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Deformational Behavior of Soil-Cement Reinforced with Microfibers

Comportamento Deformacional do Solo-Cimento Reforçado com Microfibras

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Abstract: This article is part of a study undertaken in the Geotechnics Laboratory of Faculty of Engineering of the University of Porto (FEUP) in partnership with the Federal University of Pernambuco (UFPE) on the deformational behavior of the elastic and plastic phases of a soil-cement reinforced with synthetic microfibers, for use as a primer for low-cost roads. A brief study was first developed on the resistance mechanical behavior of the local soil. Through economic and technical criteria it was established that: cement content (CC) = 5%, maximum dry mass density (γ_d) = 19.8 kN/m^3 and optimum water (w_{Op}) = 11%. The maximum dry mass density values and their respective optimal water content were obtained using the soil in its pure state (without cement incorporation), after performing the compaction test applying the intermediate Proctor energy. The 5% cement content incorporated into the soil was adopted because it provides a resistance of 2.1 MPa (NBR-12253/2012), which was considered to offer satisfactory durability and economic feasibility, suitable for use as a primary overlay in rural roads. After setting the cement content (CC = 5%) the second stage of research began consisting of analyzing the mechanical behavior of the soil-cement mix with added contents of 0.25%, 0.50% and 0.75% of synthetic fibers, 6 mm and 24 mm in length and 18 μm in diameter. At the end of the study, it was found that the 0.75% content of 24 mm fiber offered the highest increase in strength and deformation in the soil-cement-fiber matrix. In the third and last stage of the work, in order to analyze the elastic and permanent deformation of the mixture of soil + 5% cement + 0.75% FibroMac-24, a cyclic triaxial test was performed in a high-pressure chamber. This is a special machine that permitted confining pressure to oscillate parallel with the cyclic distortional axial load. The analysis of the results under these loading conditions helped to extract the following instructions that will be presented in the article: it was found that the soil-cement-fiber mixture presents a reduction in the cyclic deformation modulus when compared to the soil-cement mixture, which also presents higher values of permanent deformation (plastic or irreversible), as it presents less difficulty in relation to the soil-cement mixture.

Keywords: Rural Road; Fiber; Cement; Testing; Deformation.

Resumo: Este artigo faz parte de um estudo realizado no Laboratório de Geotecnia da Faculdade de Engenharia da Universidade do Porto (FEUP) em parceria com a Universidade Federal de Pernambuco (UFPE) sobre o comportamento deformacional das fases elástica e plástica de um solo-cimento reforçado com microfibras sintéticas, para uso como revestimento primário em estradas rurais. Inicialmente foi desenvolvido um breve estudo sobre o comportamento de resistência mecânica do solo local. Através de critérios econômicos e técnicos foi estabelecido: teor de cimento (CC) = 5%, densidade máxima de massa seca (γ_d) = 19,8 kN/m^3 e teor ótimo de água (w_{Op}) = 11%. Os valores de densidade máxima de massa seca e respectivo teor ótimo de água, foram obtidos utilizando o solo no estado puro (sem a incorporação do cimento), após a realização do ensaio de compactação aplicando a energia do Proctor intermediário. O valor de 5% de cimento incorporado ao solo foi adotado por proporcionar ao mesmo uma resistência de 2,1 MPa (NBR-12253/2012), o qual adotou-se ser uma resistência de durabilidade satisfatória e de ordem econômica, a ser utilizada como revestimento primário em estradas rurais. Após a definição do teor de cimento (CC = 5%) iniciou-se a segunda etapa da pesquisa que consistiu na análise do comportamento mecânico da mistura solo-cimento com adição de teores de 0,25%, 0,50% e 0,75% de fibras sintéticas de, 6 mm e 24 mm. de comprimento e 18 μm de diâmetro. Ao final do estudo constatou-se que o teor de 0,75% de fibra de 24 mm proporcionou o maior aumento de resistência e deformação na matriz solo-cimento-fibra. Na terceira e última etapa do trabalho, para analisar a deformação elástica e permanente da mistura de solo + 5% cimento + 0,75% FibroMac-24, foi realizado um ensaio triaxial cíclico em câmara de alta pressão. Esta é uma máquina especial que permitiu que a pressão confinante oscilasse paralelamente à carga axial distorcional cíclica. A análise dos resultados nestas condições de carregamento ajudou a extrair as seguintes conclusões que serão detalhadas no artigo: constatou-se que a mistura solo-cimento-fibra apresenta redução no módulo de deformação cíclica quando comparado com a mistura solo-cimento, a mesma também apresenta maiores valores de deformação permanente (plástica ou irreversível), por apresentar menor rigidez em relação à mistura solo-cimento.

Palavras-chave: Estrada Rural; Fibra; Cimento; Ensaios; Deformação.

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1. Introduction

This article is part of a study developed in the geotechnical laboratory at Faculty of Engineering of the University of Porto (FEUP) in partnership with Federal University of Pernambuco (UFPE) on the deformation behavior in the elastic and a plastic ranges, of a soil-cement mixture reinforced with synthetic microfibers, for use as primary coating on low cost roads existing in the Metropolitan Park "Armando de Holanda Cavalcanti" (PMAHC) in "Cabo de Santo Agostinho", 41 km from the city of Recife / PE - Brazil.

The soil used in this study came from the Barreiras geological formation, which is a soil commonly used in geotechnical projects in the Recife metropolitan region and 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 from various coastal basins.

In this study, a rapid high strength cement was added to the local soil with 5% content (relative to dry mass weight of the soil) in order to artificially bond the soil particles, so as to make it less susceptible to the action of water (particularly rainfall) and more resistant to wear caused by the frequent circulation of passenger vehicles.

In other words, the value of 5% of cement incorporated into the soil was adopted to provide it with a resistance of 2.1 MPa (NBR-12253/2012), which means it is a resistance of durability, guarantee and economic order, to be used as primary coating on rural roads.

