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Study of the geotechnical behavior of soil-cement reinforced with plastic bottle fibers

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ABSTRACT. This study aimed to evaluate the influence of adding plastic bottle fibers to soil-cement mixtures and the possible improvements generated by the addition of a blend of two types of additives, namely, additive 1 (waterproofing improver) and additive 2 (adhesion enhancer), in the compactability and shear strength parameters of soil-cement-plastic fiber mixtures, considering a tropical residual soil. The fibers used in this study are made of Polyethylene Terephthalate (PET), produced from soft drink bottles, and added to the soil with 2 mm width and 1 cm length, in the content of 1% in relation to soil dry mass. Also, contents of 3% and 5% Portland cement, in relation to soil dry mass and two additives, additive 1 at a ratio of 0.25 kg m^{-3} dry soil and additive 2 at a ratio of 0.60 kg m^{-3} dry soil, were used to evaluate the possible effect of these variables on the investigated engineering behavior parameters. The compaction results indicated that the inclusion of PET fibers in soil-cement mixtures tends to decrease the maximum dry unit weight compared to fiber-free mixtures. Also, if compared to soil-cement-fiber mixtures, the incorporation of additives to soil-cement-fiber composites resulted in higher values of maximum dry unit weight and lower values of optimum moisture content, but still maintaining values lower than obtained for compacted soil. Results of the direct shear test showed enhanced shear strength with the addition of fibers to soil-cement, for both the parameter of cohesion and the internal friction angle of the material in comparison to fiber-free composites, which demonstrates the potential application of these composites in geotechnical works.

Keywords: Fiber reinforcement; soil improvement; soil-cement-fiber; plastic fibers.

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Introduction

Since the most remote times, soil is a material widely used in various types of engineering works. However, in its natural state, depending on its conditions, it can be a complex, variable material that does not offer satisfactory behavior for use in a particular type of application.

In this context, Consoli, Vendruscolo, Fonini, and Rosa (2009) state that soil stabilization and reinforcement techniques are often used to obtain geotechnical improvements for this material, either by adding cementitious agents or by including discrete elements randomly oriented or distributed, such as fibers. Furthermore, the principle of fiber-reinforced soil can be defined as the inclusion of discrete components randomly distributed in a soil mass. In this case, fibers are responsible for improving engineering properties and mechanical behavior of the soil matrix (Hejazi, Sheikhzadeh, Abtahi, & Zadhoush, 2012).

Additionally, soil stabilization involves the use of stabilizing agents to improve soil geotechnical properties, such as compressibility, strength, permeability and durability (Raghavendra, Rohini, Divya, Sharooq, & Kalyanbabu, 2018). There are several materials that act as soil stabilizers, such as cement, lime and additives, among others. Also, soil stabilization technique, which is normally used for improving local soils, is considered an affordable solution in places where granular materials are not available (Portelinha, Lima, Fontes, & Carvalho, 2012).

Addition of cement to soils can produce effects in two different ways, whether referring to granular soils or cohesive soils. In the first case, Portelinha, Lima, Fontes, Carvalho, and Stehling (2012) state that cement is mainly intended to create connections in intergranular contacts, in order to guarantee more effective mechanical resistance of the material to external stresses, by increasing the resistant parcel related to cohesion. In the second case, the author describes that cement grains act as cores, to which tiny particles surrounding them are adhered, developing regions of flocculated materials that present connections from cementation phenomena

According to Hamidi and Hooresfand (2013), techniques such as grouting and artificial cementation have been widely used to increase the bearing capacity of foundations and for ground improvement. However, the addition of cement to soil results in a brittle behavior that can be reduced and controlled by the application of fibers.

In this context, some studies have been carried out with the objective of analyzing the inclusion of several types of fibers, such as glass, polypropylene, corn cob, Polyethylene Terephthalate (PET) fibers, in soils improved with cement and the effects caused, aiming at the application in several geotechnical areas. Among the most relevant studies, it is possible to point out the those conducted by Consoli et al. (2009), Consoli, Bassani, and Festugato (2010), Tang, Shi, and Zhao (2010), Hamidi and Hooresfand (2013), Marri, Uddin, and Wanatowski (2014), Chen et al. (2015), Nguyen, Fatahi, and Khabbaz (2016), Yadav and Tiwari (2016), Tran, Satomi, and Takahashi (2017, 2018), Lv and Zhou (2019) and Ng, Xiao, Armediaz, Pan, and Lee (2020).

In addition, it is extremely important to take into consideration the current environmental issues, such as the growth in world plastic production, which generates, consequently, an increase in the amount of plastic waste. As an example, we can mention the Polyethylene Terephthalate (PET), which is originated from soft drink bottles, one of the most common plastic waste nowadays.

Botero, Ossa, Sherwell and Ovando-Shelley (2015) believe that cultural changes in consumption habits, together with the growth of the world population and the increased demand for industrialized products made of plastic compounds, resulted in a continuous increase in the generation of non-degradable waste. The Polyethylene Terephthalate (PET) is one of the most common plastic waste because it is frequently used in the production of soft drink bottles. In this scenario, the search for new uses of these materials is important, in order to reduce environmental impacts in engineering works, especially those generated by large-scale construction (Botero et al., 2015).

Furthermore, the use of improving additives can be mentioned, such as the addition of a combination of two additives, one of which is waterproofing and the other is adhesion enhancers, to produce enhancements in the characteristics of shear resistance and the optimal compaction parameters.

In this sense, the first additive, according to Aderinola and Nnochiri (2017), can add a hydrophobic characteristic to the mixtures, contributing to reduce the necessary amount of water for the composite to obtain its optimal behavior, thus reducing optimum moisture if compared to additive-free mixtures.

The second additive could contribute to increase maximum dry weight values, by carrying out, according to its manufacturer, a grouping of soil particles, enhancing its hardness and durability, which would imply a superior mechanical performance to that presented by the additive-free material.

In this context, the present study sought to study the effect of adding PET fibers to soil-cement and the possible improvements generated by the addition of a blend of two types of additives (a waterproofing and an adhesion enhancer) in the soil-cement-PET fiber mixture, particularly on the compaction and shear strength properties, considering a tropical residual soil typical of the region of Viçosa, state of Minas Gerais.

