

Laboratory tests for evaluation of shear strength and tensile effect generated by fibers present in Muribeca's landfills of municipal solid waste

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Article

Keywords

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Abstract

Understanding the geotechnical behavior of a municipal solid waste landfill (MSW) requires the filtering of several studies. Regarding the mechanical behavior, there are several discussions about the conditions for the stability maintenance of these structures. This stability depends a priori on the resistance of the compacted material to remain itself stable in a way that it does not generate ruptures or slips. Of various materials compacted found in the MSW landfills, high percentages of fibers (such as plastic, fabric and wood) are verified, these materials have a great influence on the mechanical behavior of the structure. These fibers in turn produce in general an increase in the geotechnical parameters: cohesion (c), friction angle (ϕ) and tensile (ζ), which consequently increase the degree of stability of the landfill. In this context, the present work performed evaluations of the effect of fiber tensile and shear strength in samples of Muribeca's MSW landfills, the analyzes were performed by laboratory tests using a specimen of aged residues collected in the field, with a deposition age of 10 years. With the collected sample, direct shear tests were performed on 3 different sample proportions of fibers: 0%, 16.17% and 32.33%, in two conditions of test: flooded and non-flooded. From the results obtained in the tensile angles (ζ) in the condition of flooded of 10.2° and 5.0°, for the percentages of 16.17% and 32.33%, respectively.

1. Introduction

According to Fan et al. (2016), solid wastes from aged sanitary landfills generally exhibit higher shear resistance than waste from newly compacted landfills or those with a short deposition period. This behavior is related to the natural decomposition process of organic matter present in the landfill, which transforms it into an inert material with a mechanical behavior similar to a very heterogeneous granular soil with coarse granulometry. As a consequence, the volume of fibrous materials increases proportionally over time, resulting in an increase in shear strength of the waste mass through the tensile effect of these fibrous materials, promoting landfill stability over time.

Municipal solid wastes (MSW) have a very heterogeneous composition in size, weight, shape, type of their components, decomposition/age, normal stress, and moisture content (Babu et al., 2015). Therefore, to analyze their mechanical behavior, this composition is commonly divided into two

matrices: basic (such as non-fibrous components) and reinforcement (such as plastic, textiles, among others). While the former is predominantly responsible for compressive strength, the latter is mainly responsible for tensile strength (Jessberger et al., 1995).

Kölsch (1993, 1995, 1996) found differences between the properties of soils and residues, noting limitations in slope stability calculations for solid waste landfills based on conventional methods of Soil Mechanics for not incorporating the fiber tensile effect present in the waste mass. Kölsch (1993, 1995, 1996) indicated the need to consider that residues present a resistance behavior, for large deformations, similar to reinforced soils. That is, the resistance to total shear is composed of friction in the shear plane and tensile forces in the fibers. Thus, solid waste is considered a material consisting of two components: a basic matrix, comprised of fine to medium-grained particles, which exhibit frictional behavior, and a reinforcement matrix, which contains the fibrous components of solid waste, in agreement with Jessberger et al. (1995).

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Several authors, including Kölsch (1993, 1995, 1996), Lamare-Neto (2004), Fucale (2005), Martins (2006), Calle (2007), Borgatto (2010), Motta (2011), Corrêa (2013, 2020), Karimpour-Fard et al. (2014), Abreu (2015), Fucale et al. (2015), Keramati et al. (2016, 2019a, b), Araújo-Neto (2021), Gurjão (2021), and Huang et al. (2022), have performed studies regarding the influence of fibrous materials present in MSW on total shear-strength, which showed an increase in strength with the addition of these fibers.

Given this scenario, this research aims to evaluate the effect of fibers, for different levels, on shear strength considering the tensile strength of these fibers. For this purpose, samples of MSW were collected with an approximate age of 10 years of deposition to perform conventional direct shear tests in flooded and non-flooded conditions.

The technical literature generally recommends that direct shear tests for solid urban waste samples be carried out in large-scale equipment, given the variability of the material. In this work, analyses were carried out using small-scale tests with the objective of verifying whether this equipment can capture the behavior of the resistance of fibrous materials. This is an alternative for greater dissemination of resistance tests in samples of solid waste, considering that small-scale direct shear test equipment is more widespread in the technical environment.

The application of laboratory experimental studies with solid waste samples containing fibers can be technically justified to assess the shear strength and stability of landfills due to recent research findings. For instance, a study by Zhang et al. (2021) investigated the effect of fiber type and content on the shear strength of municipal solid waste (MSW) using direct shear tests. The results showed that the presence of fibers in the MSW samples improved the shear strength of the material. Another study by Zhou et al. (2020) focused on the effect of fiber addition on the shear behavior of MSW in a large-scale direct shear apparatus. The study found that fibers can significantly improve the shear resistance of MSW, and the effect is influenced by the type and content of fibers. These findings suggest that laboratory experimental studies with solid waste samples containing fibers can provide valuable insights into the shear strength and stability of landfills.

2. Materials and methods

2.1 Study area

An experimental landfill cell from Muribeca (8°9'50"S 34°59'00"W), located in the state of Pernambuco, Brazil, in the city of Jaboatão dos Guararapes, was used as the study area for the collection of samples (Figure 1).

