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TECHNICAL PAPER

A Laboratory Investigation on a Mechanical Behavior of Sandy and Clayey Soils with Kraft Paper Fiber

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Abstract
The literature has several studies on the addition of several agglomerating materials, waste, natural and artificial fibers, among others. Most of them aim to improve soil engineering properties. Certain studies combine this investigation with the environmental issue, that is, the issue of making the best use of a certain material that is discarded in nature and generates a significant environmental impact. Thus, this study aims to use paper fiber, from the cement bag, which is a construction waste, as reinforcement of a sandy soil and a clayey soil. Fiber-reinforced soil is considered an effective technique for soil improvement due to cost, adaptability, and reproducibility. Thus, the choice was to study the fiber of natural multifoliated kraft paper (NKP) as soil reinforcement, which was added randomly at the percentages of 5, 10, and 15% of dry soil mass. This study focused on soil resistance and its behavior with the addition of NKP fibers to a sandy soil (SC) and to a clayey soil (ML). Compaction, shear strength, and unconfined compression tests were performed in samples with the fiber contents mentioned. The results of the tests showed an improvement and an increase in the friction angle of the soils when 10% and 15% of fibers were added to the SC, and for ML, a significant increase in the friction angle was found in both optimum moisture and 28 days, with emphasis on 5% dosage and flooded for 15% dosage. Regarding the unconfined compression, an improvement was verified in the resistance at 10% for the CS, while for ML soil, the better dosage was 5% of fibers. One concludes that the use of NKP fibers can be considered a reinforcement material. The results indicated that the fibers made the soils ductile, able to maintain shear strength at high levels of strain.

Keywords Construction waste · Soil addition · Kraft paper fiber · Cement bag

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1 Introduction

Among the serious contemporary problems faced by environmental management, one can highlight the impact of solid waste generation on the various production processes by the construction industry and its recycling potential. Although reducing the amount of waste during production and even post-consumption is possible and a priority, residues will always be generated. The construction industry is certainly the largest waste generator in the entire society, and its environmental impact is associated with the intensive use of non-renewable natural raw materials, as well as a large volume of generated and totally untapped waste (Chinda 2016; Ding et al. 2018; Magalhães et al. 2017). Ding et al. (Ding et al. 2018) show in their simulation that waste management can reduce 40.6% generation, thus reducing greenhouse gas emissions.

Solid construction waste, also called construction and demolition waste, are those arising from the construction activities, including new works, reforms, demolitions and land clearing (Shi et al. 2019; Umar et al. 2017). In 2014, with the increase in the construction industry in Brazil, 45 Mt of construction demolition waste (CDW) were generated (Penteado and Rosado 2016). This value can exceed 70 Mt per year, depending on the human development index (HDI) of the region (Contreras et al. 2016).

The transformation of waste into a commercial product effectively used by society not only offers great opportunities to increase social and environmental sustainability, but also offers significant environmental, technical, and financial risks to the workers' health (Umar et al. 2017; Sodangi 2018; Der Yu et al. 2018).

Cement is one of the most used materials in the construction industry, extremely important for economic development; however, its production generates a lot of pollution (Zhang et al. 2018). The construction industry has a growth forecast from 0.8 to 1.2% per year, and this can result in a production from 3700 to 4400 Mt of cement by 2050 (Stafford et al. 2016). In addition to the cement manufacturing waste, the one referring to its consumption stands out, including organic waste, such as the packaging that is manufactured from NKP. This packaging generally is not reused or recycled, as the residual cement deposited on the packaging contaminates the paper, generating thus a huge volume of waste (Buson 2009). The waste is generally neglected by public administrators, although they have the knowledge that the volume discarded in a single day is high (Alves 2016). The cement bags must be deposited in a controlled landfill, or preferably in places that may direct them to recycling (Mori et al. 2016; Ervasti et al. 2016; Van Ewijk et al. 2018).

Not only the production and consumption of cement generate environmental impact, but also the production of paper as well, because, in addition to the high water consumption, its manufacturing emits five times more CO_2/t in the atmosphere than in steelmaking (Rogers 2018; Silva et al. 2015). According to Gupta et al. (2019), paper waste should be reprocessed into pulp or paper mill to be reused in the production of another product. The reverse policy system is a way to remove paper waste from the environment, reducing emissions and pollutants (Hohenthal et al. 2019).

Only in Brazil, in 2018, 44 Mt of cement (SNIC 2018) were produced, and the bagged form (50 kg) represented approximately 70% of the commercialization (30.8 Mt). The cement bag weighs 0.15 kg (Leon Mogrovejo 2013), which means that, in 2018, 92.4 thousand tons of packaging waste was discarded. This waste cannot be released into the soil without a control of its deposit. The study by Baker et al. (2014) show the cement manufacturer's concern in reducing waste in the cement bagging process, aiming at reducing this waste from 0.004 to 0.002%, thus showing their concern with the disposition of the paper in the environment.

Despite the large amount generated by the use of cement bags in the world, the amount deposited in the environment has not been identified in this article and there are no records in the literature or by governmental and non-governmental agencies about such important waste. It is believed that awareness has not yet arisen; despite being a technically recyclable material, it must undergo a cleaning process due to the impregnated cement residue in the bag, making it difficult to recycle and generate a considerable environmental impact. It is clear the importance of studies that lead to either the reduction of waste releasing into the environment or, at least, that it is done in a sustainable way. The high consumption of cement throughout the world shows that not only the production process but also the deposition of post-consumption waste (cement bags) in inappropriate places are responsible for the pollution of the environment. Therefore, it is necessary to properly dispose of cement bag waste in order to reduce the environmental impact caused by it.

A purpose that can be given to this waste is to transform it into fibers and use it as soil reinforcement, following a global trend with the use of fibers (natural and artificial), considering that it is a healthy geoenvironment material (Hejazi et al. 2012; Gowthaman et al. 2018; Ngo 2018). In soil reinforcement, several types of fibers can be employed; their characteristics are closely related to the type of material they are composed of and their manufacturing process.

Firoozi et al. (2017) show the importance of soil stabilization; the authors emphasize that, if not treated, they can lead to expenses of billions of dollars in damages a year. Several studies investigate the incorporation of fibers in soils, aiming at improving their properties. In this technique, a material with high tensile strength is inserted, thus improving the mechanical properties of soils, increasing resistance, and decreasing compressibility. The literature has several studies showing the benefits of incorporating this material from the fibers to improve soil engineering properties (Bordoloi et al. 2017; Gao et al. 2017; Moghal et al. 2017; Wei et al. 2018; Yixian et al. 2016). However, there are some soil reinforcement techniques that may be inefficient and/or expensive (Hejazi et al. 2012), mainly those using expensive pozzolanic materials or chemical additives (Firoozi et al. 2017).

