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Large-scale direct shear testing in coir fibers reinforced sand

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Article

Keywords
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Shear strength
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Large scale direct shear test

Abstract

The need to develop and commercialize materials incorporating vegetable fibers has risen over the last 20 years to decrease environmental impact and achieve sustainability. In geotechnical engineering, soil reinforcement with plant-based fibers has gained a lot of interest, especially in temporary earthworks. Soil reinforcement with plant-based fibers is a low-cost, environmentally friendly method with excellent reproducibility and accessibility. In this context, growing appeals for using plant-based fibers such as sisal, coir, curauá, and kenaf for manufacturing new geomaterials have been verified. This paper aims to evaluate the mechanical behavior of soil-fiber composites by insertion of natural coir fibers into a sandy soil matrix with different fiber lengths and contents, where the fibers were randomly distributed in the soil mass. Large-scale direct shear test evaluated the strength-displacement behavior in samples with dimensions of 300 x 300 mm and 200 mm in height. The tests were carried out using fibers with 25 and 50 mm lengths, in 0.50 and 0.75% of fiber contents (in relation to the dry weight of the soil), in a relative density of 50% and 10% moisture content. The overall analysis of the results showed that the coir fibers addition in the well-graded sand increased the shear strength parameters and the ductility, compared with the unreinforced sand.

1. Introduction

Brazil is the world's fourth-largest producer of the coconut fruit. However, the industry only processes a small part of coconut wastes, which has resulted in a variety of environmental challenges. Coconut shells account for between 80% and 85% of the weight of the fruit and around 70% of the waste produced on Brazilian beaches, posing a severe environmental challenge, particularly in tropical nations. Nevertheless, coconut fiber applications are limited to evapotranspiration coverage (Sotomayor & Casagrande, 2018). In Brazil, most coconut output is deposited in landfills, occupying a reasonable amount of space. Coconut shell biodegradation takes approximately eight years, and its landfilling also produces methane (CH_4), which contributes to the climate impact if not recovered for electricity generation (Carijó et al., 2002; Themelis & Ulloa, 2007).

Vegetal fibers are increasingly being used to reinforce soil masses, notably in applications involving the stability of earth slopes, ground improvement for shallow foundations, as well as steep cover systems for landfills (Sadek et al., 2010). Furthermore, fiber-reinforced soils (FRSs) are being utilized for recycling and reusing shredded and fibrous inorganic wastes in engineering applications, as viable backfills, and as enhanced pavement materials. Empirical evidence from laboratory research on composite FRS specimens or independent testing of soil and fiber specimens is often used to design geotechnical systems utilizing FRSs (Zornberg, 2002; Casagrande et al., 2003; Diambra et al., 2007; Consoli et al., 2007b; Sotomayor & Casagrande, 2018; Louzada et al., 2019; Correia & Rocha, 2021; Silveira & Casagrande, 2021; Silveira et al., 2022).

Research conducted on fiber-reinforced soils has shown that main parameters regarding shear strength are soil particle size and shape, soil relative density, fiber orientation, and fiber content and length (Maher & Gray, 1990; Al-Refeai, 1991; Michalowski & Cermak, 2003; Yetimoglu & Salbas, 2003; Sadek et al., 2010; Hejazi et al., 2012; Li & Zornberg, 2013; Ferreira et al., 2017; Ferreira et al., 2021). Moreover, research has shown that fibers randomly dispersed in the soil matrix have the benefit of intercepting the potential failure zone and improving the soil stress-strain behavior by mobilizing fiber tensile strength, increasing the sand-fiber composite ductility (Zornberg, 2002; Consoli et al., 2012; Li & Zornberg, 2013; Shukla, 2017).

Many researchers have shown interest in investigating coir fiber as concrete reinforcement (Majid et al., 2011; Ramli et al., 2013; Gupta & Kumar, 2019; Syed et al., 2020).

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Moreover, few studies have focused on soil reinforcement with coir fiber (Menezes et al., 2020; Kaushik & Singh, 2021), and the use of large shearing equipment, which can reduce scale effects of standard soil direct shear tests.

This research aims to evaluate the mechanical behavior of soil reinforced with randomly distributed coir fibers, as well as fiber length and content effect on soil shear strength parameters. The findings apply to the use of fiber-reinforced composites in geotechnical engineering, as well as the selection of parameters in associated numerical analyses.