Material and methods

Soil

In the study region, the saprolite soil has a gray color, predominantly sandy texture, and a deep C horizon, resulting from a weathering profile developed from gneiss, basically quartz. This soil is classified as non-lateritic sandy (NA') by the Miniature, Compacted, Tropical classification (MCT methodology), according to Trindade et al. (2005).

A disturbed sample was collected at Vila Secundino, located at 20°45'48.25"S latitude and 42° 51'29.44" W longitude, between the Department of Medicine and Nursing and the Department of Animal Science, on the campus of the Federal University of Viçosa, in the municipality of Viçosa, state of Minas Gerais.

Fibers

Fibers used in this study (Figure 1) consisted of Polyethylene Terephthalate (PET), from soft drink bottles, with 2 mm width, using a PET bottle fillet for this purpose, and 1 cm length, being added to the soil in the content of 1% in relation to the dry mass of the soil-fiber mixture.

Figure 1. PET bottle fibers used in the experimental study.

Cement and additives

The Portland cement used was CP II E 32, in the contents of 3% and 5% in relation to the dry mass of the soil. This cement was chosen because it provides the mixture with a greater rigidity, an appropriate condition for investigating the effect of fiber inclusion.

Two additives were used together (Figure 2). The first one, called additive 1, improves waterproofing in the proportion of 0.25 kg m^{-3} dry soil, and the second enhances the adhesion (additive 2) in the proportion of 0.60 kg m^{-3} dry soil.

Additive 1 is a waterproofing improver material, 100% organosilanes, capable of reacting with soil at the molecular level, forming, according to Aderinola and Nnochiri (2017), Si-O-Si bonds with the surface molecules, resulting in a prolonged efficiency in the hydrophobic behavior of the mixture over time and preventing water from entering. According to Pandagre and Jain (2017), additive 1 is not only a water-soluble material, but also ultraviolet, heat stable and reactive soil modifier that also reduces water permeability and maintains breathability of the soil layer. In addition, Gayathri, Singh, and Prashanth (2016) state that this additive is reported to increase the friction value of the soil and decrease its permeability.

In this case of additive 2, it is a sub-micron acrylic co-polymer emulsion (Mulla & Guptha, 2019), known for improving the adhesion of soil particles, used for bonding their fractions (Zahoor & Jassal, 2020). According to its manufacturer, soils treated with this additive acquire better cohesion characteristics of their particles, improving their stability. In addition, by increasing the cohesion of fine surface fractions, they start to weigh more, which helps to avoid problems arising from the generation of dust on roads.

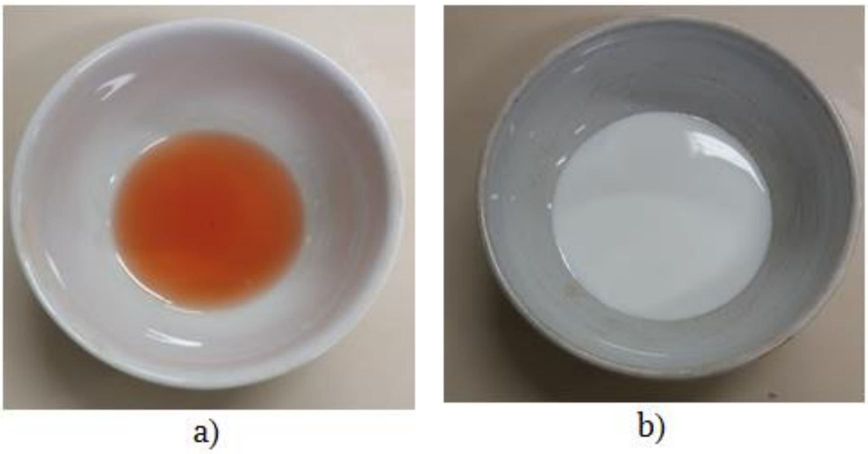

Figure 2. Additives used in this study: a) additive 1; b) additive 2.

Methods

Soil collection and preparation

After collecting deformed soil samples, they were bagged, identified, transported and later stored at the Soil Mechanics Laboratory of the Military Institute of Engineering (IME), in Rio de Janeiro, state of Rio de

Janeiro. Samples were air dried, ground, passed through a 2 mm nominal opening sieve and stored for use in experimental procedures described below, in compliance with NBR 6457 (Associação Brasileira de Normas Técnicas [ABNT], 2016a).

Geotechnical characterization tests

For traditional characterization of soil samples, the following geotechnical tests were carried out, according to ABNT standards: particle size analysis (Associação Brasileira de Normas Técnicas [ABNT], 2016b), Atterberg limits (Associação Brasileira de Normas Técnicas [ABNT], 2016c, 2016d) and specific weight of solid grains of soil (Associação Brasileira de Normas Técnicas [ABNT], 1984).

Proctor compaction test

Compaction tests were performed according to NBR 7182 (Associação Brasileira de Normas Técnicas [ABNT], 2016e), both for soil samples in the natural state and for all soil samples with cement, fibers and additives, in the Standard Proctor energy, without reuse of material, and using a large cylinder.

Preparation of specimens for the direct shear test

The preparation of specimens for the direct shear test was carried out in three steps (mixing, molding, and curing for seven days) in the case of mixtures with cement, and two steps (mixing and molding) in the case of cement-free mixtures. Regarding mixtures with additives and cement, five steps were conducted:

. First step: additive 1 was mixed with water and soil. First, additive 1 was added with the necessary amount of water to obtain the optimum soil moisture (Figure 3a). Then, 2/3 of this solution was added to dry soil, homogenizing the mixture, following with the addition of the rest of the solution and new homogenization (Figure 3b), generating mixture 1 (Figure 3c).

a) b) c)

Figure 3. First step of the preparation of specimens with mixtures of soil with cement and additive: a) Solution of additive 1 and water; b) Homogenization of soil with the solution of additive 1 and water; c) Mixture after homogenization.

. Second step: mixture 1 was dried at ambient temperature until a moisture content of less than 4% was obtained.

. Third step: additive 2 was mixed with water and mixture 1. To do this, firstly, additive 2 was added with the necessary amount of water to obtain the optimum soil moisture. Then, cement was added to the soil treated with additive 1 (Figure 4a) and the solution with additive 2 was added to this mixture, and homogenized (Figure 4b). In composites with fibers, these were added after this step, and again homogenized.

a) b)

Figure 4. Third step of the preparation of specimens with mixtures of soil with cement and additive: a) Addition of cement to mixture 1; b) Addition of solution of additive 2 and water to mixture 1 with cement.

