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Effect of varying the content and length of fibers in the behavior of a cemented soil

Efeito da variação do teor e do comprimento de fibras no comportamento de um solo cimentado

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Abstract: This study presents the results of the effects of variation in the content and length of polypropylene fibers, when inserted into a soil-cement mixture, aiming its use as a primary coating for dirt roads. In this study, the experimental models were used: 5% fast-curing cement, clay sand of the Barreiras geological formation and polypropylene fibers of 6 mm and 24 mm lengths, at levels from 0.25%, 0.50% and 0.75% relative to the total dry soil-cement mass. After completion of the unconfined compression tests and tensile strength by diametrical compression, it was found that increasing fiber content in the soil-cement matrix provides: increase in resistance of the materials, increase on the voids content and the strain, but, significantly reduces the initial tangent modulus making the more ductile material. In the terms of length, it observed clearly that the 24 mm fiber has a stronger influence on the mechanical behavior when inserted into the matrix of the developed composite material.

Keywords: Fiber; Soil-Cement; Mechanical behavior.

Resumo: Este estudo apresenta os resultados dos efeitos da variação do teor e do comprimento das fibras de polipropileno, quando inseridos em uma mistura solo-cimento, visando seu uso como revestimento primário para estradas de terra. Neste estudo, foram utilizados os modelos experimentais: 5% de cimento de alta resistência incial, areia argilosa da Formação Geológica Barreiras e fibras de polipropileno de 6 mm e 24 mm de comprimentos, em teorers de 0.25%, 0.50% e 0.75% em relação a massa de solo-cimento total seca. Após a realização dos ensaios de compressão não confinada e de tração por compressão diametral, foi verificado que o aumento do teor de fibras na matriz de solo-cimento proporcionou: aumento da resistência dos materiais, aumento do teor dos vazios e das deformações, entretanto, reduz significativamente o módulo tangente inicial tornado o material mais dúctil. Em termos de comprimento, observou-se claramente que a fibra de 24 mm tem uma influência mais forte sobre o comportamento mecânico quando inserida na matriz do material composto desenvolvido.

Palavras-chave: Fibras; Solo-Cimento; Comportamento Mecânico.

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1. Introduction

In a country with the size of Brazil paving solutions may require a regional approach. The use of non-traditional materials and construction solutions and techniques can be very diversified. Materials that have been used, sometimes without specific and well-grounded studies of their geomechanical behavior, should be analyzed in more detail, leading to specifications that allow its widespread safe use.

In the case of existing low-cost roads, as in the case of the unpaved roads of Metropolitan Park “Armando de Holanda Cavalcanti” (PMAHC), in the Metropolitan Region of Recife (GPS: lat: 8°21'30.66"S; long: 34°56'42.21"W), the circulation platforms are deeply damaged by erosion phenomena, due to natural causes, such as the intense tropical rainfall alternating with very high temperatures and insolation, as well as human actions, such as the very aggressive off-road vehicles that circulate in the park.

In order to use the same of the degraded areas and use it as a primary coating on the unpaved roads, this material has to be improved in order to give satisfactory resistance to erosion due to natural weathering (climatic) and the actions induced by the wheels of vehicles that circulate all over the year.

Therefore it was decided to develop geotechnical studies of the behaviour of that soil when improved/reinforced, respectively by cement and polymeric fibers.

Based on studies carried out by Feuerharmel (2000), Foppa et al (2007), Viana da Fonseca et al. (2008), Marques et al. (2014), Consoli (2014), Foppa & Consoli (2014), Maghous et al (2014), Silva et al (2013), Severo (2011), the incorporation of cement to the soil, has influence in the following properties: resistance to uncofined compression and diametral tensile strength, initial stiffness and service deformation modules, yield stress, volumetric strain during loading, and, particularly, hydraulic conductivity and resistance to chemical attack. In the case of including fibers in the soil-cement mixture, most studies prove that there is an improvement of strength by the action of the fibers, which induce an increase in ductility, Guedes (2013), Consoli et al (2013), Festugato & Consoli (2013) and Festugato (2011).

Although cemented geomaterials present an increase in resistance and stiffness, some disadvantages can be identified, such as: the materials become too fragile, the tensile strength, although higher evolve rapidly to zero values post rupture, giving rise to dangerous brittle behavior and there is tendency to cracking on drying, particularly when exposed to environment.

To avoid the disadvantages mentioned, polypropylene fibers were added to the matrix, since polymeric materials present a higher elasticity, with consequent more variable and broad ductility, a good resistance in tension, after breakage of the cement bonds, become much more versatile for intensively loaded situations, such cyclic loading in climatic transient situations. The combination of these components forms the so-called composite geomaterial, which tend to develop more suitable geomechanical and hydraulic characteristics: strength, stiffness, ductility, brittleness, energy absorption, capacity of deformation and post-cracking behavior, higher permeability, when compared with soils or soil-cement mixtures, that gave rise. Therefore, more suitable for use as primary coating.

In this study, the fixed parameters were: soil type, type and cement content, curing time, fiber type, density and moisture content in molding. The variable parameters are the strength and length of the fibers. The laboratory tests were conducted to characterize the mechanical behavior of the composite materials, by analyzing the evolution of the unconfined compression strength or indirect tensile strength by diametrical compression.

The soil of the Barreiras geological formation used in this work is widely used in geotechnical works in the Recife metropolitan region, which is a major geological unit throughout the northeastern coast stretching from the northern coast of Amapá to the east coast of Rio de Janeiro state, covering Mesozoic sedimentary deposits of various coastal basins (SEVERO, 2011).

