1. Standard Proctor compaction curves for clayey soil with fiber contents of 0 and 0.25%.

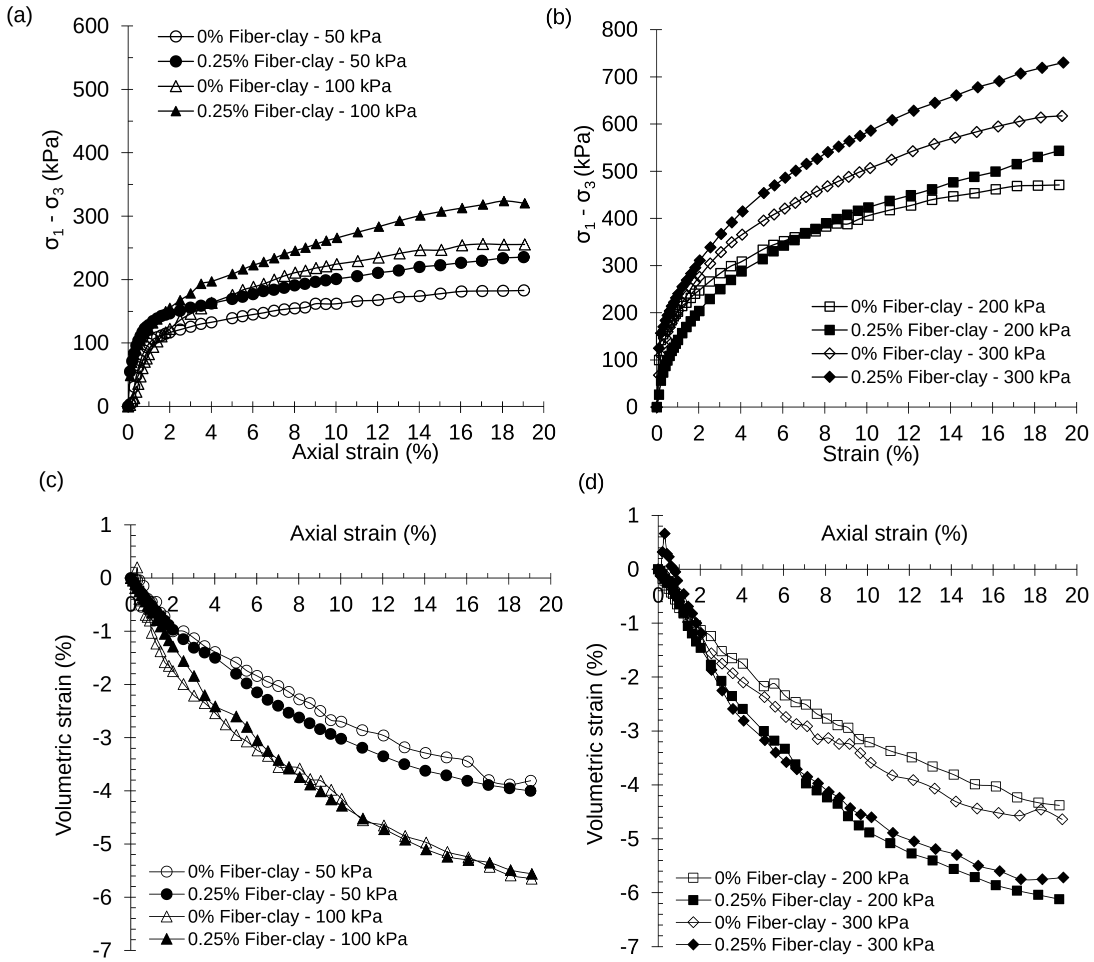


Fig. 2. Results from CD triaxial tests: (a) Deviator stress-strain curves for mean effective stresses of 50 and 100 kPa; (b) Deviator stress-strain curves for mean effective stresses of 200 and 300 kPa; (c) Volumetric strain-axial strain curves for mean effective stresses of 50 and 100 kPa; (d) Volumetric strain-axial strain curves for mean effective stresses of 200 and 300 kPa.