Some studies have analyzed the addition of fibers as soil reinforcement material, such as the study by Chebbi et al. (2017), who investigated the addition of natural fibers as a reinforcement element for compacted soils. The results showed an improvement in the stress-strain characteristics, with the reduction in the speed of cracks in the soil. The addition of natural fibers was studied by Tran et al. (2019) in the evaluation of tensile strength, stress-strain curve, energy absorption, and crack patterns, using additions of 0%, 0.25%, 0.5%, and 1% of corny silk and cement in the proportions of 0%, 4%, 8%, and 12%; the authors concluded that the tensile properties of the soil improved with the addition of fibers. Heineck et al. (2011) obtained excellent results with the addition of pulp and paper fibers in the improvement in soil properties, showing increased friction angle and reduction in hydraulic conductivity. Al Adili et al. (2012) used various contents of papyrus fibers for reinforcement and noticed significant increase in the values of cohesion and friction angle, indicating that 10% would be the ideal amount of fibers in the soil. Kraus et al. (2002) in their studies verified the good performance or reduction in the hydraulic properties of the soils when adding paper fibers as reinforcement.

Regarding the addition of NKP, one can cite those who developed studies on the addition of this waste in the improvement of physical and mechanical properties of the matrices in soil and cementitious material, obtaining promising results regarding the addition of NKP in the gain in resistance, indicating this waste as a promising material in the mechanical properties of the soil (Alves 2016; Wisky Silva et al. 2015; Schweig et al. 2018).

Thus, this article aimed to study the addition of NKP fibers in clayey and sandy soils, in order to evaluate its behavior when submitted to a compaction, UCS, and direct shear tests.

2 Experimental Program

The experimental development of the study was composed of three parts. The first one studied the geotechnical properties of the soils used; the second, the preparation and addition of fibers; and the third, the molding of the specimens and the direct shear and unconfined compression tests.

The experiments were directed to soil characterization and soil-mixed fibers of NKP for soil stabilization purposes, comparing the behavior of mixtures with the soil without fiber; different percentages of dispersed NKP fibers were added until the appropriate proportion was obtained.

2.1 Material

Two soil samples from the southeastern region of Brazil were used in the experimental program. The samples were obtained by manual excavation in sufficient quantity to conduct the tests. Table 1 shows the results of the characterization tests, and Fig. 1 shows the distribution curve of the grain sizes.

2.2 Preparation and Addition of NKP Fibers

The fibers employed were obtained through the processing of the NKP cement bags collected in 10 construction works. The transformation of NKP into fiber followed the procedure prescribed by Buson (2009) and Lessa Dias et al. (2016*)*, with some modifications made for this study. Figure 2 shows the six steps of paper processing into pulp.

This research proposal aims to analyze only the fibers of the cement bags, discarding the beneficial effects that the cement could possibly bring. Therefore, they were internally brushed, and the residues released were weighed in a tray. Then, a mechanical shredder (commonly used for printers) was used to fragment the bag.

For each cement bag, approximately 3.25 l of water was needed for the pulp production process, which makes the high consumption of water visible. However, the water from filtering was reused to return the NKP shredding. Figure 3a–c show steps 2, 3, and 6, performed in the laboratory. It is noteworthy that, during the cleaning

Table 1 Physical properties of the soil samples

Property	Value	
	Soil 1	Soil 2
Liquid limit (%)	35	46
Plasticity index (%)	14	13
Specific gravity (Gs)	2.70	2.93
Medium sand according to USCS (0.425–2.00 mm (%)	2.5	4.8
Fine sand according to USCS (0.075–0.425 μm) (%)	44.0	21.5
Fines according to USCS (< 0.075 mm) (%)	53.5	73.7
Mean particle diameter D_{50} (mm)	0.053	0.006
USCS class	SC	ML
MCT classification (Nogami and Villibor 1995)	NG′	LG′

MCT (tropical soil classification)

NG′ non-lateritic clayey soil, *LG′* clayey laterite

stages of the bags, an average of 10 g of cement per pack was obtained, which is equivalent to 0.02% of the amount of cement in the package.

The pulps were dispersed to facilitate their incorporation to the soil and obtain homogeneous mixtures. This dispersion was performed using a planetary motion mortar mixer (Fig. 4). This step took approximately 4 min. The dispersed fibers are shown in Fig. 5.

For the correct mixture of the soil with the fibers and for a homogeneous sample, the following order of placement of the materials was followed:

– Placement of fibers in the mortar mixer and start of rotation.
– Addition of a quantity of soil to uniformly cover the fibers so that a thin layer is formed, preventing them from agglomerating.

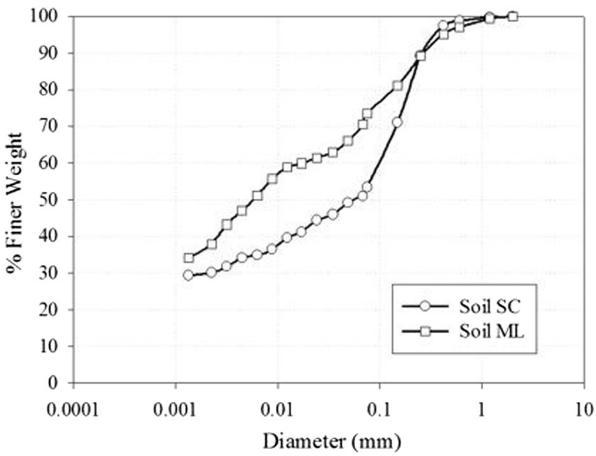

Fig. 1 Soil grain distribution

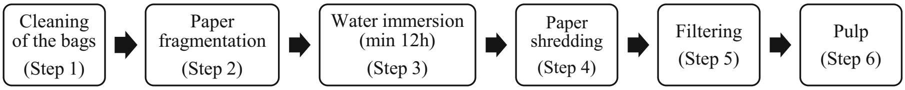

Fig. 2 Paper processing cycle

– Placement of the rest of the soil gradually, alternating with the necessary water until the optimum compaction moisture is obtained.
– When the mixture became homogeneous, it was removed from the equipment, and samples began to be prepared.

The variables of the mixture (soil and fiber percentages) were introduced in a way that resulted in ideal proportions and in the stabilization of the soil. The study by Buson (2009) concluded that the best performance of compacted earth blocks with cement occurred when 6% of NKP fibers was added, and Schweig et al. (2018) showed that the best performance occurred with the addition of 10%. Thus, the decision was to evaluate the percentages of 5%, 10%, and 15% of NKP fibers in relation to dry soil weight. In this study, cement was not used as stabilizer; the study was restricted to the use of fibers, because its only purpose is to evaluate the soil behavior with the addition of fibers to obtain a sustainable way of disposing the NKP waste.

By defining the fiber content, mixing and preparation of the samples of soil 1 (SC) and 2 (ML) started. Initially, compaction tests were performed with normal energy (ASTM D698 - 12e2 2012), aiming at obtaining optimum moisture for sample preparation. Based on these results, the samples were prepared to perform the direct shear tests and unconfined compression tests. Three repetitions were performed for each test to eliminate the variabilities inherent in the execution process.

For the preparation of the samples, the proposal by Ladd (1978) for the production of homogeneous material was accepted, and it could be used in the studies performed. Through tactile-visual analyses, from samples used in the tests, the mixtures were found to be satisfactorily uniform.