2. Materials and methods

2.1 Test materials

The composite matrix is formed by a sand soil (Figure 1A) with a specific gravity (*Gs*) of 2.68, a uniformity and curvature coefficient (C_u and C_c) of 2.40 and 1.06, respectively. As well as an average diameter (D_{50}) of 0.39 mm (Figure 2), and minimum and maximum void ratios of 0.58 and 0.89, respectively. The USCS classifies this material as SW, corresponding to a well-graded sand.

The use of specific fiber lengths and contents was required to accomplish the testing program's objectives, which included investigating the influence of fiber content relative to soil granulometry on the strength enhancement caused by fiber inclusion. The fibers utilized in this research were obtained using a customized tool to cut the fibers to the desired lengths to control fiber geometry.

A collaboration between the municipal company of urban cleaning and the department of public services conservation of Rio de Janeiro gathered coir fibers provided for this research. Before being employed, the fibers were cut to the necessary length (25 and 50 mm) and subjected to a beneficiation process to remove any residues attached to their surface (grease and natural resins). The fibers were washed in boiling water and air-dried throughout this procedure. Figure 1B depicts the coir fibers after all preparation procedures. The fiber average dimensions were 25 and 50 mm in length, and 0.50 and 0.75% contents were utilized according to soil dry weight. Prior research suggests that a 0.50% fiber content can be adopted as an upper limit considering workability and homogeneity (Consoli et al., 2003; Consoli et al., 2009b; Consoli et al., 2007b; Anagnostopoulos et al., 2013). However, limited research has examined this upper limit for coir content influence.

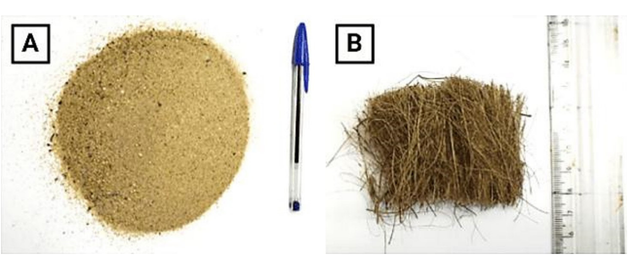

Figure 1. (a) Sand soil; (b) 50 mm length coir fiber.

2.2 Laboratory testing program

A comprehensive direct shear testing program was planned and conducted to explore the characteristics known to affect the composite shear strength of fiber-reinforced sands. Five series of drained large direct shear tests were conducted using a well-graded sand with varying fiber lengths and contents. Large direct shear testing was used because of the relative simplicity of sample preparation and testing procedure. This testing procedure was selected despite the inherent test restrictions, such as the kinematic constraints imposed on the sample, the nonuniform shear zone thickness, and the non-uniform stress distribution. A 300 x 300 x 220 mm shear box was utilized in all experiments to minimize the restrictions' influence and obtain reliable and representative samples (Figure 3). The tests were conducted by ASTM (2011) at a constant displacement rate of 0.508 mm/min. Using a load cell and LVDTs, the shearing load and vertical displacement were recorded as functions of the horizontal displacement. Total horizontal displacements of at least 35 mm were recorded.

The direct shear system consists of two hydraulic circuits equipped with two hydraulic jacks, and two 100 kN load cells and three LVDTs. Figure 3 also depicts the reaction system composed of a 1000 kN workload steel gantry. The hydraulic systems are employed to apply both shear, and normal loads, which also function with the support of a gear set arranged according to the test required velocity. The equipment's operation is driven utilizing hydraulic hose connections, thus allowing a constant and pre-established load transfer. Load cells and displacement sensors (Figure 4) are connected to a data acquisition system (*Spider 8*), with a 1 Hz acquisition frequency and Catman v 2.0® software.