. In the fourth step, specimens were molded and in the fifth one, they were cured for seven days.

Specimens were directly molded (Figure 5) in a cylindrical ring, with a radius of 10.15 cm and height of 2.00 cm, at the optimum soil moisture and maximum dry unit weight obtained in the Standard Proctor energy. Mixtures were subjected to static compaction, and specimens were molded in three layers of the same height and transferred to the shear box after curing. Specimens were cured for seven days, wrapped with plastic, to prevent moisture loss (Figure 5c).

Figure 5. Molding of specimens for direct shear tests: a) static molding of the specimen; b) specimen molded in the ring; c) curing of specimens; d) specimen transferred to the shear box after 7 curing days.

Direct shear test

Direct shear tests on the investigated material were performed based on the ASTM D-3080 standard (ASTM International, 2011). Before the shear step of the test, each specimen was submerged in water, aimed at flooding, followed by densification under the normal stress expected for the test. Normal stresses of 100 kPa, 200 kPa and 300 kPa were adopted, and the horizontal displacement speed, in the failure stage, was 1.2 mm minute^{-1}.

For each normal stress level, two specimens were tested for the unreinforced soil and for each composite studied, and then the average of the peak shear stress and the peak volumetric variation were determined. After, the peak shear strength envelope for each material was determined, getting, from them, the respective resistance parameters (intercept of cohesion and internal friction angle) of the soil and studied composites. Figure 6 illustrates the equipment used in the test and a specimen after the shear test.

Figure 6. Direct shear test: a) equipment used; b) specimen after test.

Results and discussion

Table 1 lists the results of the particle size analysis, the Atterberg limits and the specific weight of solid grains of the studied soil. The particle size distribution of soil following the ABNT standard (Associação Brasileira de Normas Técnicas [ABNT], 1995) is shown in Figure 7.

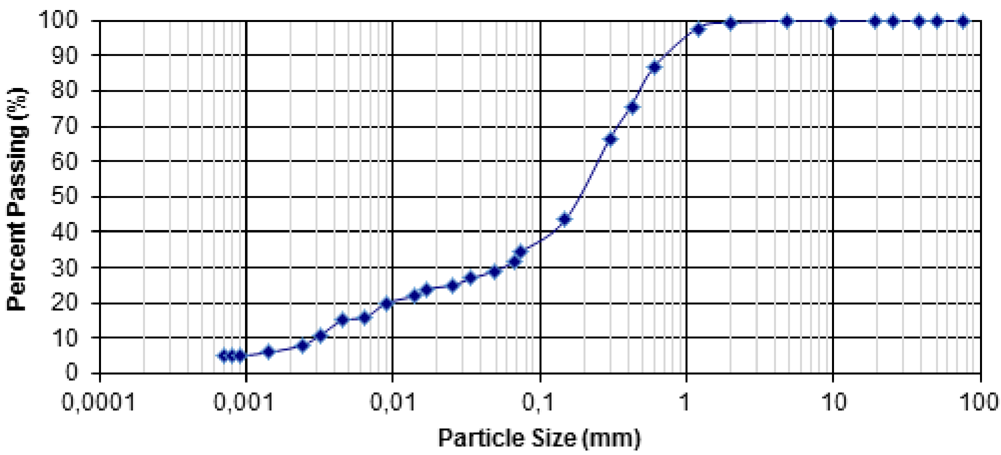

Figure 7. Particle size distribution of soil following the ABNT standard (ABNT, 1995).

Table 1. Results of the geotechnical characterization tests of the studied soil.

Particle Size Analysis (%)					Atterberg limits (%)			Specific Weight of Solid Grains (kN m^{-3})
Sand[1]			Silt[1]	Clay[1]	Liquid Limit (LL)	Plastic Limit (PL)	Plasticity Index (PI)	
Coarse[1]	Medium[1]	Fine[1]						
13	41	15	24	07	28	18	10	26.29

[1] Classification according to NBR 6502 (ABNT, 1995).

According to geotechnical classification systems TRB (Transportation Research Board) and USCS (Unified Soil Classification System), the studied soil is classified as presented in Table 2.

Table 2. Geotechnical classification of the soil according to the traditional classification systems TRB and USCS.

TRB	USCS
A-2-4 (0)	SC (clayey sands)

Compaction test

Results of the Proctor Compaction Tests for unreinforced soil and mixtures of soil-cement, soil-cement-additives, soil-cement-fibers, and soil-cement-additives-fibers are presented in Figure 8.