2.2 Sample collection

The collection was performed in November 2018. The cell used was finished in 2008, estimating the age of the

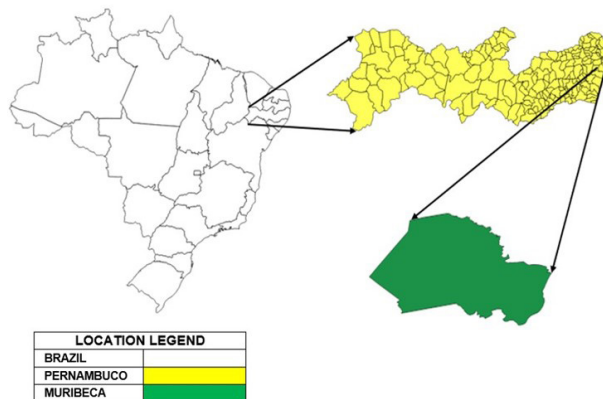


Figure 1. Location of the study area.

waste at 10 years. The residues collected for gravimetry and laboratory tests were removed from a layer approximately 2 meters deep in the experimental cell, the total height of this cell being 9 meters.

2.3 Gravimetry

Gravimetry of the collected residues was performed using the methodologies specified by Kaartinen et al. (2013) and Holanda et al. (2016), wherein the typology used has 10 subcategories: plastic, paper/cardboard, glass, metals, organic, wood/coconut, sanitary ware, textiles, fines and other waste.

2.4 Direct shear tests

2.4.1 Preparation of the MSW's sample

The sample used in the molding of the direct shear tests came from the collection of about one ton of material from the landfill cell. The collected material was divided in order to obtain a representative sample, after the division process the sample was selected for the tests. The collected sample was stored and packaged in order to maintain field conditions.

The preparation and separation of samples collected in the laboratory followed the methodology used in the literature and the Technical Recommendation of the German Geotechnical Society GDA – EMPFEHLUNGEN E 1-7 (DGG, 1997).

After selecting, it was necessary to cut the fibrous materials to adjust the dimension of the shear box, 101,6 x 101,6 x 45 mm. The length's adequacy of the fibers with the box was performed a procedure similar to that performed by Motta (2011) and Corrêa (2013). According to Corrêa (2013), this procedure was necessary so that the sample length was sufficient for the grained material to hold it with its weight, since plastic and other fibers are extremely bulky and have low densities compared to inert materials (basic matrix), making placement difficult in the box. At first, the ratio of

the fiber length to the box was 1/10, however, due to the difficulty of adjustment, a length of 5 cm and a width of 2 cm to the fibers, with a ratio of 1/2.

2.4.2 Specimen weight

According to Borgatto (2006) and Motta (2011) densities in the range of 11.00 kN/m³ are conventional for landfills of MSW with a high degree of decomposition, this being the value adopted in the research. With the specific weight and dimensions of the square section shear box, 101.6 mm and 45 mm of width, it was possible to calculate the weight of the specimen, 512.98 g.

To determine the weights of mixtures between grained material (Material which passed through sieve #10) and the fibers, for the three sample percentages studied, it was based on the gravimetric percentages obtained from the experimental cell of Muribeca. The percentages of fibers used in the direct shear tests were: 100% of the basic matrix, material which passed through sieve #10; 16.17% fibers + 83.83% of the basic matrix, material which passed through sieve #10 and 32.33% fibers + 67.67% of the basic matrix, material which passed through the sieve #10 (Table 1). The justification for using the three percentages was to assess the influence of the variation in the percentage of fibers on the shear strength behavior of the waste mass.

Performing laboratory experiments with different proportions of waste fiber samples is essential to understand the behavior of shear strength in waste materials containing fibers, because the addition of fibers in the waste materials can significantly alter their mechanical properties, particularly in terms of their shear strength. By conducting experiments with varying proportions of waste fibers, it is possible to investigate the effect of the fibers on the shear strength of the waste materials and determine the optimum proportion of fibers that can provide the best mechanical performance.

For example, a study by Wang et al. (2021) evaluated the shear strength of waste fiber-reinforced soil using triaxial compression tests. The results showed that the waste fiber content significantly affected the shear strength and deformation behavior of the waste materials. The authors found that the optimal fiber content for maximum shear strength was between 0.75% and 1.25%, indicating the importance of testing different proportions of fibers. Similarly, a study by León-Fuentes et al. (2020) investigated the effect

of different fiber contents on the shear strength of MSW using a direct shear test. The authors found that the shear strength increased with the addition of fibers and that the optimum fiber content was 2.5%.

Overall, conducting experiments with different proportions of waste fibers is crucial for understanding the behavior of waste materials containing fibers and determining the optimal fiber content for maximum shear strength.

2.4.3 Moisture test

While many researchers commonly utilize the optimal moisture value, in this particular case, field humidity was chosen to better emulate the conditions of the experimental cell, with a humidity level of 23%. It should be noted that this humidity level may vary seasonally, as it is influenced by external factors such as temperature and precipitation.

2.4.4 Molding of specimen

Molding was performed by layers, after mixing the fibers with the grained material, when necessary. Each layer inserted was manually compacted with the aid of a wooden block of dimensions compatible with the shear box. In the transition among compacted layers, a scarification process was performed, so that the layers would adhere better to one another and there would be no formation of preferential rupture surfaces. To standardize the tests, compaction was performed in six layers for all specimens. When there was the presence of fibers in the specimens, due to the difficulty of compacting the mixture due to the low density of the fibers, the aid of one-axis stress in the molding was necessary, so that all material was completely compacted into the box.