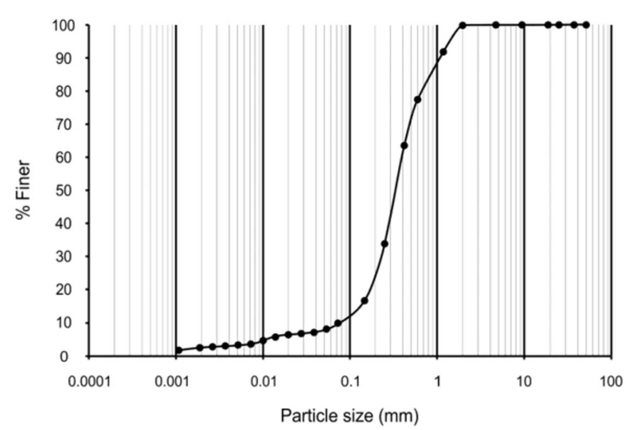

Figure 2. The grain-size distribution curve of unreinforced sand soil.

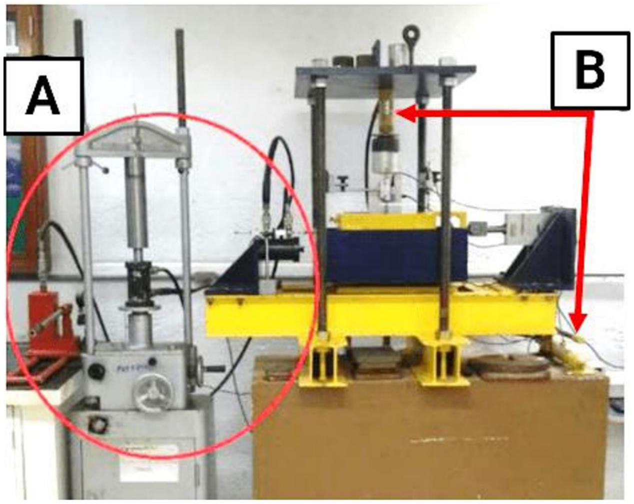

Figure 3. Large direct shear test setup (a) hydraulic system which applies shearing loads; (b) hydraulic system which applies normal loads.

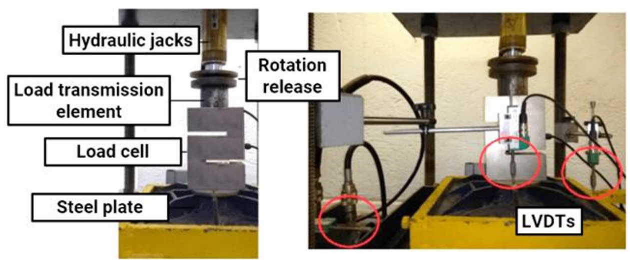

Figure 4. Large direct shear test setup: load cells and LVDTs.

2.3 Specimen preparation and testing

The molding parameters used for the non-reinforced sandy soil and the soil-fiber composite were identical, with a relative density of 50% and an initial moisture content of 10% in proportion to the soil dry weight. The soil-fiber mixes were made using fibers randomly dispersed in lengths of 25 and 50 mm, with fiber contents of 0.50 and 0.75% of the soil dry weight. To avoid segregation of the fibers and the sand, both the compacted sand and the fiber-reinforced specimens were first manually homogenized with the appropriate amounts of dry sand, vegetable fibers (if used), and water. The homogeneity of the components was visually verified after the mixture of all parts was prepared. All specimens were prepared by static compaction onto the direct shear box in a square mold 300 mm in length and 200 mm in height (Figure 5). The sample in the direct shear box was divided into five layers with 40 mm in size (Figure 6). The final height of each layer was controlled to ensure the 50% soil relative density.

Therefore, the specimen preparation method detailed above was adopted for molding soil samples at 50% relative density and 10% moisture content. The choice of relative density as the reference parameter was made since: (1) it allows better visualization of soil-fiber interaction effect (Consoli et al., 2007b; Consoli et al., 2007a; Consoli et al., 2009a) and (2) as the composite relative density increases, fiber mobilization within the soil mass occurs rapidly, due to a better interlock between the fibers and the soil matrix.

A summary of the testing program and sample notation is shown in Table 1. The fiber content of the well-graded sand ranged from 0 to 0.75%, about soil dry weight. Additionally, a minimum of three specimens were studied at normal stress levels of 25, 50, and 100 kPa for each set of parameters, for a total of nearly 15 large direct shear tests. These normal stresses were chosen to represent usual stress ranges in relevant geotechnical engineering applications.

