Revista Perspectivas Online: Exatas & Engenharia
Dezembro/2024, v.15 , n.39 , p.1-18
ISSN: 2236-885X (Online)
DOI: 10.25242/885X153920242811

ANÁLISE DO COMPORTAMENTO MECÂNICO DE AGREGADO DE BASE TRATADO COM CIMENTO E ADIÇÃO DE FIBRA SINTÉTICA

Rodrigo Pires Leandro[1], Márcio Antônio Zardini Santos[2], Ana Luiza R. Rodrigues[3], Luis Miguel Gutierrez Klinsky[4]

RESUMO

LEANDRO, R, P.; SANTOS, M. A. Z.; RODRIGUES, A. L. R.; KLINSKY, M. G. Análise do comportamento mecânico de agregado de base tratado com cimento e adição de fibra sintética. **Perspectivas Online: Exatas & Engenharia**, v.15 , n.39 , p.1 -18 , 2024.

Foi realizado um estudo experimental com o objetivo de investigar o efeito da adição de fibras de polipropileno no comportamento mecânico de britas graduadas tratadas com cimento. O programa experimental envolveu os seguintes ensaios mecânicos: resistência à compressão, ensaio de flexão, módulo de flexão e tenacidade, além de análises por microscopia eletrônica de varredura. Foram testadas duas misturas com adição de fibras (0,25% e 0,50% em massa em relação ao agregado) e comparadas com a mistura de referência, sem fibra. A fibra utilizada foi do tipo polipropileno, com comprimento de 60 mm. Todas as misturas foram ensaiadas após 28 dias de cura úmida, exceto as amostras destinadas aos ensaios de tenacidade, que foram curadas por 100 dias. As misturas utilizaram cimento CP-II-E-32 (norma brasileira para cimentos compostos com 34% de escória), com teor de 5%. Os resultados indicaram que a inserção de fibras dificulta a compactação da mistura, resultando em uma redução do grau de compactação e, consequentemente, da resistência à compressão simples. No entanto, a presença das fibras proporcionou aumentos significativos na tenacidade e na resistência à tração. O entrelaçamento das fibras na estrutura interna da matriz promoveu um efeito de ancoragem.

Keywords: Pavimento. Base. Cimento.

[1]Professor, Departamento de Engenharia Civil, Universidade Federal de Uberlândia, Uberlândia, Brasil; rodrigo.leandro@ufu.br
[2]Pesquisador, Departamento de Engenharia Civil, Universidade Federal de Uberlândia, Uberlândia, Brasil; marcio.zardini@ufu.br
[3]Pesquisador, Departamento de Engenharia Civil, de Construção e Ambiental, Universidade Estadual de Iowa, Ames USA; analuiza@iastate.edu
[4]Engenheiro Chefe, Engenharia de Projetos de Pavimentação, CCR S.A. São Paulo, Brasil; Luis.klinsky@grupoccr.com.br

Data de recebimento: 29/02/2024 Aceito para publicação: 13/02/2025 Data de publicação: 21/05/2025

Online Perspectives: Exact and Engineering
December/2024, v.15 , n.39 , p.1-18
ISSN: 2236-885X (Online)
DOI: 10.25242/885X153920242811

MECHANICAL BEHAVIOR ANALYSIS OF THE CEMENT TREATED AGGREGATE BASE WITH ADDITION OF SYNTHETIC FIBER

Rodrigo Pires Leandro[1], Márcio Antônio Zardini Santos[2], Ana Luiza R. Rodrigues[3], Luis Miguel Gutierrez Klinsky[4]

ABSTRACT

LEANDRO, R, P.; SANTOS, M. A. Z.; RODRIGUES, A. L. R.; KLINSKY, M. G. Mechanical Behavior Analysis of the Concrete Treated Aggregate with Addition of Synthetic Fiber. **Online Perspectives: Exact and Engineering**, v.15 , n.39 , p. 1 - 18 , 2024.

An experimental study was conducted to investigate the effect of the addition of polypropylene fiber on the mechanical behavior of cement-treated crushed stones. The experimental program involved the following mechanical tests: compressive strength, flexural bending test, flexural modulus, and toughness, in addition to scanning electron microscopy. Two mixes with fiber addition (0.25% and 0.50% by weight of aggregate) were tested and compared to the standard mixture without fiber. The fiber used was polypropylene type with 60 mm length. All mixtures were tested after 28 days of wet curing, except for samples used in the toughness tests, which were cured for 100 days. The mixtures utilized CP-II-E-32 cement (a standard used in Brazil for cements composed of 34% slag), with a content of 5%. The results indicated that fiber insertion hinders the compaction of the mixture. This causes a reduction in the degree of compaction and, consequently, a decrease in unconfined compressive strength. However, fiber inserts resulted in considerable increases in toughness and tensile strength. The interlacing of the fibers in the internal matrix structure promoted an anchorage effect.

Keywords: Pavement. Base. Cement.