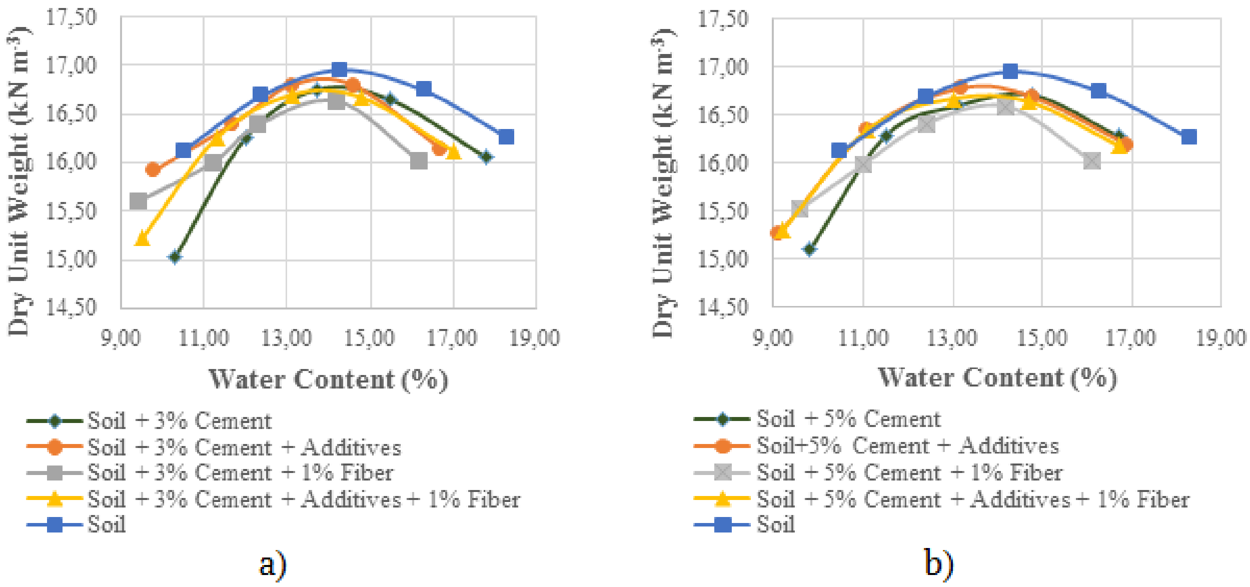

Figure 8. Results of Proctor Compaction Tests: a) Compaction curve of soil and mixtures with 3% cement; b) Compaction curve of soil and mixtures with 5% cement.

From the compaction curves, the inclusion of fibers resulted in a decrease in the maximum dry unit weight of the mixture in relation to unreinforced soil, the soil-cement, and the soil-cement-additives.

This can be explained due to occupation, by the fibers, of the voids that would be filled by grains of composites in the compaction, being those lighter (less dense) than grain particles. As the maximum apparent dry specific weight is influenced by the weight of all composite components, the fact that fibers are lighter than grains of the material present in the mixture-leads to a reduction in this parameter, thus reducing the density of mixtures with fibers compared to those without fibers.

It is also possible to infer that fibers formed a physical barrier to the rearrangement of solid grains under the action of the compaction effort, preventing them from concentration in smaller volumes of the internal structure of the composite and, consequently, limiting the possibility of increasing the mass of solid grains per unit volume of the system. When supported by solid grains of composites, these fibers are also capable of absorbing part of the compaction energy that should be transmitted to them, reducing the efficiency of compaction of the solid phase of the soil-fibers, soil-cement-fibers, and soil- cement-additives-fibers.

Regarding the compaction moisture content, it was not possible to establish a direct relationship between the addition of fibers and the value of optimum moisture.

Considering the effect generated by the inclusion of additives to soil-cement-fiber mixtures, an increase in the maximum dry unit weight values and a reduction in optimum moisture compared to additive-free composites were observed. This reduction is justified by the action of additive 1, which adds a hydrophobic characteristic to the mixtures and can cause the reduction of the necessary amount of water for the composite to obtain its optimal behavior, thus reducing its optimum moisture, compared to additive-free mixtures.

The increase in the maximum dry unit weight values can be explained by the action of additive 2, which, according to Rohith, Kumar, Paul, and KumaraSwamy (2018), binds soil particles, and leads to a reduction of the voids between the grains in the mixture and, consequently, generates an increase in the values of maximum dry unit weight in comparison to additive-free composites.

Direct shear test

Table 3 and Table 4 list the results of peak shear stress, peak volumetric variation and shear strength obtained for soil and all its mixtures with cement, additives, and fibers, while their shear strength envelopes are shown in Figure 9.

From the obtained peak shear strength parameters, it is possible to observe that the values of cohesion intercept and friction angle of all studied composites were higher than obtained for unreinforced soil.

Table 3. Peak shear stress and peak volumetric variation of the direct shear test of the soil and mixtures with cement, additives and fibers.

Mixture	Normal Stress (kPa)	Peak shear stress (kPa)			Peak volumetric variation (%)		
		Test 1	Test 2	Average	Test 1	Test 2	Average
Soil	100	84	89	86	-0.08	-0.06	-0.07
	200	132	127	130	-0.19	-0.19	-0.19
	300	229	233	231	-0.41	-0.32	-0.37
Soil + 3 % Cement	100	147	131	139	0.01	0.08	0.05
	200	238	246	242	-0.02	-0.03	-0.03
	300	327	315	321	-0.17	-0.21	-0.19
Soil + 3% Cement + Fiber	100	152	149	151	-0.02	-0.03	-0.03
	200	258	255	256	-0.17	-0.14	-0.16
	300	340	335	338	-0.17	-0.25	-0.21
Soil + 3% Cement + Additives	100	148	143	145	0.1	0.05	0.08
	200	230	255	243	-0.03	-0.05	-0.04
	300	317	346	331	-0.09	-0.09	-0.09
Soil + 3% Cement+ Additives + Fiber	100	168	155	161	0.02	0.11	0.07
	200	258	253	255	-0.09	-0.01	-0.05
	300	361	355	358	-0.22	-0.15	-0.19
Soil + 5% Cement	100	160	159	160	0.16	0.16	0.16
	200	269	273	271	0.04	-0.01	0.02
	300	357	353	355	-0.08	-0.07	-0.08
Soil + 5% Cement + Fiber	100	180	178	179	0.08	0.05	0.07
	200	323	333	328	-0.09	-0.04	-0.07
	300	410	413	412	-0.08	-0.13	-0.11
Soil + 5% Cement + Additives	100	179	175	177	0.11	0.10	0.11
	200	234	275	254	-0.05	-0.05	-0.05
	300	379	384	382	-0.08	-0.13	-0.11
Soil + 5% Cement + Additives + Fiber	100	188	188	188	0.11	0.07	0.09
	200	312	281	296	-0.08	-0.02	-0.05
	300	417	407	412	-0.11	-0.14	-0.13

Table 4. Peak shear strength parameters obtained in direct shear tests of the soil and mixtures with cement, additives and fibers.

