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Hydromechanical behavior of sandy-clayey soil mixtures with polypropylene fibers

Comportamento hidromêcanico de misturas de solos areno argilosos com fibras de polipropileno

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Abstract: Using polypropylene fibers as soil reinforcement is applicable when the soil in its natural state does not have the necessary geotechnical properties to withstand the expected stresses in the field. Fibers can bring improvements such as increasing shear strength and decreasing soil compressibility. Regarding permeability, there is an increase in soil added with fibers; this effect may not represent a negative point as long as the permeability of the mixture is suitable for field application. This work aims to study the hydromechanical behavior of sandy-clay soil used as covering material for a landfill in the State of Ceará, with the insertion of polypropylene fibers in different fiber contents and lengths and to verify the influence on geotechnical parameters in soil layers of dry covers. As part of the research, laboratory tests for geotechnical and mineralogical characterization were carried out. Polypropylene fibers 6 and 12 mm long were used, with gravimetric contents from 0,25%, 0,75%, and 1.25%. The results indicated gains in strength with the addition of fibers. Permeability increased progressively with increasing fiber content, but the composite can still be used as a waterproofing layer to cover landfills.

Keywords: Reinforced soil; Polypropylene fibers; Hydromechanical.

Resumo: O uso de fibras de polipropileno como reforço de solos é aplicável quando o solo em seu estado natural não possui as propriedades geotécnicas necessárias para suportar as solicitações previstas em campo. As fibras podem trazer melhorias como o aumento da resistência ao cisalhamento e diminuição da compressibilidade do solo. Com relação à permeabilidade ocorre aumento no solo adicionado com fibras, esse efeito pode não representar um ponto negativo, desde que a permeabilidade da mistura seja adequada à aplicação em campo. Este trabalho tem como objetivo estudar o comportamento hidromecânico de um solo areno-argiloso, utilizado como material de cobertura de aterro sanitário do Estado do Ceará, com inserção de fibras de polipropileno, em diferentes teores e comprimentos de fibra e verificar a influência nos parâmetros geotécnicos do solo de camada de cobertura de aterro sanitário. Como parte da pesquisa, foram realizados ensaios laboratoriais de caracterização geotécnica e mineralógica. Foram utilizadas fibras de polipropileno de 6 e 12 mm de comprimento, nos teores gravimétricos de 0,25%, 0,75% e 1,25%. Os resultados indicaram ganhos de resistência com a adição de fibras. A permeabilidade aumentou progressivamente com o aumento do teor de fibras, mas o compósito ainda pode ser utilizado como camada impermeabilizante na cobertura de aterros.

Palavras-chave: Solo reforçado; Fibras de polipropileno; Hidromecânico.

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1. Introduction

Finding a soil with suitable physical-mechanical properties is essential in geotechnical engineering. However, available soils often have insufficient characteristics for use in geotechnical works that meet the technical specifications of the projects. The Soil is a heterogeneous material with complex and variable behavior, which leads to improving its properties to suit the project needs.

Fiber-reinforced soils, called composites, are often used when the soil has low bearing capacity. They are also used for shallow foundations, landfill cover layers, and slope stabilization applications. This practice has been very effective due to the improvement in the strength of the resulting material, especially in shear strength.

A wide variety of fibers can be used in fibrous composites. To define the type of fiber to be used, it is necessary to know the interaction mechanisms between the matrix and the reinforcement and how each part will contribute to the behavior of the composite. The fiber choice will depend on the matrix to be reinforced, the characteristics obtained in the final composite material, and the cost of receiving it.

In the last two decades, there has been a growing number of studies on using fibers, such as steel, glass, rubber, and plastic, to act as soil reinforcement. Several studies have observed an increase in soil strength when mixed with fibers, such as steel (NOURI; SHAHROUZI, 2021), glass (RABAB'AH et al., 2021; SUJATHA et al., 2020) rubber (JARAMILLO et al., 2022; MEDDAH; MERZOUG, 2017; ROCHA et al., 2021), vegetables (LEOCÁDIO, 2005; LOPES, 2019; SILVEIRA, 2018) and polypropylene (CASAGRANDE, 2001, 2005; FESTUGATO, 2008; SOUSA et al., 2020; TEODORO, 1999; TRINDADE et al., 2004, 2006; VENDRUSCOLO, 2003).

The length of the fibers present in a composite directly influences its strength. The contact area in longer-length fibers is greater, implying greater friction between soil and fiber. Therefore, increasing the length means gaining strength, but this gain was only observed up to a specific fiber length, which will be considered ideal. The ideal fiber length must be defined in a laboratory, taking into account the specificities of each soil and fiber since there is no predefined dosage (HEINECK, 2003; ROQUE, 2017; TEODORO, 1999; TRINDADE et al., 2004). According to the authors, the optimum fiber content is not very high, at around 10 to 25 mm. However, it is necessary to carry out laboratory tests to precisely define this value since the variables (soil type and fiber) must be considered.

In addition to length, fiber content is directly related to the strength of the soil-fiber mixture. According to Santos et al. (2016), there are several ideal fiber contents since several parameters can modify this content, such as the type of fiber used, the type of soil, the addition of waste, the addition of additives, and the load applied to the experiment.

Trindade et al. (2004) carried out a study using a red-yellow latosol with a sandy-clay texture and polypropylene fibers with lengths of 10, 15, 20, and 30 mm and contents of 0.25%, 0.50%, and 0.75% about the mass of dry soil. The compaction test results showed a tendency for a higher fiber content to reduce the dry unit weight of the soil progressively. In contrast, the optimum water content progressively increased. The authors often report that as the fiber content increases, the dry unit weight decreases and the optimum water content increases; this behavior was observed by Rocha (2019), Castro (2020), and Barboza et al. (2022).

As for shear strength, the increase due to the inclusion of fibers has been reported by several authors (BIANCHINI, 2013; BUENO et al., 1996; GRAY; OHASHI, 1983; SENEZ, 2016). Some authors report increased friction angle and cohesive intercept with increasing fiber content (BUENO et al., 1996; GRAY; OHASHI, 1983). However, other authors only report an increase in the cohesive intercept (CASAGRANDE, 2001; LEOCÁDIO, 2005; TEODORO, 1999; TRINDADE et al., 2006). Some show only an increase in the friction angle (HEINECK, 2002; MARÇAL, 2019; TEODORO, 1999).

A study by Bueno et al. (1996) found that the permeability of clay soils increased due to the addition of fibers at different levels; however, in granular soils, there was a reduction of an order of magnitude in permeability. Pinto and Machado (2022) reported that adding polymeric fibers to alluvial sand did not generate significant changes in permeability. Clay soils have low permeability, and the presence of fibers increases this permeability due to the creation of preferential paths through which the fluid can percolate more quickly (through the fibers).

Because of the relevance of applying polymeric fibers as soil reinforcement, this study aims to contribute to understanding the hydromechanical behavior of sandy-clay soils reinforced with polypropylene fibers, evaluating the performance of the soil reinforced with different fiber contents and lengths. This study used landfill layer cover soil to verify the influence of the strength parameters (cohesion and friction angle) of the insertion of fibers and whether the inclusion of fibers allows the application of landfill cover soil.

2. Methodology

The soil comes from a deposit used as the final cover material for the West Caucaia Municipal Landfill (ASMOC), located in Caucaia, the metropolitan region of Fortaleza, Ceará, in northeastern Brazil. The soil samples collected in situ were deformed, air-dried, cleaned (removing branches and pieces of plastic), crushed, sieved, and stored in plastic bags. The procedure followed was described by NBR 6457 (ABNT, 2024).