In Figure 2 are shown the three percentages used in the samples, before mixing and molding procedures. It is important to observe the volume of the fibrous material in relation to the grained material.

The sample preparation process for carrying out laboratory tests differs slightly from sample conditions in the field, this is due to the fact that the scale of the material tested in the laboratory is much smaller than the field scale. As the focus of this work was to understand the influence of fibrous materials on strength, samples of fibrous materials were adjusted so that the laboratory scale was similar to the field scale.

Table 1. Setting the percentages of molded samples for the direct shear test.

Sample	Material that passed through sieve #10		Fibers	
	Percentage (%)	Weight (g)	Percentage (%)	Weight (g)
1	100	512.98	0	0
2	83.83	430.05	16.17	82.93
3	67.67	347.12	32.33	165.86



Figure 2. Molding process for solid waste specimens: (a) 100% basic matrix; (b) 83.83% basic matrix + 16.17% fibers; and (c) 67.67% basic matrix + 32.33% fibers.

2.4.5 Control of final specimen density

The samples were compacted using a manual press for simple compression testing ASTM D 2166-06 (ASTM, 2010). As it was not possible to guarantee that at the end of each molding the samples had the same density value, the initial density of each specimen was calculated. The density of each calculated sample should be in a fixed range of variation from $11.00 \pm 0.50 \text{ kN/m}^3$.

2.4.6 Test types and characteristics

The tests were performed in a direct shear press produced by Ronald Top S/A, with a stress charging system by hanging weights. In the readings of vertical and horizontal displacements, extensometers with a sensitivity of 0.01 mm. The horizontal force was determined using a dynamometric ring with a capacity of 500 kgf. Tests were performed in flooded and non-flooded conditions for six normal stresses: 25, 50, 100, 150, 200 and 250 kPa, which were applied and maintained until the vertical displacements were stabilized. The shear of the specimens for each applied normal stress was performed with a constant velocity of 0.483 mm/min. Peak shear stress values or maximum values were adopted as the rupture criterion when the horizontal stress-displacement curve did not indicate well-defined peak values.

The criterion of normal stress levels for tests had as a criterion the state of maximum stress that the waste was subjected to in the solid waste landfill cell at Muribeca.

Seeing the high fiber content of some samples and the delay in stabilizing the specimens in vertical displacements, the same time of 45 minutes was adopted for all tests performed, to standardize the test. After this step, it performed the direct shear. The test was performed by controlled displacement, and the specimens were tested until a horizontal displacement of 18%, the maximum possible value for measuring the equipment.

Although flooded tests are not usual in solid waste samples with fibers, it was decided to carry out this research

to understand the effect of flooding on the geotechnical parameters of MSW samples with fibrous elements. A total of thirty-six direct shear tests were performed in flooded and natural conditions.

Performing direct shear tests under non-flooded and flooded conditions is crucial to understanding the shear strength behavior of waste materials containing fibers. This is because the presence of water in landfills or waste disposal sites can significantly affect the mechanical properties of the waste materials, particularly in terms of their shear strength.

For instance, a study by Liu et al. (2021) investigated the shear strength of MSW containing recycled fibers under both dry and saturated conditions using direct shear tests. The results showed that the shear strength of the waste materials increased under saturated conditions compared to dry conditions, indicating the importance of considering the effects of water on the shear strength of waste materials. Similarly, a study by León-Fuentes et al. (2020) investigated the effect of moisture content on the shear strength of MSW containing fibers using direct shear tests. The authors found that the shear strength of the waste materials decreased with increasing moisture content, highlighting the importance of testing the materials under both submerged and unsubmerged conditions.

Overall, performing direct shear tests under the non-flooded and flooded conditions is essential for understanding the shear strength behavior of waste materials containing fibers, particularly in landfill or waste disposal settings where the presence of water can significantly affect the mechanical properties of the waste materials.

3. Analysis and results

3.1 Gravimetric analysis

In Figure 3 the results of the gravimetric characterization of the experimental cell of the Landfill of Muribeca, Jaboatão dos Guararapes city, state of Pernambuco, Brazil.

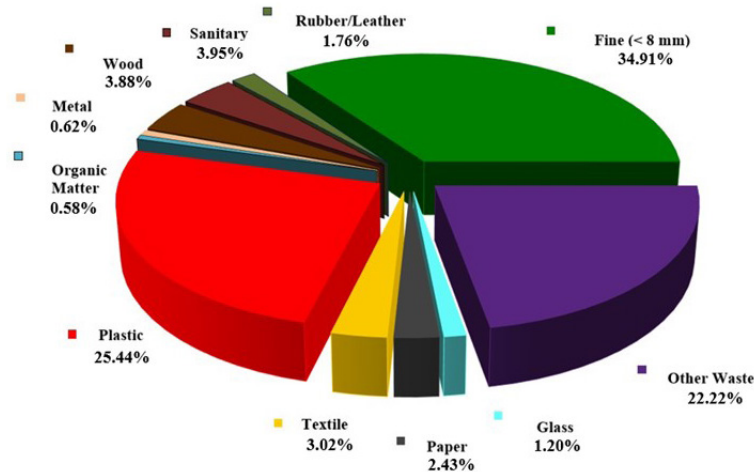


Figure 3. Gravimetric characterization of the sample of residues extracted from the Muribeca experimental cell.