Mixtures	Peak shear strength parameters		
	Cohesion intercept c (KPa)	Internal friction angle ϕ (°)	R^2
Soil	4	36	0.9475
Soil + 3% Cement	52	42	0.9869
Soil + 3% Cement + Fibers	61	43	0.9939
Soil + 3% Cement + Additives	54	44	0.9788
Soil + 3% Cement + Additives+ Fibers	61	45	0.9964
Soil + 5% Cement	66	44	0.9931
Soil + 5% Cement + Fibers	74	49	0.9737
Soil + 5% Cement + Additives	66	46	0.9608
Soil + 5% Cement + Additives + Fibers	75	48	0.9893

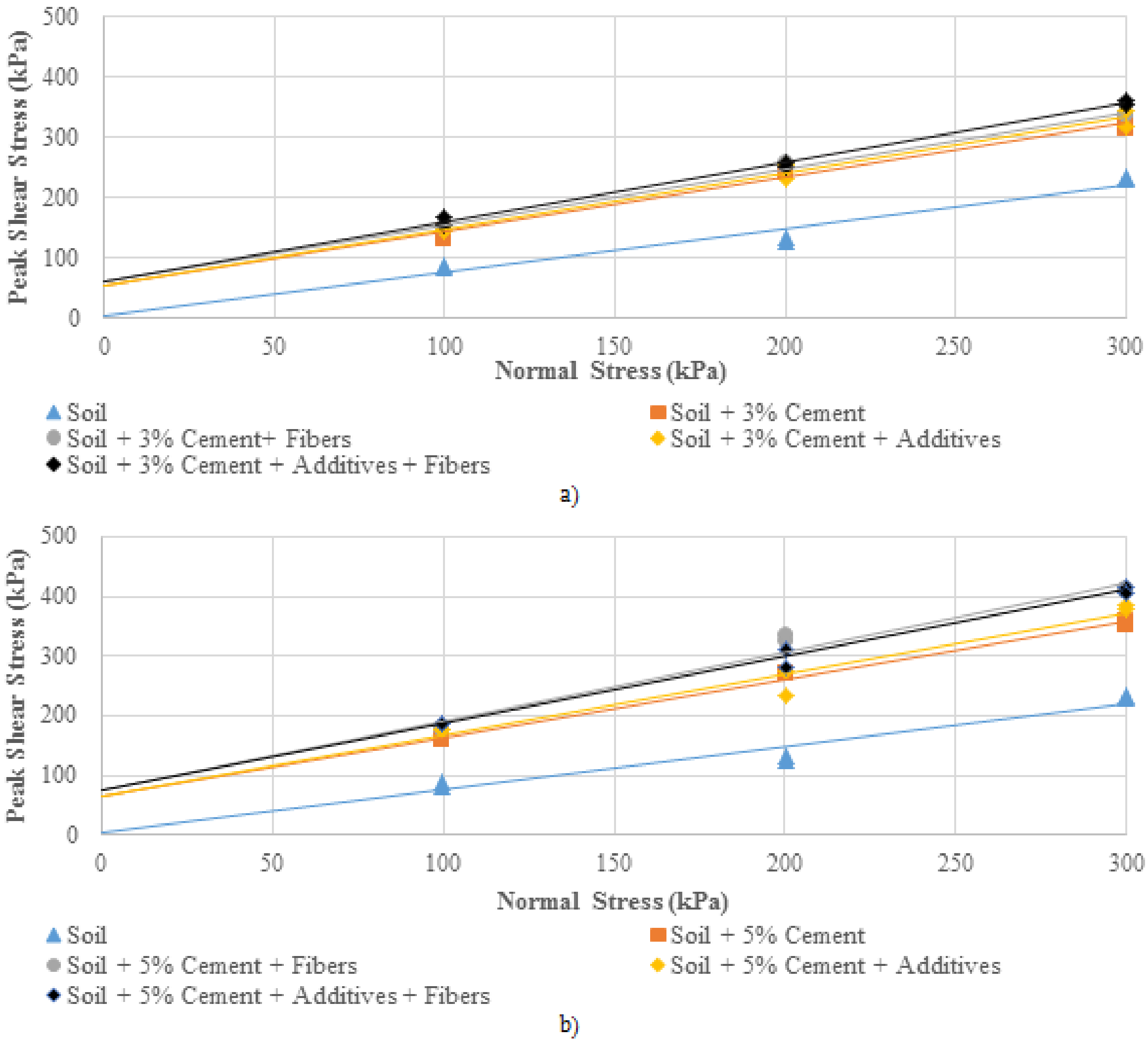

Figure 9. Peak shear strength envelopes of the soil and mixtures with cement, additives and fibers: a) Mixtures with 3% cement; b) Mixtures with 5% cement.

Regarding the effect of adding fibers to the soil-cement and to the soil-cement-additive, there was an increase in the peak shear strength, both in relation to the portion corresponding to cohesion, as well as that corresponding to the internal friction angle of the material, in comparison to non-fiber composites (Figure 10). Furthermore, for the studied mixtures, this increase was more perceptible in the cohesion intercept than in the internal friction angle values. This occurs because the fibers act, mainly, generating anchorage to soil particles, which mostly affects the cohesion intercept parameter, especially in granular soils.

In this context, Liu et al. (2017) state that mixing fibers with a soil mass might act as a spatial three-dimensional network to interlock soil particles to form a unitary coherent matrix and restrict the displacement. Also, hard soil particles (such as sands) contribute by impacting and eroding the fiber surface, generating grooves (Tang et al., 2010) that can constitute an interlock and improve the interaction between the soil-cement matrix and the fiber surface, improving the shear resistance of the mixture with respect to the cohesion intercept parameter.

In addition, cement particles act to unite soil grains, generating crystals from hydration reactions, which cover the fiber surface. Because of this, the binding characteristics of the soil / fiber interface are improved, increasing the interlocking force and the friction coefficient, which contributes to restricting their rearrangement on the shear interface. According to Tang et al. (2010), a lower probability of rearrangement and/or a good interconnection of soil particles are important factors to obtain higher values for shear strength parameters.

Regarding the increase in the internal friction angle, Tang, Shi, Gao, Chen, and Cai (2007) state that, unlike soil particles, hydrated cement crystals are harder than fibrous material, which facilitates their penetration into the fibrous structure and probably generates an effect of interface wear during the shear process, which results in a higher interface friction force compared to the addition of fiber in cementless soil.