[1]Teacher, Department of Civil Engineering, Federal University of Uberlandia, Uberlandia, Brazil; rodrigo.leandro@ufu.br
[2]Researcher, Department of Civil Engineering, Federal University of Uberlandia, Uberlandia, Brazil; marcio.zardini@ufu.br
[3]Researcher, Civil, Construction, and Environmental Engineering Department, Iowa State University, Ames, USA; analuiza@iastate.edu
[4]Head Engineer, Pavement Project Engineering, CCR S.A. Sao Paulo, Brazil; Luis.klinsky@grupoccr.com.br

Received: 29/02/2024 Accepted: 13/02/2025 Published online: 21/05/2025

1. INTRODUCTION

Cement-treated aggregate and composites are common alternatives for constructing pavement structural layers in high-volume traffic roadway projects (Souza, 2018). Balbo (2007) and Haifang et al. (2014) describe that cemented materials' characteristic strength provides thinner base thicknesses and better stress distribution to the subgrade. The cemented layer's presence reduces the tensile stresses of the asphalt surface course layer, reducing its thickness compared to the thickness required for an equivalent conventional flexible pavement Suzuki (1992). However, when subjected to tensile stresses, the cement-treated aggregate base (CTAB) presents a brittle behavior and low deformation before rupture. In this context, the addition of synthetic fibers is an alternative to improve the mechanical properties of cemented mixtures when subjected to bending stresses.

According to Figueiredo (2011), fibers with the capacity to reinforce cementitious matrices present greater deformation capacity at failure, and greater tensile strength than the concrete matrix. These aspects are essential because the behavior of concrete reinforced with fibers depends on their role as a bridge, transferring stresses through the cracks that arise precisely when the matrix ruptures.

Considering CTAB behavior and the benefits that the addition of fibers can bring to this material, the main objective of this research is to evaluate the effect of adding polypropylene fibers on the mechanical properties of CTAB and to investigate its behavior after matrix cracking, especially when this material is subjected to bending stresses.

1.1. CTAB properties

In general, CTAB can be defined as the resulting product from the mixture of crushed rock and Portland cement with a certain amount of water. The design of a CTAB is based on the granulometry, cement and moisture contents (Xuan et al. 2012).

The cement levels recommended for the manufacture of CTAB are variable. The Brazilian standard NBR 12261-2013 (ABNT 2013a) establishes the cement content, by total mixture weight, between 3 and 5% for a unconfined compressive strength (UCS) ranging from 3.5 and 8.0 MPa. Likewise, DAER (1998) defines the limits of 3.5 to 5% of cement content to the dry aggregate weight, while Halsted et al. (2006) establishes the minimum content of 3%. ARTERIS (2016) defines 5% as the lowest cement content for a minimum UCS of 4.5 MPa after 7 days of curing. In Nusit & Jitsangiam (2016), the cement contents needed to stabilize CTAB mixtures ranged from 3 to 7%.

Some standards, such as NBR 11803-2013 (ABNT 2013b) and ES-P-16/18 (DER/PR 2018), do not indicate cement levels but have a guideline for the UCS between 3.5 and 8 MPa at 7 days of curing. Halsted et al. (2006) also suggest defining the cement content as a function of the UCS at 7 days of curing, with 2.1 to 2.8 MPa for mixtures prepared in place and 5.5 MPa for plant mixed concretes.

However, there is concern about the upper limit of cement added to the mixture since it can increase the possibility of cracking due to shrinkage (Halsted et al. 2006, Nusit & Jitsangiam 2016). The shrinkage of cement mixtures occurs due to water loss during drying and self-drying during cement hydration. Considering this, both the cement content and the moisture content of the mixture influence the structural performance of CTAB (Jitsangiam et al. 2011, Haifang et al. 2014).

According to Andrade et al. (2015), the water added to the mixture, in addition to facilitating compaction, has the function of hydrating the cement that mixes with the fine fraction of aggregates. Balbo (1993) demonstrates that the mixture moisture content (w/c ratio) is a conditioning factor for the mechanical behavior and fracture of this type of material. According to Jitsangiam et al. (2011), the minimum amount of water necessary for adequate cement hydration corresponds to the water-cement ratio (w/c) of 0.25. On the other hand, the Oklahoma-DOT (2013) specifies mixtures of CTAB with a w/c ratio of 0.75 to 1.25, considering the compaction moisture.

The mechanical resistance characteristics of CTAB result from the contribution of two phases: the compacted granular skeleton and the cemented matrix phase. The granular skeleton phase determines the mechanical stability of the CTAB under loading, while the cemented matrix phase governs the bond strength between the particles (Klinsky & Faria, 2015). n this sense, the paste, constituted by the association of cement and water with the fine fraction of aggregate, forms specific connections between the aggregates, but does not completely envelop them, as occurs in Portland cement concrete.

Due to the granular skeleton's importance, the material compaction becomes a relevant factor for the CTAB behavior. When compacted in the modified energy and in the compaction curve's dry branch, it presents a more homogeneous matrix and less porosity than those compacted in the optimum moisture content (Balbo,1993).

However, the standard NBR 11803-2013 (ABNT 2013b) specifies the compaction of this type of material at intermediate energy levels. Several authors recommend the use of modified energy (Balbo 1993, Chummuneerat et al. 2014, Haifang et al. 2014, Nusit & Jitsangiam 2016). Higher compaction energy will provide mixtures with higher densities, resulting in increased material resistance and improved mechanical behavior. In the studies of Chummuneerat et al. (2014), Nusit & Jitsangiam (2016) and Santos (2019), the optimum moisture levels were 6.26%, 6.5%, and 6.1%, respectively, with maximum dry specific masses of 2.327 g/cm^3, 2.270 g/cm^3 and 2.237 g/cm^3, considering the modified compaction energy.