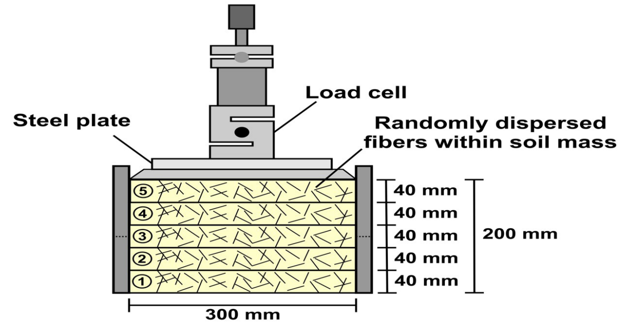

Figure 5. Specimen molding procedure.

Figure 6. Inner view of the direct shear box during sample preparation.

3. Analysis and results

Shear stress and vertical displacement versus horizontal displacement plots for soil specimens evaluated at typical stress values of 25, 50, and 100 kPa are included in the experimental findings. These plots were examined to determine the effect of fibers on stress-displacement behavior, shear strength and friction angle increase, and volume change. Table 2 summarizes the relevant test parameters and calculated internal friction angles for unreinforced and fiber-reinforced samples.

Plots depicting the variation in shear stress and vertical displacement with horizontal displacement for unreinforced and fiber-reinforced soil samples with fiber lengths of 25 and 50 mm, as well as 0.50 and 0.75% fiber contents, are presented in Figures 7-8. Curves in Figure 7 correspond to soil samples reinforced with 25 mm length fibers with a fiber content of 0.50 and 0.75%, whereas curves in Figure 8 correspond to soil samples reinforced with 50 mm length fibers with a fiber content of 0.50 and 0.75%. The results presented in Figures 7-8 indicate increases in strength for 25 and 50 mm long fibers, particularly the first. Except for an increase in the slope of the stress-displacement curve at small displacements, the general form of the stress-displacement curves of fiber-reinforced specimens was like that of unreinforced samples. However, as normal stresses increased, fiber-reinforced specimens curves showed a shear stress growth at a horizontal displacement range between 10 to 40 mm, indicating a typical hardening behavior as observed by Silveira & Casagrande (2021).

Figures 7-8 indicate that fiber reinforcement inhibits dilatancy, particularly at high normal stresses. This result endorses prior research findings from direct shear testing (Gray & Ohashi, 1983) and triaxial tests (Michalowski & Zhao, 1996; Michalowski & Cermak, 2003). On the other hand, other researchers (Sadek et al., 2010; Hazirbaba, 2017) have shown that the presence of fibers consistently increases the tendency for dilation in fiber-reinforced, particularly for longer fibers, which was the case to some extent for fiber-reinforced samples with 50 mm fiber lengths. The main distinction between published results and results reported in this paper is the soil relative density, which was taken as 50% in the current study but was always greater than 50% in the studies mentioned above, as well as the shear box size (scale effect), which may have contributed to the observed discrepancies since direct shear test results are known to be sensitive to the size of the soil specimen.

The maximum shear stress was attained for practically all unreinforced samples with a horizontal displacement of approximately 15 mm. Further than this value, the shear stress became nearly constant, which is evident that soil samples were prepared in a loose to medium dense state (DR ≈ 50%). On the contrary, reinforced specimens indicated increasing shear stress as normal stress, and horizontal displacement also rose. The mobilization of the fiber unit tensile stress

Table 1. Laboratory testing program.

Sample	Fiber length (mm)	Fiber content (%)
S	—	—
RS2550	25	0.50
RS2575	25	0.75
RS5050	50	0.50
RS5075	50	0.75