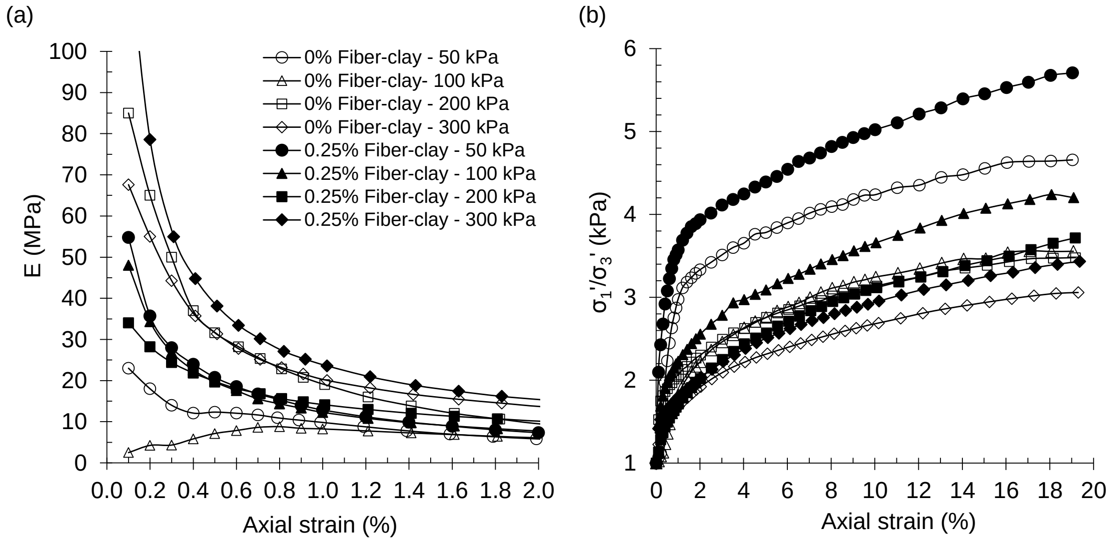


Fig. 3. Results of CD triaxial tests for natural and PP fiber-clay: (a) secant modulus; (b) σ_1'/σ_3'.

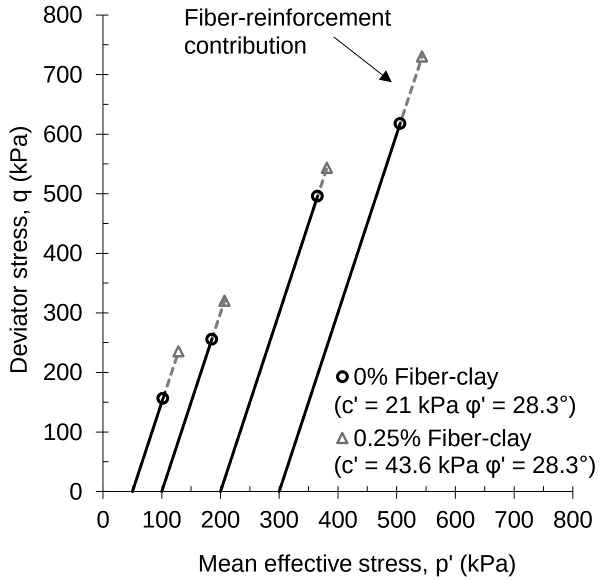


Fig. 4. Stress paths and effective shear strength parameters from CD triaxial tests on clayey soil with fiber contents of 0 and 0.25%.