CTAB mixtures compacted with moisture content lower than the optimum have greater strength and less tensile toughness (Balbo & Cargnin 2023). Therefore, the material's fragility would increase when compacted in the dry branch of the compaction curve, in the opposite direction to the increase in strength (Balbo 2007). A similar situation occurred in Nusit & Jitsangiam (2016) for the condition of 5% cement. However, the highest UCS values in that study were for situations in which test samples were compacted to the optimum moisture content. According to Nusit & Jitsangiam (2016), this result occurred due to the lower dry density for moisture contents different from the optimum, resulting in a higher voids volume. These initial voids associated with the heterogeneous matrix of the CTAB make this type of material highly sensitive to fracture (Balbo & Cargnin 2023).

Considering the stresses that the CTAB is submitted in the field, the test types for its mechanical analysis must involve determining the material stiffness, fracture resistance, and how the process of fatigue damage occurs (Albuquerque & da Silva Nascimento 2018). For these evaluations, the studies on CTAB have been developed based on test results of resilient modulus by dynamic triaxial tests (Jitsangiam et al. 2011, Chummuneerat et al. 2014), flexural modulus by four-point flexural test (Fedrigo et al. 2018), tensile strength by four-point flexural test (Songtao et al. 2018) or diametrical compression test (Xuan et al. 2012, Hossain et al. 2017, Fedrigo et al. 2018), three or four-point bending fatigue tests (Nusit & Jitsangiam 2016, Ghani et al. 2018, Songtao et al. 2018), UCS tests (Nusit & Jitsangiam 2016) and fracture toughness testing (Hou et al. 2011, Songtao et al. 2018). Thus, from these tests is possible to characterize the mechanical behavior of the CTAB, and it could contribute to extending the pavement service life. In this scenario, the incorporation of fibers into CTAB mixtures is an alternative to enhance both deformation capacity and flexural strength.

1.2. Synthetic fibers and their applications in cemented mixtures

One of the main objectives of adding fibers to concrete is to obtain a composite material with a greater capacity for absorbing energy after cracking the matrix, consequently minimizing its characteristic fragility (Figueiredo 2011). The use of fibers also results in great impact on resistance and load capacity, even after the matrix has cracked.

Polypropylene fibers can be classified according to their geometric shape: monofilament, multifilament (fibrillated film), and extruded tape. These forms are successfully used for reinforcing mortar and concrete. However, to avoid cracks, the suggestion is to use monofilament fiber, which is more effective than fibrillated fiber (Bentur & Mindess 2006).

The fiber length is an important parameter to be evaluated to improve the composite material’s mechanical behavior. Carnio (2009) evaluated concretes with insertion of different lengths of steel and polypropylene fibers, ranging from 35 to 60 mm. The results indicated that the 54 mm polypropylene fibers provided better behavior to the concrete concerning crack propagation due to fatigue.

Zhang et al. (2013) investigated the effects of synthetic fibers’ insertion on the fracture behavior of CTAB-type mixtures. The results showed an increase in the mixtures’ fracture resistance due to the increase in the volume of fibers. On the other hand, Peng & Qingfu (2009) found that the addition of fibers can reduce the CTAB elastic modulus and the flexural modulus (FM). In contrast, the insertion of fibers resulted in a reduced propensity to thermal shrinkage (constant temperature) and drying (with temperature variation). Thus, there is a potential for the use of polypropylene fibers to reduce the effects of cement shrinkage and improve the mechanical behavior of CTAB mixtures when subjected to bending stresses.

2. MATERIALS AND METHODS

The materials used in this research (aggregates and cement) are typically used in civil construction and paving works. For the CTAB composition, aggregates of basaltic origin were used, and the results of the physical characterization are shown in Table 1 . The granulometric distribution consisted of proportions of fine and medium gravel and stone powder. These materials’ fractions were combined to meet the grain size range B of ABNT (2013b). Figure 1 shows the range B and the project distribution for this study.

The Portland cement type used was CP-II-E-32 for commercial use. The fiber chosen was a synthetic polypropylene macrofiber for concrete (Figure 2) of 0.9 g/cm^3, with a length of 60 mm, and a rectangular shape (width 1.2 mm and thickness 0.21 mm). The fiber contents used were 0.25% and 0.50% by weight of the aggregates.

The experimental method was divided into stages. The first stage consists of collecting, preparing, and characterizing the materials. The second stage was characterized by the compaction test and the CTAB dosage. In the third stage, the samples were molded, and laboratory tests were carried out to evaluate the mechanical behavior of the mixtures.

Table 1: Aggregates physical characteristics

Test	Standard	Reference value	Test results
Los Angeles Abrasion	ABNT (2001)	Loss < 40	12.15%
Shape index	ABNT (2019)	IF ≤ 2	2
Sand Equivalent	ABNT (1992)	EA > 35	83%
Soundness of Aggregates	ASTM (2013)	loss < 30	15%