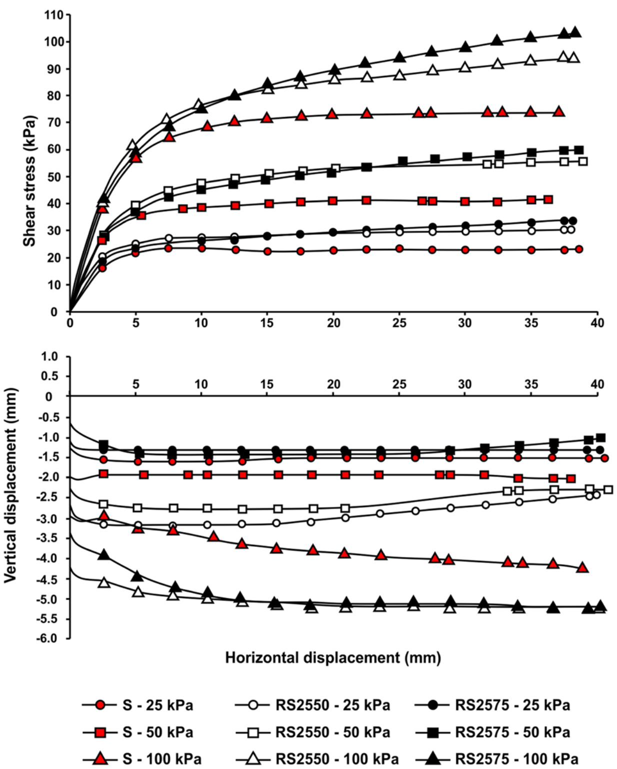

Figure 7. Variation of shear stress and vertical displacement with horizontal displacement for fiber-reinforced sand with 25 mm fiber lengths.

Table 2. Laboratory testing program.

Sample	Fiber length (mm)	Fiber content (%)	Internal friction angle (°)	Improvement in shear strength parameters (%)
S	—	—	34.0	—
RS2550	25	0.50	40.0	18
RS2575	25	0.75	42.0	24
RS5050	50	0.50	39.0	15
RS5075	50	0.75	40.0	18

produced by a set of effects (interface bonding, friction, and interlocking) when the composite is under load can be attributed to the shear stress rise for fiber-reinforced specimen curves (Gowthaman et al., 2018). It is worth noting that the fiber strengthening effect requires some amount of deformation to initiate, as observed by Lawton et al. (1993) while performing triaxial tests on fiber-reinforced soil specimens. For the case without an obvious peak point, the failure criteria proposed by Campos & Carrillo (1995), based on the slope of the stress–displacement curve was adopted. In these cases, shear failure was assumed when the stress–displacement curve indicated a constant slope (d ≈ 35 mm for all reinforced specimens).

A considerable soil stiffness improvement due to fiber inclusion occurs in the initial test stage at small displacements of about 5 mm for all reinforced samples. Beyond this value, the stress-displacement curves evidence increases in shear stress of the sand-fiber composite compared to unreinforced specimens (Figures 7-8). The inclusion of fibers changes the failure mechanisms observed for non-reinforced sand. Soil hardening behavior (a constant rise in strength with increasing horizontal displacement) was observed for all normal stresses regarding the soil reinforced with coir fibers. When comparing the results of the fiber lengths and contents, it becomes evident that the samples reinforced with 25 mm length and 0.75% fiber content presented higher shear strength for all normal stresses.

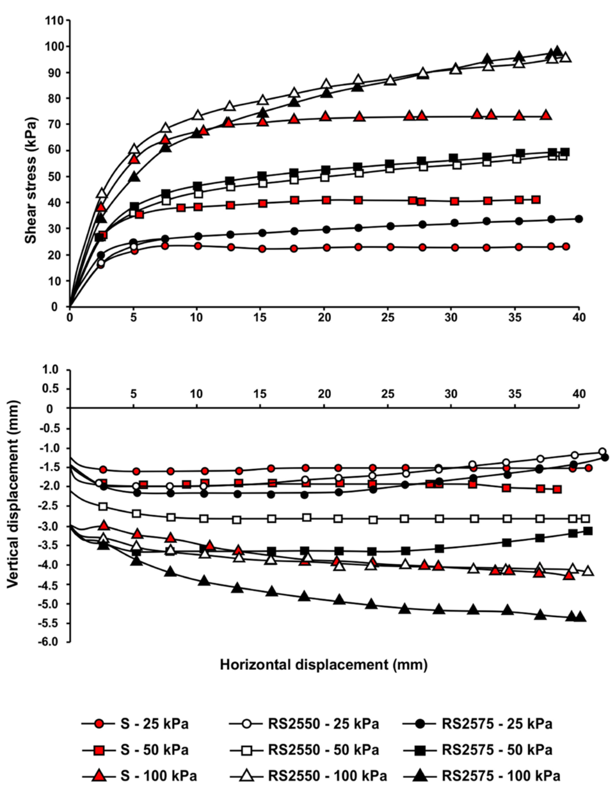

Figure 8. Variation of shear stress and vertical displacement with horizontal displacement for fiber-reinforced sand with 50 mm fiber lengths.