It is observed that the gravimetric composition of the experimental cell is predominantly of thin material (material passing through sieve #10), with 34.91%, followed by plastic, 25.44%. Other fibers present in the composition of interest in this research, in addition to plastic, are wood/coconut and textiles which presented percentages of 3.88% and 3.02%, respectively.

The low content of organic matter in the solid waste mass, 0.58%, and the high content of fine material indicate that the landfill in the study is ending its biodegradation activity, being able to characterize the material as stabilized.

The high amount of fibers present in the waste mass, 32.34% (plastic, wood/coconut and textile) is of paramount importance for the study of the shear strength of MSW, as it is known that a portion of the shear strength is due to the tensile of the fibers, as described by Kölsch (1993, 1996) and proved by Lamare-Neto (2004), Fucale (2005), Motta (2011) and Abreu (2015).

3.2 Evaluation of shear-strength

3.2.1 Direct shear – non-flooded

Three direct shear tests were performed in the natural condition: basic matrix (BM), basic matrix + 16.17% fibers and basic matrix + 32.33% fibers. The shear strength curve by the peak deformation criterion of the tests is shown in Figure 4. Table 2 presents a summary of the results of the curve in Figure 4.

There is a parallel between the curve shown in Figure 4, indicating a low variation in the angle of friction obtained in the shear strength tests (Table 1). And for cohesion, it is noted that the highest value was presented for the sample with the percentage of 16.17% fibers, with the cohesion of 40.17 kPa, this indicates that the mobilization of shearing effort at the beginning of the horizontal displacement process of the three samples was greater for the percentage of 16.17% fibers.

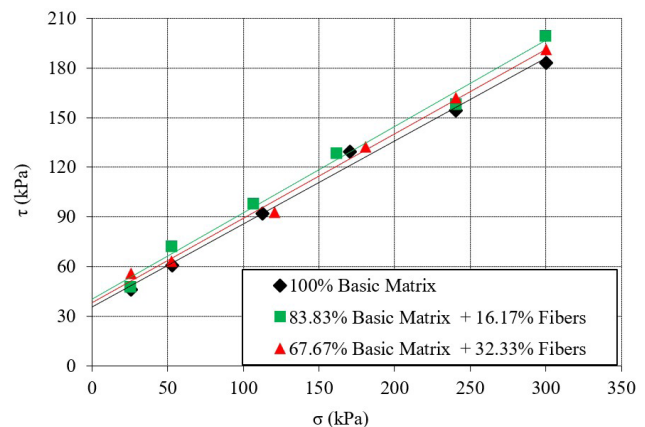


Figure 4. Shear strength curve by the criterion of peak displacement for the three samples tested - non-flooded test.

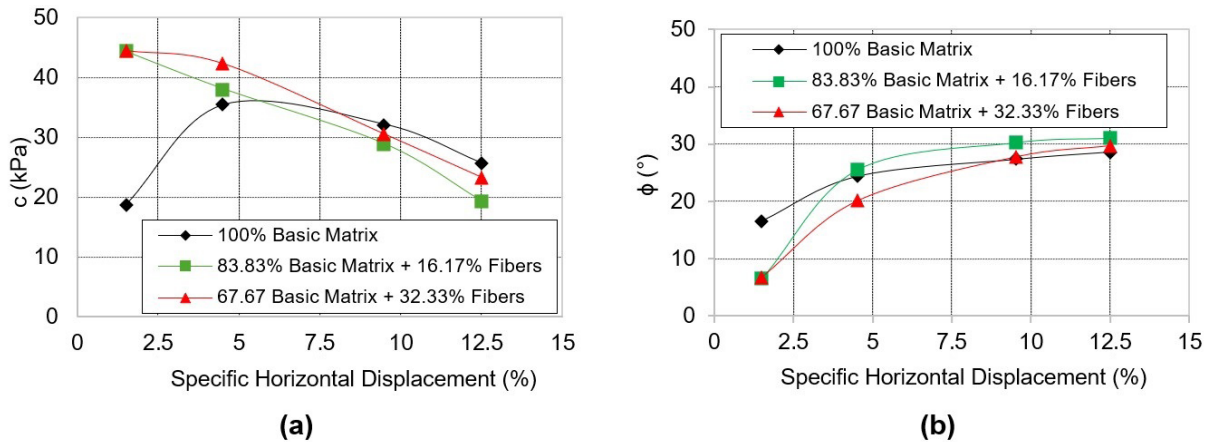
Besides the sample with 32.33% fibers having presented higher resistance parameters than those of the sample without fibers, it is noted that the same did not occur when compared with the sample with 16.17% fibers. This behavior can be explained by the high content of fibers, indicating that most of the fibrous elements have slid together during shear, instead of having been pulled to generate an increase in strength and its parameters.

Keramati et al. (2019a) comments that changing fiber orientation from horizontal to vertical leads to a decrease in mobilize cohesion and an increase in the angle of internal friction. As the mixture of fibers in the tests of this research was done at random, the result may indicate the possible predominance of the presence of vertical fibers in the executed samples.