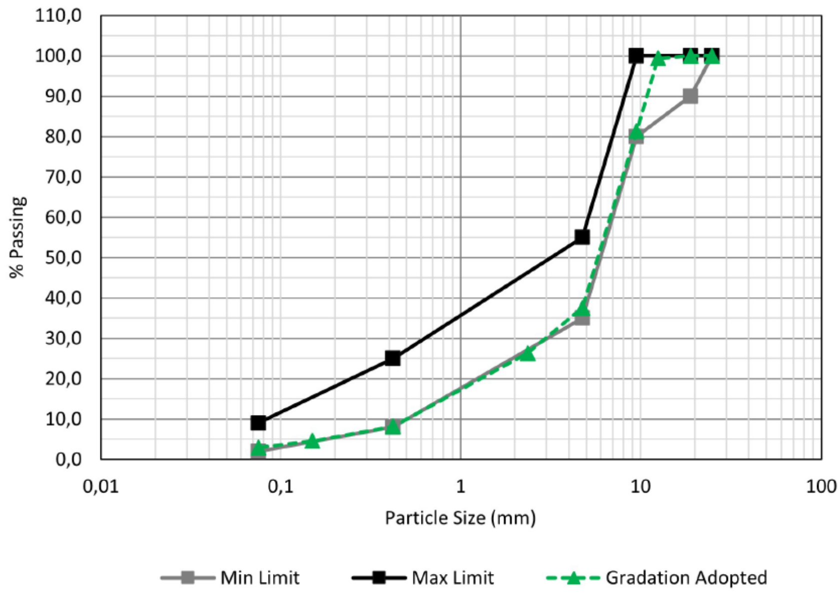


Figure 1: Particle-size distribution and size range B from ABNT (2013b)

Figure 2: Synthetic polypropylene macrofiber used in the study

2.1. Determination of CTAB compaction and design parameters

The maximum dry density and optimum moisture content of the standard mixture (CTAB with 4% cement without fiber) were determined using compacted samples with modified energy. For this condition, the optimum moisture content was 6.1% for a maximum dry density of 2.237 g/cm^3. To determine the design cement content, new sets of samples (3 samples for each cement content) were molded for the contents of 3, 4, and 5% of cement. During this process, the moisture content and the degree of compaction (DC) were controlled. After 7 days of curing, the samples were subjected to simple compression. The cement content of 5% was sufficient to meet the requirements of the Brazilian ABNT (2013a) standard. Thus, 5% of cement was defined as the design cement content.

2.2. Unconfined compressive strength tests (UCS) of CTAB compaction and design parameters

The UCS tests were performed according to ABNT (2007), with 3 samples molded for each of the proposed mixtures: (i) CTAB without fiber; (ii) CTAB with 0.25% fiber and (iii) CTAB with 0.50% fiber. The samples were compacted in a metal cylinder with a diameter of 100 mm and a height of 200 mm, using modified energy to achieve optimum moisture content and maximum dry density. After molding, the samples were placed in a humid chamber with controlled temperature and humidity for the first 24 hours before being demolded. They remained in the same curing conditions until they were tested at 28 days.

2.3.Flexural tensile strength tests (FTS)

To perform the FTS tests, 3 samples were also molded for each of the mixtures. The mold was in a prismatic format with dimensions of 100 mm x 100 mm x 400 mm. Using a vibratory compaction system, the compaction condition was defined to the optimum moisture content and maximum dry bulk density.

The samples were compacted in three equal layers by a vibration system developed by the Road Research Center of the CCR Nova Dutra Concessionaire. The system consists of a 16.8 J vibrating hammer capable of applying up to 1,890 impacts per minute, in this case, with a weight of 30 kgf. A metallic device was adapted to the hammer, utilizing a rod strong enough to carry out the compaction of the prisms. The compaction system used is shown in Figure 3.

For the development of this compaction equipment, the Road Research Center adopted the recommendations of Method 8 of the South African Standard (Asphalt-Academy, 2009). To control the degree of compaction, the vibration time per layer was used. Initially, the time of 60 seconds per layer was defined as ideal to achieve the required compaction in the mixture without fiber samples. Likewise, the times of 80 and 90 seconds were obtained for the compositions with 0.25% and 0.50% fiber, respectively. The samples were demolded after 48 hours of curing and then kept in a humid chamber for 28 days until the test was performed. The prismatic samples were tested according to the ABNT (2010).

Figure 3: Vibratory compaction equipment to prismatic samples

2.4. Flexural modulus test (FM)

The test to determine the FM consisted of the application of cyclic loads on the molded prismatic samples for the FTS test. The test procedure followed the recommendations of the Austroads AP-R462-14 report (Alderson & Jameson 2014). This test was characterized by the application of cyclic load pulses of the haversine type, with 100 ms of application time and 900 ms of rest time. The applied load was 100 N, estimated at 10% of the flexural rupture stress. Initially, 50 pulses were applied for sample conditioning, followed by another 100 load pulses. The vertical deflection in the center of the sample was measured using Linear Variable Differential Transducers (LVDTs).

2.5. Toughness tests

To carry out the toughness tests, the recommendations of the Japanese Society of Civil Engineer were used. They define the toughness as the area under the force-displacement curve of the flexural tensile test. As recommended by the JSCE (1984), four replicates were molded for each of the mixtures. The dimensions of the samples and the molding conditions (preparation and compaction) were the same as those adopted in the FTS and FM tests. The samples were cured for 100 days.

The loads were applied by means of two upper cleavers supported on the middle third of the central span of the prism. The prism was supported on two lower cleavers. Vertical displacements were measured using two LVDTs placed in the central region of both sides of the samples. Figure 4 shows an example of the toughness test on a CTAB sample.