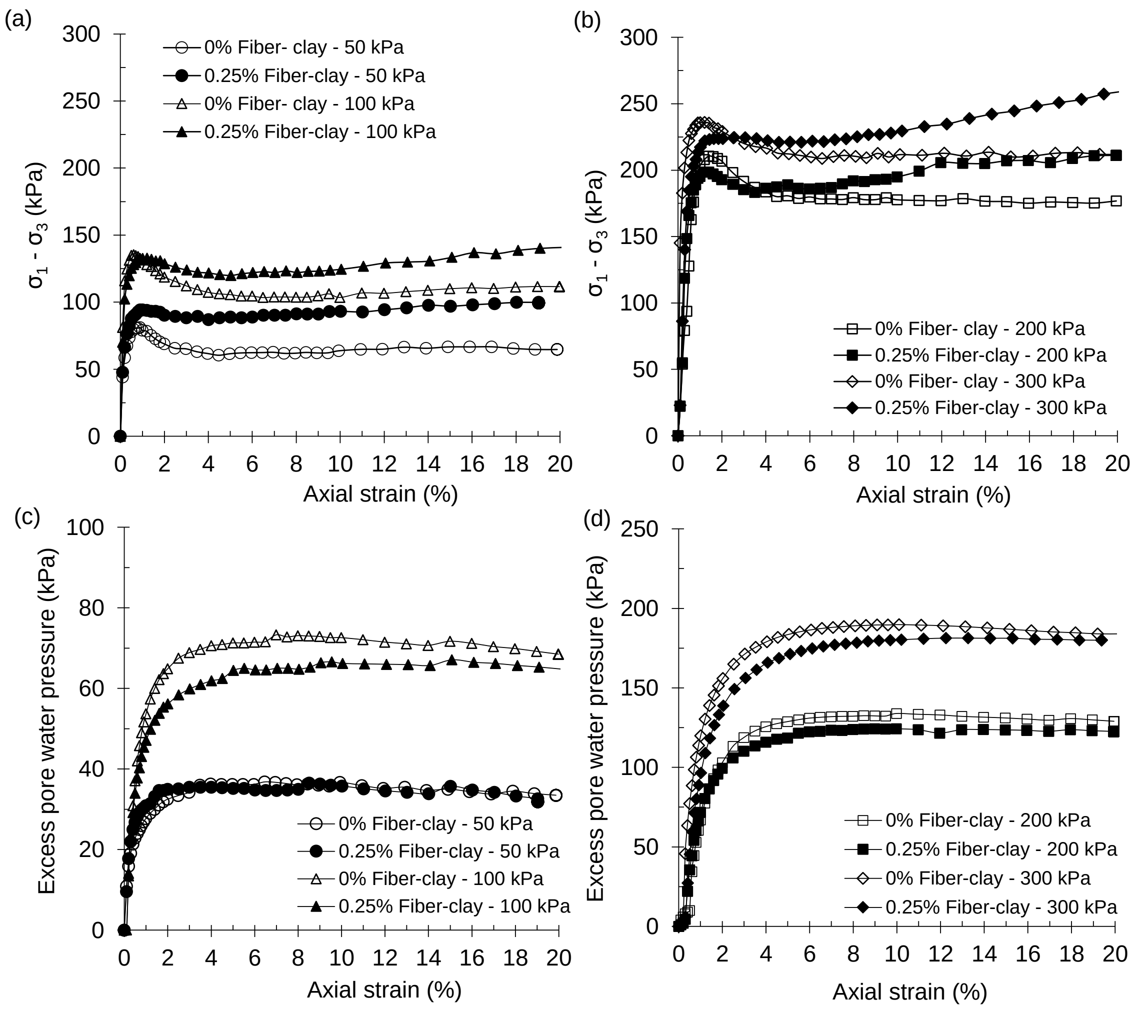


Fig. 5. Results from CU triaxial tests: (a) Stress-strain curves for confining stresses of 50 and 100 kPa; (b) Stress-strain curves for confining stresses of 200 and 300 kPa; (c) Pore-water pressure for confining stresses of 50 and 100 kPa; (d) Pore-water pressure for confining stresses of 200 and 300 kPa.

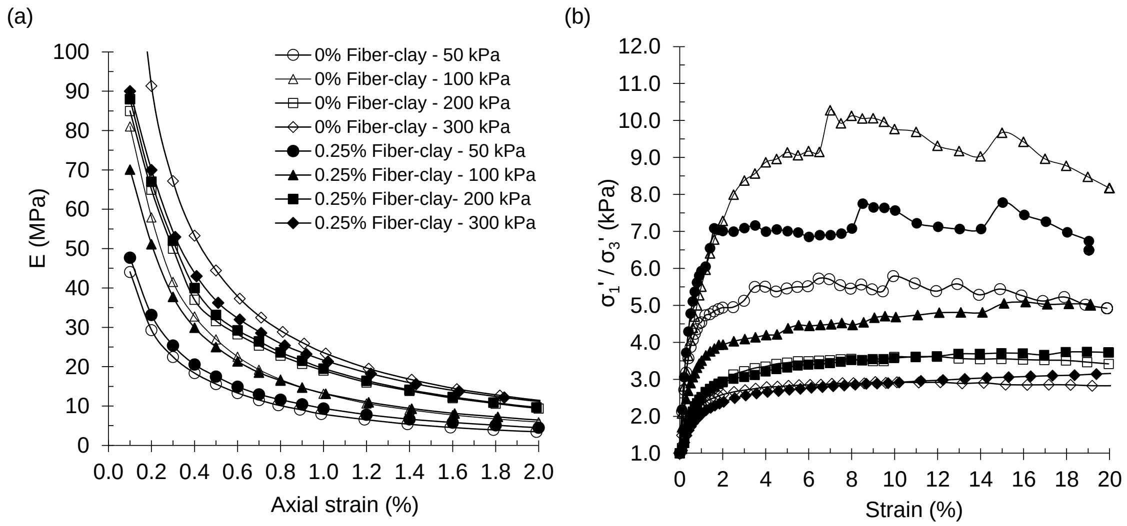


Fig. 6. Results from CU triaxial tests for natural and PP fiber-clay mixtures: (a) Initial stiffness; (b) σ_1'/σ_3'.