Based on studies carried out by Feuerharmel (2000), Foppa et al (2007), Viana da Fonseca et al. (2009), Marques et al. (2014), Consoli (2014), Foppa & Consoli (2014), Maghous et al (2014), Silva et al (2013), Severo (2011), the incorporation of cement into the soil influences the following properties: unconfined compressive strength, diametrical tensile strength, initial stiffness, deformation modulus, yield stress, volumetric deformation and, mainly, hydraulic conductivity and resistance to chemical attack. In the case of the inclusion of fibers in the soil-cement mixture, most studies show that there is an improvement in resistance due to the action of the fibers, which lead to 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 rigidity, some disadvantages can be identified, such as: the materials become too fragile, the tensile strength, although superior, quickly evolves to zero values after rupture, giving rise to fragile and dangerous behavior and there is a tendency to crack during drying, especially when exposed to the environment.

To avoid the aforementioned disadvantages, polypropylene fibers were added to the matrix, since polymeric materials have greater elasticity, with consequent more variable and wider ductility, good tensile strength, and after breaking the cementitious bonds, they become much more versatile for intensive load situations, such as cyclic loading in transient climatic situations. The combination of these components forms the so-called composite geomaterial, which tends to develop more suitable geomechanical and hydraulic characteristics: strength, rigidity, ductility, fragility, energy absorption, deformation capacity and post-cracking behavior, greater permeability, when compared with soils or soil-cement mixtures, from which they originated. Therefore, more suitable for use as a primary coating.

The incorporation of fibers with a diameter of 18 μm and length of 24 mm, and a 0.75% content in relation to the dry mass weight of soil and cement, was intended to develop a composite material, more flexible (but as resistant as the soil-cement), which reduces the number of cracks developing with the local constant variation in humidity and temperature, and providing a residual strength even after possible breakage of the cement bonds between the soil particles in the matrix, after subject to heavy vehicle traffic.

A high-pressure chamber was used to analyze the elastic and permanent deformation of the soil-cement-fiber mixture. This is a special machine that allowed triaxial confining pressure to oscillate parallel with a cyclic axial distortional load. The elastic and plastic deformation of the ground mixture with 5% cement, used as a reference, were compared with the mixture subject to more detailed study: soil-cement (5,0%) and (0.75%) fiber. Both mixtures were subjected to cyclic loading with the deviatoric stress, but with constant confining pressure, by one side, and variable confining pressure, by other, in this case with the confining stress increase in phase with the increase of the axial distortional stress. This latest model test is the most representative of the stress state to which the materials of the layers of a pavement are submitted. The mixtures underwent 260.000 cycles with constant ranges of axial deviatoric stresses and a constant frequency of 1 Hz.

The analysis of the results, within these loading conditions, permitted the conclusions that will be detailed in the article below; it was found that the mixture of soil-cement-fiber displays lower cyclic deformation modulus values when compared with the corresponding soil-cement mixture; the soil-cement-fiber mixture develops higher values of permanent deformation (plastic or irreversible), due to its lower stiffness when compared with the soil-cement mixture; it was also found that the variation in the multiple (axial and confining) cyclic pressurizing, i.e. when there was a simultaneous variation of confinement and axial loading in phase, a higher permanent deformation occurred, which means that this is a higher damaging stress-path for the material microstructure, revealing the importance of this test protocol.

2. Experimental Program

The experimental program was developed in three stages.

The first stage consisted of the study to determine the cement content that should be included in the ground, so that the resulting mixture would achieve strength of 2100 kPa after seven-day curing, as stated in NBR-12253/2012. At this stage, the study was undertaken using three different pairs of compaction results (γ_d; w_{Op}), submitted to four different cement contents. At the end of the present stage the cement content and pair (γ_d; w_{Op}) were chosen and established in later studies.

In the second stage of the research, a study was undertaken based on carrying out Unconfined Compression Strength tests, in which the resistive and deformational behavior of the soil-cement was observed when polymer fibers 6 mm and 24 mm in size were included in the contents 0.25%; 0.50% and 0.75%, in relation to the soil-cement ratio. After finalizing the study, the size of the fiber and its content were chosen that had stronger influences on the stress-deformation behavior of the soil-cement mixture.

In the third and last stage, the elastic and plastic behavior of the soil-cement and soil-cement-fiber were examined by carrying out a cyclic triaxial test, with and without variation in the confinement stress (σ_3). At this stage, both mixtures underwent a total of 260.000 loading-unloading cycles, with the deviation stress (σ_1) being applied with equal frequency 1 Hz.

2.1. Characterization of soil from the Barreiras geological formation

The studied soil belongs to the so-called Barreiras geological formation, which is a major geological unit stretching throughout the 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 $w_P = 18\%$.

The fine fraction of the soil belongs to the group of inorganic low plasticity clays. The clay fraction is considered inactive, since it has an activity index of IA = 0.4. Due to the dispersion ratio Middleton (1930) the soil is considered erodible because PD = 100% was obtained. 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 test and classifications.

The resulting characteristic curve, a bimodal curve, is typical of soils in which grain size distribution is poorly graded, with an open gradation. This is in accordance with the uniformity of the soil, having a narrow distribution of particle sizes (see Table 1). Through direct shear tests in a flooded condition, the soil presents a cohesive intercept c' = 2.1 kPa and friction angle of $\phi' = 31.1^o$.

The soil permeability, determined by a permeameter in lab, was: $k = 6.45.10^{-6}$ m/s. Table 2 shows the values of the maximum dry mass density results and their optimum water for the three types of Proctor energy applied. Further information on the laboratory tests and results can be found in Guedes (2013) and Lafayette (2006).

Table 1 – Grain Size Distribution.

Fraction	Grains	Content
Fine Gravel	2.0 mm < ø < 6.0 mm	3%
Coarse Sand	0.6 mm < ø < 2.0 mm	12%
Medium Sand	0.2 mm < ø < 0.6 mm	28%
Fine Sand	0.06 mm < ø < 0.2 mm	20%
CoarseSilt	0.02 mm < ø < 0.06 mm	3%
MediumSilt	0.006 mm < ø < 0.02 mm	2%
Fine Silt	0.002 mm < ø < 0.006 mm	2%
Clay	ø < 0.002 mm	30%

Source: Authors (2025).