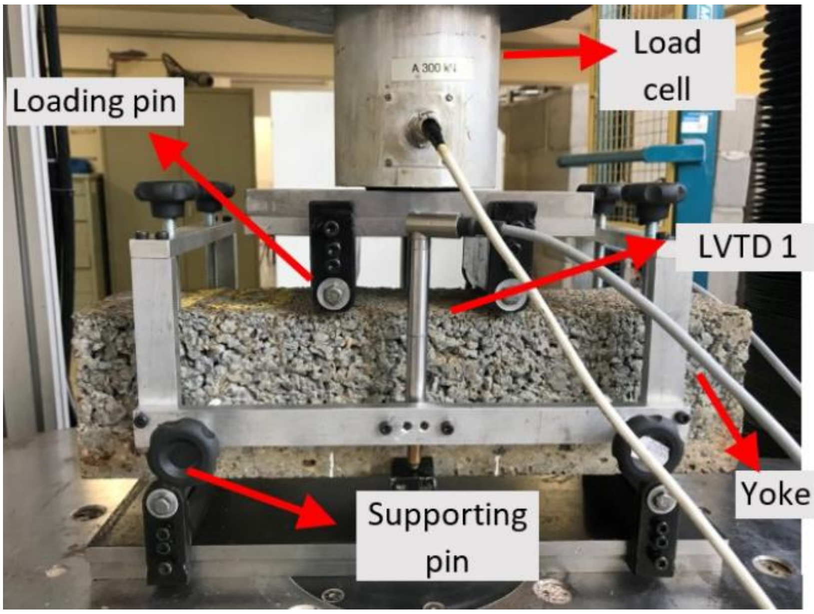


Figure 4: CTAB sample during the flexural toughness test

3. RESULTS AND ANALYSES

The average results from the tests proposed in the Methods section are presented in the following items. The analyses were based on the effects of different polypropylene fiber content on the mechanical properties of the CTAB mixture.

3.1. Scanning electron microscopy (SEM) analysis

Bearing in mind that the insertion of polypropylene fibers can modify the internal structure of the CTAB and, consequently, influence the mechanical behavior of the mixtures, the Figure 5 shows the images obtained from SEM. To analyze the images, the following microscopic aspects were considered: voids, cracks, and interaction between cement paste, aggregates, and fibers.

Among the polymeric fibers, polypropylene fibers are known to have less anchoring capacity in cementitious matrices due to their low surface roughness. However, upon analyzing Figure 5, it is evident that the fibers exhibit superficial roughness, which contributes to better adhesion between the fiber and the matrix. Additionally, complete adherence of the mortar to the fiber surfaces is observed. Furthermore, the fiber connections with the matrix did not exhibit flaws or fragile areas at the interfaces. Moreover, in all matrix-fiber interactions analyzed, the fibers remained intact after the samples ruptured, indicating their greater resistance compared to the CTAB matrix. Figure 5 also illustrates the formation of microcracks, pores, and voids distributed throughout the matrices, both in mixtures without fibers and in those with added fibers. This characteristic is typical for this type of material because it has a heterogeneous structure.