2. Experimental Program

The experimental program was developed in three stages. The first step consisted of characterization of the materials involved in the study. In the second stage, a large number of uncofined compression tests were conducted to study the influence of the cement content (CC) and the applied compaction effort on the resulting strength of soil-cement mixture. It was then possible to determine, in view of the correlations derived from the soil studied, the resistance that could be achieved when an applied compaction was attained and cement content used. Four cement contents were adopted (3%. 4%, 5% and 6%), testing at least three samples for each mixture, and one set with the maximum dry density with its optimum moisture content, obtained from compression tests applying energy of the Standard Proctor (maximum dry density, γ_{dmax} = 18.6 kN/m^3 and optimum moisture content wopt = 12.5%), another with intermediate compaction energy

(γ_{dmax} = 19.8 kN/m^3 and w_{opt} = 11%) and the last, corresponding to Modified Proctor (γ_{dmax} = 20.5 kN/m^3 and w_{opt} = 10.2 %) defined first with the clean soil (no additions).

In the last stage, after fixing the conditions of the design parameters (γ_{dmax} = 19.8 kN/m^3, w_{opt} = 11% and cement content, CC = 5%), the study followed aiming to evaluate the influence of the content and length of the polymer fibers on the mechanical behavior of soil-cement mixture. In this step three, several values of the content in fibers were used: 0.25, 0.50 and 0.75% (in weight: that is the weight relative to the total weight of soil-cement + 5%). Two different lengths of fibers were used: 6 mm and 24 mm.

2.1. Characterization of soil from the Barreiras geological formation

The studied soil belongs to the geological formation called “Barreiras”, which is an important geological unit stretching along the entire northeastern Brazilian coast, from the northern Amapá coast to the east coast of Rio de Janeiro state (SEVERO, 2011).

This formation covers Mesozoic sedimentary deposits of various coastal basins. Based on the results of geotechnical characterization, the collected soil is classified as sand clay, with w_L = 30% and IP = 12%.

The fine fraction of the soil belongs to the group of Inorganic Low Plasticity Clays. The clay fraction is considered inactive, since its value of activity index is IA = 0.4. Due to the Middleton dispersion ratio (1930) the soil is considered erodible as a result of the Dispersion Ratio (PD) = 100%. Based on the classification MCT the soil was classified as lateritic loamy sand (LA').

The soil has no clear expansive or collapsible behavior, as inferred from the usual tests and classifications. The characteristic curve obtained, a bimodal curve, is typical of soils in which grain size distribution is poorly graded, with an open gradation. Through direct shear tests in flooded conditions, the soil presents a cohesive intercept c' = 2.1 kPa and friction angle of ϕ'= 31.1º. The soil permeability, determined by a permeameter in the lab, was: k = 6.45x10^{-6} m/s.

2.2. High initial strength cement

The cement used throughout the research was High Initial Strength Cement also known as Fast-Curing Cement. The used cement is produced in Pacatuba plant, Sergipe state, and is referred to as the acronym CPV-ARI.

2.3. Polypropylene fibers

The fibers used were produced by the polymerization of propylene, a petroleum byproduct and provided by the company MACCAFERRI - Latin America in the form of continuous filaments. The fibers have a Young's modulus of 3000 MPa, specific gravity of 9.1 kN/m^3, 10^{-6} m diameter and lengths from 6 mm to 24 mm.

3. Methods

3.1. Molding processes, curing and testing the samples to failure – 2nd stage

The samples used in the studies involving only soil and cement were 100 mm in height and 50 mm in diameter. After drying and dispersing the small aggregates, the soil was passed through an ASTM sieve N^0 4 (4.8 mm) and the retained material discarded. The justification for screening the material with 4.8 mm open mesh is that the possible maximum size of a soil grain for the dimensions of the samples to be tested should be 10.0% or less than the smallest dimension of that specimen (i.e. 50 mm).

After preparing the material and equipment necessary for the molding, the next step consisted of molding test samples, for each applied compaction energy, with cement content initially set at 3%, 4%, 5% and 6% over the dry soil mass. For each cement content, nine samples were molded, resulting thus in a total of 36 samples, 12 for each compaction energy. Only six were molded each day, three in the morning and another three in the afternoon.

The soil-cement compaction process was performed in three layers, aiming at a better density distribution along the specimen height. Then the samples were wrapped in PVC film and stored in a wet chamber where they remained for a period of six days. On the seventh day, the samples were immersed in distilled water for 24 hours and then taken to a mechanical frame where they were loaded at a constant strain speed of 1.00 mm/min. Finally, samples were taken to measures the moisture of the tested sample.

3.2. Molding processes, curing and testing the samples to failure – 3rd stage

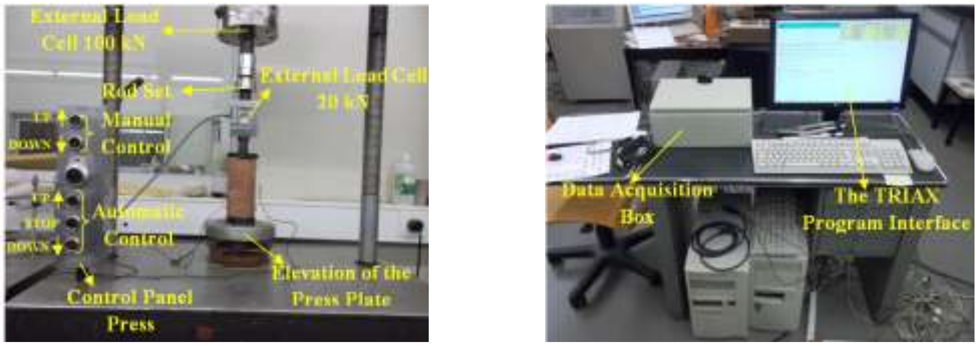
The samples used in the studies involving soil, cement and fibers, were 140 mm in height and 70 mm in diameter. Initially, the materials were prepared under the procedure described above (2nd stage). In the case of fibers it was necessary to blow on them using an air gun in order to separate the strands and thereby provide better mixing conditions with the moistened soil-cement.

Immediately after a certain amount of fiber spreading, a quantity of soil-cement was mixed in order to cover the entire fiber surface. Subsequently, another small amount of fibers was spread creating a new layer to cover the entire surface spread soil-cement. This process was repeated until the entire quantity of fiber was used.