For the tests involving the soil+fibre mixture (compaction, shear strength, permeability, and SEM), homogenizing the soil was necessary, which was carried out following the recommendations of Casagrande (2001). The dry components (soil and fiber) were mixed, followed by adding water. Mixing was carried out manually until homogeneity was visually observed. During the tests, it was observed that the higher the fiber content, the greater the difficulty of homogenization since fiber agglomerations formed during the preparation of the samples.

Table 1 describes the properties of polypropylene fibers. As indicated in Figure 1, the fibers selected for the study are 6 and 12 mm long.

Table 1 – Physical properties of polypropylene fibers.

Physical properties	Lengths
	6 and 12 mm
Diameter (µm)	18
Elongation (%)	80
Unit weight (kN/m³)	9.1
Tensile strength (MPa)	300
Young's Modulus (MPa)	3000
Melting Temperature (ºC)	160
Ignition Temperature (ºC)	365

Source: Maccaferri (2016).

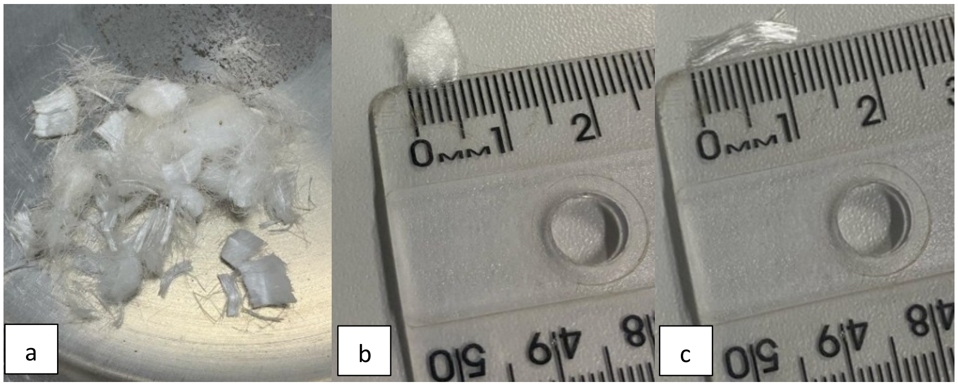


Figure 1 – a) Polypropylene fibers o; b) Fibers of 6 mm; c) Fibers of 12mm.
Source: Authors (2024).

2.1 Geotechnical characterization

This section presents the geotechnical characterizations of the soil and the composite. The particle size distribution curve was obtained according to NBR 7181 (ABNT, 2016b). The specific gravity using a pycnometer was described in ME 093 (DNER, 1994). Atterberg limits were calculated following NBR 7180 (ABNT, 2016c) and NBR 6459 (ABNT, 2016d).

The samples were prepared according to NBR 6457 (ABNT, 2024), and the compaction test was carried out following NBR 7182 (ABNT, 2016a) to conduct the compaction tests on the pure soil and soil-fiber mixtures. The material was reused and compacted in the large cylinder using normal Proctor energy, which requires a significant 4.5 kg socket, five layers, a drop height of 0.45 m, and the application of 12 blows per layer.

To perform the permeability, compaction, and shear strength tests, samples of pure soil and mixtures of soil with fiber in different percentages (0.25%, 0.50%, 0.75%, 1%, and 1.25%) were used.

The choice of fiber content was based on data obtained in studies using soil-fiber mixtures (CASAGRANDE, 2005; CASTRO, 2020). Shallow fiber contents do not provide significant strength gains, and very high contents cause homogenization difficulties.

2.2 Hydromechanical tests

A rigid wall permeameter was used to carry out the permeability tests, and the test followed method B of NBR 14545 (ABNT, 2021d), as the soil is a material with a permeability of less than 10^{-5}m/s. The specimens were molded at normal Proctor energy, and the optimum water content was obtained from the compaction test. Saturation was carried out in an upward flow. Tests were carried out on pure soil and soil with the addition of 0.25%, 0.75%, and 1.25% fibers concerning the dry mass of the soil. The samples were tested in triplicates, and the percolating fluid was used as public water.

The procedure described in D3080-04 (ASTM, 2012) was used to obtain the strength parameters. The material passing through the sieve with a mesh opening of 2 mm (No. 10) was used in the tests. The specimens were compacted in the small cylinder of the compaction test, using the normal Proctor energy and at the optimum water content, followed by cutting the samples to the dimensions of the specific mold for the direct shear test, 0.05 m in diameter and 0.02 m high. The samples were tested for three loads, 50 kPa, 100 kPa, and 200 kPa, with a shear speed of 0,3063 mm/min. The tests were carried out on pure soil samples and soil-fiber mixtures in percentages of 0.25%, 0.75%, and 1.25% of the soil mass.

2.3 Mineralogical characterization

X-ray diffraction and scanning electron microscopy (SEM) tests were carried out to obtain data on the mineralogy and structure of the soil studied. X-ray diffractometry is one of the fundamental techniques for the microstructural characterization of crystalline materials. The sample submitted for analysis was previously sieved through a 2.0 mm sieve and placed in an oven at 105°C for drying. 20 g of the powdered material was used. The equipment used for the analysis was a diffractometer for polycrystalline samples model X'Pert Pro - Panalytical. Scanning electron microscopy made it possible to observe the structure of the soil and see the distribution and adhesion of the fibers to the soil and the arrangement of the voids inside the test sample. Analyses were carried out on samples with contents ranging from 0 to 1.25%. The equipment used was a Hitachi Scanning Electron Microscope with EDS detector model TM3000. The test was carried out on samples measuring 5 x 5 mm, using pure soil and soil+fiber mixtures with contents of 0.50%, 0.75%, and 1.25%.

3. Results and discussion

3.1 Soil characterization

The results of the soil characterization tests are listed in Table 2.

Table 2 – Physical properties of the soil.

Properties	Values
Specific gravity, Gs	2,68
Boulder (Diameter > 4.2 mm)	8.10 %
Coarse sand (0.6 < Diameter < 2 mm)	13.30 %
Medium sand (0.2 < Diameter < 0.6 mm)	8.44 %
Fine sand (0.06 < Diameter < 0.2)	24.33 %
Silt (0.002 < Diameter < 0.06 mm)	13.37 %
Clay (Diameter < 0.002 mm)	16.73 %
Liquid Limit	37 %
Plasticity Limit	18 %

Plastic Index	19 %
Dry unit Weight	1.892 g/cm³
Optimum water content	11.83%
Activity Index	1.13
AASHTO classification	Clay soil (A-6)
SUCS classification	Sandy Clay (SC)

Source: Authors (2024).

The actual density value defines the soil as silty sand. Using the particle size curve, it was possible to classify the soil using the Unified Soil Classification System (USCS) and the Highway Classification System, also known as the Highway Research Board (HRB). Using the USCS, the soil was classified as clayey sand (SC) while using the AASHTO, it was classified as clayey soil (A-6). Based on the results of Atterberg limit tests and consulting the plasticity chart proposed by Atterberg, the soil can be classified as highly plastic, as it has an IP >15%.

3.2 Compaction

The compaction curves obtained for the natural soil and the soil-fiber mixtures are shown in Figures 2 and 3 for different fiber contents and lengths. It can be seen that the compaction curves for soil mixtures with 6 mm fiber follow the behavior described by some authors, in which the addition of fibers leads to an increase in optimum water content and a decrease in dry unit weight, and this effect occurs progressively with increasing fiber content (CASTRO, 2020; TRINDADE et al., 2004). For soil mixtures with 12 mm fiber, a decrease in dry unit weight was observed with increasing fiber content, similar to that found for 6 mm fiber. However, there was a decrease in the optimum water content compared to the pure soil with the composite containing 0.25% fibers. Subsequently, an increase in optimum water content was observed as the fiber content increased.