Table 2 – Parameters Obtained in Function of the Applied Compaction Energy.

Parameters	Compaction Energy		
	Normal	Intermediate	Heavy
1 - Applied Compaction Energy (kg.cm/cm^2)	5.7	12.6	26.6
2 - Optimum Water Content (%)	12.5	11.0	10.2
3 - Maximum Unit Weight (kN/m^3)	18.6	19.8	20.5
4 - Void Ratio	0.43	0.34	0.29
5 - Porosity (%)	29.9	25.3	22.6
6 - Degree of Saturation (%)	77.8	86.2	92.4
7 - Air Content (%)	6.6	3.5	1.7

Source: Authors (2025).

2.2. Characterization of Polypropylene Fibers

The fibers used were developed 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 3.000 MPa, a specific gravity of 9.1 kN/m^3, 1.10^{-6} m diameter and lengths from 6 mm to 24 mm.

2.3. Characterization of The Rapid Strength Cement

The cement used throughout the research was the High Initial Strength Cement also known as Fast-Curing Cement. In Portuguese it is called “Alta ResistênciaInicial” (ARI). The used cement is produced in Pacatuba plant, Sergipe state, being referred to as the acronym CPV-ARI. Table 3 below identifies its characteristics.

Table 3 – Chemical, physical and mechanical properties of cement ARI.

Type of Tests							
Chemical (%)				Physical (kN/m^3)	Mechanical: Uniaxial Comp. Strength - MPa		
Loss of fire	RS	SO_3	CaO free	Specific mass	1 day	3 days	7 days
4,50	0,54	3,50	2,15	31,2	19,7	20,7	29,4

Source: Authors (2025).

3. Methods

3.1. Determination of Content Cement

After characterizing the materials the study began to determine the cement content.

At this stage, a brief study was developed using the Unconfined Compressive Strength (UCS) test, on the influence of the cement content and compaction energy on the strength of the soil-cement mixture.

In the UCS test, cylindrical specimens 50 mm in diameter and 100 mm in height were molded in optimum water (w_{Op}) and dry maximum density (γ_d), determined by the compaction tests in the normal Proctor energies, intermediary and modified for pure soil (Table 2).

For each pair (w_{Op}; γ_d) the contents 3%, 4%, 5% and 6% of cement were used in weight in relation to the dry soil mass.

The curing time set for the specimens was six days in a wet chamber and 24 hours immersed in a recipient containing distilled water at room temperature. Then they were superficially dried and broken at a constant deformation velocity of 1.00 mm/minute.

For each cement content adopted, three (3) specimens were molded. As an acceptance guideline for the test, it was assumed that the individual strengths of the three specimens considered identical were not more or less than 10% of the average strength of this group. Thus, a total of the specimens molded were of: three (3) (applied compaction energy) x four (4) (cement contents used) x three (3) (number of replicas of each adopted condition) = 36 CPs.

3.2. Determining Fiber Content

After performing the study on the influence of the cement on the soil-cement strength, a second study was developed involving polymer fibers in the soil-cement matrix. In this study, the fixed parameters were: content cement = 5%, w_{Op} = 11% and γ_d = 19.8 kN/m^3. The variable parameters were: fiber content (0.25%; 0.50% and 0.75%) and length (6 mm and 24 mm). The Maccaferri polypropylene fibers were chosen during the study since they had more homogenous characteristics in terms of dimension and physical and chemical properties.

At this stage, cylindrical specimens were used 70 mm in diameter and 140 mm in height.

After preparing and molding the specimens, they were placed inside a wet chamber where they remained for a 24-hour period and then demolded, weighed and their dimensions measured. Next, the specimens were again placed in the wet chamber where they remained for a 19-day period. On the 20th day they were immersed in drinking water and removed after two (2) days to carry out the Unconfined Compressive Strength test. Lastly, after the failure of the specimen, the process began to determine the suction present, placing filter paper (Whatman N^0 42) exactly on the two parts of the zone where the strain wedge occurred.

A total of 18 specimens were molded, and the acceptance criterion of the test was the same as adopted when determining the cement content. At the end of the study, it was found that the 0.75% content of 24 mm fiber, when included in the soil-cement matrix, more strongly influenced the stress-deformation behavior of the mixture.

3.3. Analysis of Cyclic Deformational Behavior

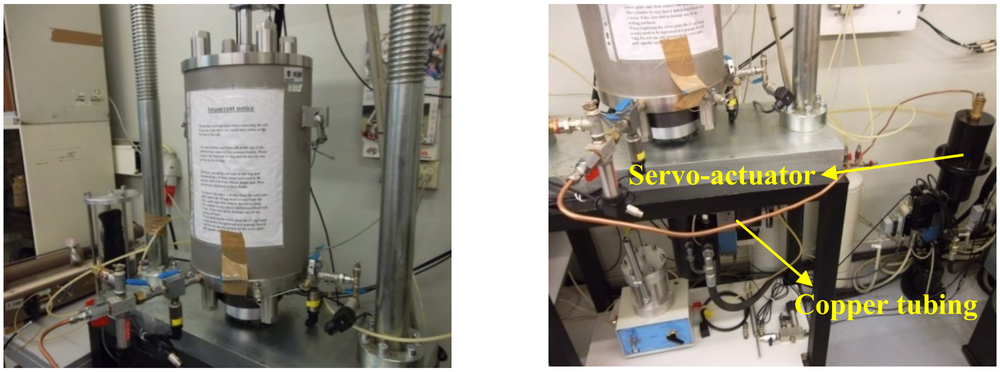
The cyclic deformational behavior of the soil-cement-fiber mixture was analyzed by performing the cyclic triaxial test, with and without a variation in the confining stress.

Cyclic triaxial tests were conducted using test specimens of ø = 70.0 mm and h = 119.0 mm.