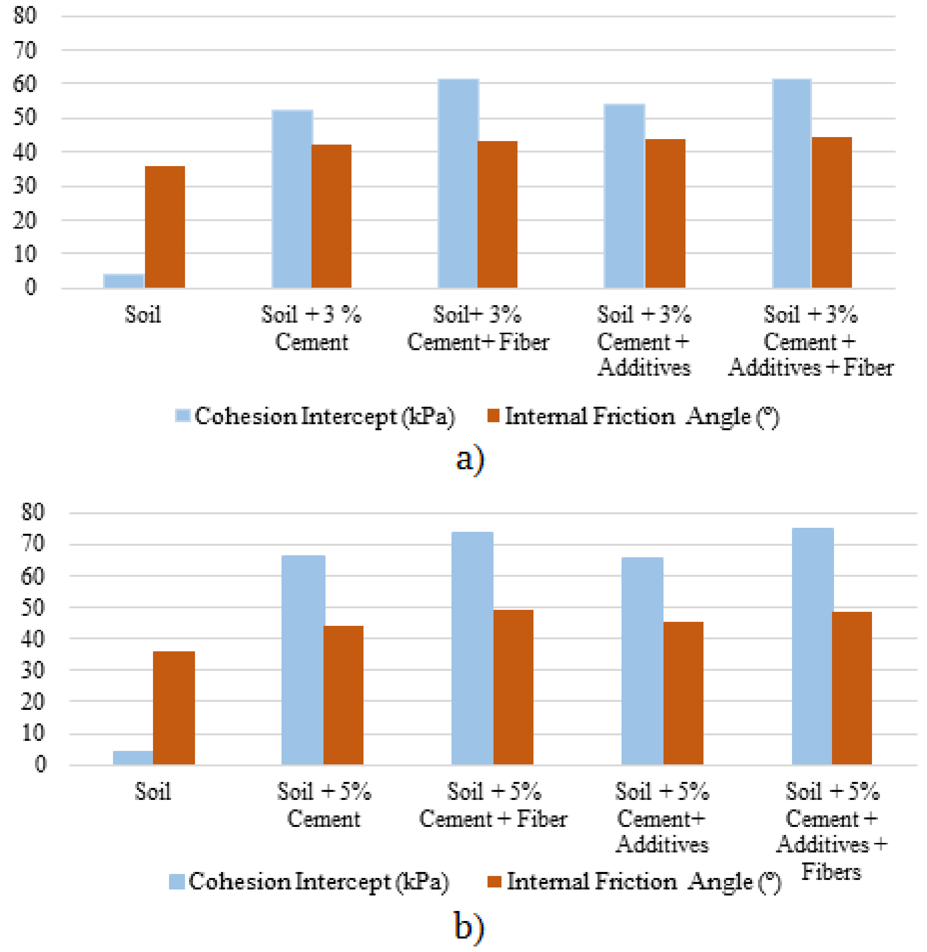

Figure 10. Analysis of the effect of adding fibers and additives to soil-cement: a) soil with 3% cement; b) soil with 5% cement.

Moreover, for mixtures of soil with cement and fibers, in the two percentages of cement studied, the incorporation of additives generated little or no variation in the results obtained with respect to peak shear strength, which showed its low efficiency for soil stabilization, with respect to these parameters. Therefore, it is possible to state that the improvements achieved in composites with fibers and additives were caused by the addition of fibers. Thereby, additives had no significant effect on shear parameters of the analyzed composites.

As for peak volumetric variations obtained in the shear test (Figure 11), it can be seen that, for the soil, there was a variation in volumetric compression in the three normal stresses applied, indicating a reduction in specimen height, which is typical of less rigid and soft sands.

With an increase of 3% cement in relation to the dry mass of the soil, an expansive peak volumetric variation was observed for the normal stress of 100kPa and a compressive peak volumetric variation for the other stresses, while for the addition of 5% cement, the compression variation was found only for the normal stress of 300kPa. Also, it is possible to observe that the compression peak volumetric variations, obtained for the two cement contents, was smaller than that presented by the soil, which means a smaller reduction in specimen volume during the shear test, compared to the soil, and indicates a gain in stiffness generated by the addition of cement to the soil.

Considering the use of additive in the soil-cement mixtures, in the case of the 3% cement, higher values of expansion peak volumetric variation were obtained for the normal stress of 100kPa and lower values of compression peak volumetric variation were obtained for the normal stresses of 200kPa and 300kPa in comparison to the additive-free mixture. Regarding the 5% cement in relation to the dry mass of the soil, there were higher values of expansion peak volumetric variation for the normal stress of 100 kPa compared to soil-cement without additives and little or no effect for the normal stress of 200 kPa and 300 kPa. This indicates that the addition of the additives generated a gain of stiffness in the mixtures with cement, which was less expressive for 5% cement in relation to the dry mass of the soil.

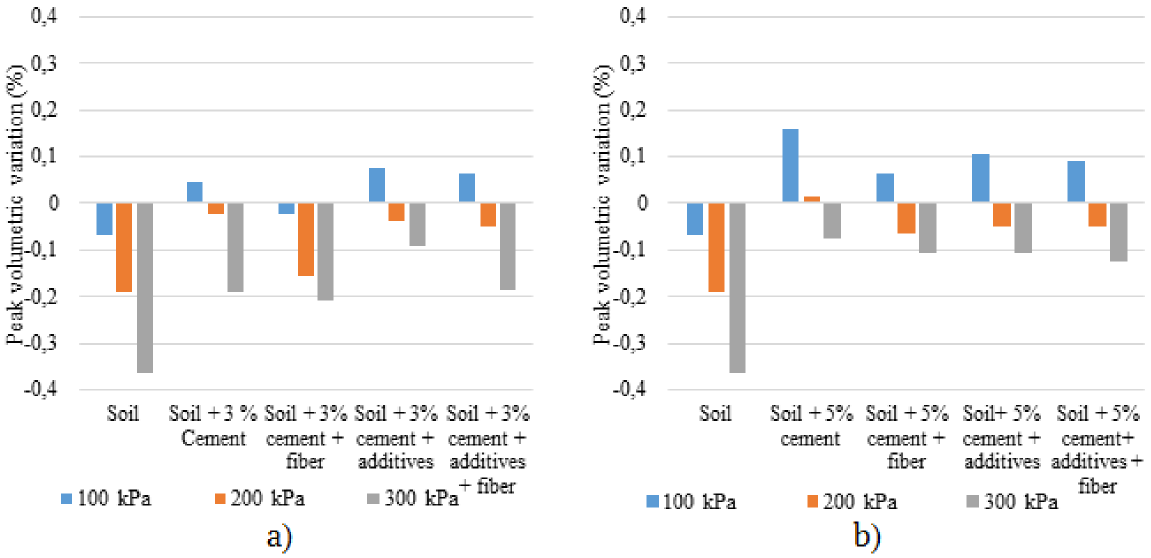

Figure 11. Peak volumetric variations obtained in direct shear tests: a) soil with 3% cement; b) soil with 5% cement.