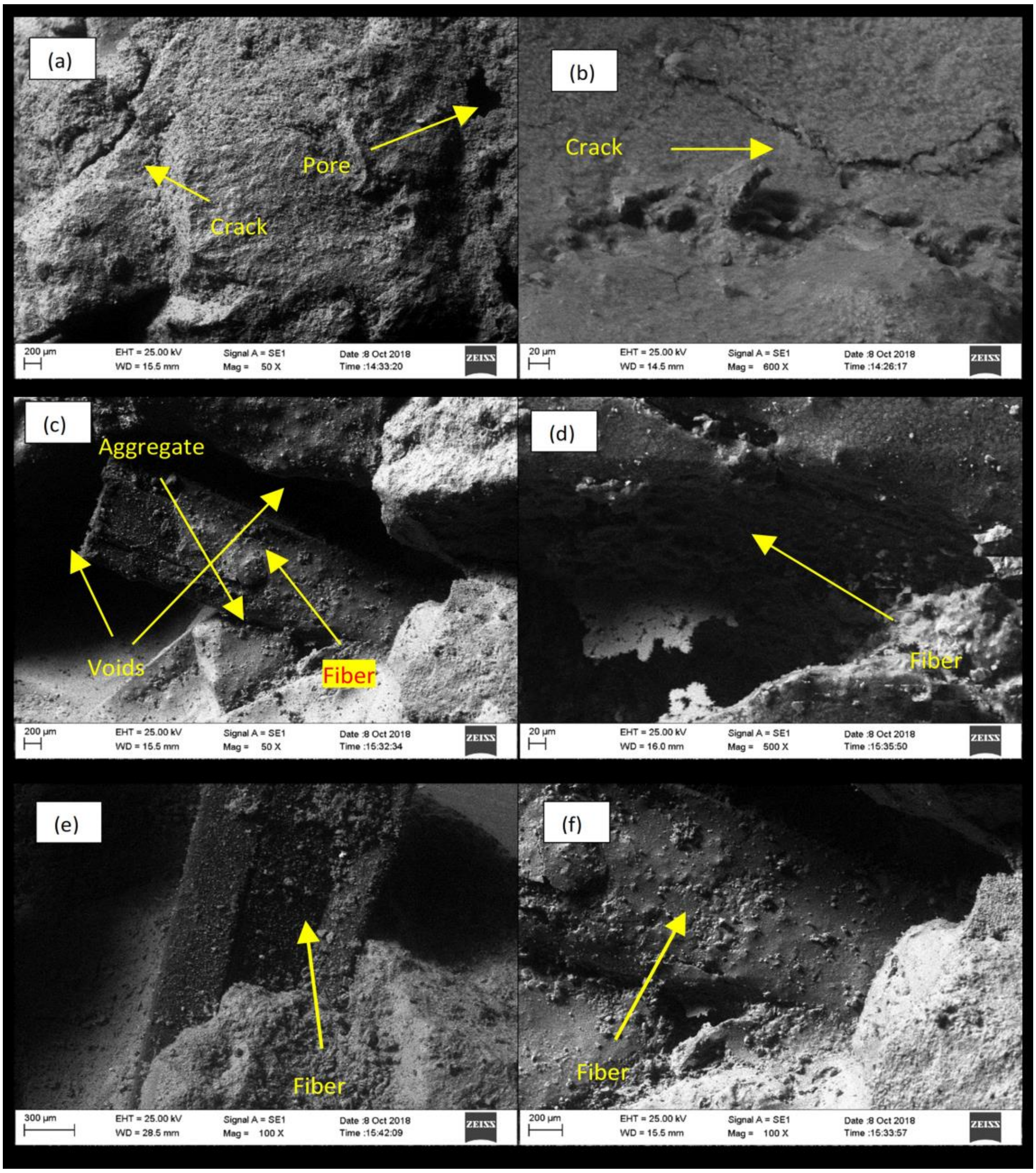


Figure 5: Microscopic characteristics of CTAB - cement paste, aggregate and fiber interaction: (a) and (b) CTAB without fiber; (c) - (f) CTAB with fiber

3.2. Unconfined compressive strength (UCS)

In Table 2, the average results of UCS after 28 days of cure are shown. A reduction is noted in UCS with an increase in fiber content. A reduction in UCS is noted with an increase in fiber content. This reduction may be associated with the lower degree of compaction obtained during the molding of specimens that contained fibers. The average degrees of compaction for samples with 0%, 0.25%, and 0.5% fiber was 100.7%, 99.7%, and 97.5%, respectively. Another factor that may have contributed to this behavior is the insertion of fibers in the matrix, which can create empty spaces in the CTAB structure.

Table 2: UCS (average) results at 28 days of cure

Fiber content (%)	UCS mean (MPa)	UCS absolute variance (MPa)	UCS percent variance (%)	Standard deviation	Coefficient of variation (%)
0	5.38	-	-	0.06	0.01
0.25	4.94	-0.44	-8.22	0.21	0.04
0.50	4.61	-0.74	-14.21	0.39	0.08

The results presented in Table 2 can be considered low compared to the study by Balbo (1993) study, which obtained a UCS result of 13.25 MPa at 28 days of cure. In addition to the differences in materials and granulometry, the author's premise was to mold specimens in the dry branch of the compaction curve to obtain greater strengths. On the other hand, the results in Table 2 are in the range of values verified by Davis et al. (2007), who found considerable variations in UCS depending on the mineralogy of the source rock. Besides mineralogy, Davis et al. (2007) observed significant effects of the amount of fines and the pH of the aggregates. These factors may justify the differences in the behavior of CTABs manufactured with materials from different sources and under different conditions of compaction and granulometric distribution.

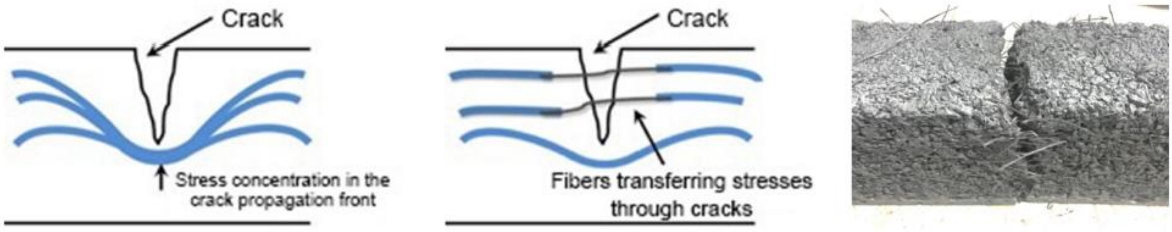
3.3. Flexural tensile strength (FTS)

The average results of the FTS trials at 28 days are shown in Table 3. Upon analyzing this Table, it can be noticed that although the results are lower than values found in the literature, the expected effect was achieved. The results presented by Peng & Qingfu (2009) indicated an FTS of about 1.3 MPa for CTAB condition without fiber. There was a gradual increase in FTS for the mixtures with the higher amount of fibers, resulting in an increase of up to 23% in the FTS compared to the standard mixture.

The main reason for the increase in FTS is the effect ogf the on the fracture section of the prismatic samples during the matrix rupture. At the exact moment of the matrix rupture, the fiber is tensioned as the microcrack increases, supporting the imposed tensile stresses. At the same time, the concentration of stresses in the microfissure is reduced, minimizing its propagation. Figure 6 illustrates this mechanism for mixtures with fiber insertion.

Table 3: FTS (average) results at 28 days

Fiber content (%)	FTS mean (MPa)	FTS absolute variance (MPa)	FTS percent variance (%)	Standard deviation	Coefficient of variation (%)
0	0.60	-	-	0	1.2
0.25	0.69	0.09	15.17	0.09	12.4
0.50	0.74	0.14	23.00	0.05	6.9



(a) (b) (c)

3.4. Flexural modulus (FM)

The average results of the FM tests carried out at 28 days of cure are shown in Table 4. This Table also presents the variations in the results of the mixtures with fiber compared to the standard mixture (without fiber).