With the objective during the radial cycling process of eliminating possible deformations in the sides of the conventional triaxial cell (the side made of acrylic) and to obtain further accuracy in the variation of the confining pressure logged by the pressure gauge, it was decided to use the high-pressure chamber (figure 1 a)), which has all its parts made in steel and can withstand a maximum pressure inside of 10 MPa (ten megaPascal).

For further contribution to the accuracy of the oscillation of the confining pressure, instead of using rubber tubing that could dilate during the radial cycling process, copper tubing was used (figure 1 b)) that would connect the servo-actuator (confining pressure servo-actuator – responsible for the oscillation of the confining pressure inside the chamber) to the triaxial high-pressure chamber.

For the triaxial system used, the water piping connecting the servo-actuator and triaxial chamber must be adapted to the circulating flow, admitting as short and as rigid as possible, so that its elasticity does not interfere in the pressure servo-command.



a) b)

Figure 1 – a) High Pressure Chamber and b) Copper Tubing.
Source: Authors (2013).

The test specimen cycling process used two (2) models:

3.3.1 Axial Cycling

In this model, the test specimens were submitted to stress increasing and decreasing cycles only in their axial direction, keeping the confining pressure constant at 20 kPa. The choice of their value was due to the fact that the material examined is designed as a paving primer, the structure being located on the road surface.

The maximum axial stress applied corresponded to tire-pavement contact stress, considering the standard axle established by AASHTO (American Association of State Highway and Transportation Officials), known as a highway standard axle, which consists of a single axle with double tires, whose tire-pavement contact pressure stress is 5,6 kgf/cm^2 = 560 kPa.

After the general inspection of the system, the cycling process began consisting of an application of 260.000 non-stop loading-unloading cycles. Assuming a frequency of 1 Hz, that is, one loading and unloading cycle in a one-second period (T), the test lasted around 72 hours (three days x 24 hours x 60 minutes x 60 seconds = 259.200 seconds → 259.200 cycles).

Since this is a non-destructive test, only one test specimen was used for each material.

3.3.2 Axial and Radial Cycling

In this cycling model, the test specimens underwent pressure increasing and relief cycles both in the axial and radial direction.

To perform the axial and radial cycling tests, both at the same time, the first procedures adopted were the same as described for the axial cycling test. However, the increase in confining pressure was programmed in the electromechanical system at 20 kPa at the same time as the axial stress reached 560 kPa. When the axial stress reached the pressure of 560 kPa, the confining pressure was 40 kPa. At the moment of relief, that is, zero axial stress, the confining pressure dropped to 20 kPa.

These two types of procedures were performed to the mixture of soil + 5% cement and soil + 5% cement + 0.75% FibroMac-24. Figure 2 illustrates the diagram of the load application for the two cycling models used.

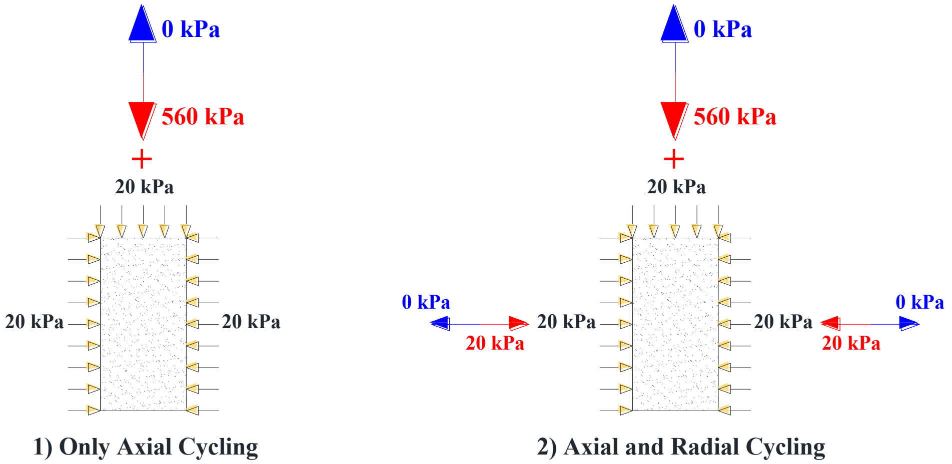


Figure 2 – Cycling Process.
Source: Authors (2013).

4. Results and Discussion

4.1. Analysis of The Influence of Cement Content and The Compaction Energy on The Characteristics of The Mixtures

4.1.1. Analysis of the Effect of Cement Content on the Resistance of Soil-Cement

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. (2009), 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.

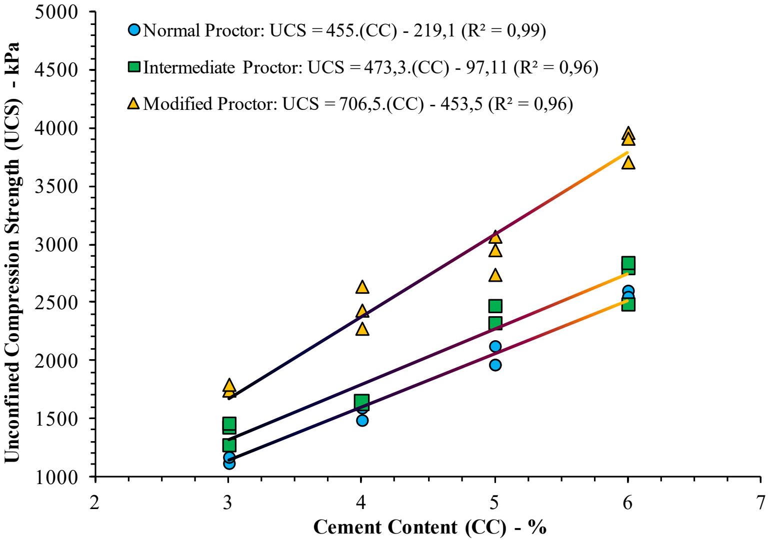


Figure 3 – Variation of mechanical strength due to cement content and compaction.
Source: Authors (2013).

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.