The samples were compacted into four layers and immediately stored in a wet chamber where they remained for a period of 24 hours. Then they were demolded, weighed and their dimensions measured. Next they were wrapped in PVC film and remained inside the wet chamber for 20 days. After 20 days, they were immersed in a container containing distilled water for 24 hours and then tested to failure on an automated frame at a constant strain rate of 1.00 mm/min. Data were automatically stored in an Excel file using specific software (Figure 1).

After failure, the present suction was recorded by, placing filter paper (Whatman N^{0} 42) exactly in the two parts of the zone where the strain wedge occurred.

Figure 2 illustrates the methodology used to conduct an indirect tensile test by diametrical compression.



a) b)

Figure 1 – a) Details of the frame. b) Electronics data acquisition system.
Source: Author (2013).

a) b)

Figure 2 – Indirect tensile test by diametrical compression, with high precision displacement transducers: a) CP diameter alignment with steel brackets; b) Example of failure of a specimen.
Source: Author (2013).

4. Results and Discussion

4.1. Analysis of the influence of cement content and compaction energy on the characteristics of the mixtures

This first section contains details of the results of the influence of the increase in cement content in the soil of the Barreiras geological Formation and the increase in the maximum dry density of soil-cement mixtures, obtained as a function of the compaction results in the Proctor energies, normal, intermediate and modified.

4.1.1. Analysis of the effect of cement content on soil-cement strength

Figure 3 shows the graph of the variation of uncofined compression strength with the cement content (CC), revealing a straight-line correlation, for different void ratios after compaction, which means for different applied compaction energy.

Analyzing the linear adjustment, individually, it is found that there is a linear increase in strength with increasing cement content. Regarding the set of straight lines, the rate of increase in strength is noticeable, represented by the slope of the straight adjustment, and proportional to the applied compaction energy (the unit weight and its optimum water content). It follows, therefore, that the cementation is more effective for smaller voids of the mixture.

The mechanical behavior of unconfined specification tests, in a soil mixture with increased cement content in its matrix, as shown in Figure 3, was also presented in the works of Chaiyaput et al. (2022), Wang et al. (2022), Karpisz et al. (2018), Jaritngam et al. (2012), Rios et al. (2012), Viana da Fonseca et al. (2008), Foppa et al (2007) and Consoli et al. (2006). This is a common behavior when adding cement content to a soil, whether clayey, silty, sandy or gravel.

For example, Cruz (2008) analyzed the mechanical characteristics, by carrying out unconfined specification tests, of fine sand from the city of Osório – Rio Grande do Sul, by incorporating cement into it. The same source that, as the cement content in the sand increased, keeping the density of the mixture constant, the greater the increase in resistance and initial stiffness of the soil-cement sample. Cruz (2008) also analyzed other variables such as porosity and void index in the influence of the mechanical behavior of the soil-cement mixture when the cement content increases and also transmitted the same behavior observed in Figures 3, 4 and 5. Cruz (2008) studied the behavior of this soil, due to the fact that it is widely used in geotechnical works in his region and also because it has geotechnical characteristics that do not always fit into civil construction project specifications.

It should be stressed that this ratio is only valid for the studied cement content range, and it is believed that it may behave differently for high cement percentages, tending to a limit value.

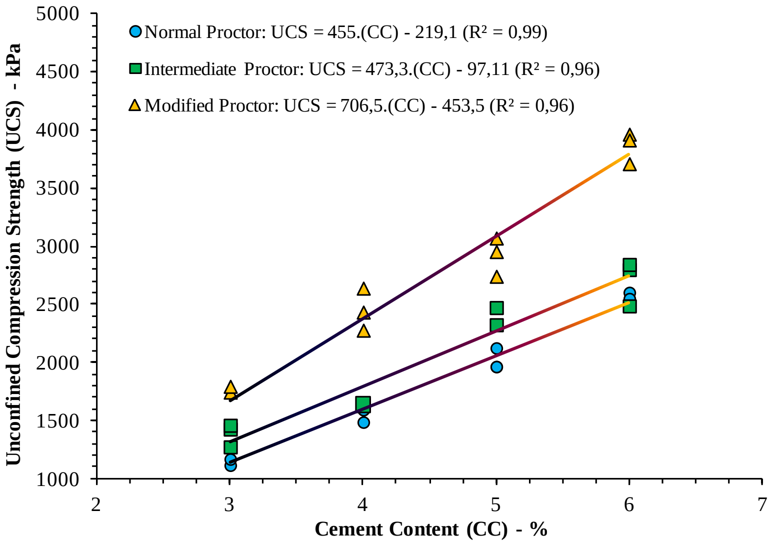


Figure 3 – Variation of mechanical strength due to cement content and compaction.
Source: Author (2013).

4.1.2. Analysis of porosity variation on soil-cement stre

Figure 4 shows the fitting curve (exponential) for the mean values of unconfined compression strength (UCS) in each composition, varying the porosity (n) and the cement content. By analyzing individually these curves, it is observed that the UCS increases exponentially with decreasing porosity, which is the consequence of the limitation of the achieved maximum dry density condition when varying the compaction energy. For the 4% and 6% cement contents, the relationship was not quite satisfactory, but it is clear that porosity significantly influences the strength.

According to Foppa et al. (2007), the mechanism by which the reduction in porosity influences the increase in the soil-cement strength is related to the existence of a greater number of contacts and improved interlocking between the soil particles. According to the authors, the closer are the contacts between the particles of soil, the highest is the cement hydration, improving largely the effective connections between them.

4.1.3. Analysis of the voids/cement ratio versus soil-cement strength

Figure 5 presents the graph of the variation of UCS with the ratio between volume of voids and the cement content.

The fitting curve was obtained based on the average of UCS and the voids/cement, ratio of all three relevant samples in each cement content and compaction.

On analyzing the graph, the increased UCS is found to be proportional to the increase in cement content and inversely proportional to the increase in void volume. Therefore, a reasonable correlation can be inferred between UCS and voids ratio (or porosity) over cement content. For the conditions tested, the fitting curve that resulted in the highest correlation coefficient is the power type.