2.3 Laboratory Testing

The samples with and without the addition of fibers used in the direct shear (DS) tests were statically compacted using the optimum moisture obtained in the compaction test in a mold of 0.10 m of height and 0.10 m in diameter, which after completion of the compaction was spied with steel ring (height = 0.02 m and diameter = 0.05 m) to

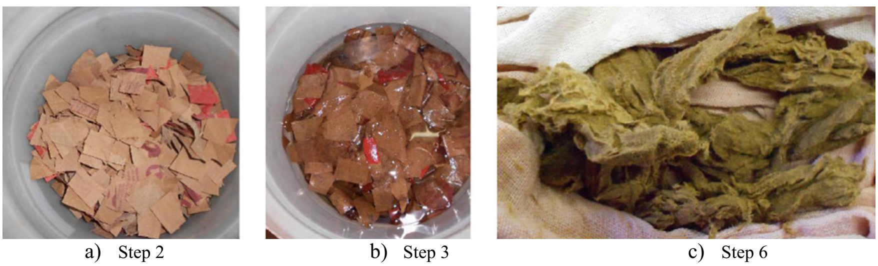

Fig. 3 Conversion process of paper into pulp: **a** step 2, **b** step 3, and **c** step 6

Fig. 4 Fiber dispersion

transfer the sample to the shear test chamber. The DS tests were performed with samples under three different conditions (Table 2).

For the flooding of the samples, the three rings were placed in a container with geotextile in the bottom and a blade of 1 cm of water, leaving them saturating by capillarity for 24 h. After completing the established time, the ring was transferred to the water, and the specimens were finally tested with their normal stresses. The procedure for the DS tests with failure at 28 days was to compress the samples in the mold of 0.10 m of height and 0.10 m in diameter, put it in a sealed plastic box, and take it to the moist chamber for 28 days. After the completion of the established time, the specimens were prepared for each test, followed by the tests.

The unconfined compression tests (UCS), the specimens were molded with 0.10 m of height and 0.05 m in diameter. The specimens were dynamically compacted into five layers in the optimum compaction parameters (w_{opt}) in a metallic mold. The UCS tests were performed only in samples in the optimum moisture condition, considering the impossibility of flooding and the loss of material in the curing process of 28 days, which prevented the performance of the tests.

Fig. 5 Dispersed fibers

Table 2 Different samples used in the tests

Sample 1	Sample 2	Sample 3
Optimum moisture	28 days of curing	Flooded conditions

3 Results and Analysis

The results and analyses obtained in the tests performed with the soil in the natural condition and with the additions, as well as in the three conditions (optimum moisture, flooded and 28 days), are presented below. It is noteworthy that three replications were performed in all tests, and the value presented is the mean of the results.

3.1 Compaction Test

This test used normal energy according to the standard ASTM D698-12e2 (2012). In Figs. 6 and 7, the variations in the maximum dry specific weight and optimum moisture, respectively, are presented for the natural soil without (0%) and with fibers (5%, 10%, and 15%).

Figures 6 and 7 show that higher values of the maximum dry unit weight and lower values of optimum moisture were obtained in the SC, as expected in the case of a sandy soil. This behavior was also observed by Al Adili et al. (2012) in their study with addition of papyrus fiber and by Rahgozar et al. (2018) when they added rice husk ash in clayey soil. The addition of 5%, 10%, and 15% of fibers led to lower values of maximum dry unit weight of the order of 5%, 8%, and 13%, respectively, in the SC, and of the order of 4%, 8%, and 11% in the ML. Regarding optimum moisture, an increase of 8%, 15%, and 30% was observed in the sandy soil and of 5%, 10%, and 16% in the clayey soil, when added 5%, 10%, and 15% of fibers, respectively. The increase in the moisture content with the addition of the amount of fibers was also observed in the studies by Jain (1994), Sapuan et al. (2010), Venkatachalam et al. (2016), and Kumar and Gupta (2016).

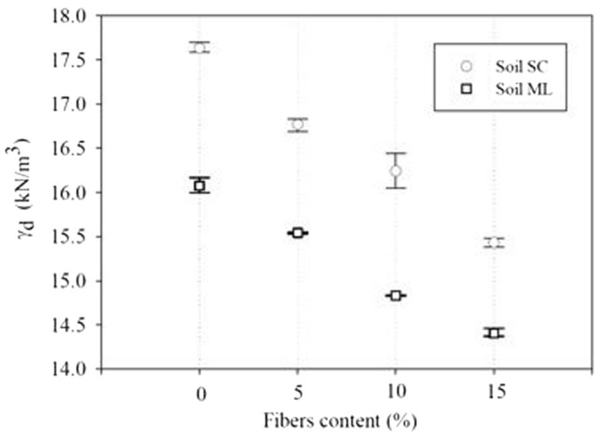

Fig. 6 Maximum dry unit weight

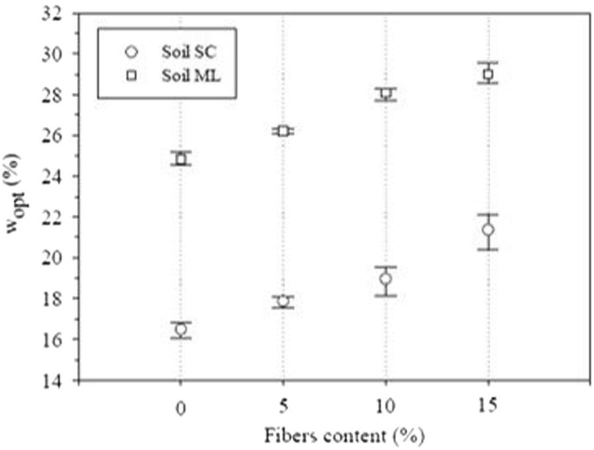

Fig. 7 Optimum moisture

The Dunnet test (1955), at a significance level of 5%, showed that the addition of fibers, regardless of the percentage, significantly decreased the value of the maximum dry unit weight in both soils. As to optimum moisture, the statistical analysis indicated a significant increase in both soils, and the highest values of optimum moisture were achieved by applying 15% of fibers, followed by 10% and 5%.

Increased optimum moisture content with the addition of the NKP fibers in the mixtures is believed to be due to the water consumption of the fibers because of their water absorption potential. The reductions in the maximum dry unit weight values can be attributed to the formation of flakes, establishing links between smaller particles and favoring (by grouping these smaller aggregates formed by the addition of the fibers) the formation of larger aggregates that consequently produce a material with a structure with more voids.

3.2 Shear Strength

Direct shear tests were performed according to the prescriptions of ASTM D3080 (2012). The tests were performed in optimum moisture and flooded conditions and with failure at 28 days with normal stresses (σ) of 50, 100 and 205 kPa and velocity following the requirements of the aforementioned standard for SC-ML of a minimum test time of 200 min. No repetitions were performed in these tests.

The shear stress and volumetric strain vs. horizontal strain curves for soils in optimum moisture and for all fiber contents are shown in Figs. 8, 9, 10, 11, 12, and 13.

The graphs in Figs. 8, 9, 10, 11, 12, and 13 show that the behavior of the soil is significantly influenced by the amount of fibers, as observed in the peak and ultimate stresses and in the volumetric variation. For the SC soil (Figs. 8, 10, and 12), the highest peak stress was the soil without addition of fibers and the smallest one was the soil with the addition of 15%. As for the ML (Figs. 9, 11, and 13), the highest peak stress was for the dosage of 5% of fibers (σ = 205 kPa) (Fig. 13), being 36% higher than the sample without fibers. The behavior of samples with dosages of 10 and 15% of fibers was similar (ductile) to that for all normal stresses.