4.1.2. Analysis of the Ratio Voids/Cement in Soil-Cement Strength

Figure 4 presents the graph of the variation of UCS with the ratio between volume of voids and the content of cement. The fitting curve was obtained based on the average of UCS and the ratio Voids/Cement, of all three relevant specimens in each cement content and compaction. Analyzing the graph it can be observed that UCS increase is 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 a ratio of Voids Ratios (or Porosity) over Cement Content. For the conditions tested, the fitting curve resulting in the highest correlation coefficient is the power type.

The exponent value of the voids/cement parameter ($n/C_{iv}^{0.77}$) obtained during this study, was less when compared to those obtained for soils with a larger particle composition than that of the present soil in the study. But, agrees with the results of the tests performed by Severo et al. (2010), Vitali (2008), Cruz (2008) and Foppa (2005). These researchers found that the large the particle composition of the soil, the larger the adjustment exponent in the denominator of the voids/cement parameters $[n/(C_{iv})^{\mathrm{Exponent}}]$ in the curves of the UCS x $n/(C_{iv})^{\mathrm{Exponent\ ratio.}}$

At the end of the study, for both economical and technical reasons, it was decided to use the variables: CC = 5%; w_{Op} = 11% and γ_d= 19.8 kN/m^3.

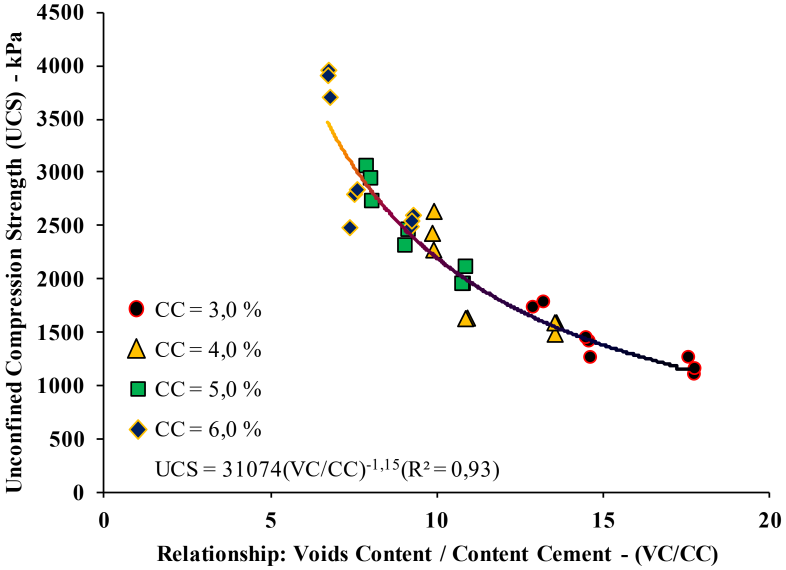


Figure 4 – Unconfined Compression Strength Variation of the Voids/Cement Ratio.
Source: Authors (2013).

4.1.3. Analysis of the influence of the content and length of the fibers on the Soil-Cement

In this study, it was observed that the inclusion of fibers in the soil-cement matrix contributes to increasing compressive strength. It was observed that the increase in resistance was more pronounced when using larger fiber lengths (24 mm).

The results shown in figure 5, refer only to the resistance developed by the cohesive cement bonding (structural-chemical resistance), the degree of compaction (physical component: fabric) and influence of the presence of fibers (flexibility) in the matrix, i.e., the value failure or ultimate load subtracted from the suction pressure that can be acting in non-saturated conditions.

This last component of suction was considered irrelevant, since, in average its value corresponds to 3,22 % of the UCS.

Looking at the graph of figure 5 it can be seen that even for the lowest fiber content (0.25%) in addition to the contribution of soil-cement matrix, a significant increase in the uniaxial compressive strength is observed.

It is noticed first that it is not the maximum cement content that provides maximum strength to soil-cement mixture, because a small amount of fiber in the soil-cement matrix does not incur in an increase of UCS of the composite, in view of the breakdown of bonding links between soil grains developed by cement. Therefore, one would expect a proportionate reversal of strength, due to the drop in cement links between soil grains caused by the presence of the fibers and also a possible reduction of the friction between the grains because of the presence thereof.

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

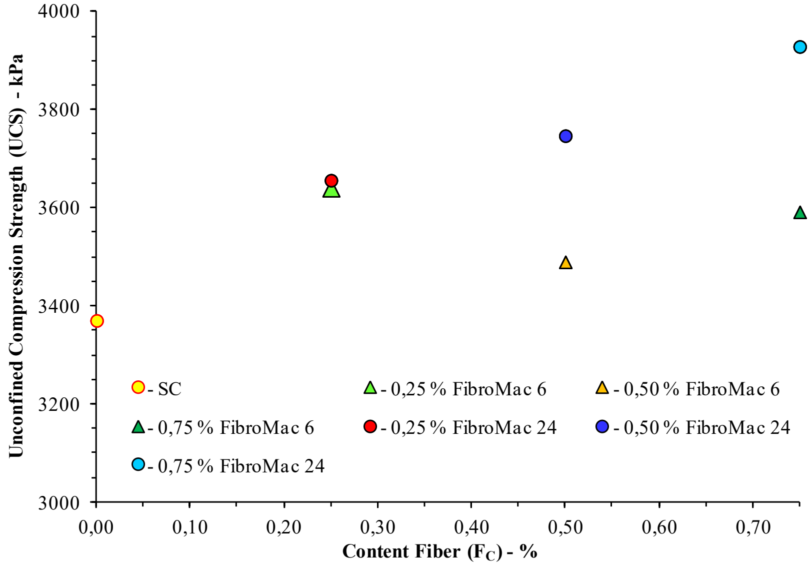


Figure 5 – Average Unconfined Compression Strength Versus Content and Length of the Fibers.
Source: Authors (2013).

4.1.4. Analysis of the ratio between Unconfined Compression Strength and Fiber Content and Length

Figure 6 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.