Since the physical explanation and measurement of soil cohesion are challenging, especially in materials like MSW, the concept of cohesion for MSW may differ from that of soil. To understand the cohesion in MSW, some studies in the technical literature can be referred to. For example, a study by Lu et al. (2017) evaluated the shear

Table 2. Summary of the result of the shear strength curve of the three samples tested – non-flooded test.

Sample	R^2	c (kPa)	ϕ (°)
100% Basic Matrix	0.9938	35.39	26.60
83.83% Basic Matrix+ 16.17% Fibers	0.9910	40.17	27.59
67.67% Basic Matrix+ 32.33% Fibers	0.9946	37.99	27.05

**Figure 5.** Comparison of Variation in: (a) cohesion; and (b) friction angle throughout different levels of specific horizontal displacement of solid waste samples – non-flooded test.

strength of MSW using direct shear and triaxial tests. The results indicated that the shear strength of MSW is dominated by the frictional force between particles, while cohesion is relatively insignificant. Additionally, another study by Prakash et al. (2018) investigated the stability of MSW landfills using finite element models and found that cohesion has no significant influence on the landfill stability. These studies suggest that cohesion may not be a significant property for MSW compared to other geotechnical materials. Instead, the shear strength of MSW is predominantly governed by the frictional force between particles.

When comparing the results of the parameters obtained in this research with the range of values presented by Petrovic et al. (2016), which outlined the relationship between the degree of waste decomposition and a range of resistance parameters variation (ϕ and c), with Safety Factor (SF) confidence levels the stability of MSW landfill slopes. The values of the friction angles obtained in this work were in the waste classification range with medium decomposition (22° to 37°), the comparative with the cohesion, the values were outside the range of variation (5 to 31 kPa) presented by Petrovic et al. (2016).

Comparing the results of this research with the results of Karimpour-Fard et al. (2014), who carried out shear strength tests of solid waste with the presence of fibrous materials in the percentages of 0, 6% and 12%. The results of the friction angles of Karimpour-Fard et al. (2014) vary between 20° and 29°, while cohesion ranged from 12 to 21 kPa. It is possible to observe that the friction angles in this work and in the work by Karimpour-Fard et al. (2014) presented very close orders of magnitude, regarding

cohesion, the results of this research presented higher cohesion values. This high cohesion may be linked to the scale of the equipment, with Karimpour-Fard et al. (2014) using larger-scale equipment.

Then in Figure 5 is presented the comparison of the variation of resistance parameters (ϕ and c) on the three samples tested related to the specific horizontal displacement throughout the tests. It is important to stand out that four horizontal displacement levels have been standardized (1.5%; 4.5%; 7.5% and 12.5%). These levels were chosen because they were the ones that presented points in zones of variation in the shear stress versus horizontal displacement curves.

In the analysis of the variation of cohesion throughout the horizontal displacement of the three samples, a similar behavior was verified among the samples with 16.17% and 32.33% fibers. The cohesion for these samples was decreasing throughout the displacement, and both presented the maximum value in the displacement of 1.5%. The sample with 0% fibers, basic matrix, had different behavior, presenting a minimum value in the displacement 1.5%, and had its value of increasing cohesion until the displacement of 4.5%, after this displacement, cohesion declined to the other levels of horizontal displacement.

As for the friction angle behavior, for all samples it was similar, presenting minimum values in the horizontal displacement 1.5% and maximum values in the displacement of 12.5%. The sample with 16.17% presented the highest values, followed by the sample with 32.33% and 0% fibers. The stabilization of the friction angle occurs when the displacement reaches 7.5% for all the samples. In the

displacement of 4.5% it is possible to verify that the samples start to mobilize in relation to the friction angle.

When comparing the results of Kockel (1995) with this research it was possible to verify a similar behavior of the horizontal displacement curves in the results for the friction angle of the samples, but divergent in the comparison of the cohesion results. Kockel (1995) performed a resistance analysis of aged MSW with ages ranging from 9 months to 20 years. With a sample composed of a basic matrix with fine to medium grain (diameter < 120 mm) with a reinforcement matrix containing the fibrous components (diameter > 120 mm), which includes plastics, cloths and branches.

3.2.2 Direct shear – flooded

The results of the direct shear tests in the flooded condition for the three studied samples are presented in a similar way to that performed for the tests in the non-flooded condition. The Figure 6 and Table 3 present a comparison of the resistance curves and their geotechnical parameters corresponding to the tests in the flooded condition.

When comparing the results of the resistance curves, it was verified that the curves corresponding to the samples with 0% and 16.17% fibers are parallel to each other, while the sample curve with 32.33% shows different behavior from the others. As for the shear strength parameters, cohesion was higher for the percentage of fibers with higher fiber content (32.33%) with the value of 26.02 kPa, followed by the sample with 16.17% fibers with a cohesion of 20.17 kPa and for the last with 0% fibers, with the cohesion value of 9.52 kPa. For the friction angle, samples with 0% and 16.17% fibers had similar friction angles, with values in 32.05° and

32.03° respectively. The sample with 32.33% had a lower friction angle value of 29.10°.