Larnach (1960) quoted by Foppa (2005), Foppa (2005), Severo (2011) and Rios et al. (2012), have conducted studies analyzing factors influencing strength of soil-cement mixtures, observing that an increase in the voids/cement ratio reflected in a decrease in soil-cement strength.

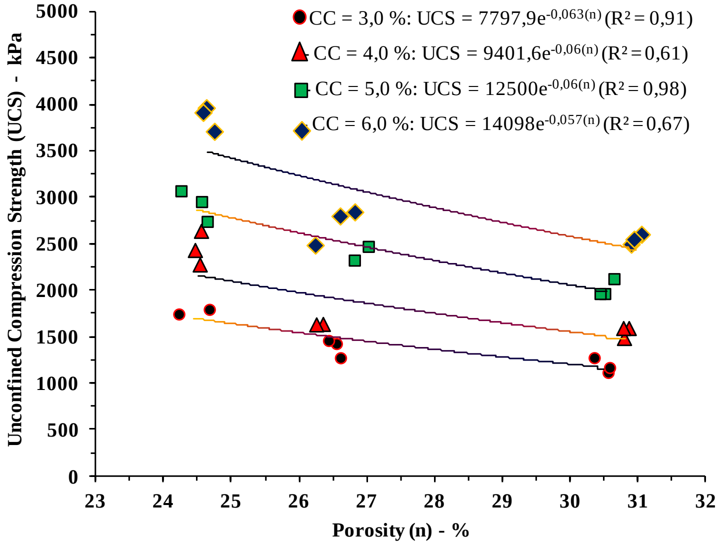


Figure 4 – Variation of the unconfined compression strength as a function of porosity and cement content. Source: Author (2013).

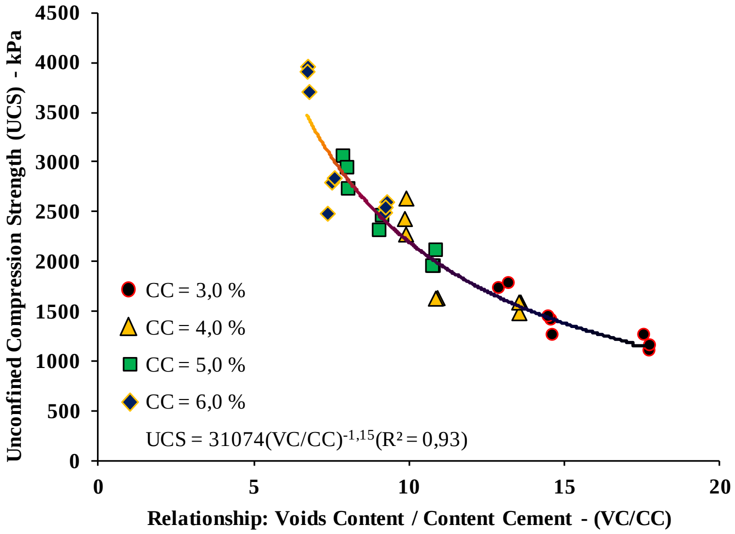


Figure 5 – Unconfined compression strength variation of the voids/cement ratio.
Source: Author (2013).

4.2. Analysis of the influence of the content and length of the fibers on soil-cement

This section presents the results of the unconfined compression, diametral compression and durability tests, due to the variation of three fiber contents (0.25%, 0.50% and 0.75%) and two lengths (6 mm and 24 mm) of fibers embedded in the soil-cement matrix.

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4.2.1. Analysis of the ratio between unconfined compression strength and fiber content and length

Before starting the detailed analysis of the results of unconfined compression tests results on composite materials, it is important to note that many researchers who used fibers in their studies claimed that the factors affecting the soil-fiber composite behavior, or even more, the soil-cement-fiber mixtures, are diverse and complex (Figure 6). There are numerous combinations of variables that significantly alter the interaction mechanisms.

For example, for a certain combination of variables, the results may be convenient for a given application of the composite, but may not be for another. Therefore, it is important to first understand the mechanical behavior of the material and the factors that condition it, to then be able to compare the material reinforced with fibers, with or without cement.

In this study, it was found that the inclusion of fibers in the soil-cement matrix contributes to increasing compression strength. It is observed that the increase in strength was more pronounced when using longer fibers (24 mm).

For 0.50% fiber content, incorporated into the soil-cement matrix, there is already an increase in strength for the longer fiber. On the other hand, there is less strength when shorter fibers are used, although with higher values than the corresponding soil-cement mixture. This result is justified by the difficulty of assuring good separation and homogenization of 6mm fibers compared to 24 mm fibers.

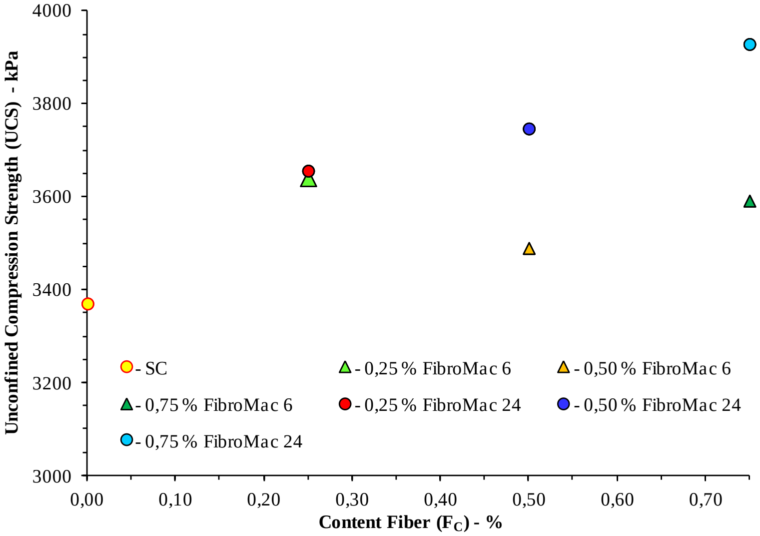

Figure 6 – Average unconfined compression resistance strength versus fiber content and length of the fibers. Source: Author (2013).