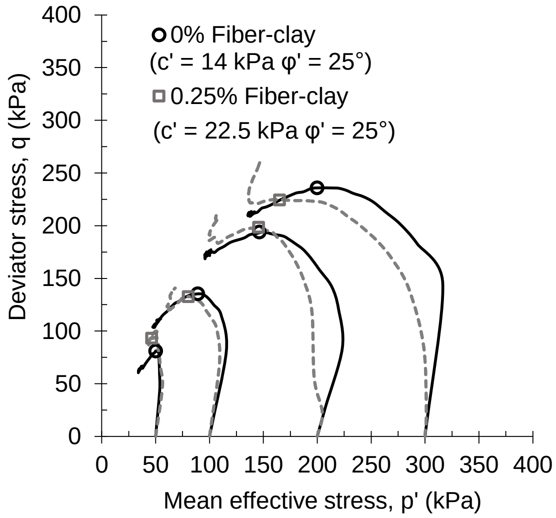


Fig. 7. Stress paths and effective shear strength parameters from CU triaxial tests on clayey soil with fiber contents of 0 and 0.25%

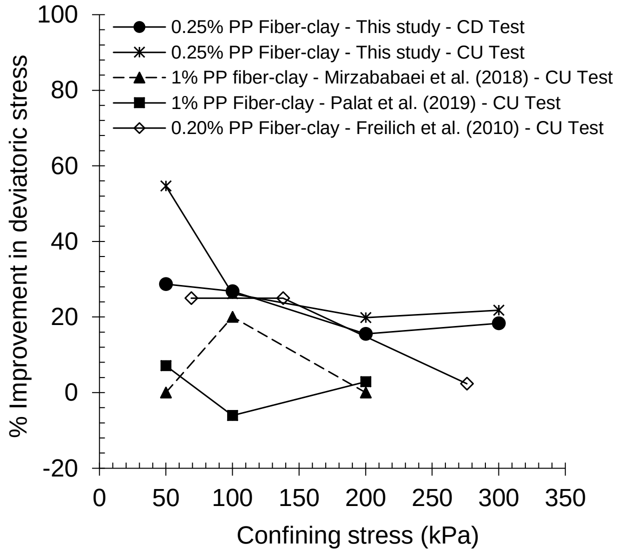
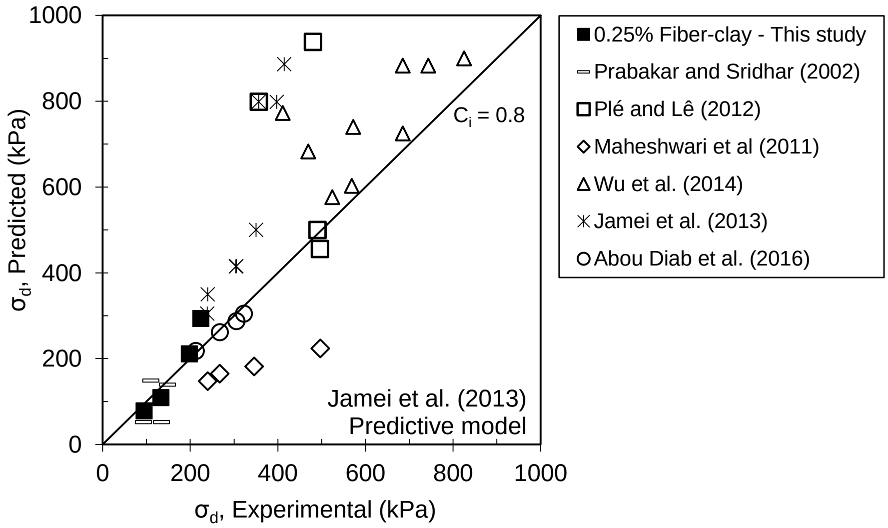


Fig. 8. Improvement in peak deviator stresses observed in this study with other CD triaxial test results from the literature.



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613 **Fig. 9.** Comparison of undrained shear strength values at failure from the CU triaxial tests performed at

614 different confining stresses with predictions from the model of Jamei et al. (2013).

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TABLES

Table 1. Parameters of the model of Jamei et al. (2013) for the soil tested in this study.

PP fiber content (%)	L_f (m)	d_f (m)	$\chi_{F,v}$ (%)	σ_3 (kPa)	σ'_3 (kPa)	$\sigma_{d\ Measured}$ (kPa)	c' (kPa)	φ' (°)
0	-	-	-	50	23.1	81.1	14	25
				100	44.0	131.0		
				200	81.6	193.9		
				300	117.6	235.9		
0.25%	0.012	0.000396	0.48	50	19.6	94.2	-	-
				100	36.1	132.7		
				200	73.4	197.6		
				300	101.2	223.8		