In addition, it was observed that the soil mixture with 6 mm fibers for all fiber contents resulted in higher dry unit weight values than the soil mixture with 12 mm fibers for the same fiber contents, with up to a 1.7% increase. The same effect was observed with the optimum water content, except for the 1.25% fiber content. As a hypothesis, larger voids may have formed because the 12 mm fibers are twice as long as the 6 mm fibers. During the tests, it was observed that the homogenization of the soil with fibers was more difficult for the 12 mm fiber due to the formation of agglomerates.

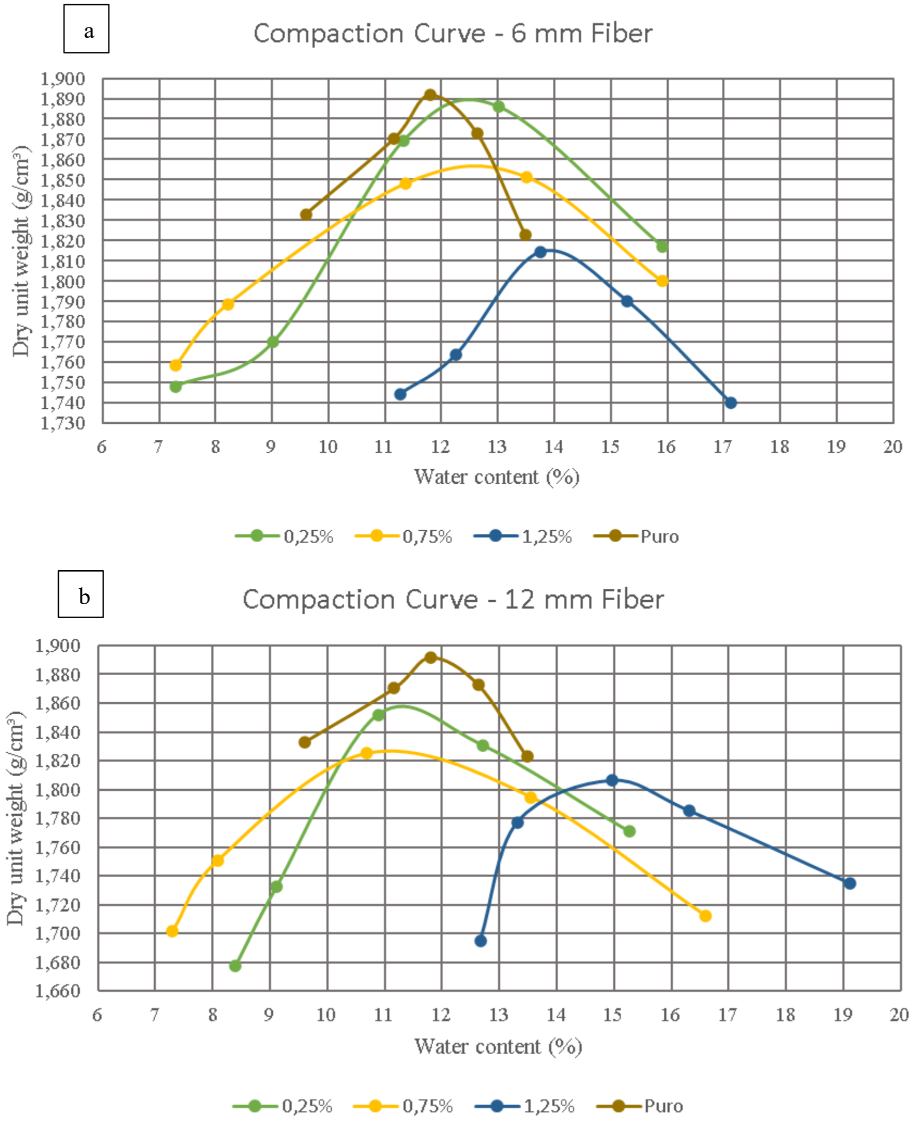


Figure 2 – Compaction curve; (a) Soils with added 6 mm fibers; (b) Soils with added 12 mm fibers.
Source: Authors (2024).

3.3 Permeability

The permeability coefficients obtained for the soil+fiber mixtures behaved similarly to those observed in the literature (BUENO et al., 1996; ISAIAS, 2022; MAHER; HO, 1994), which showed an increase in the permeability coefficient of the composite as the fiber content increased. The natural soil presented a permeability coefficient of 9.8 10^{-10} m/s, and the inclusion of fibers in the soil, for a fiber content of 1.25%, increased the permeability to 8.2. 10^{-8} m/s, for the 12 mm fiber.

Table 3 shows the results obtained from the permeability tests, considering pure soil and mixtures with different fiber contents and lengths. According to Figure 4, the results indicate that the soil mixture with 6 mm fiber resulted in higher permeability coefficients than those obtained by the soil mixture with 12 mm fiber, with the same fiber content. As a hypothesis, it can be assumed that fibers are not an impermeable material, which indicates that water can percolate through them. The 6 mm fiber constitutes a more homogeneous composite for the soil due to its ease of handling; in other words, there will be better-distributed fibers throughout the soil, creating preferential paths for the percolation of water, leading to its greater permeability of the composite. The maximum increase in soil permeability due to including fibers was almost two orders of magnitude. This may have occurred due to the formation of preferential flow paths created by the fiber that facilitate the passage of fluids. However, it is essential to note that the material can still be used in cover layers even with the increased permeability coefficient. During the tests, it was observed that homogenization of the soil was more difficult for the longest fiber (12 mm) due to the formation of fiber agglomerates (as the percentage of fibers increased, the effect became even more evident). As a hypothesis, the 6 mm fibers may have created preferential paths due to their more homogeneous shape in the composite, unlike the 12 mm fibers, in which regions of the composite showed more significant fiber agglomeration. This may have led to the higher permeability of the composite with 6 mm fibers.

No Brazilian standards define the permeability coefficient of the low-conductivity layer cover of the landfill. However, Albright, Benson, and Waugh (2010) report that the final low-conductivity layer cover should have a permeability of less than $1.\,10^{-7}$ m/s. Considering that the test values are within the requirements for soils in general, we can assume that the composite material could be used for this purpose. The permeability coefficients (k) found through the test are shown in Table 3 and Figure 3.

Table 3 – Permeability coefficients in m/s.

Percentage of fiber (%)	**Length**	
	6 mm	**12 mm**
0	9.80E-10	9.80E-10
0.25	2.00E-08	1.50E-08
0.5	2.50E-08	1.00E-08
0.75	4.70E-08	1.60E-08
1	5.70E-08	4.10E-08
1.25	8.20E-08	4.20E-08

Source: Authors (2024).

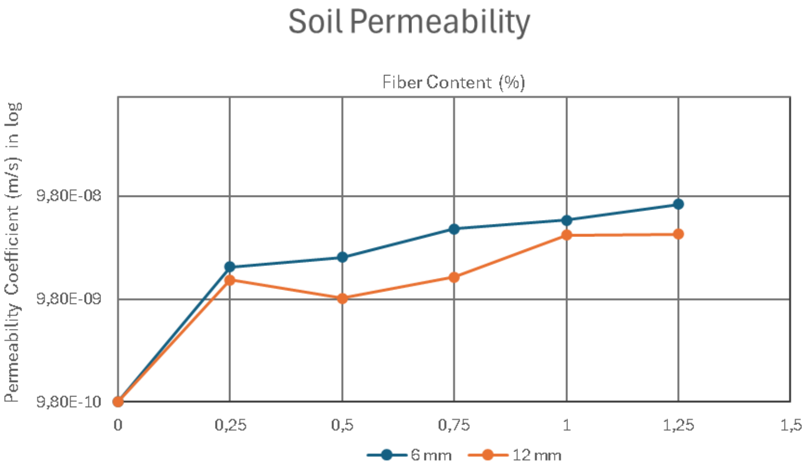


Figure 3 – Permeability of soil with added fibers.
Source: Authors (2024).