The UCS values for the 0.75% fiber content are also justified on the basis of the interpretation described in the previous paragraph. Therefore, the strength developed by 6 mm fibers (due to the increase provided by the number of contacts between the grains of the soil-cement matrix and fibers) continued to increase, although to a lesser extent when compared to the 24 mm fibers.

Based on the results, in the case of increasing strength with fiber content, an optimum fiber content can be defined: 0.25% for 6 mm fibers and 0.75% for 24 mm fibers. For shorter fibers, it seems that the soil-cement matrix are reinforced with high fiber content associated with a very large number of filaments, and the fibers are not sufficiently engaged between the soil-cement particles, thereby diminishing the benefits of this reinforcement (creation of tensile nets into the soil + cement matrix).

In the technical literature there are many academic works developed, involving composite mixtures such as: soil-cement, soil-fiber and also soil-cement-fiber. However, to date, no research has been developed involving the same type of soil, fiber, cement content, density and humidity used in the present research to compare results.

4.2.2. Analysis of the ratio between void ratio versus cement content and length of fibers

Analyzing the relationship between the void ratio of the mixtures according to the cement content and fiber length used, a proportional increase in the void ratio is clear from the graph in Figure 7, due to the increase of incorporation of fibers in the soil-cement matrix, and this increase is more pronounced in mixtures that used 24 mm fibers.

In this study, it was observed that increasing the fiber content caused an unfavorable effect on the maximum dry density, due to the fact that the inclusion of the polymer elements creates a “spongy" matrix implying the recovery of the initial volume after compaction. In view of this behavior, always after compacting the last layer, the specimen continued pressed for a further five minutes.

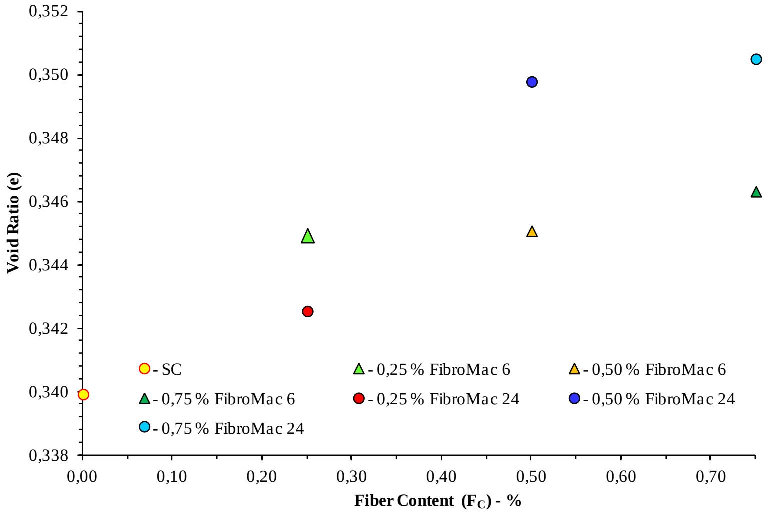

Figure 7 – Average voids ratio versus fiber content and length.
Source: Author (2013).

Therefore, during the tests, the target density was ensured and not the compaction energy to be applied. As a result, the density of each specimen stayed within the acceptable range established in the experimental program. Thus, the increase in void ratio with the inclusion of the fibers was well controlled.

4.2.3. Analysis of the ratio between the elastic tangent modulus (E_T) and the content of fibers and their length

Figure 8 illustrates the obtained individual behavior of the initial tangent modulus of each specimen of the mixtures that have been studied. It is clearly observed a very high reduction of the modulus on increasing the content of fibers in the soil-cement matrix. It is also observed that, for the same content, the influence of the length of the fibers on the Young's modulus is insignificant.

To calculate the initial elastic tangent modulus (ET) the criteria adopted were from the European standard EN 13286-43/March 2004 (Unbound and Hydraulically Bound Mixtures – Part 43: Test Method for the Determination on the Modulus of Elasticity of Hydraulically Bound Mixtures).

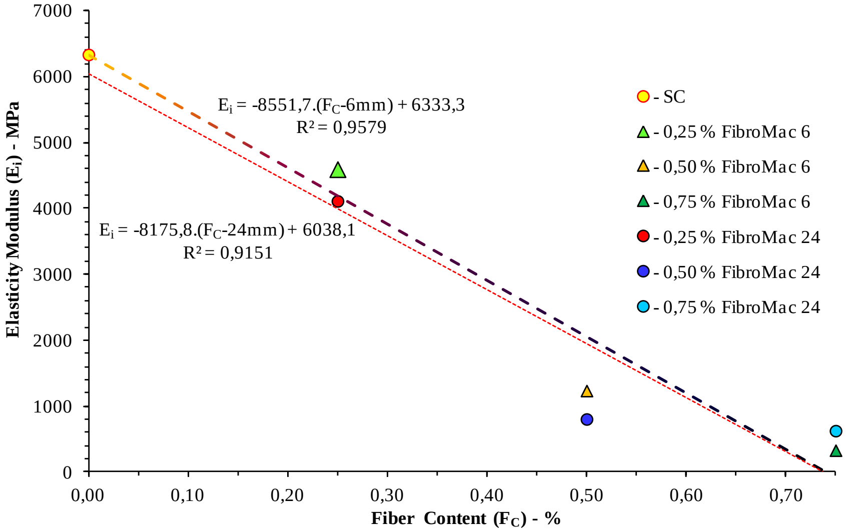

Figure 8 – Average initial tangent Young modulus versus fiber content and length.
Source: Author (2013).

Mixtures with longer incorporated fibers, despite the increased strength achieved from the fiber content, showed a significant reduction in stiffness compared to the unreinforced soil-cement.