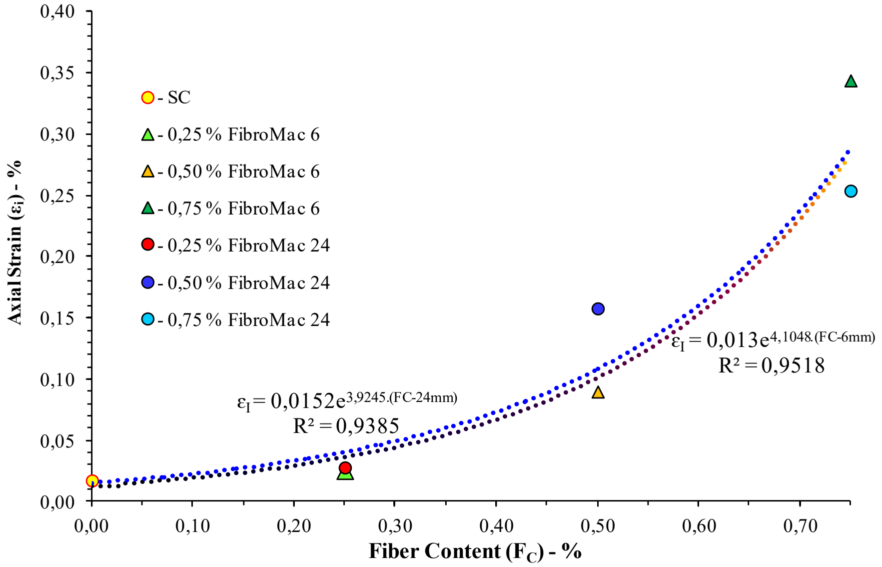


Figure 6 – Variation of The Average Axial Deformation With Fiber Content and Length.
Source: Authors (2013).

. It is observed that the initial tangent Young's modulus (E_I) was greatly reduced by increasing the inclusion of fibers in the soil-cement matrix, and this reduction was strongly influenced by the high increase in deformability of the mixtures with added fibers. This behavior is justified by the increase in strain due to the increase in flexibility of the soil structure where the fibers tend to give a "spongy" effect, 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 non-elongated in the matrix, i.e., the fibers are not included already stretched, which implies that they need to deform to trigger their strength.

For concentrations of 0.25% to 0.50%, longer compounds formed by the longer fiber compared to shorter fiber is a consequence of the need for the longer fibers to deform more to trigger their strength.

For a fiber content of 0.75% this behavior was not noted probably due to the influence of the more satisfactory homogenization by the larger fibers in relation to smaller fibers. The latter may have adhered more effectively to form a larger diameter filament, which, when mobilized in strain, first began to slide over each other to better accommodate in the layout in order to begin contributing to the compressive strength of the mixture.

4.2. Analysis of The Cyclic Deformational Behavior of The Materials

Data from the irreversible and reversible deformations and the resilient modules of each material were obtained for the following numbers of cycles: 1, 2, 3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16, 17, 18, 19, 20, 50, 100, 200, 400, 1.000, 2.500, 5.000, 7.500, 10.000, 12.500, 30.000, 40.000, 50.000, 60.000, 70.000, 80.000, 90.000, 100.000, 120.000, 140.000, 160.000, 180.000, 200.000, 220.000, 250.000 and 260.000.

The cyclic module (CM) was obtained by calculating the tangent of the straight line joining the maximum and minimum points of the deformation caused during a loading and unloading cycle.

The formula used for calculating the cyclic module, with the confinement pressure varying in phase with the deviatoric stress, depends not only on the axial deformation but also on the radial deformation, as can be see in the following equation (1).

$$MC = \frac{(\sigma_1 - \sigma_3).(\sigma_1 + 2.\sigma_3)}{(\sigma_1 + \sigma_3).\varepsilon_I - 2.\sigma_3.\varepsilon_R} \tag{1}$$

4.3. Behavior of the Cyclic Module (CM)

In the figure 7 shows in detail the behavior of the cyclic module during the 260.000 loading and unloading cycles for the soil-cement-fiber compared to the soil-cement.

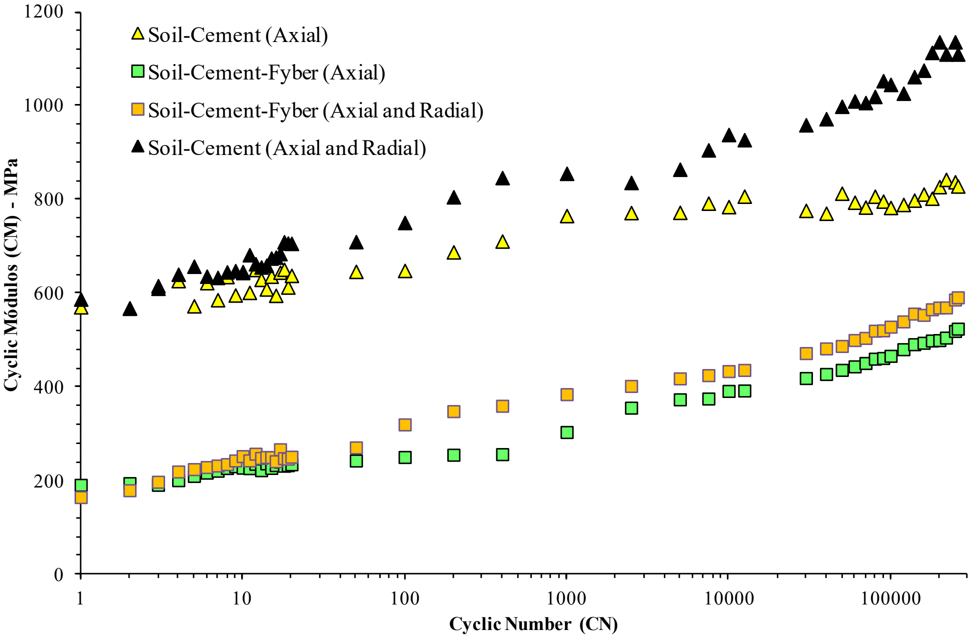


Figure 7 – Cyclic Modulus Function Cyclic Number.
Source: Authors (2013).