3.4 Shear strength

Figure 4 shows the strength envelopes of the reinforced soil with fibers of different lengths. For the soil mixed with 6 mm and 12 mm fibers, the shear strength was higher for the 1.25% fiber content, which can be considered the ideal content for improving soil strength for both lengths. Taleb and Unsever (2022) obtained a similar result for clay soil with 12 mm polypropylene fibers at gravimetric contents of 0%, 0.5%, 1%, and 1.5%.

Several authors report the existence of an optimum fiber content to be added to the soil, varying according to the characteristics of the soil, type of fiber, content, length, and how homogenization was carried out. Studies made by Silveira

(2018), Leocádio (2005), Trindade (2004), Rocha (2020), and Yazici and Keskin (2024) indicated that the gain in strength is not necessarily proportional to the increase in the number of fibers at a certain point the maximum strength is reached. The increase in fibers causes a reduction in strength. However, this increase or decrease in strength depends on the distribution of fibers on the rupture surface of the test.

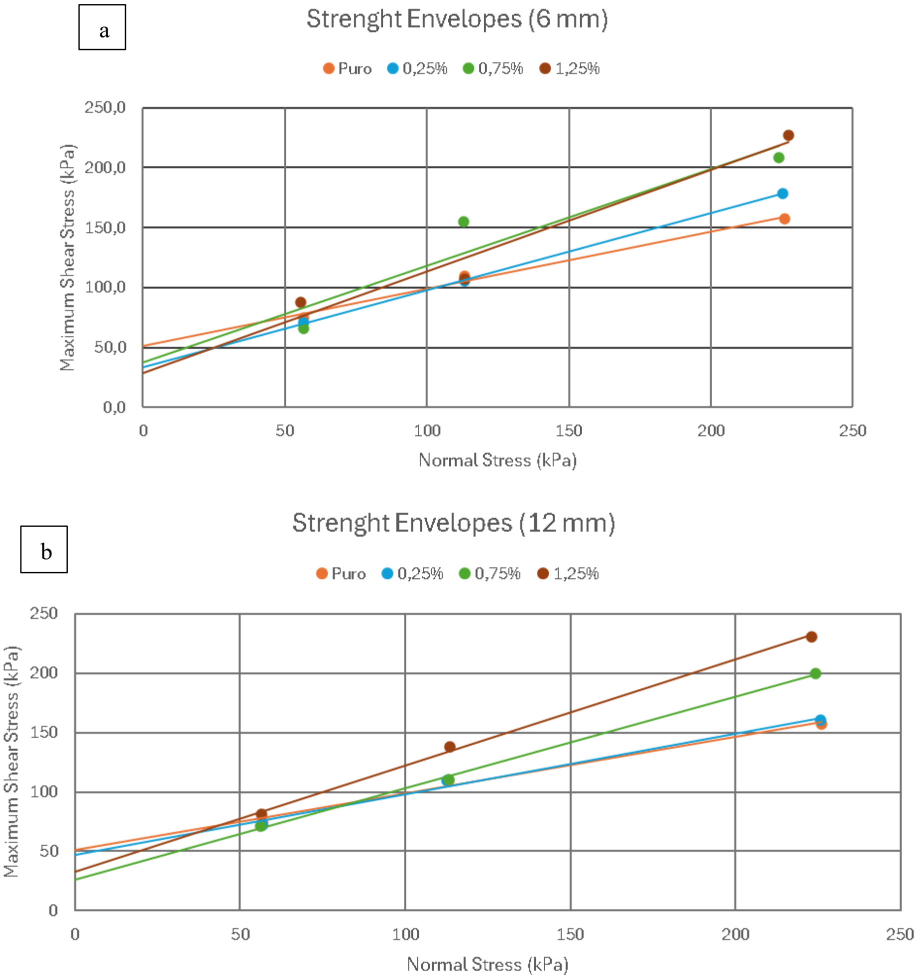


Figure 4 – Strenght envelope of pure soil and soil with fiber additions; a) 6 mm fibers; b) 12 mm fibers. Source: Authors (2024).

Figure 5 (a, b, and c) shows the shear stress variation by shear displacement for soil samples with 12 mm fibers in percentages of 0, 0.25, 0.75, and 1.25%, subjected to normal stresses of 50, 100, and 200 kPa. It is possible to observe a tendency of increasing maximum shear stress with increasing fiber content. It can be seen that the addition of fiber content leads to strain hardening, with shear stresses increasing with shear displacement. In this case, the rupture criterion adopted a limit displacement to allow comparisons of 6mm.