This behavior is justified by the fact that the increase in strength is due to triggering the fiber yield under tensile stress after breaking the soil-cement matrix, occurring with progressive overall deformation.

4.2.4. Analysis of the ratio between axial deformation (ε_I) and the fiber content and length

Based on the above results, it is observed that the axial deformation (ε_1) was greatly reduced by increasing the inclusion of fibers in the soil-cement matrix, and this reduction was significantly influenced by the high rise of the deformability of the mixtures with added fibers. Figure 9 illustrates the variation of the deformations of each specimen due to the increase of the content and length of the fibers used in the mixture.

This behavior is justified by the increase of strains due to the increased flexibility of the soil structure where the fibers tend to the give an effect "sponge", inducing higher deformability when the strength is gradually transferred from the cemented matrix to fibers.

A non-negligible factor for the high deformability of the composite soil-cement-fiber is the fact that when assembling these mixtures the fibers are shown in the matrix to be non-yielding, i.e., the fibers are not included already stretched, which implies that they need to deform to trigger their strength.

It is found that, for concentrations of 0.25% to 0.50%, longer compounds are formed by the longer fiber compared to shorter fibers, the consequence of which is that longer fibers need to deform more to trigger their strength.

For a fiber content of 0.75%, this behavior was not observed probably due to the influence of the most satisfactory homogenization provided by the larger in comparation to the smaller fibers.

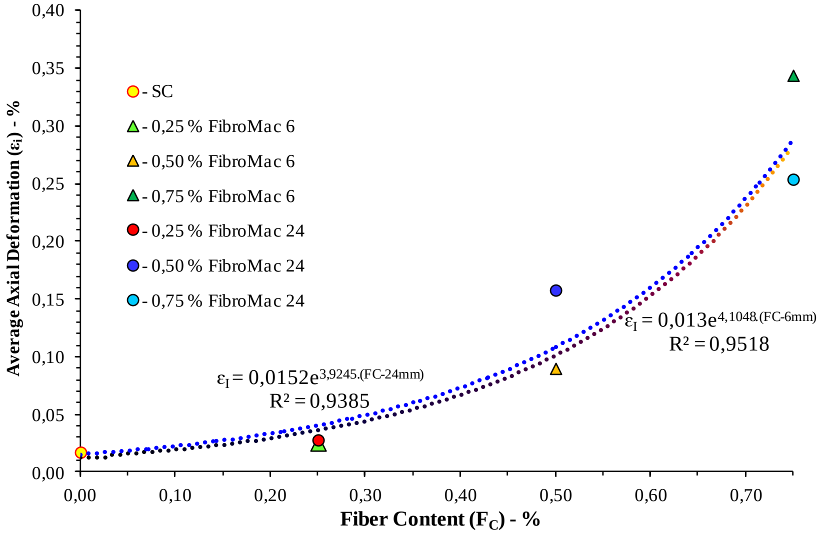

Figure 9 – Variation of the average axial deformation with fiber content and length.
Source: Author (2013).

4.2.5. Analysis of the ratio between unconfined compression strength and void ratio (e)

Although there is no particularly satisfactory correspondence for the shorter fibers, the longer fibers are seen to fit better, albeit below the minimum acceptable value for the correlation factor (R^2). As four points were used on the graph to plot the trend line for each fiber type and a maximum significance level of $\alpha = 5\%$, the lowest critical value should be $R^2 = 0.95$.

Analyzing the graph in Figure 10 it is found that the smaller fiber incorporated in the soil-cement matrix has no significant increase in the voids. However, for the longer fibers there is a more significant variation of this physical index.

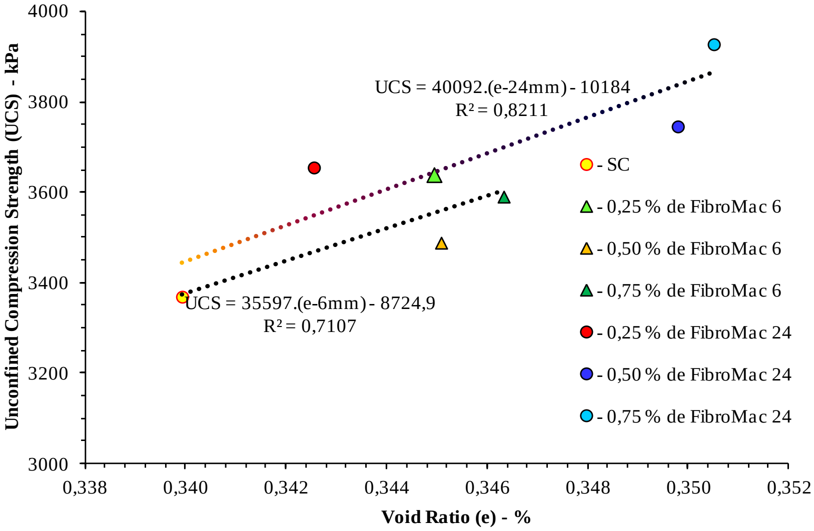

Figure 10 – Relation between the means of resistance obtained in reference to the void ratio for each variable investigated.

Source: Author (2013).

Based on the above reasons, it is understood that the mixtures with the longer fiber resist more in compression, possibly due to a better distribution between the fibers and the soil and cement particles providing a “spongy” cushioning effect (Falorca et al., 2002).

Perhaps because of the smaller size, the 6 mm fiber fits better between the voids left by the grains, thus having less contact between the grains and, thereby reducing the phenomenon of the "sponge", thus reducing the need for increased effort which contributes to a reduction in the number of contacts between the constituent elements of the matrix.

However, the structure of the soil plus cement, together with the degree of compaction exerted, is by nature dense, contributing low voids (e = 0.340) that the fibers do not tend to fill.

An attempted explanation is that, due to their shorter dimension, the fibers have a higher resistance to the separation of the filaments, particularly for higher contents, tending to form tangles and also groups of aggregated filaments, which behave as one large diameter filament that will mostly be working disassembled in the soil-cement matrix.