Note that in the flooded test the cohesion increases with the addition of fibers in the samples. As for the friction angle, there was a reduction with increasing fiber content in the sample. The Figure 7 presents the comparison of the variation of the friction and cohesion angle throughout the variation of the horizontal displacement, for the three sample percentages, in the condition of flooding of the tests.

In Figure 7a, cohesion variation throughout the displacement of the three samples, it was verified that from the displacement of 4.5% the samples with 0% and 16.17% of fibers showed a reduction in cohesion until the end of the test, and as for maximum cohesion, which for both samples the deformation of 4.5%. The sample with 32.33% fibers presented a different behavior from the others, which increased during the displacement and reached a well-defined flow level.

The friction angle (Figure 7b) showed similar behavior for all samples, where it increases throughout the horizontal displacement. The maximum value was obtained for the sample with 16.17%, 32.6°, followed by the sample with 0%, 32.3° and 32.33%, 29.1°, for the displacement of 12.5%. It is observed in the angle of friction little variation after reaching the displacement of 7.5% for all the samples.

When comparing with the results presented by Kockel (1995), it was possible to verify a similar behavior for the friction angle of the samples, whereas for cohesion the results diverged, just as it happened with the results in the non-flooded condition.

In a comparative analysis between the shear strength in the non-flooded condition, it is possible to verify that the results of shear strength in the non-flooded condition, showed that for the sample with 16.17% fibers, the resistance gain (c and ϕ) was greater than the other samples. As for the test in the flooded condition, it observed different behaviors, where the sample with 32.33% fibers showed a higher cohesion intercept value, but a lower friction angle value than samples with 0% and 16.17% fibers. In view of the above, the percentage of 16.17% presented the best results in terms of geotechnical parameters.

3.3 Fiber tensile effect

Following the analysis of the results, the present item has the results of the tensile effect on the fibers in the shear strength described by Kölsch (1993, 1995, 1996) through the relationship of the bilinearity effect between samples of waste without fibers and with fibers. Bilinearity behavior

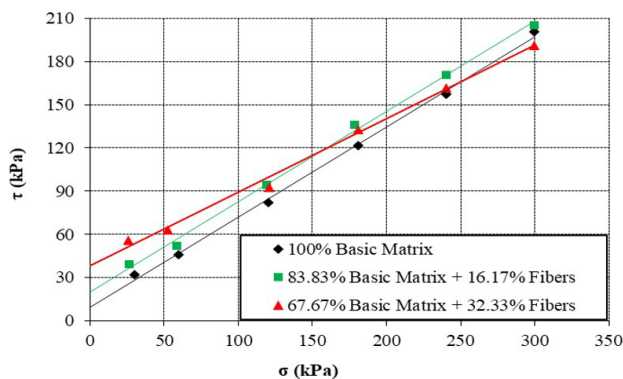


Figure 6. Shear strength curve by the criterion of peak displacement for the three samples tested - flooded test.

Table 3. Summary of the result of the shear strength curve of the three samples tested - flooded test.

Sample	R^2	c (kPa)	ϕ (°)
100% Basic Matrix	0.9519	9.52	32.05
83.83% Basic Matrix + 16.17% Fibers	0.976	20.17	32.02
67.67% Basic Matrix + 32.33% Fibers	1	26.02	29.10

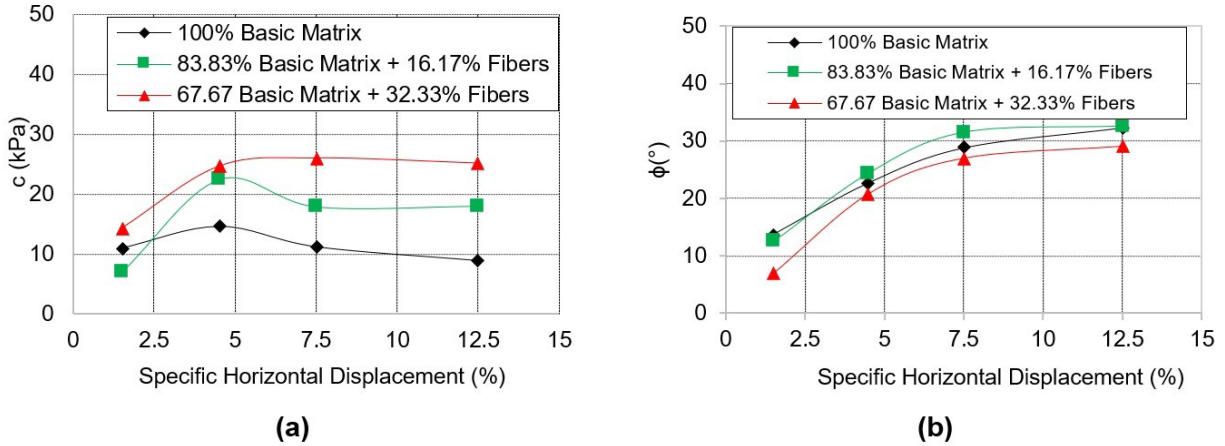


Figure 7. Comparison of Variation in: (a) cohesion; and (b) friction angle throughout different levels of specific horizontal displacement of solid waste samples - flooded test.