On the effect of the addition of fibers, there was a trend to lower values of expansion peak volumetric variation for the normal stress of 100 kPa and higher values of compression peak volumetric variation for the normal stresses of 200kPa and 300kPa, in comparison to those obtained for mixtures of soil-cement and soil-cement-fibers. Thus, it is possible to infer that the fibers tend to reduce the effect of the expansion force, contrary to the normal stress generated in mixtures with cement and additives, for lower stresses. At the same time, they increase the deformability at the failure for higher normal stresses, in comparison to fiber-free composites.

These greater maximum compression peak volumetric variations for higher stresses, presented by fiber-reinforced materials in relation to fiber-free mixtures, represent a gradual loss in stiffness of composites and may indicate a geotechnical advantage acquired since greater deformability tends to reduce the risk of crack formation in certain geotechnical solutions and the occurrence of sudden breaks, characteristic of more rigid materials.

Conclusion

From the results of this study, it was possible to verify the effects of the addition of plastic fibers, with 2mm width and 1 cm length, to soil-cement mixtures, in terms of compactability and peak shear strength parameters. Also, it was possible to evaluate the action of a blend of two types of additives, additive 1 (waterproofing improver) and additive 2 (adhesion enhancer), in the mixture of soil, cement and plastic fibers.

Regarding the compactability, it was possible to verify that the inclusion of fibers results in a decrease in the maximum dry unit weight of the mixture in relation to the soil, soil-cement and soil-cement-additives. The inclusion of additives to soil-cement-fiber mixtures resulted in an increase in the values of maximum dry unit weight and a reduction in optimum moisture–if compared to composites without additives, but still maintaining lower values than that obtained for compacted soil.

From the results of the direct shear tests, it was observed that the values of cohesion intercept and friction angle of all studied composites are higher than those obtained for the soil. Additionally, improvements in peak shear strength parameters were obtained with the addition of fibers to soil-cement and soil-cement-additives in comparison to composites without fibers, which demonstrates the potential application of these composites in geotechnical works. Also, there was little or no efficiency in the addition of additives in the process of soil stabilization in all studied mixtures with respect to the peak shear strength parameters.

Regarding the peak volumetric variations obtained for the studied mixtures, it was found that the addition of fibers to the soil-cement and soil-cement-additive composites tended to reduce, for lower normal stresses, the effect of the expansion generated in these composites, contrary to normal stress, while it generated greater deformability at the highest normal stresses, which indicates a loss of stiffness of the composites with the addition of fibers.

By comparing the trends observed in the compaction tests with those obtained in the direct shear test, it was found that, even with a reduction in the maximum dry unit weight in the soil-cement-fiber and soil-cement-additive-fiber mixtures compared to compacted soil, this did not imply restrictions on workability and there was no reduction in engineering properties of these mixtures, represented by the peak shear strength parameters. This allows to conclude that, for such systems and for particularities of this study, the densification expressed by the compaction curve and the optimum parameters is not the most recommended physical property to estimate probable improvements in indices resulting from this testing modality.

Finally, with these findings, it can be concluded that the addition of plastic fibers tends to improve the engineering response from the reinforced systems, which was indicated by the increases in the peak shear strength parameters from the direct shear test. Therefore, it is possible to consider the technique of adding plastic fibers to soil as an efficient method of improvement of the investigated soil and composites.

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References

Associação Brasileira de Normas Técnicas [ABNT]. (1984). *NBR 6508 de 10/1984: Grãos de solos que passam na peneira de 4,8 mm - Determinação da massa específica*.

Associação Brasileira de Normas Técnicas [ABNT]. (1995). *NBR 6502 de 09/1995: Rochas e solos*. Rio de Janeiro, RJ: ABNT.

Associação Brasileira de Normas Técnicas [ABNT]. (2016a). *NBR 6457 de 03/2016: Amostras de solo — Preparação para ensaios de compactação e ensaios de caracterização*.

Associação Brasileira de Normas Técnicas [ABNT]. (2016b). *NBR 6459 de 04/2016: Solo — Determinação do limite de liquidez.*

Associação Brasileira de Normas Técnicas [ABNT]. (2016c). *NBR 7180 de 03/2016: Solo — Determinação do limite de plasticidade*.

Associação Brasileira de Normas Técnicas [ABNT]. (2016d). *NBR 7181 de 09/2016: Solo - Análise granulométrica.*

Associação Brasileira de Normas Técnicas [ABNT]. (2016e). *NBR 7182 de 09/2016: Solo - Ensaio de compactação*.

Aderinola, O. S., & Nnochiri, E. S. (2017). Stabilizing lateritic soil using terrasil solution. *SSP - Journal of Civil Engineering, 12*(1), 19-28. DOI: http://doi.org/10.1515/sspjce-2017-0002

ASTM International. (2011). *D3080/D3080M-11: Standard test method for direct shear test of soils under consolidated drained conditions*. West Conshohocken, PA: ASTM International.

Botero, E., Ossa, A., Sherwell, G., & Ovando-Shelley, E. (2015). Stress-strain behavior of a silty soil reinforced with polyethylene terephthalate (PET). *Geotextiles and Geomembranes, 43*(4), 363-369. DOI: http://doi.org/10.1016/j.geotexmem.2015.04.003

Chen, M., Shen, S.-L., Arulrajah, A., Wu, H.-N., Hou, D.-W., & Xu, Y.-S. (2015). Laboratory evaluation on the effectiveness of polypropylene fibers on the strength of fiber-reinforced and cement-stabilized Shanghai soft clay. *Geotextiles and Geomembranes, 43*(6), 515-523. DOI: http://doi.org/10.1016/j.geotexmem.2015.05.004

Consoli, N. C., Bassani, M. A. A., & Festugato, L. (2010). Effect of fiber-reinforcement on the strength of cemented soils. *Geotextiles and Geomembranes, 28*(4), 344-351. DOI: http://doi.org/10.1016/j.geotexmem.2010.01.005