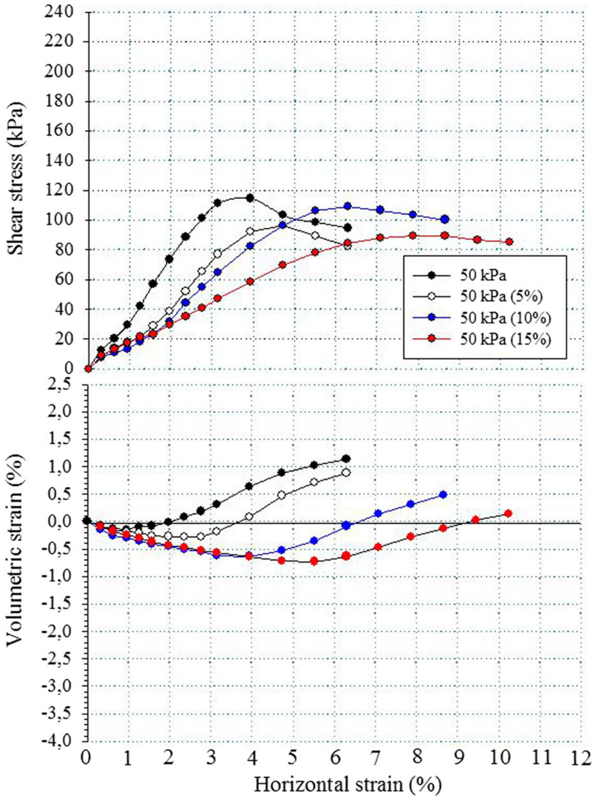

Fig. 8 Stress-strain volumetric response—$\sigma = 50$ kPa (soil SC)

Regarding the volumetric variation for SC for samples with fibers (only), the change in contraction behavior for expansion, for the normal stress of 50 kPa, was observed starting from 3.5% of horizontal strain, reaching a maximum order value of 9% strain for 15% fiber dosage (Fig. 8). For the 100 kPa, there is a behavior change for 5% of fibers from contraction to expansion, for a strain from 7%, in the other fiber dosages, the behavior was only of contraction (Fig. 10). For the 205 kPa, all samples showed contraction (Fig. 12). For ML samples with fibers (only), the change in contraction behavior for expansion for the normal stress of 50 kPa was observed starting from 4% of horizontal strain, reaching a maximum order value of 10% strain for 10% fiber dosage (Fig. 9). In the case of 100 kPa, it stated from 5.5% only for 5% fibers while in the other fiber dosages, the behavior was only of contraction (Fig. 11). For 205 kPa, similarly to SC soil, all samples showed contraction (Fig. 13).

A pronounced effect on the behavior of both soils was observed when fibers were inserted, showing loss of stiffness, and an increase in the ultimate stress and a contraction behavior for all dosages of 15% of fibers. In general, the addition of fibers reduced the volume of the samples, which can minimize the expansion-contraction cracks in the soils, as verified by Benessalah et al. (2016) and Ziegler et al. (1998). The relation between the increase in fiber content and the volumetric behavior of the samples is clear, indicating a contraction behavior for values of 10% and 15% of NPK fibers for 100 kPa and 205 kPa, since the starting of the loading process. This fact

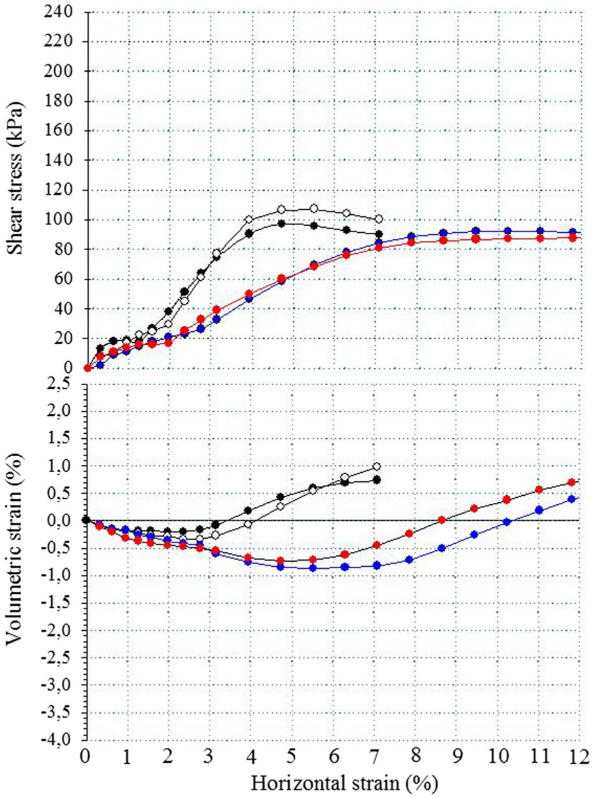

Fig. 9 Stress-strain volumetric response—$\sigma = 50$ kPa (soil ML)

was also observed in the study by Patel and Singh (2019), when they studied the inclusion of fibers in a sandy soil.

Figures 14 and 15 show the variation of the friction angle values for the different sample conditions shown in Table 2.

The results for the SC soil showed that the minimum value was about 28° for 5% of fiber addition in all sample conditions, with a maximum of 36° for the flooded conditions with 15% fibers and 28 days with 10% fibers (Fig. 14). For the ML soil, the lowest value obtained from the friction angle was approximately 25° for the soil without fibers and a maximum value of approximately 37° for 5% of fibers at the optimum moisture condition. While in the flooded condition, the best performance was for 15% fiber dosage (Fig. 15).

The Dunnet test (SC), at a significance level of 5%, indicated that, in optimum moisture, the addition of 15% of fibers significantly increased the value of the friction angle; the same did not occur for other fiber dosages. In the flooded condition, the additions of 10% and 15% of fibers significantly increased the value of the friction angle. In the 28-day tests, regardless of the percentage, no significant differences were found between the friction angle values. For the ML, the same test indicated that, regardless of the fiber dosage, the friction angle increased significantly both in optimum moisture and in flooded conditions when compared with the soil without addition. The 28-day tests indicated that the addition of 5% of fibers significantly increased the

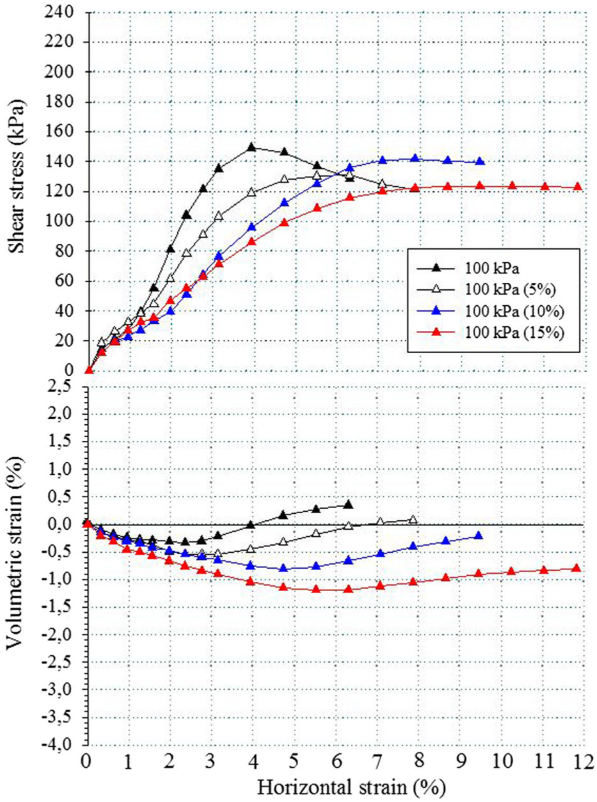

Fig. 10 Stress-strain volumetric response—$\sigma = 100$ kPa (soil SC)

value of the friction angle, but also showed that no differences were found in values when added 10% and 15% of fibers. The statistical analyses showed that the addition of 15% to the SC and 5% fiber to the ML contributed to a significant improvement in the friction angle values of the direct shear tests in the three conditions evaluated, when compared with the soil without fiber.