The authors of this study believe that because the 24 mm fibers are better distributed in the array, a larger number of fibers will be intercepting the failure planes in the break, and therefore this reinforcement will be more efficient. Benson & Khire (1994), state that the number of fibers intersecting the failure plane is more important than the triggered tensile strength.

Figure 11 illustrates the distribution of 6 mm to 24 mm in a fiber-soil-cement matrix, with the 0.75% content in samples after failure by uncofined simple compression.

Endeavoring to make the aforementioned relationship more visible, related to unconfined compression strength with void ratio, it was found that this resulted in a very low correlation with mixtures prepared with smaller fibers, and slightly improved (R^2 = 0.8337) for mixtures molded with longer fibers. Figure 12 illustrates the graph of this relationship.

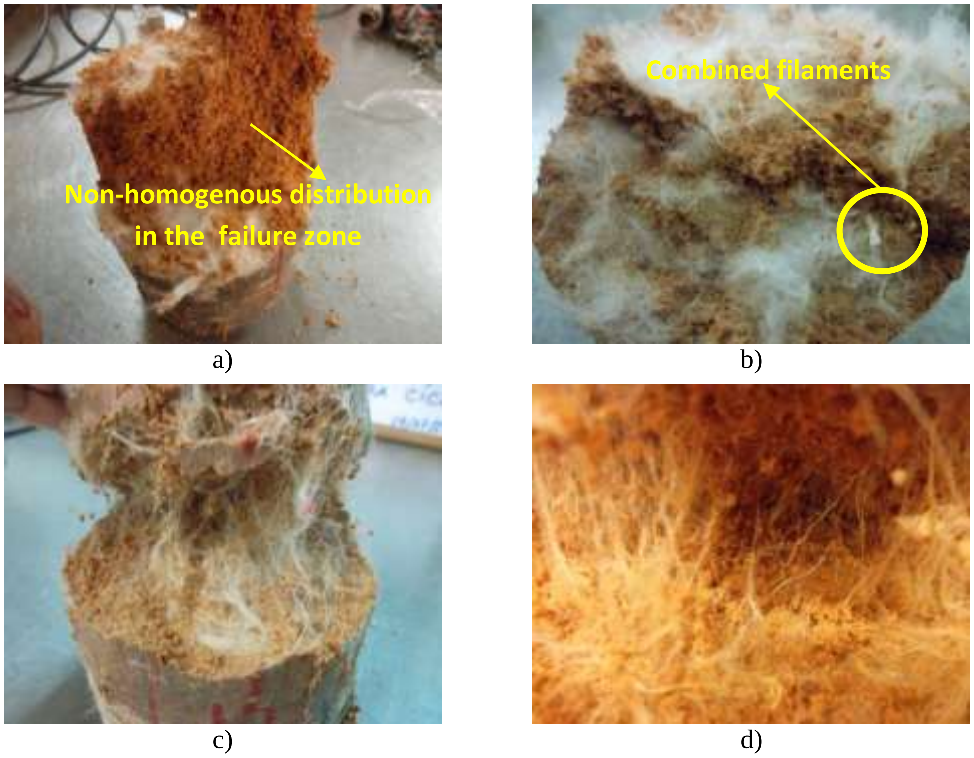

Figure 11 – Examples of fiber distribution in the matrix of composites formed with 0.75% fiber content: a) and b) FibroMac 6 mm; c) and d) FibroMac 24 mm.
Source: Author (2013).

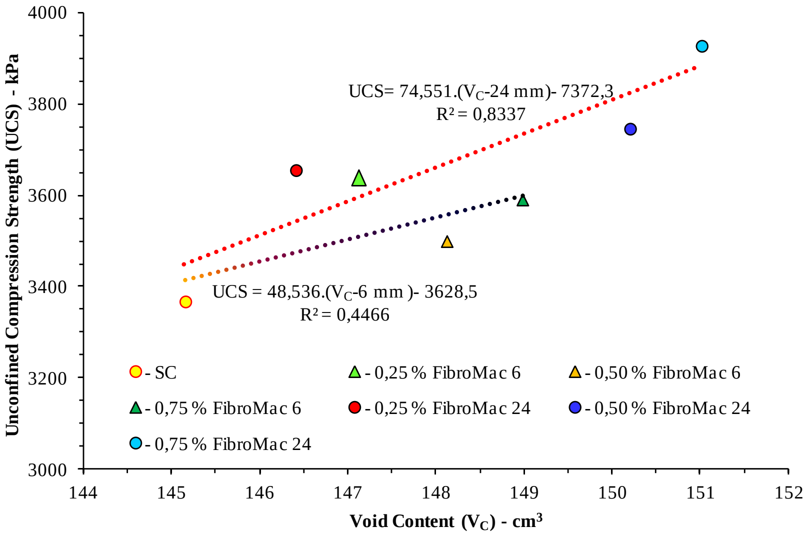

Figure 12 – Illustration of the influence of the fiber distribution in the matrix for different fiber contents and lengths.
Source: Author (2013).

4.2.6. Analysis of indirect tensile test results

To analyze more simply the results of tensile diametral compression of mixtures, Figure 13 illustrates the relation between the average values of tensile strength with the fiber content. Analyzing the graph in the figure, it is apparent that the incorporation of fibers in the soil-cement matrix led to an increase in the mixture's tensile strength, similar to the pattern observed in the unconfined compression tests.

It is noted that the increase in strength was more pronounced when using a 24 mm fiber. It is observed that the results obtained for tensile strength show the same behavior as in unconfined compression tests results: the tensile strength increases with longer fibers.

In the case of shorter fibers, this increase is also noted, but to a lesser extent when compared to the strength provided by the longer fibers. In the case of shorter fibers there was also a slight decrease in tensile strength for the 0.50% fiber content, similar to the results observed for the compression tests.

It is then concluded that increasing the fiber length provides greater benefit by including this fiber. A good correlation is obtained ($R^2 = 0.9673$) with a higher tensile strength with longer fiber content, while in the case of shorter fiber this correlation is significantly lower ($R^2 = 0.5641$).