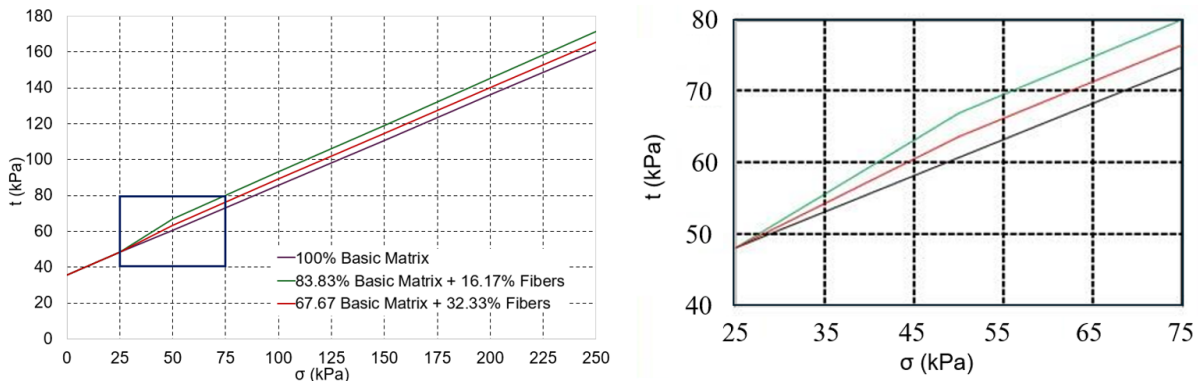


Figure 8. Resistance curves of solid waste samples, considering the effect of fibers, according to the Kolsch model for MSW – test in non-flooded condition (Kolsch, 1993, 1995, 1996).

curves were built from Kolsch (1993, 1995, 1996), for the results of the curves from Mohr-Coulomb of the direct shear tests in the flooded and non-flooded conditions, the following items present these results.

3.3.1 Bilinearity curve - non-flooded

The estimate of the bilinearity curve for the direct shear tests in a non-flooded condition, obtained from the three sample percentages used in the present research is presented in Figure 8.

From the resistance curve it is possible to calculate the tension angle due to the fibers (ζ), also called Kolsch's angle. The angle values for samples with 16.17% and 32.33% fibers were 10.2° and 5.0°, respectively. The other sample evaluated has no fibers, and therefore has no tensile angle, it is the basis for calculating the tensile angle of the others.

As for the sample with the highest percentage of fibers, 32.33%, this one presented a value of tensile angle lower than the sample with 16.17% fibers, which has half the amount of fibers from the previous one. According to Fucale (2005) this behavior may have occurred due to the

increase of sliding surfaces in the sample, which is greater in samples with higher fiber volume, and this consequently gradually reduces the tensile angle.

When comparing the values obtained for the tensile angles of the samples with 16.17 and 32.33% fibers, with values from DGG (1997). Initially analyzing the sample with 16.17% fibers, which presented the tensile angle value of 10.2°, this value was within the variation range that is 10 – 14°, this range of values corresponds to mechanical-biological treated waste samples and with a percentage value of the fibers less than 20% of the sample weight. For the sample 32.33% fibers, the table does not have values of tensile angle for samples of mechanically-biological treated waste above 20% of the percentage of fibers.

Fucale et al. (2015) obtained for degraded solid waste resulting from aerobic biological pre-treatment at the Freiburg Landfill 10° and 14°, corresponding to fiber percentages of 20% and 10%, respectively. The result of Fucale et al. (2015) for the percentage of 20% ($\zeta = 10.0^\circ$) was very close to the value obtained in this research for the percentage of 16.17% ($\zeta = 10.2^\circ$).

3.3.2 Bilinearity curve – flooded

Similar to the one performed for the direct shear test in a non-flooded condition, the construction of the curve for the test in the flooded condition was also performed, the result is shown in Figure 9.

Unlike the resistance curves in the condition of the non-flooded test, the sample showed almost parallel curves, in this situation the curves are not parallel, with emphasis on the sample with 32.33% fibers, which in some points crosses the other two straight lines.

The values of the tensile angles obtained for the flooded test were $\zeta = 16.7^\circ$ for the sample with 16.17% fibers and $\zeta = 18.5^\circ$ for the sample with 32.33% de fibers. Opposite to what happened in the curves presented for samples non-flooded, which presented a higher tensile angle value for the sample with 16.17% fibers, in this case the situation was reversed. Such fact may have happened due to the higher percentage of grained material in the sample with 16.17% fibers, since if the behavior of the curves in the flooded test is analyzed, it is possible to verify the initial cohesion intercept is reduced as the percentage of grains increases (Cohesion without fibers) > (Cohesion 16.17% fibers) > (Cohesion 32.33% fibers).

In comparison with the values of DGG (1997), the sample with 16.17% fibers which presented a value of 16.7° for the tensile angle, which was outside the range of $10 - 14^\circ$, which are for samples of mechanical-biological treated waste and with a percentage value of the fibers less than 20% of the sample weight. This difference may be justified by this case of dealing with a flooded test, and the German standard does not present a range of values for this situation.

As for the comparison between the tests in the flooded and non-flooded conditions, it was possible to verify that higher percentages of fibers (32.33%) present higher tensile values in situations of higher humidity (flooded test), and percentages of intermediate fibers (16.17%) behave better in tensile in more natural humidity conditions (non-flooded). This

occurs because in tests flooded with higher percentages of fibers, they suffer smaller reductions in the cohesive intercept, as verified, and a smaller reduction in cohesion favors the achievement of higher values of tensile angles. As for the non-flooded condition, the effect of mobilization between fibers prevails, samples with higher percentages of fibers enhance the formation of sliding surfaces, the increase of these surfaces favors the reduction of geotechnical parameters.