It is clearly evident that the soil-cement is the material that has the higher cyclic module value. This behavior is justifiable based solely and exclusively on its rigidity, which contributes significantly to a smaller axial deformation when applying a certain increase in load, compared to the soil-cement-fiber.

Soil-cement-fiber is the material that has less cyclic module (CM) value by becoming more deformed in the direction of applying the load, due to the presence of the fibers that make the material less rigid by increasing the spongy behavior with the increase in fiber content.

Comparing the behavior of the cyclic modules of both materials, it is found that both have an upward trend due to the number of cycles. Possibly this increase is caused by the reduction in elastic deformation with a growing increase in plastic or irreversible deformation, due to the breaks in the cementious bonds.

It is also noticeable that the results of the cyclic modules are always higher for the condition where the confinement pressure oscillates at the same time as the deviatoric stress (condition: axial and radial).

Possibly the variation in confining pressure with the deviatoric stress has contributed to less elastic deformation of the material by increasing the confinement, which in turn immediately increases the consolidation of the material's structure during the application of the axial load.

It is also found that the usual condition of determining the cyclic module (σ_3 = constant) offers greater damage to the pavement structure by causing greater elastic deformation in the materials of the layers.

4.4. Elastic Deformation Behavior (ε_E)

When comparing the materials (figure 8), it is found that the soil-cement-fiber is the material that has the greatest decrease in elastic extension with the increase in the number of cycles (which provided a greater increase in the cyclic model).

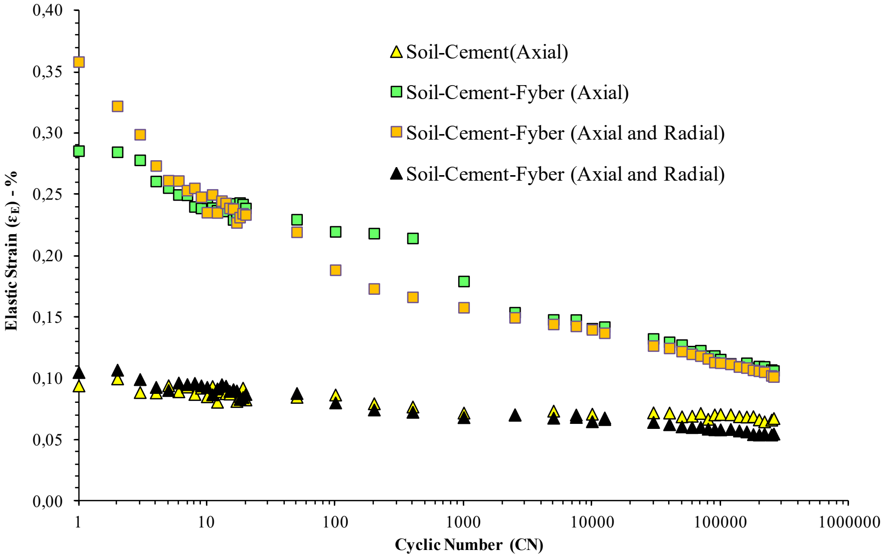


Figure 8 – Elastic Length Function Cyclic Number.
Source: Authors (2013).

The justification for this behavior is due to the sharper increase in the accommodation of particles caused by the number of cycles.

This increased accommodation of particles in the matrix contributed to a higher number of contacts between them, which gave rise to greater friction and consequently less displacement between the particles, to cause smaller elastic deformation during the cycles.

For the soil-cement mixture, the elastic deformation during the cycles has almost the same behavior for the two cycling conditions. However, around 30.000 cycles, the axial and radial condition provides less elastic deformation, thereby contributing to higher values of the cyclic module.

For the soil-cement-fiber mixture, greater deformations are found for only the axial cycling condition, therefore, higher result for the cyclic module. However, there is a trend to be closer to the results along the numbers of cycles.

The cyclic triaxial test, with constant confining stress, is the most commonly used test when determining elastic parameters of the materials for study in order to dimension the thicknesses of the layers of a pavement, but the cyclic triaxial test, with oscillating confining stress in accordance with the deviatoric stress, is the test model closest to the actual stress state to which the materials of the pavement layers are submitted. Nevertheless, it is seen that the most frequently used cycling process (only axial) contributes to a more secure dimensioning by providing larger thicknesses for the pavement layers due to the low value obtained from the cyclic module.

4.5. Permanent Deformation Behavior (ε_P)

When analyzing the permanent deformation of the materials during the 260.000 cycles performed in the cyclic triaxial test with σ_3 = constant, it is found that this increases as a result of the increase in the number of cycles (figure 9).

It is found that the soil-cement-fiber is the material with the greatest irreversible deformation, that is, the greatest plastic deformation among the materials. Probably the significant increase in permanent deformation in this particular material is caused by the low rigidity provided by the structure of its matrix.

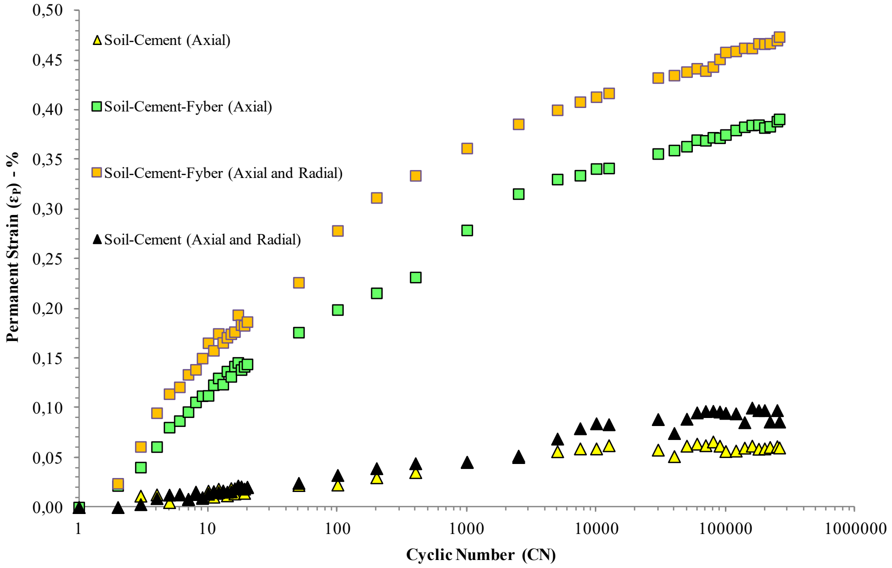


Figure 9 – Permanent Strain function cyclic number.
Source: Authors (2013).