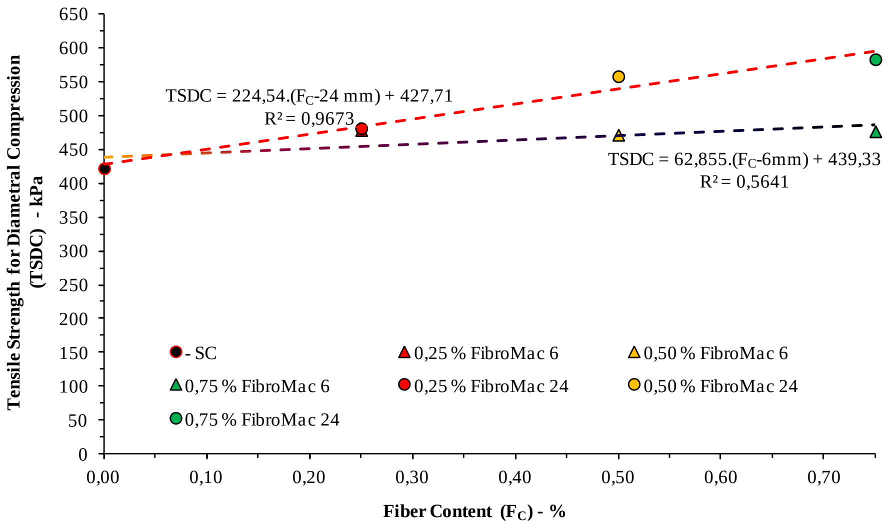

Figure 13 – Average tensile strength by diametral compression of the mixtures versus fiber content and length. Source: Author (2013).

On average, the shorter fiber contributes to about 13% increase compared to the tensile strength of the soil-cement mixture. The longer fiber of 24 mm improves much more significantly the tensile strength due to better distribution in the array of the filaments, providing a satisfactory separation when compared to the smaller fiber, and also due to its size, corresponding to four times the smallest fiber size.

For 0.75% fiber content the longer fibers can increase the tensile strength by about 38.1%. For the 0.25% fiber content both fibers provide substantially the same value. Comparing results from the behavior of both compression and tensile tests, the same pattern of variation is observed, namely, for the 0.25% content both fibers showed quite similar results.

For a fiber content of 0.50% the shorter fibers even reduce the strength, while the longer fibers continue increasing almost linearly the values of strength up to 0.75% fiber content. The homogenization process of the fibers with the soil-cement did not influence the behavior of the results.

5. Conclusions

Based on the tests and results obtained in this study, it can be concluded as follows:

The inclusion of fibers in the soil-cement matrix contributed to increasing the unconfined compression strength, while this increase was more pronounced for the longer fiber (24 mm).

It was also found that the increase in the volume of voids is proportional to the increase in fiber content, and this increase is more pronounced for the longer fiber.

It was clear that the higher the percentage of fibers embedded in the soil-cement matrix, the greater the compaction energy required to maintain the design density and that the increase in fiber content contributed to developing the spongy effect.

It could be alleged that the longer fiber is distributed more homogeneously between the contacts of cemented soil particles, with a stronger impact on the compression strength.

There is evidence that the increase in the axial yield developed during the failure process of the samples is proportional to the increase in polymer fiber content included in the soil-cement matrix.

Based on the results of tensile strength by diametral compression, it was found that the inclusion of fibers in the soil-cement matrix helped increase the tensile strength of the formed composite, in the same way as seen in the unconfined compression strength test results.

It was also found that, irrespective of the content used, the 6 mm fibers contributed to an average tensile strength corresponding to 13.3% in relation to their unconfined compression strength, while the longer fiber contributed to a tensile strength corresponding to 14.9% of their unconfined compression strength, for the 0.50% and 0.75% contents.

It is wishful thinking that the inclusion of fibers in a matrix, cemented or otherwise, increases the tensile strength of the material far more than the unconfined compression strength. To date, in studies reporting the use of fibers as a reinforcement material, no case has been found that claims an increase in tensile strength above the maximum limit of the above-specified interval.

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Notation

The following symbols are used in this paper:

ABNT = Brazilian Association of Technical Standards;
c = effective cohesive intercept;
CC = Cement content;
CP = test specimen;
CP V – ARI = High Initial Strength Portland Cement (HS PC);
D = diameter of the test specimen, expressed in millimeters (mm);
$E_T = (1.2.FR)/(\pi.D^2.\varepsilon_3)$ = elastic modulus in tension, expressed in MegaPascals (MPa);
F_C = Fiber content;
F_R = maximum force sustained, expressed in Newtons (N);
I_A = Activity Index of clay fraction;
$I_P = W_L - W_P$ = Plasticity index;
IR= Insoluble residue
ISSMFE = International Society for Soil Mechanics and Geotechnical Engineering;
LA’ = Lateritic clay sand;
L_F = final axial length of specimen;
L_I = initial axial length of specimen;
W_L = Liquid limit;
W_P = Plastic limit;
k = Permeability;
MCT = Miniature, Compacted, Tropical;
n = Porosity;
NBR = Brazilian standard;
PD = Dispersion ratio;

PMAHC = Metropolitan Park Armando de Holanda Cavalcanti;
PVC = Polyvinyl Chloride;
R^2 = Coefficient of determination;
TSDC = Tensile strength by diametral compression;
UCS = Unconfined compression strength;
$U_{\text{CSSoil-Cement(7 Day)}}$ = Unconfined compression strength of soil-cement after 7-day curing;
V_C = Voids content;
$W_{\text{Ópt}}$ = optimum water content;
γ_{dMax} = dry unit weight;
ΔL = axial variation in length of specimen after testing;
ε_1 = Axial deformation;
ε_3 = longitudinal strain of the specimen, when F = 0.3.FR;
$\varepsilon_v = (L_F - L_I)/ L_I = \Delta L/ L_I$ = axial yield;
ϕ' = Effective friction angle.

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