The values of the highest resistance parameters obtained in this research may be in line with what Huang et al. (2022) comments that the total shear strength of MSW increases with the age of the landfill, the greater the vertical pressure, the greater the impact of landfill age on the shear strength of MSW. Huang et al. (2022) that this is because, as the MSW landfill ages, c decreases and ϕ increases. And that according to the Mohr-Coulomb theory, ϕ dominates in the process of increasing vertical pressure, thus, the shear strength of MSW tends to increase with increasing age of the MSW landfill.

Other analyzes carried out in the present work can be observed in Norberto's master's dissertation (Norberto, 2019), such as the graphs of normal stress by horizontal displacement. Work from which the data was withdrawn for the development of the present work.

4. Conclusion

This study not only highlights the influence of fibers (plastics, textiles, and wood) on the shear strength parameters of municipal solid waste (MSW) landfills, but also focuses on the evaluation of bilinear envelopes for these materials. Data obtained from bilinear envelopes, such as the tensile angle (ζ), are crucial to understanding the stress-strain behavior of these fiber-reinforced materials. The results revealed, for samples with 16.17% and 32.33% fibers, traction angles of 10.2° and 5.0° , respectively, in non-flooded conditions; in the flooded condition, these values were 16.7° and 18.5° , respectively.

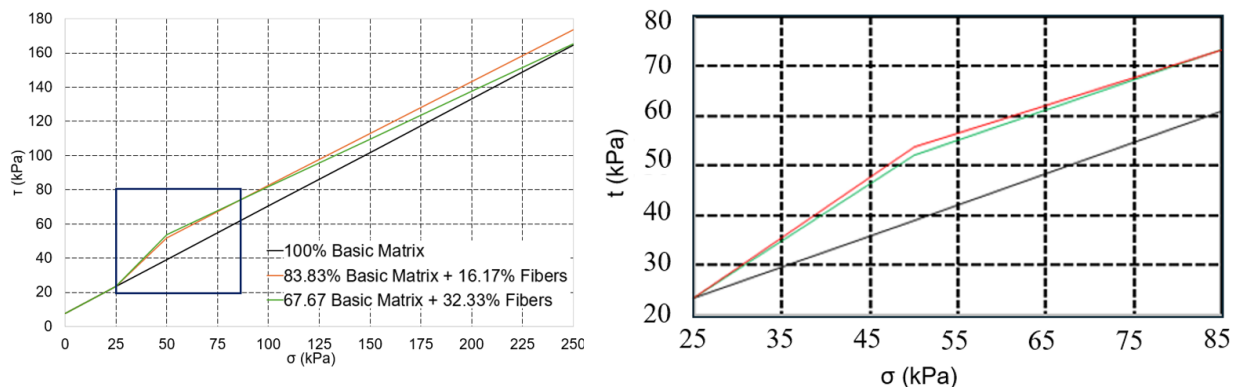


Figure 9. Resistance curves of solid waste samples, considering the effect of fibers, according to Kölsch model for MSW – test in a flooded condition (Kölsch, 1993, 1995, 1996).

These numbers highlight the significant variation in traction angles with the presence of fibers and changes in environmental conditions, providing valuable insights to understand the stress-strain behavior of these materials in different scenarios, reinforcing the need to consider these envelopes in the stability analysis of materials in MSW landfills. This often-overlooked aspect can play a fundamental role in predicting behaviors and improving the design of these waste management structures.

It is essential to highlight that, although the results are based on reduced-scale tests, they consistently align with those reported in the technical literature, reinforcing the robustness and the relevance of the data achieved in this study.

Understanding the variation of fibers in MSW and its impact on landfills is extremely important, as it can strengthen the stability of slopes in these environments. The addition of fibers to the fine matrix of solid waste can considerably increase the shear strength and stability of landfills, reducing their susceptibility to failure and collapse. Therefore, the study of these fiber-reinforced materials in landfill slopes is crucial to improving the safety and longevity of these essential structures for waste management.

By analyzing the performance of fiber-reinforced MSW under different conditions, this study offers valuable insights for engineering and waste management professionals. This data can be used to support more informed decisions in the design and operation of landfills, aiming to improve their structural safety and minimize the risks of adverse environmental impacts.

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Declaration of interest

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

Authors' contributions

Alison de Souza Norberto: conceptualization, data curation, visualization, methodology, writing – original draft, software. Rafaella de Moura Medeiros: conceptualization, data curation, supervision, validation, writing – review & editing. Christiane Lyra Corrêa: formal analysis, methodology, resources. Maria Odete Holanda Mariano: supervision, validation, writing – review & editing. José Fernando Thomé Jucá: supervision, validation, writing – review & editing.

Data availability

The datasets generated analyzed in the course of the current study are available from the corresponding author upon request.

List of symbols and abbreviations

c	cohesion
MSW	municipal solid wastes
R^2	adjustment coefficient
SF	safety factor
γ	density
ζ	tensile stress angle
σ	normal strength
τ	shear strength
ϕ	friction angle

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