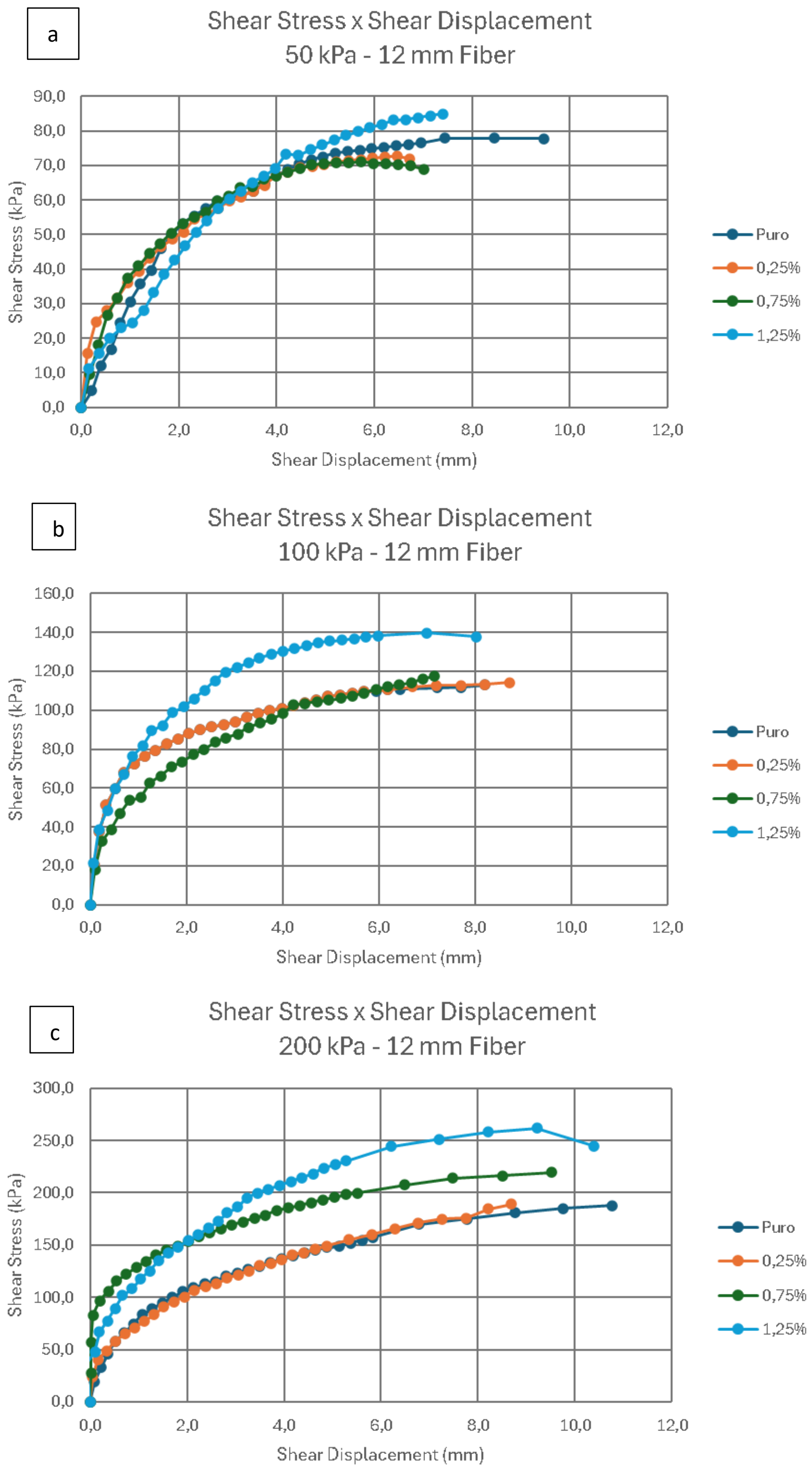


Figure 5 – Comparison between the shear stress x shear displacement curves of pure soil and soil with 12 mm fiber additions, subjected to the normal stress of a) 50 kPa; b) 100 kPa; c) 200 kPa.
Source: Authors (2024).

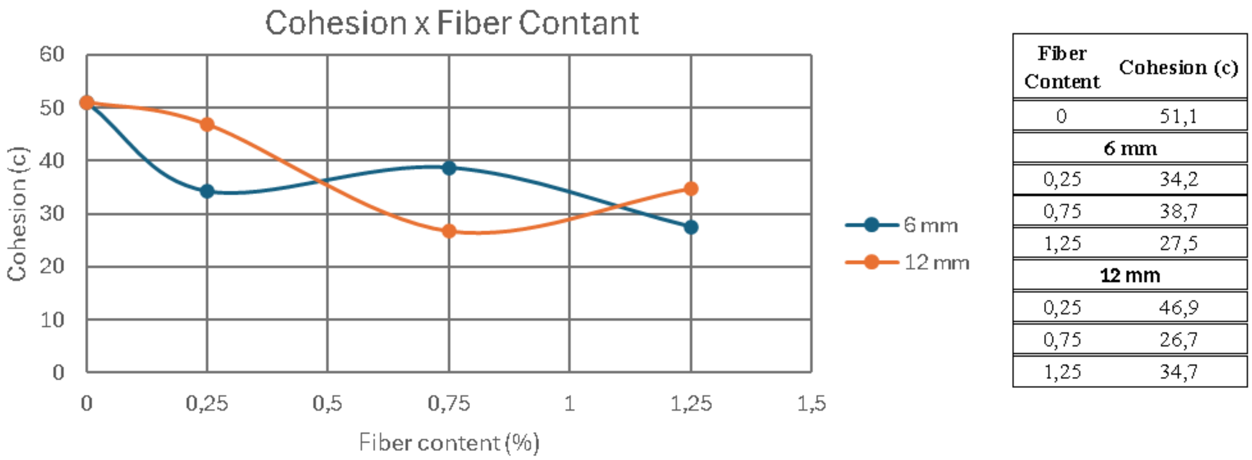
Table 4 shows the shear strengths for the rupture criterion adopted in the direct shear test. For the soil mixture with 6 mm fiber, there was an increase in the maximum shear stress as the fiber content increased, reaching a maximum value for the 1.25% fiber content. Concerning the behavior of the soil mixture with the 12 mm fiber, there was an increase in the maximum shear stress with increasing fiber content, reaching a maximum fiber content of 1.25%. These results reflect an increase in soil strength by including polypropylene fibers.

Table 4 – Strengths achieved for horizontal deformation of 6 mm.

		6 mm			**12 mm**		
	Pure	**0.25%**	**0.75%**	**1.25%**	**0.25%**	**0.75%**	**1.25%**
Normal stress (kPa)	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**	**Maximum shear stress (kPa)**
50	74.8	70.7	65.6	87.5	72.1	71.1	80.9
100	109.9	105.5	155.2	107.4	109.6	110.7	138.2
200	157.3	178.5	208.8	227.1	160.1	199.5	230.6

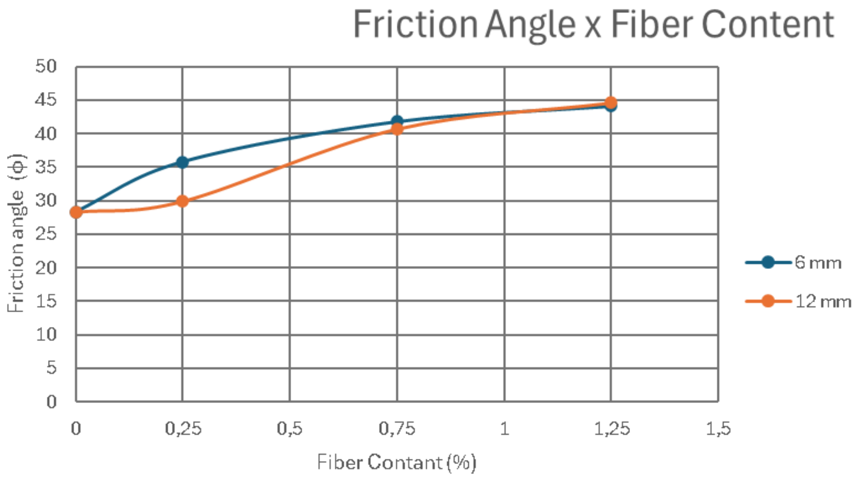
Source: Authors (2024).

Figure 6 shows that for both fiber lengths, there was a tendency for cohesion to decrease, followed by a slight increase. However, the increase was not significant enough to exceed the cohesion value of the pure soil. Figure 7 shows a tendency for the friction angle to increase with the inclusion of fibers. The increase in friction angle and decrease in cohesive intercept were also reported by Marçal (2019). In his work, Heineck (2002) showed that adding fibers only increased the friction angle.



Fiber Content	Cohesion (c)
0	51,1
6 mm	
0,25	34,2
0,75	38,7
1,25	27,5
12 mm	
0,25	46,9
0,75	26,7
1,25	34,7

Figure 6 – Cohesion x fiber content.
Source: Authors (2024).



Fiber Content	Friction Angle (ϕ)
0	28,3
6 mm	
0,25	35,8
0,75	41,8
1,25	44,1
12 mm	
0,25	29,9
0,75	40,7
1,25	44,6

Figure 7 – Friction angle x fiber content.
Source: Authors (2024).

Analyzing the influence of fiber length on strength, for fiber contents of 0.25 and 0.75% (Figure 8- a and Figure 8- b), there was a tendency for the mixture with the 6mm fiber to have a higher strength than the mixture with the 12mm fiber. For a fiber content of 1.25% (Figure 8-c), the soil mixture with 12 mm fibers generally had a higher maximum shear stress, except for the stress of 50 kPa, which was similar to the soil mixture with 6 mm fibers. Therefore, the mixtures with the most significant strength gains were those with 1.25% fibers added for both lengths.