Consoli, N. C., Vendruscolo, M. A., Fonini, A., & Rosa, F. D. (2009). Fiber reinforcement effects on sand considering a wide cementation range. *Geotextiles and Geomembranes, 27*(3), 196-203. DOI: http://doi.org/10.1016/j.geotexmem.2008.11.005

Gayathri, M., Singh, P. N., & Prashanth, M. G. (2016). Soil stabilization using terrasil, cement and flyash. *I-Manager's Journal on Civil Engineering, 6*(4), 31–36. DOI: http://doi.org/10.26634/jce.6.4.8237

Hamidi, A., & Hooresfand, M. (2013). Effect of fiber reinforcement on triaxial shear behavior of cement treated sand. *Geotextiles and Geomembranes, 36*, 1-9. DOI: http://doi.org/10.1016/j.geotexmem.2012.10.005

Hejazi, S. M., Sheikhzadeh, M., Abtahi, S. M., & Zadhoush, A. (2012). A simple review of soil reinforcement by using natural and synthetic fibers. *Construction and Building Materials, 30*, 100-116. DOI: http://doi.org/10.1016/j.conbuildmat.2011.11.045

Liu, J., Feng, Q., Wang, Y., Bai, Y., Wei, J., & Song, Z. (2017). The effect of polymer-fiber stabilization on the unconfined compressive strength and shear strength of sand. *Advances in Materials Science and Engineering, 2017*(2370763), 1-9. DOI: http://doi.org/10.1155/2017/2370763

Lv, X., & Zhou, H. (2019). Shear characteristics of cement-stabilized sand reinforced with waste polyester fiber fabric blocks. *Advances in Materials Science and Engineering, 2019*(3758413), 1-12. DOI: http://doi.org/10.1155/2019/3758413

Marri, A., Uddin, S., & Wanatowski, D. (2014). Sample preparation technique for fiber reinforced cemented soils. *Procedia Engineering, 77*, 140-147. DOI: http://doi.org/10.1016/j.proeng.2014.07.028

Mulla, A. A., & Guptha, K. G. (2019). Comparative study and laboratory investigation of soil stabilization using terrasil and zycobond. In B. Das & N. Neithalath (Eds.), *Sustainable Construction and Building Materials. Lectures Notes in Civil Engineering, (Vol. 25*, p. 757–769). Singapore, SI: Springer. DOI: http://doi.org/10.1007/978-981-13-3317-0_68

Ng, Y. C. H., Xiao, H., Armediaz, Y., Pan, Y., & Lee, F. H. (2020). Effect of short fibre reinforcement on the yielding behaviour of cement-admixed clay. *Soils and Foundations, 60*(2), 439-453. DOI: http://doi.org/10.1016/j.sandf.2020.03.009

Nguyen, L., Fatahi, B., & Khabbaz, H. (2016). Predicting the behaviour of fibre reinforced cement treated clay. *Procedia Engineering, 143*, 153-160. DOI: http://doi.org/10.1016/j.proeng.2016.06.020

Pandagre, A. K., & Jain, R. (2017). Experimental study on index properties of black cotton soil stabilized with terrasil. *International Research Journal of Engineering and Technology (IRJET), 4*(1), 1337-1343.

Portelinha, F. H. M., Lima, D. C., Fontes, M. P. F., & Carvalho, C. A. B. (2012). Modification of a lateritic soil with lime and cement: an economical alternative for flexible pavement layers. *Soils and Rocks, 35*(1), 51-63.

Portelinha, F. H. M., Lima, D. C. d., Fontes, M. P. F., Carvalho, C. A. B. d., & Stehling, R. S. (2012). Influência dos mecanismos de reação nas propriedades físicas e químicas de dois solos tropicais melhorados com cimento e cal. *Geotecnia, 124*, 5–30.

Raghavendra, T., Rohini, B., Divya, G., Sharooq, S. A., & Kalyanbabu, B. (2018). Stabilization of black cotton soil using terrasil and zycobond. *International Journal of Creative Research Thoughts (IJCRT), 6*(1), 300–303.

Rohith, M. S. R., Kumar, R. S., Paul, W., & KumaraSwamy, N. (2018). A Study on the effect of stabilizers (zycobond & terrasil) on strength of subgrade on BC soil. *Indian Journal of Scientific Research, 17*(2), 86–92.

Tang, C., Shi, B., Gao, W., Chen, F., & Cai, Y. (2007). Strength and mechanical behavior of short polypropylene fiber reinforced and cement stabilized clayey soil. *Geotextiles and Geomembranes, 25*(3), 194-202. DOI: http://doi.org/10.1016/j.geotexmem.2006.11.002

Tang, C. S., Shi, B., & Zhao, L. Z. (2010). Interfacial shear strength of fiber reinforced soil. *Geotextiles and Geomembranes, 28*(1), 54-62. DOI: http://doi.org/10.1016/j.geotexmem.2009.10.001

Tran, K. Q., Satomi, T., & Takahashi, H. (2017). Study on strength behavior of cement stabilized sludge reinforced with waste cornsilk fiber. *International Journal of GEOMATE, 13*(39), 140-147. DOI: http://doi.org/10.21660/2017.39.28994

Tran, K. Q., Satomi, T., & Takahashi, H. (2018). Improvement of mechanical behavior of cemented soil reinforced with waste cornsilk fibers. *Construction and Building Materials, 178*, 204-210. DOI: http://doi.org/10.1016/j.conbuildmat.2018.05.104

Trindade, T. P. d., Lima, D. C. d., Machado, C. C., Carvalho, C. A. B. d., Schaefer, C. E. G. R., Fontes, M. P. F., & Caneschi, F. P. (2005). Estudo da durabilidade de misturas solo-RBI grade 81 com vistas à aplicação em estradas florestais e camadas de pavimentos convencionais. *Revista Árvore, 29*(4), 591-600. DOI: http://doi.org/10.1590/s0100-67622005000400011

Yadav, J. S., & Tiwari, S. K. (2016). Behaviour of cement stabilized treated coir fibre-reinforced clay-pond ash mixtures. *Journal of Building Engineering, 8*, 131-140. DOI: http://doi.org/10.1016/j.jobe.2016.10.006

Zahoor, S., & Jassal, K. (2020). Sub-grade stabilisation using nano particles. *International Research Journal of Engineering and Technology (IRJET), 7*(6), 2206–2209.