The increase in the maximum shear stress as a function of the fiber content is illustrated in Figures 7-8 for sands reinforced with 25 and 50 mm length fibers. An increase in fiber content from 0.50 to 0.75% results in about a 12% improvement in shear strength for a fiber length of 25 mm and about a 4% improvement for a fiber length of 50 mm. This result is relevant because it indicates that more extensive improvements in shear strength can be obtained with relatively small fiber content variation.

Stress-displacement curves for reinforced-sand specimens with 25 mm fiber lengths show a consistent rise in maximum shear stress as fiber content increases. Unlike reinforced-sand samples with 50 mm fiber lengths and fiber contents of 0.50 and 0.75%. This suggests that the relative dimensions of the reinforced sand grains and the diameters of the reinforcing fibers significantly impact the level of improvement brought about by fiber inclusion in sands. When the fiber concentration is around 0.75%, the reinforcing effect in reinforced-sand specimens with 25 mm fiber lengths is more pronounced, whereas the relative increase in reinforcing effect in reinforced-sand samples with 50 mm fiber lengths is slightly smaller for similar fiber content.

Vertical displacement versus horizontal displacement curves were recorded to verify the sample volume change as the large direct shear test progresses. The vertical displacement curves indicate that unreinforced and fiber-reinforced sand specimen's behavior was similar to typical loose sand samples. The sample vertical displacement decreases as the shear stress increases to a maximum value. After that, a constant vertical displacement value is observed. A similar trend was verified for all samples at 25, 50, and 100 kPa normal stresses. However, for samples reinforced with 25 mm length fibers, the addition of fibers decreased the contraction behavior, indicating that the fibers merged the sandy soil grains, inhibiting particle movement. While fiber inclusion for samples reinforced with 50 mm length fibers had no significant effect on the sample volume change.

The friction between the soil and the reinforcement appears to control the soil-fiber composite strength, and it does not appear to be dependent on the ultimate strength properties of the coir fibers. Direct shear test results are compiled in Table 3 and the shear strength envelopes for unreinforced and reinforced sand specimens are depicted in Figure 9. The friction angle value is also affected by the confining stresses under which the samples are tested, implying that the general envelope is nonlinear. However, given the restricted range of effective normal stresses applied in this research and the simplicity by which the effects of fiber reinforcement can be quantified, a linear envelope determined using linear regression would be a reasonable estimate of the soil stress state at failure. This line's extrapolation towards zero effective normal stress yields a cohesion intercept.

As an uncemented particle system, sand soils should lack genuine cohesion under effective stresses. However, the inter-particle contacts (interlocking) created by the

Table 3. Shear strength parameters for all test series.

Sample	Fiber length (mm)	Fiber content (%)	Internal friction angle (°)	Improvement in shear strength parameters (%)	Cohesion intercept (kPa)
S	—	—	34.0	—	6
RS2550	25	0.50	40.0	18	11
RS2575	25	0.75	42.0	24	11
RS5050	50	0.50	39.0	15	14
RS5075	50	0.75	40.0	18	14

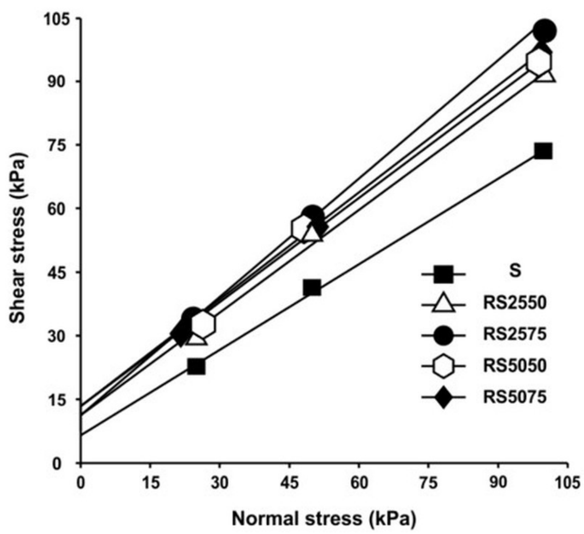

Figure 9. Unreinforced and fiber-reinforced sand samples shear strength envelopes.