Regarding cohesion, the results obtained for the SC and ML are shown in Figs. 16 and 17. For the SC, the results of optimum moisture and in flooded condition showed the addition of the fibers reduced this parameter, and the 15% dosage showed the highest reduction, equivalent to 33% when compared with the natural soil (Fig. 16). The results of 28 days showed similar behavior to those obtained in optimum moisture; however, the 5% dosage showed better performance than the soil without the addition of fibers. In the ML (Fig. 17), for optimum moisture, the cohesion was close to the 5% dosage when compared with the soil without fibers. In the case of flooded soil, the 15% dosage had the worst performance. The 28-day test showed a tendency close to the test in optimum moisture; however, it showed a small increase in cohesion.

The statistical analysis (Dunnet test) indicated a significant decrease in the cohesion values in the SC, and the lowest values were achieved by the addition of 15% of fibers, followed by 5% and 10%. As to the ML, no significant difference was found between the values of cohesion in treatments with 5% and 10%; however, a significant decrease was found in treatment with 15% of fibers.

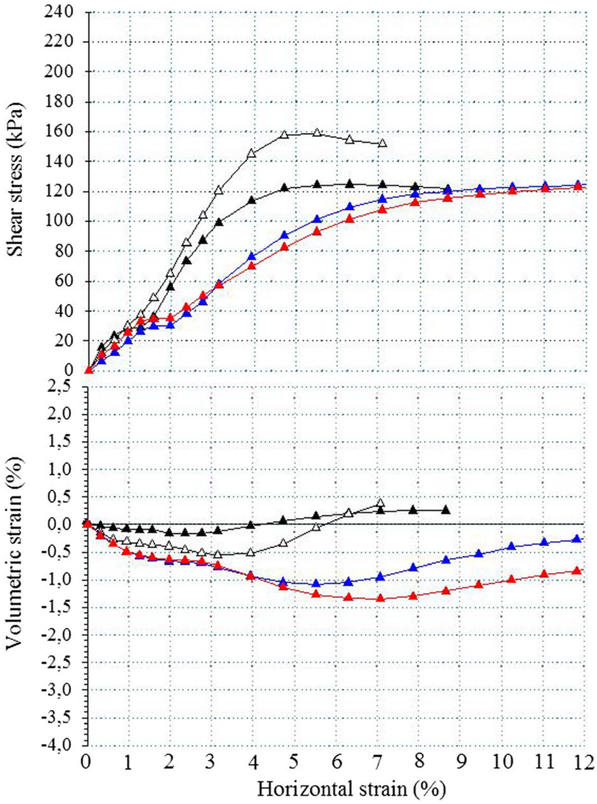

Fig. 11 Stress-strain volumetric response—$\sigma = 100$ kPa (soil ML)

It is generally observed for both soils a nonlinear relationship in the variations of the friction angle and the cohesion, except for 10% of fibers (SC). Such behavior was also verified by Muntohar et al. (2012), who showed that the addition of fibers initially increases the cohesion and that a reduction in this parameter is found after increasing the dosage. Yixian et al. (2016) in their study with the addition of jute also show the cohesion reduced in low fiber contents; however, this effect was not repeated with the increase in the fiber content.

3.3 Stress-Strain Behavior and Failure Mode

The UCS tests followed the prescriptions of ASTM D2166-13 (2013) and were carried out on compacted soil samples (normal energy) in the optimum moisture prepared with and without the addition of fibers. The tests were performed following a penetration rate of 0.5%/min up to a minimum strain of 8% of the height of the specimen. These tests were performed only in the optimum moisture condition. The determination of the resistance to UCS tests was performed through the mean of failure stresses of three specimens, admitting a tolerance of ± 10%. The results are shown in Table 3. Figures 18 and 19 illustrate the stress vs strain graphs for each repetition.

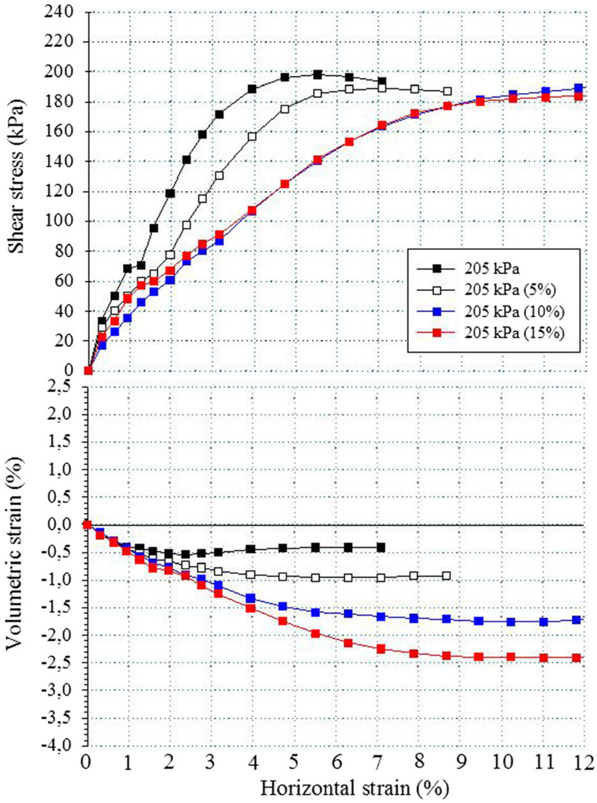

Fig. 12 Stress-strain volumetric response—σ = 205 kPa (soil SC)

Table 3 shows that the values of the coefficient of variation (COV) were less than 10%, indicating a low dispersion of the results (OCDI 2009) and validating the use of the average values of the tests in the data analyses.

Figures 18b, c and 19b, c show a strain-hardening behavior for both soils in the fiber-free condition and for the SC and ML with 5% fibers, and, for the other dosages, a strain-softening behavior was observed (Figs. 18d, e and 19d, e).

Based on Table 3 and Fig. 18, the addition of 5%, 10%, and 15% fiber in the SC led to higher values of simple compressive strength at mean values of 3%, 17%, and 6%, respectively. The Dunnet test, at a significance level of 5%, indicated that no significant difference was found between the values of simple compressive strength when added 5% and 15% of fibers in the SC, but indicated that the addition of 10% of fibers increased this value significantly.