Table 4: FM (average) results at 28 days

Fiber content (%)	FM mean (MPa)	FM absolute variance (MPa)	FM percent variance (%)	Standard deviation	Coefficient of variation (%)
0	16.77	-	-	1.57	9.4
0.25	15.50	-1,27	-7.60	0.87	5.6
0.50	11.03	-5,74	-34.22	1.51	13.7

Analyzing Table 4, it is noticed that there is a reduction in FM values due to the increase in fiber content. Peng & Qingfu (2009) obtained values of the same magnitude, but at the age of cure above 60 days. They also recorded decreasing values of moduli for increasing fiber contents. Thus, considering the increase in FTS (Table 3), the reduction in FM results after fiber insertion could represent an improvement in the fatigue life of the material. However, considering UCS results (Table 2), the reduction in moduli values due to the increase in fiber content may also result from changes in the original structure of the CTAB, leading to an even more heterogeneous condition of the mixtures. During specimen molding, the task of homogenization became more difficult with the insertion of the fibers. The addition of fibers reduced the CTAB densification level due to its lower density and the probable creation of several voids in the matrix.

3.5. Toughness

For each of the mixtures, four prismatic samples were molded for the flexural toughness test. The areas under the force-displacement curves were calculated up to the displacement limit of 2 mm, obtaining the respective toughness value. Figures 7, 8 and 9 shows the force-displacement curves of the CTAB without fiber and with additions of 0.25% and 0.5% fiber content, respectively.

Analyzing these Figures, it is noted that the fibers altered the residual resistance after cracking and that there was a reduction in the peak load to the 0.5% fiber content due to changes in the CTAB structure. Besides, the initial elastic response, ranging from 0 to the one corresponding to the peak load, is practically unchanged by the addition of fiber, regardless of the content used. The average results of the toughness tests can be seen in Table 5, which shows that CTAB mixtures with fiber insertions respond with a considerable increase in toughness compared to the mixture without the fiber.

The main reason for the improvement of toughness after the addition of fibers is that it acts as a bridge between the faces of the crack and relieves stresses in the rupture region. Zhang et al. (2013) also found an increase in toughness due to the short fiber amount (10 to 20 mm). However, the results of those authors showed disruptions of the samples for lower deflection levels. Thus, it is possible to see a better behavior of material with the insertion of long fibers (60 mm).

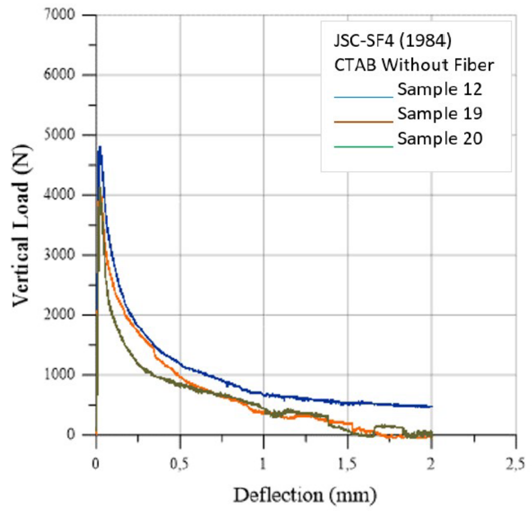


Figure 7: Vertical Load x Deflection curves of CTAB mixtures without fiber

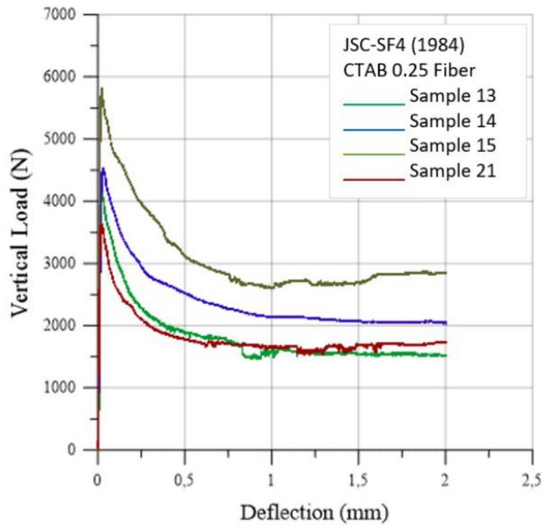


Figure 8: Vertical Load x Deflection curves of CTAB mixtures with 0.25% fiber

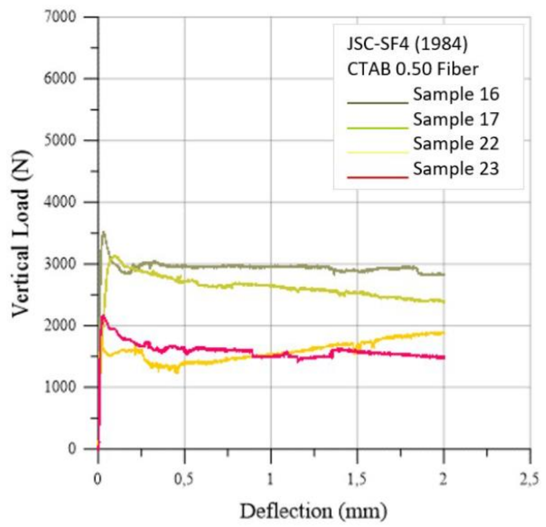


Figure 9: Vertical Load x Deflection curves of CTAB mixtures with 0.50% fiber

Table 5: Toughness (average) results

Fiber content (%)	Toughness mean (MPa)	Toughness absolute variance (MPa)	Toughness percent variance (%)	Standard deviation	Coefficient of variation (%)
0	1,595.64	-	-	366	22.9
0.25	4,074.08	2,478.44	155.33	548	13.5
0.50	4,853.28	3,257.64	204.16	115	23.8

5. CONCLUSIONS

The objective of this research was to verify the effect of adding polypropylene fiber on the mechanical properties of CTAB, especially when this material is subjected to bending stress. Polypropylene fiber plays a fundamental role in the pavement structure, absorbing tensile forces and preserving the integrity of the asphalt layer.