tamping fabrication approach appear to be relevant, which might explain the presence of an apparent cohesion that rises marginally with fiber addition (Ibraim & Fourmont, 2006). Although more research is needed to determine the cause of this apparent cohesion, the failure envelopes in this study are defined in terms of the soil friction angle and cohesion intercept. Table 3 presents a maximum improvement in shear strength of 24% percent for the highest fiber content (0.75%). The increased maximum shear stress causes the composite's friction angle to increase from 34 ° for unreinforced sand to 42 ° for sand reinforced with 0.75% fiber content.

4. Conclusions

In this research, the shear strength behavior of a well-graded sand reinforced with coir fibers of different content and lengths was studied using a series of large-scale direct shear tests. The unreinforced and fiber-reinforced sand samples were compacted at 50% relative density and a moisture content of 10%. The following conclusions can be made based on the undertaken experimental study:

- The fiber-reinforced sand samples with coir fibers showed a significant increase in shear stress as the normal stress increased. This increase is attributed to the fiber's anchoring action (interface bonding, friction, and interlocking) in the soil mass under load. The addition of fibers alters the failure mechanism observed in unreinforced sand. Furthermore, the modification of the failure mechanism may be seen as a plausible explanation for the soil hardening behavior observed in all stress-displacement curves of fiber-reinforced samples.
- The addition of coir fibers with lengths of 25 and 50 mm and fiber contents varying from 0.50 to 0.75% percent to a well-graded sand produced at a relative density of 50% improved the sand-fiber composite's shear strength and ductility. For sand reinforced with 0.75% fiber content and 25 mm fiber length, the most significant improvement in shear strength was nearly 32%.
- At low normal loads (25 kPa), the shear strength presents a slight increase for all reinforced specimens. However, for higher normal stresses, the shear strength increase with all fiber contents and lengths are more evident, particularly for 25 mm fiber lengths.
- Shorter (25 mm length) coir fibers resulted in a more significant improvement in the shear strength of fiber-reinforced sands, according to the limited experiments in this research. The results reported by Michalowski & Cermak (2003) on the relative dimensions impact of the reinforced sand grains and the reinforcing fiber diameters in determining the level of improvement provided by fiber inclusion might be one explanation for this finding.
- More broadly, the findings concerning the dilatancy of fiber-reinforced composites are consistent with previous studies that revealed a tendency for fibers to restrict sand dilatancy. According to the results of the experiments conducted in this study, the vertical displacements recorded during shearing for reinforced specimens with 25 mm fiber lengths were reduced with the addition of fibers. However, vertical displacements increased with fibers in reinforced specimens with 50 mm fiber lengths for both 0.50 and 0.75% fiber content. The increase in recorded vertical displacement during shear represents a greater tendency for dilatation of a narrow band of soil impacted by the presence of fibers, as also noted by Sadek et al. (2010).

The current research's broad implication is that the inclusion of coir fibers as soil reinforcement has a substantial potential for application in landfills on soft soils, slopes, and shallow foundations, giving this material a better end in the technical scope while also attending to economic, social, and environmental aspects.

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Declaration of interest

The authors have no conflicts of interest to declare. All co-authors have observed and affirmed the paper's contents, and there is no financial interest to report.

Authors' contributions

Leila Maria Coelho de Carvalho: investigation, data curation, visualization, writing – original draft, formal analysis. Fernando Feitosa Monteiro: investigation, writing – review & editing. Michéle Dal Toé Casagrande: conceptualization, methodology, supervision, funding acquisition.

Data availability

All data produced or examined in the course of the current study are included in this article.

List of symbols

d	Horizontal displacement
C_c	Curvature coefficient
C_u	Uniformity coefficient
D_{50}	Average diameter
DR	Relative density
FRS	Fiber reinforced soil
G_s	Specific gravity
$LVDT$	Linear variable differential transformer
$USCS$	Unified soil classification system

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