The soil-cement showed high rigidity, due to the low void index, combined with the high cohesion caused by the artificial cementation, and is the material with the least permanent deformation during the cycles. Possibly, due to the close bonding existing between the soil and cement particles, the permanent deformation develops by breaking the cementitious bonds and not because of the accommodation of the particles.

When addressing the soil-cement-fiber material, due to the structure model of its matrix, possibly the permanent deformation has developed initially through the rearrangement of the particles followed by the break in cementitious bonds.

In both types of mixtures, it was found that the axial and radial cycling provided greater permanent, say plastic, deformation, while this behavior was more developed for the soil-cement-fiber mixture.

5. Conclusions

Based on the tests and results in the study herein, the following can be concluded:

Concerning the analysis of the influence of Cement Content and the Compaction Energy on the characteristics of the mixtures:

It was understood that the mechanism by which the reduction in porosity influences the increase in soil-cement strength is related to the existence of a larger number of contacts and greater interlocking between soil particles, and that the increase in unconfined compression strength was proportional to the increase in the volume of cement and inversely proportional to the increase in the volume of voids.

When addressing the voids/cement parameter $(n/C_{iv}{}^{0.77})$ obtained during this study, the exponent value (0.77) was less when compared to those obtained for soils with a larger particle composition than that of the present soil in the study. But agrees with the results of the tests performed by Severo et al. (2010), Vitali (2008), Cruz (2008) and Foppa (2005). These researchers found that the large the particle composition of the soil, the larger the adjustment exponent in the denominator of the voids/cement parameters $[n/(C_{iv})^{Exponent}]$ in the curves of the UCS x $n/(C_{iv})^{Exponent}$ ratio.

Concerning the analysis of the influence of the fiber content and length in the soil-cement:

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

It was evidenced that the increase in the axial extension developed during the failure process of the test specimens is proportional to the increase in the fiber content in the soil-cement matrix.

Concerning the cyclic deformational behavior:

The soil-cement-fiber is the material that shows least cyclic module value by becoming more deformed in the direction of load application, due to the presence of the fibers that make the material less rigid by providing an increase in the spongy behavior with the increase in fiber content.

It was found that the since the soil-cement-fiber mixture is less rigid it is the material that present the greatest irreversible deformation; that is, greater plastic deformation between the materials, while the soil-cement, by assuming high rigidity, is the material that has less permanent deformation during the cycles. However, considering the traffic and type of vehicle to which the material is submitted it will behave efficiently.

It was also evidenced that, the variation of the confinement pressure in the phase type model with the variation of the stress deviation, is the condition that provides a tension path more damaging to the structure of the material because it provides a high permanent deformation along the load cycles and discharge.

At the end of the 260000 loading and unloading cycles, the soil-cement-fiber material had an irreversible deformation of 0.46%, i.e., 0,552 mm (in the cyclic triaxial tests, test specimens 120 mm in height and 70 mm in diameter were used) of permanent deformation. This deformation is considered negligible for an unpaved road, since it only presents a default in centimeters. Transforming the load number of the standard axle (8.2 tf per axle) for the axle of a passenger vehicle (0.50 tf per axle), using the aggression factor (f), it is found that to produce the permanent deformation of 0.552 mm under the established conditions, the traffic of 9.404.106 passenger vehicles is required. This is an extremely high number of vehicles, and to repair the ruts from wheel tracks in the road, it involves a very long period between one repair and another. According to Medina & Motta (2005), in some countries, the admissible value of rut depth from wheels on paved highways is 10 mm, and for roads with less traffic volume it could be 16 mm, but if it reaches 20 mm this would require immediate repair.

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Notation

The following symbols are used in this paper:

C_{iv}- Volumetric Content of Cement
INCT-REAGEO - Geotechnical Institute for Rehabilitation of the Slope-Plain System and Natural Disasters
PRONEX - Support Program for Centers of Excellence
CNPq - National Council for Scientific and Technological Development
CAPES - Coordination for the Improvement of Higher Education Personnel
FNDCT - National Fund for Scientific and Technological Development
FAPEMIG - Minas Gerais State Research Support Foundation
FAPERJ - Carlos Chagas Filho Foundation for Research Support in the State of Rio de Janeiro
FAPESP - São Paulo State Research Support Foundation
NBR - Brazilian Standard
MCT - Minister of Science and Technology
γ_d - maximum dry mass density
w_{Op} - optimum water
w_L - liquid limit
w_P- plastic limit
PD - dispersion ratio
MCT - Miniature, Compacted, Tropical
c' - cohesive intercept
ϕ' - friction angle
k - permeability coefficient
CP - test specimen
CPs - test specimens
σ_3- confined pressure

σ_I- axial stress = stress
ε_I- axial strain
ε_R- radial strain
ε_P- permanent strain
ε_E- elastic strain
CM- Cyclic Modulus
IA - Activity index of clay fraction
LA' - lateritic clay sand
CP V - ARI - High Initial Strength Portland Cement
RS - Sulfate resistance
UCS - Unconfined Compressive Strength
ø - test specimen diameter
h - test specimen height
AASHTO - American Association of State Highway and Transportation Officials
CC - Cement content
FibroMac- Polypropylene fibers manufactured by the company Maccaferri
E_I - Young's modulus
n - Porosity

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