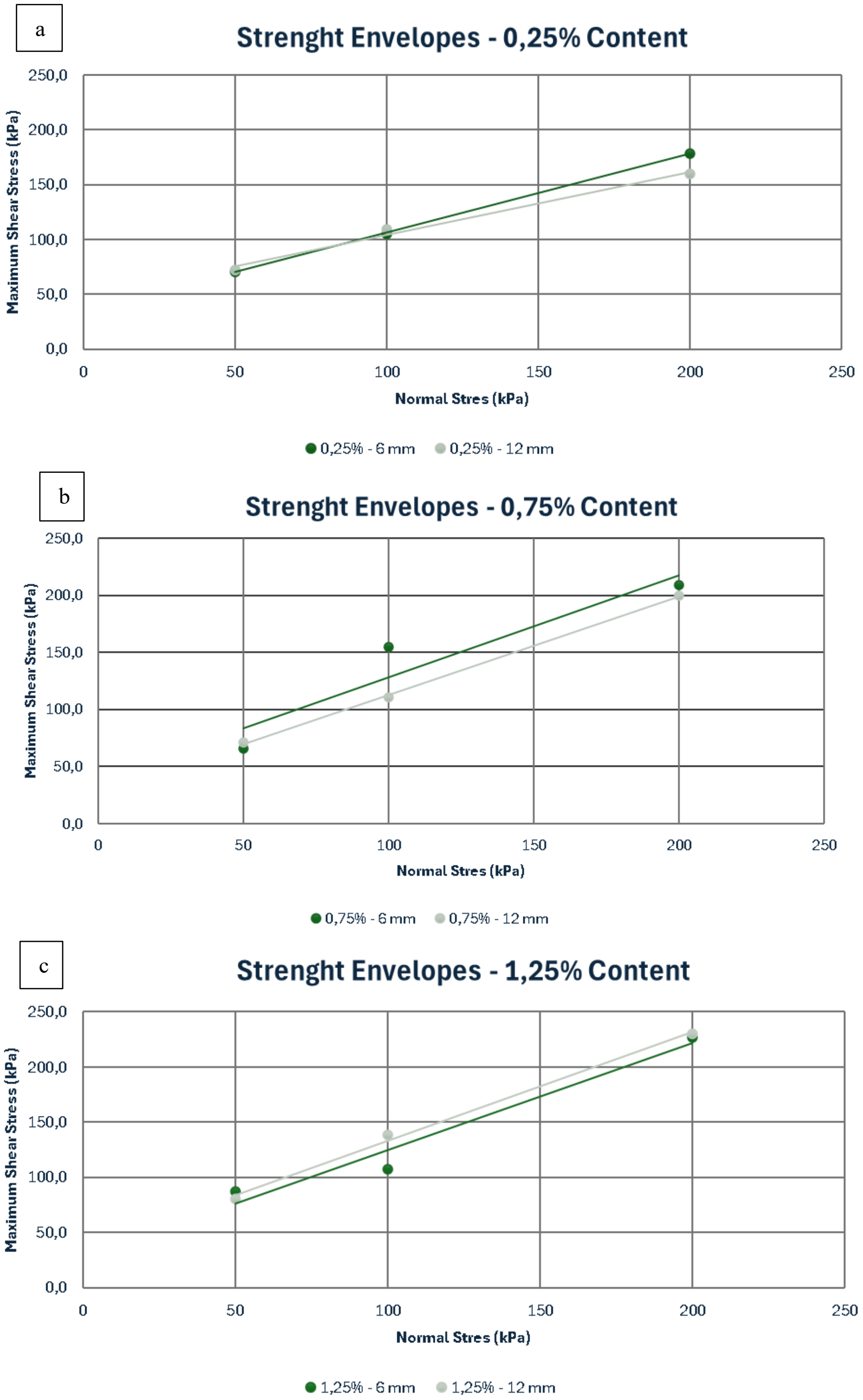


Figure 8 – Strength envelopes: a) content of 0.25%; b) content of 0.75%; c) content of 1.25%.
Source: Authors (2024).

3.5 X-ray diffraction and scanning electron microscopy

The results of the X-ray diffraction test made it possible to identify that the soil has a predominantly kaolinitic clay mineral fraction, with a percentage of sand and silt, with the possible presence of quartz and feldspar.

Using scanning electron microscopy, the morphological characteristics of the soil and the soil-fiber mixtures were observed to understand the structure, texture, and adhesion between the materials. Figure 9 shows the microscopy of the pure compacted soil at 200x magnification, on which we can see the agglomerations of particles and spherical particles.

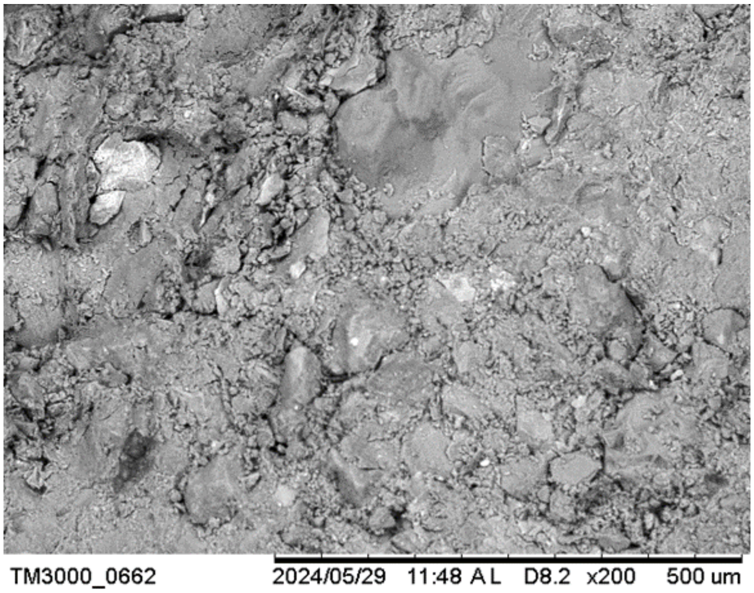


Figure 9 – Electron microscopy of pure soil.
Source: Authors (2024).

The results of the tests indicated that the interaction between the fibers and the soil does not occur appropriately for levels lower than the ideal (1.25% for the 6 mm fiber and 1.25% for the 12 mm fiber) in terms of increased strength. As can be seen in Figure 9, at 100x magnification, the presence of voids for both soil mixtures with 6 mm and 12 mm fibers can be observed.

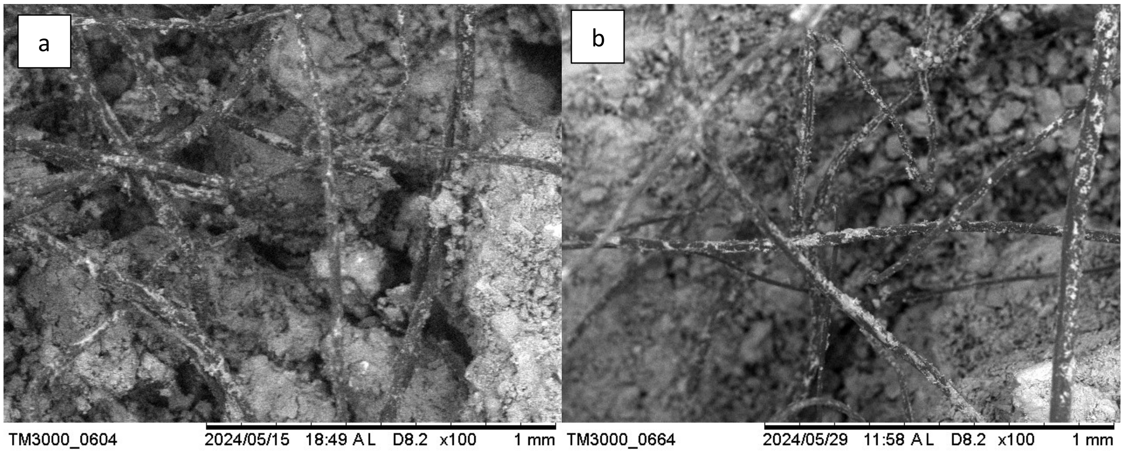


Figura 10 – Microscopia eletrônica de amostras de solo+fibra no teor de 0,50%; a) 6 mm; b) 12 mm.
Fonte: Authors (2024).