For the ML (Table 3 and Fig. 19), the addition of fibers reduced the peak stress value in terms of mean values of the order of 6%, 10%, and 11% when added 5%, 10%, and 15% of fibers, respectively. The Dunnet test showed that the addition of fibers, regardless of the dosage, did not present significant differences in the compressive strength values.

In general, the simple compressive strength had its value influenced in the peak resistance only for SC at 10% dosage, and that in ML, no significant differences were found in the results with the addition of fibers. Danso et al. (2015a, b) observed similar behavior when they added natural fibers (bagasse, coconut, and oil palm) in two soils (CH and CL).

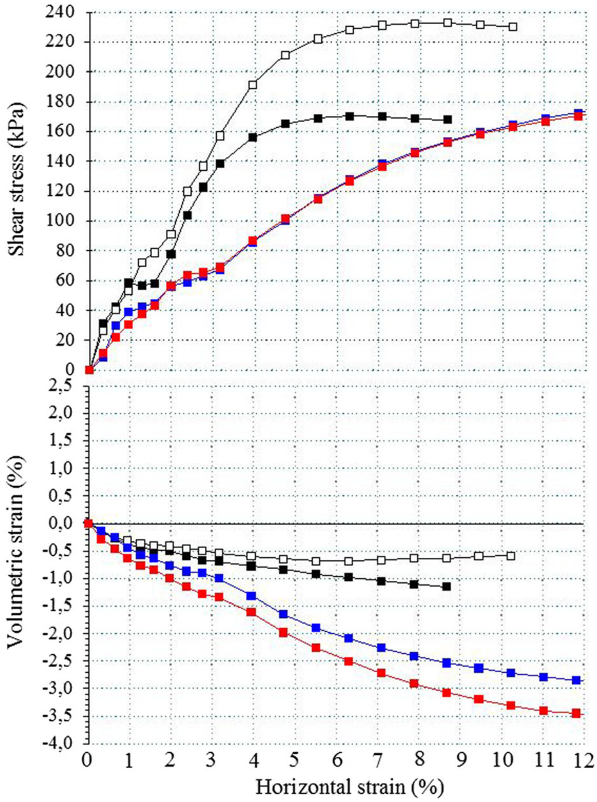

Fig. 13 Stress-strain volumetric response—$\sigma = 205$ kPa (soil ML)

Considering that the addition of fibers influences the amount of solid particles of the soil, the porosity of the sample was determined in the condition of its optimum moisture obtained in the compaction tests. Figure 20 shows the variation of the mean

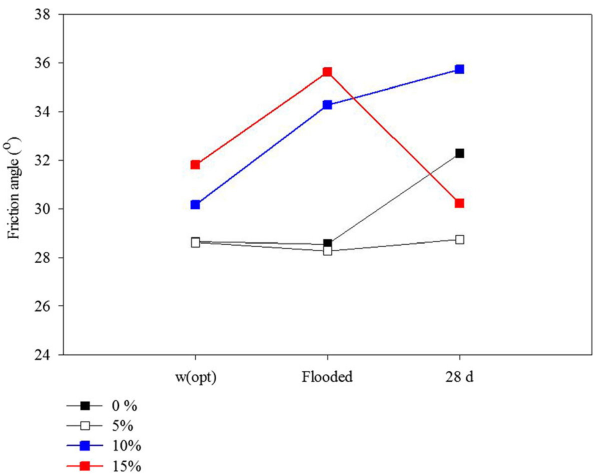

Fig. 14 Friction angle (SC)

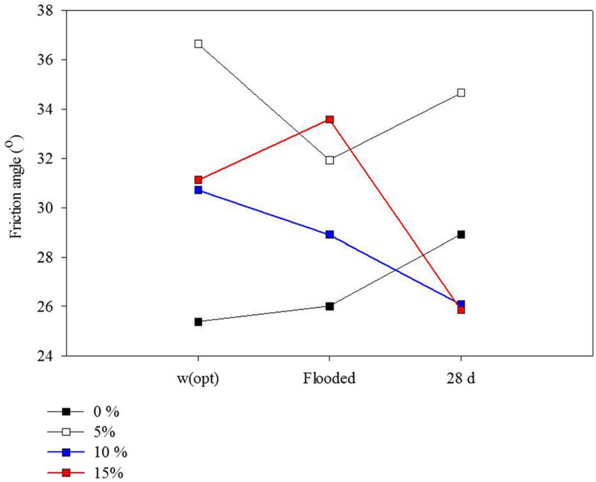

Fig. 15 Friction angle (ML)

maximum axial stress obtained in the UCS tests in optimum moisture with soil porosity. The increase of 5% of fibers in the dry mass of the soil meant an increase of 2% of porosity of both soils. Even with increased porosity in SC, resistance increased significantly, indicating that the addition of fibers in this soil improves its performance to compression.

3.4 Stiffness Behavior Analysis

Figure 21 shows the variations of the Young's modulus (E_{50}), in both soils for optimum moisture condition. The difference between the SC and ML soils without fibers is about 13% on average, which is not considered significant. For the samples

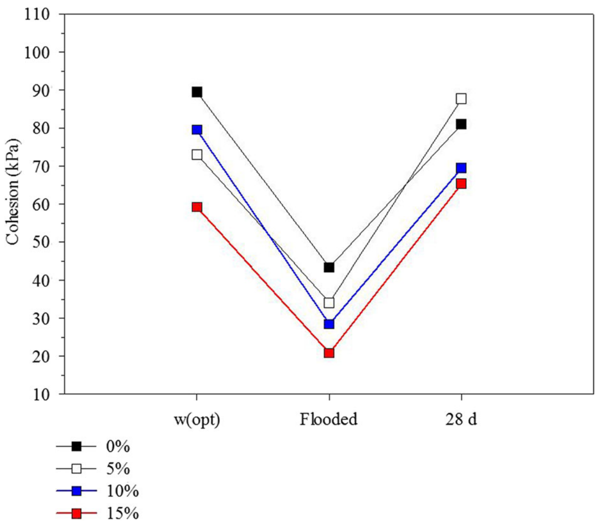

Fig. 16 Cohesion (SC)

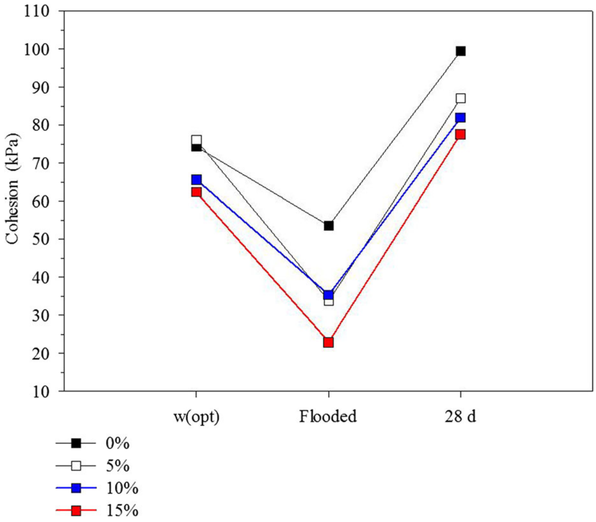

Fig. 17 Cohesion (ML)

with 5% of fiber, the ML resulted in an average value 50% higher than the SC, showing that the fiber addition resulted in an improvement in the sample's stiffness. For a 10% fiber dosage, the Young's modulus of the SC was 100% higher than that obtained for the ML. Lastly, for the dosage of 15%, the values were practically the same for both SC and ML soils.