For both fiber lengths (6 and 12 mm), the optimum fiber content, where the highest strengths were observed, was 1.25%. Excellent soil-fiber adhesion was more evident at this level, as seen in the figures below.

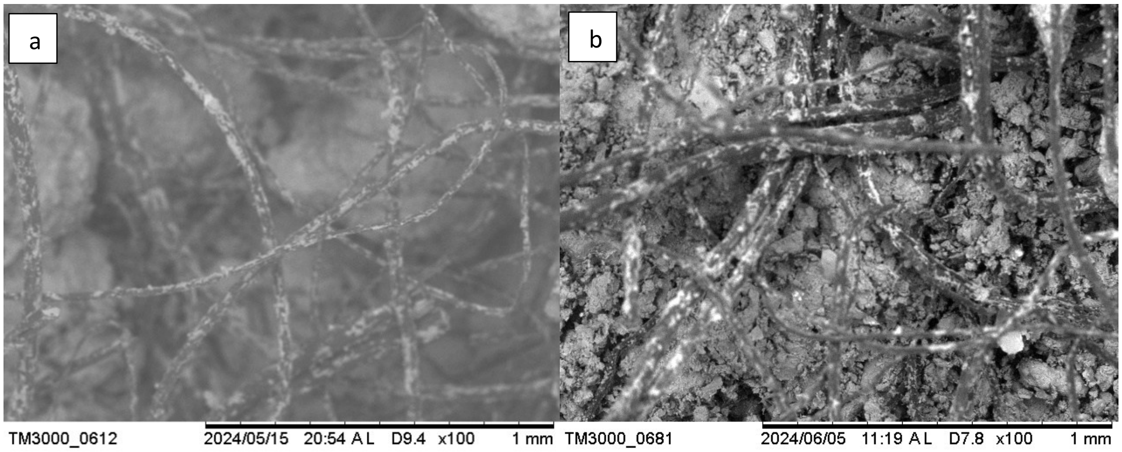


Figure 11 – Scanning electron microscopy: a) sample with 1.25% content and 6 mm length; b) sample with 1.25% content and 12 mm length.
Source: Authors (2024).

Regarding fiber content, it is impossible to be conclusive about the changes in structure with increasing fiber content because, due to the heterogeneity of the mixture, there may be sections with a higher concentration of fibers than others, even for higher fiber content.

4. Conclusions

This paper presented results on the hydromechanical properties of sandy-clay soil used as a landfill cover layer mixed with polypropylene fibers. Including fibers increased the strength of the soil compared to natural soil, which increased with increasing fiber content. Concerning permeability, the inclusion of fibers led to an increase in the permeability of the soil, which may be related to the decrease in the dry unit weight of the mixture observed in the compaction tests and to the appearance of preferential flow paths due to the insertion of fibers, that facilitate the passage of fluids. It was observed that the increase in permeability for the same fiber content was more significant with the 6 mm fiber. When working with the 12 mm fibers, greater difficulty in homogenization was observed when compared to the 6 mm fibers. This behavior was observed mainly for higher fiber contents due to the formation of fiber agglomerates. As a result, mixtures with 6 mm fibers had a higher permeability than the 12 mm fibers, possibly due to the difficulty in forming flow paths along the ground by the fiber agglomerates. This increase in permeability observed in the composites does not make it unfeasible to use the material as a low-permeability layer cover for waste landfills, as it reaches values suitable for using the layer for this purpose, in addition to obtaining a composite with greater strength to withstand the stresses in the field. The shear strength test indicated that the optimum fiber content existed and that the composite showed the most significant increase in strength for both lengths. For both fiber lengths, the optimum content was 1.25%. In addition, including fibers generated a tendency towards an initial reduction in the cohesive intercept regarding the natural soil, followed by a slight increase for both lengths. The friction angle showed a tendency to elevate as the fiber content increased. For both lengths, the friction angle was higher than that of the pure soil, and the strength parameter was responsible for the increase in the composite's strength compared to the natural soil.

When analyzing scanning electron microscopy, it was possible to identify differences in soil-fiber adhesion with different fiber contents. At 1.25% for both lengths, the adhesion between the soil and the fiber is adequate, suggesting that the interaction increases the composite's strength when subjected to loads.

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References

ALBRIGHT, W. H.; BENSON, C. H.; WAUGH, W. J. (2010) Water *Balance Covers for Waste Containment: principles and practice.* Reston, Virginia: Asce Press.

AMERICAN SOCIETY FOR TESTING MATERIALS. *ASTM D3080-04 (*2012): Standard Test Method for Direct Shear Test of Soils Under Consolidated Drained Conditions. West Conshohocken, Pa, Usa,.

BARBOZA, D. U., PELIZZOLI, L. N. FRAGOMENI, L. K., PACHECO, L. M., FLORIANO, C. F.(2022) Evaluation of the Shear Strength of a Lamite Residual Soil with the Addition of Polypropylene Fibers. [paper publication] Brazilian Congress of Soil Mechanics and Geotechnical Engineering, Campinas.

BIANCHINI, M. K. (2013). Study of the shear strength of sandy-clay soil with the inclusion of polypropylene fibers. Master thesis, Pampa Federal University].

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. (2024) NBR 6457: Soils — Preparation of samples for compaction tests, characterization and determination of moisture content. 3rd ed. Rio de Janeiro, 11 p.

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS.(2016) NBR 7180: Soil - Determination of the plasticity limit. Rio de Janeiro, 2016c. 7 p.

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. (2016) NBR 6459: Soil - Determination of liquidity limit. 2 ed. Rio de Janeiro, 9 p.

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. (2021) NBR 14545: Soil - Determination of the permeability coefficient of clayey soils to variable load. 2 ed. Rio de Janeiro

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. (2022) NBR 6502: Soils and Rocks - Terminology. 2 ed. Rio de Janeiro, 40 p.

BRAZILIAN ASSOCIATION OF TECHNICAL STANDARDS. (2016) NBR 7182: Soil - Compaction test. 2 ed. Rio de Janeiro, 13 p.

BUENO, B. S. ; LIMA, D. C. ; TEIXEIRA, S. H. C. ; RIBEIRO, N. J. . *Fiber Soil Reinforcement: Basic Understanding.* Third International Symposium on Environmental Geotechnology, 1996, San Diego-USA.

CASAGRANDE, M. D. T. (2001) Study of the behavior of soil reinforced with polypropylene fibers for use as a base for shallow foundations [Master thesis, Rio Grande do Sul University]. http://hdl.handle.net/10183/3349

CASAGRANDE, M. D. T. (2005) Behavior of fiber-reinforced soils subjected to large deformations.[Doctoral dissertation, Rio Grande do Sul Federal University]. http://hdl.handle.net/10183/3349.

CASTRO, C. L. (2020) Hydromechanical behavior of fiber-reinforced soils considering the unsaturated condition. [Master thesis, Ceará Federal University]. https://repositorio.ufc.br/handle/riufc/51882.