For the samples without fibers, it can be observed that the difference between the results between the SC and ML soils is about of 13% on average, this difference not being considered significant. For the 5% fiber, the ML resulted in an average value higher than that of the ML, about approximately 50%, showing that the fiber addition resulted in an improvement in the sample's stiffness.

The statistical analysis showed a significant decrease in the values of Young's modulus in the SC, and the lowest values were achieved by the addition of 15% fiber, followed by 5% and 10%. For the soil ML, no significant difference was found

Table 3 Unconfined compressive strength results

		Soil SC				Soil ML			
		0%	5%	10%	15%	0%	5%	10%	15%
kPa	A	211	218	232	234	242	232	207	215
	B	197	216	248	215	247	213	205	207
	C	215	216	250	212	231	231	241	218
	X	208	216	243	221	240	225	217	213
	SD	9.6	1.3	10.1	11.9	8.1	10.9	20.5	5.5
%	COV	4.6	0.6	4.1	5.4	3.4	0.4	9.3	2.6

A, B, C: sample; X: average

SD standard deviation, *COV* coefficient of variation

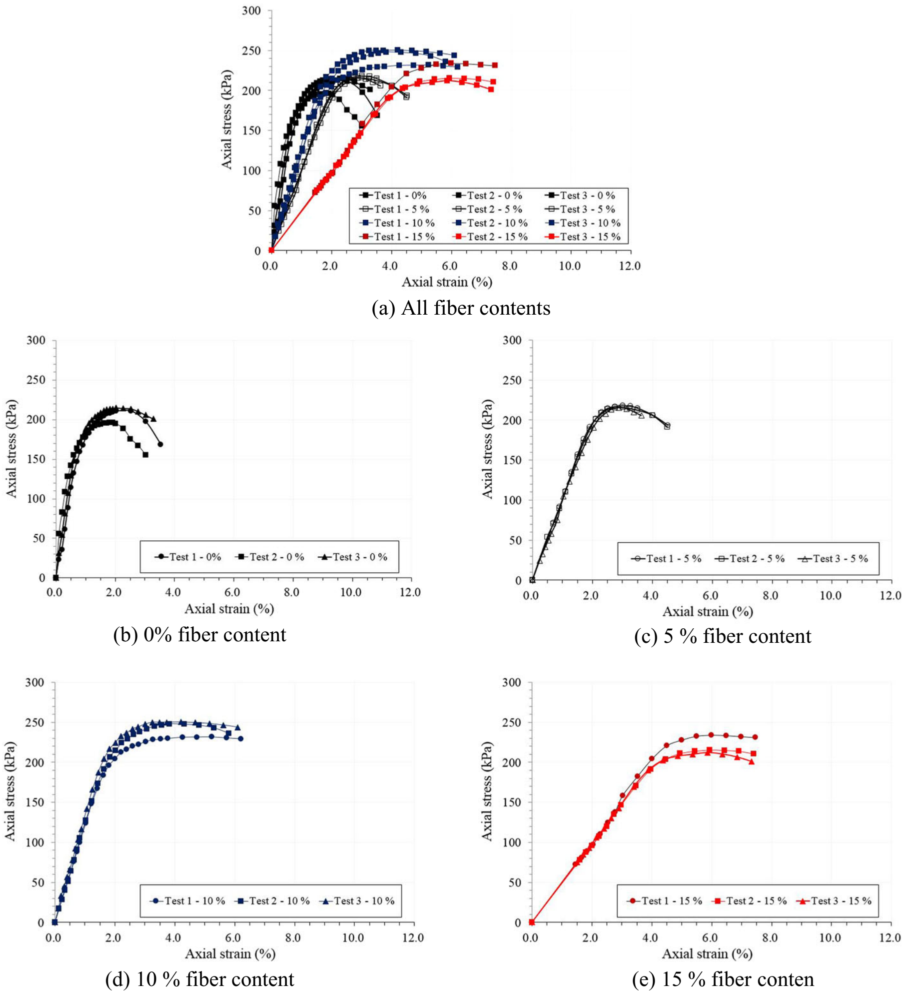

Fig. 18 Unconfined compressive strengths (SC): **a** all fiber contents, **b** 0% fiber content, **c** 5% fiber content, **d** 10% fiber content, and **e** 15% fiber content

between the values of the Young's modulus in the treatment with 5%, but a significant decrease was found in treatments with 10% and 15% fiber. Consoli et al. (1998) and Yetimoglu and Salbas (2003) obtained a reduction in Young's modulus in the triaxial compression tests in fiber-reinforced soil in their samples, even after increase in compressive strength in the samples when compared with the soil without addition of fibers. The same behavior was verified by Kafodya and Okonta (2019), who found sisal fiber contents greater than 0.5% resulted in the stiffness reduction in a CL soil.

Consoli et al. (1998) showed that the greatest advantage of a fiber-reinforced soil is the improvement in the soil ductility condition. Some studies show that fibers addition change the fragile behavior in the fiber-free condition to a little more ductile behavior, such effect was also observed by Bordoloi et al. (2018) when added natural fibers in a

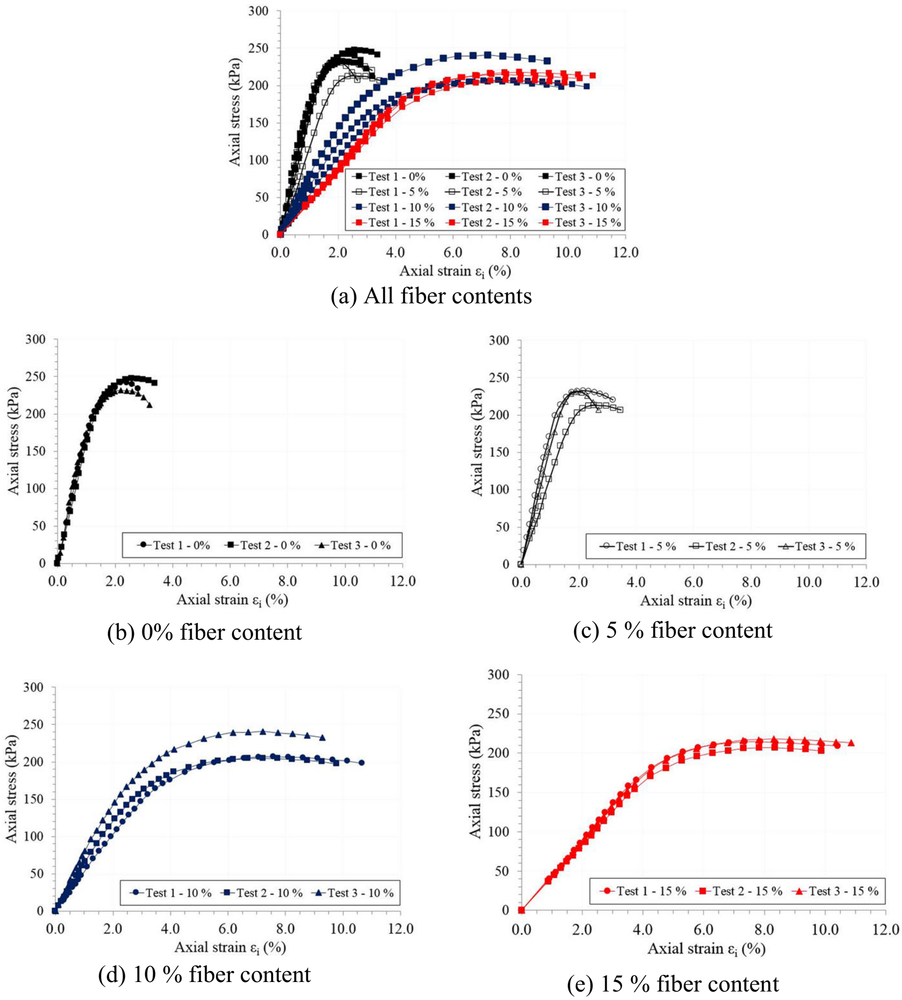

Fig. 19 Unconfined compressive strengths (ML): **a** all fiber contents, **b** 0% fiber content, **c** 5% fiber content, **d** 10% fiber content, and **e** 15% fiber content

clayey silt and by Nguyen et al. (2016) in clay. In other words, the samples tested with fiber additions showed a lower loss of post-peak resistance. The same tendency was observed in the study by Yetimoglu and Salbas (2003), Gray and Ohashi (1983), and Li and Zornberg (2012). As Consoli et al. (1998) showed in their study, the greatest advantage of a fiber-reinforced soil is the improvement in the soil ductility condition; the authors suggest the use the brittleness index (I_B), determined by Eq. 1. The closer I_B approaches zero, the more ductile is the soil.

$$I_B = \frac{q_f}{q_u} - 1 \tag{1}$$

where q_f is the failure stress and q_u is the ultimate stress.

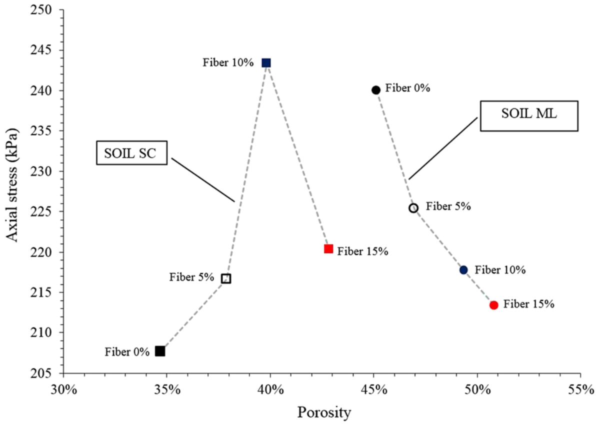

Fig. 20 Variation of compressive strength with porosity and fibers

The brittleness index values, which were obtained through the UCS test for optimal moisture, are shown in Fig. 22.

Figure 22 shows that for the SC soil average values, the brittleness index decreased from 0.19 to 0.03%, while for ML soil, a reduction in ductility can be seen from 0.07 to 0.02%. It means that both soils become more ductile as the fiber dosage is increased, especially for a 10% and 15% fiber dosage. Additionally, Figs. 18d, e and 19d, e show that the post-peak behavior is mainly brittle.

Muntohar et al. (2012) showsathat the addition of 0.4% of fibers reduced brittleness index to values lower than 0.08. Consoli et al. (2011) in their study with paper mill sludge shows the increase in soil ductility with the addition of this type of fiber. It is evident that brittleness increase is accompanied by a stiffness loss and the volumetric response becomes more compressive.

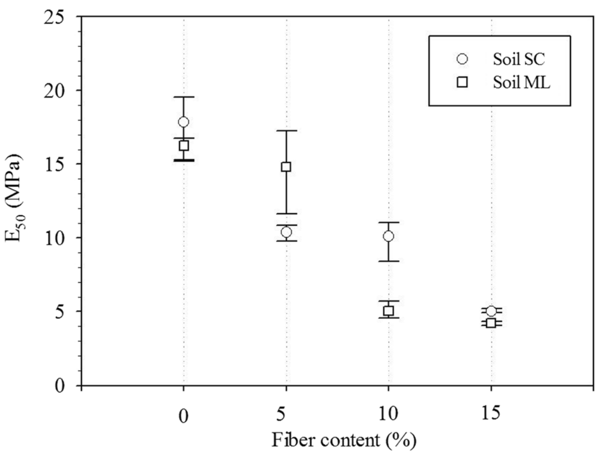

Fig. 21 Young's modulus—E_{50}

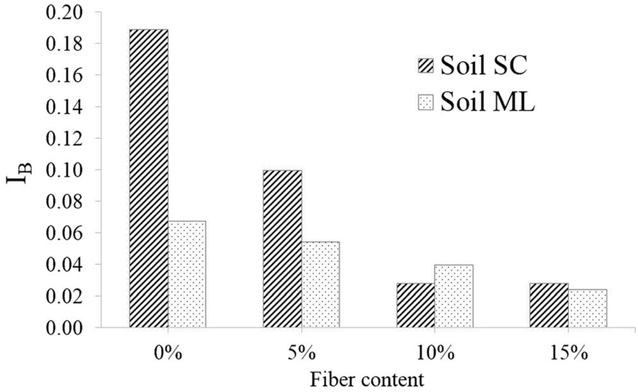

Fig. 22 Brittleness index

4 Conclusions

The addition of fibers reduced the maximum dry unit weight and increased the optimum moisture, as the amount of fiber in the samples increased.

Despite the increase of 2% of porosity for each increment of 5% fiber in both soils, the incorporation of this waste increased the axial stress only for the SC, increasing from 208 to 216 kPa for the addition of 5% fiber and for 243 kPa for the addition of 10%. No significant improvement was observed for any fiber dosage in the ML.

In general, the addition of fibers reduced stiffness as observed in the values of Young's modulus, with an average reduction of 70% when comparing the soil without fiber and with 15% fiber, thus showing that the samples became more ductile, which was confirmed by the values obtained by the brittleness index reaching values of the order of 0.02%.

Regarding the friction angle, for the SC, a significant improvement was found in the three test conditions (optimum moisture, flooded and 28 days) when 10% fiber was added when compared with the soil without addition ($\phi = 28°$), indicating an increase to 30° in the optimum condition, to 34° in the condition at 28 days, and to 36° in the flooded condition.

For the ML, regardless of the fiber dosage, a significant increase in the friction angle was found in both optimum moisture and flooded conditions, with emphasis on 5% dosage, which also indicated an increase for the test at 28 days. However, no significant differences were detected when 10% and 15% fiber were added.

The cohesion of both soils showed a reduction with the addition of the fibers, the addition of 15% showing the worst behavior when compared with the soil without fiber.

In general, the SC soil showed a better performance for a dosage of 10% NPK fiber inclusion, while for ML soil, the better dosage was 5% of fibers. It should be noted that this is an initial study of the inclusion of NPK fibers in soil without the addition of any type of cementitious material. The importance of studies aiming to raise awareness on the impact of cement bags waste in the environment is also highlighted in this work in order to reduce it.

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