DEPARTAMENTO NACIONAL DE ESTRADAS DE RODAGEM. *ME 093:* Solos - Determinação da densidade real. Brasília, 1994. 4 p.

FESTUGATO, L.(2008) *Analysis of the mechanical behavior of a micro-reinforced soil with fibers of different aspect ratios.*[Master thesis, Rio Grande do Sul Federal University].

GRAY, D. H.; OHASHI, H. (1983) *Mechanics of Fiber Reinforcement in Sand.* Journal Of Geotechnical Engineering, v. 109, n. 3, p. 335-353.

HEINECK, K. S. (2002) Study of the hydraulic and mechanical behavior of geotechnical materials for horizontal waterproof barriers. [Doctoral dissertation, Rio Grande do Sul Federal University]

HEINECK, K., CONSOLI, N., BICA, A., CASAGRANDE, M. (2003). *Behavior of micro-reinforced soils at very small and large shear deformations.* Solos e Rochas. ABMS/ABGE, *26*(1), 3-17.

ISAIAS, A. F. (2022) Permeability of mixtures of clay soil and polypropylene fibers.[Bachelor thesis, Ceará Federal University]. http://www.repositorio.ufc.br/handle/riufc/71820.

Jaramillo, N.A.D., dos Santos Ferreira, J.W., Malko, J.A.C. *et al.* (2022) Mechanical Behavior of Clayey Soil Reinforced with Recycled Tire Rubber Using Chips and Fibers. Geotech Geol Eng 40, 3365–3378 https://doi.org/10.1007/s10706-022-02101-0

LEOCÁDIO, G. A. S. (2005) *Reinforcement of lateritic soil with randomly distributed sisal fibers, surface treated with recycled EPS.* [Doctoral dissertation, Ouro Preto Federal University]. http://www.repositorio.ufop.br/handle/123456789/2550.

LOPES, M. M. (2019) Study of the physical-mechanical behavior of soils reinforced with açaí (Euterpe oleracea) fibers. [Bachelor thesis, Brasília University].

MAHER, M. H.; HO, Y. C. (1994) *Mechanical Properties of Kaolinite/Fiber Soil Composite.* Journal Of Geotechnical Engineering, v. 120, n. 8, p. 1381-1393, http://dx.doi.org/10.1061/(ASCE)0733-9410(1994)120:8(1381).

MARÇAL, R. (2019) Evaluation of soil strength parameters with recycled polypropylene fibers. [Doctoral dissertation, Paulista State University].

MEDDAH, A., MERZOUG, K. (2017) Feasibility of using rubber waste fibers as reinforcements for sandy soils. *Soil-Structure Interaction*, Egito, v. 2, n. 1, p. 1-12.

NOURI, H. H. H., SHAHROUZI, M.(2021) Experimental evaluation of compressive strength of steel fiber reinforced soil. *Journal Of Engineering Sciences And Innovation,* v. 6, n. 2, p. 121-136.

PINTO, C. M. T., MACHADO, S. L.(2022) Mechanical Behavior of an Alluvial Sand Reinforced with Polymeric Fibers.[paper presentation] Brazilian Congress of Soil Mechanics and Geotechnical Engineering. Campinas.

RABAB'AH, S., AL HATTAMLEH, O., ALDEEKY, H., & ALFOUL, B. A. (2021). Effect of glass fiber on the properties of expansive soil and its utilization as subgrade reinforcement in pavement applications. Case Studies in Construction Materials, 14, e00485. https://doi-org.ez11.periodicos.capes.gov.br/10.1016/j.cscm.2020.e00485.

ROCHA, S. A. (2019) Evaluation of the influence of polypropylene fibers on the effective strength of clay soil. [Master thesis, São Carlos Federal University]

ROCHA, L., OLIVEIRA DOS ANJOS, R., & DA CONCEIÇÃO SANTOS SOBRAL, A. (2021). Analysis of rubber waste as soil reinforcement. *Caderno De Graduação - Ciências Exatas E Tecnológicas* *7*(1), 11–30. https://periodicos.set.edu.br/cadernoexatas/article/view/10327

ROCHA, Eduardo Vieira de Goes. *Solo siltoso da formação Guabirotuba reforçado com fibras de polipropileno. 2020*. 70 f. TCC (Graduação) - Curso de Engenharia Civil, Universidade Tecnológica Federal do Paraná, Curitiba, 2020.

ROQUE, P. F. B.(2017) Use of alternative materials for soil improvement in paving [Doctoral dissertation, Brasília University].

SANTOS, G. P. V., DEMETRIO, L., FRANÇA, M. J. I. L., LAVOIE, F. L., & SCHEFFER, D. K. (2016). Evaluation of Tensile Test Results of Fiberglass and Steel Rebar for Use in Stapling the Excavation Front of Tunnels in Earth Massifs.[paper presentation] Brazilian Symposium of Rock Mechanics, Belo Horizonte.

SENEZ, P. C. (2016) Behavior of a sand reinforced with polyethylene terephthalate fibers *(PET).* [Master Thesis, Rio de Janeiro Catholic University].

SILVEIRA, M. V. (2018) *Analysis of the mechanical behavior and durability of sand composites reinforced with natural curauá and sisal fibers.* [Doctoral dissertation, Rio de Janeiro Catholic University].

SOUSA, W. D. S. V., SANTOS, A. P. F., & SOUSA, S. F. L. Use of Polypropylene Fibers for Soil Reinforcement. (2019) [paper presentation] Brazilian Congress of Environmental Geotechnics. São Carlos

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https://www.researchgate.net/publication/341734901_USO_DE_FIBRAS_DE_POLIPROPILENO_PARA_REFORCO_DE_SOLO.

SUJATHA, E. R.; ATCHAYA, P.; DARSHAN, S.; SUBHASHINI, S. (2020) Mechanical properties of glass fiber reinforced soil and its application as subgrade reinforcement**.** *Road Materials And Pavement Design,* v. 22, n. 10, p. 2384-2395. http://dx.doi.org/10.1080/14680629.2020.1746387.

TALEB, Talal; UNSEVER, Yesim S.(2022) Study on Strength and Swell Behavioral Change and Properties of the Clay–Fiber Mixtures. *Sustainability*, v. 14, n. 11, p. 6767, 1. MDPI AG. http://dx.doi.org/10.3390/su14116767.

TEODORO, J. M. (1999) Shear strength of soils reinforced with plastic fibers [Master Thesis, São Paulo University]

TRINDADE, T. P. D., IASBIK, I., LIMA, D. C. D., SILVA, C. H. C., & BARBOSA, P. S. D. A. (2004). *Red-yellow latosol reinforced with randomly distributed polypropylene fibers: a laboratory study*. Rem: Journal Escola de Minas, *57*, 53-58.

TRINDADE, T. P. D., Iasbik, I., Lima, D. C. D., MINETTE, E., SILVA, C. H. D. C., CARVALHO, C. A. B. D., ... & MACHADO, C. C. (2006). Laboratory studies of the behavior of a sandy residual soil reinforced with polypropylene fibers, with a view to application in forest roads. Journal Árvore, *30*, 215-222.

VENDRUSCOLO, M. A. (2003) *Study of the behavior of fibrous composite materials for application as base reinforcement in shallow foundations.* [Doctoral dissertation, Rio Grande do Sul Federal University].

YAZICI, M. F., & KESKIN, S. N. (2024). Experimental Investigation of the Mechanical Properties of Polypropylene Fiber-Reinforced Clay Soil and Development of Predictive Models: Effects of Fiber Length and Fiber Content. *Arabian Journal for Science and Engineering*, 1-19.