The interaction of the polypropylene fiber with the cement paste and CTAB aggregates was efficient, as observed in SEM images. The fibers remained intact after the rupture of the CTAB samples, and the connection with the matrix showed no flaws or fragile areas at the interfaces. However, it was evident that the insertion of fibers contributed to the heterogeneous characteristics of the CTAB mixtures.

The insertion of fibers makes it difficult to compact the mixtures. Vibratory compaction was not suitable because the mixture did not achieve the desired degree of compaction in these situations. Compaction became more difficult due to the agglutination characteristic of the polypropylene macrofiber, making it harder to homogenize the mixture, especially when applied at higher fiber content. When this mixture is not well combined, the fibers agglomerate, leading to the formation of fragile zones without proper matrix-fiber interaction.

The reduction in the degree of compaction of samples with fiber was reflected in the consequent decrease in unconfined compression resistance. However, the addition of polypropylene fiber promoted an improvement in the material's properties when subjected to bending, with higher fiber contents resulting in higher mean values of tensile strength and toughness. The enhancement in CTAB behavior under tensile stress occurs due to the interlacing of fibers within the matrix's internal structure, facilitating stress distribution and relief in the crack region, thereby reinforcing the structural capacity against tensile stress both before and after the rupture of the cement matrix.

REFERENCES

ABNT (1992), **Solo ou agregado miúdo - determinação do equivalente de areia - método de ensaio**, in 'NBR 12052', ABNT, Rio de Janeiro, Brasil.

ABNT (2001), **Agregado graúdo - ensaio de abrasão Los Ángeles**, in 'NBR NM 51', ABNT, Rio de Janeiro, Brasil.

ABNT (2007), **Concreto - ensaio de compressão de corpos de prova cilíndricos**, in 'NBR 5739', ABNT, Rio de Janeiro, Brasil.

ABNT (2010), **Concreto - determinação da resistência à tração na flexão de corpos de prova prismáticos**, in 'NBR 12142', ABNT, Rio de Janeiro, Brasil.

ABNT (2013a), **Dosagem de brita graduada tratada com cimento - procedimentos**, in 'NBR 12261', ABNT, Rio de Janeiro, Brasil.

ABNT (2013b), **Materiais para base ou sub-base de brita graduada tratada com cimento — requisitos**, in 'NBR 11803', ABNT, Rio de Janeiro, Brasil.

ABNT (2019), **Agregado graúdo - determinação do índice de forma pelo método do paquímetro método de ensaio**, in 'NBR 7809', ABNT, Rio de Janeiro, Brasil.

ALBUQUERQUE, F. S. & DA SILVA NASCIMENTO, R. (2018), 'Estudo de desempenho à fadiga de base cimentada tipo BGTC na br-101/SE', **Transportes** 26 (1), 157–171.

ALDERSON, A. & JAMESON, G. (2014), **Cemented materials characterisation**, Rep. No. AP-R462-14, Austroads Ltd, Sydney, Australia.

ANDRADE, L. R. D., KUCHIISHI, A. K., BESSA, I. S., VASCONCELOS, K. L., BERNUCCI, L. L. B., BEJA, I. A. & CHAVES, J. M. (2015), Comportamento mecânico de camadas de bases granular e tratada com cimento em rodovia de tráfego muito pesado, in ANPET, ed., '**XXIX Congresso Nacional de Pesquisa em Transportes da ANPET**', ANPET, Ouro Preto, Brasil.

ARTERIS (2016), Brita graduada tratada com cimento – bgtc, in 'ES 009-Ver 09', **ARTERIS**, São Paulo, Brasil.

ASPHALT-ACADEMY (2009), **'Technical guideline: Bitumen stabilised materials'**.

ASTM (2013), **Standard test method for soundness of aggregates by use of sodium sulfate or magnesium sulfat**, in 'C88-13', ASTM, Philadelphia.

BALBO, J. T. (1993), **Estudo das propriedades mecânicas das misturas de brita e cimento e sua aplicação aos pavimentos semi-rígidos**, M.S. Thesis, Universidade de São Paulo, São Paulo, Brasil.

BALBO, J. T. (2007), **Pavimentação asfáltica: materiais, projeto, e restauração**, Oficina de Textos.

BALBO, J. T. & CARGNIN, A. (2023), 'Britas graduadas tratadas com cimento de alto desempenho (BGTCAD): ensaio sobre (e entre) o “velho” e o “novo” com diálogo triádico reformulado’, **TRANSPORTES** 31(3), e2911– e2911.

BENTUR, A. & MINDESS, S. (2006), **Fibre reinforced cementitious composites**, Crc Press.

CARNIO, M. A. (2009), **Propagação de trinca por fadiga do concreto reforçado com baixos teores de fibra**, PhD thesis, Universidade Estadual de Campinas, Campinas, Brasil.

CHUMMUNEERAT, S., JITSANGIAM, P. & NIKRAZ, H. (2014), ‘Performances of hydrated cement treated crushed rock base for western australian roads’**, Journal of Traffic and Transportation Engineering (English Edition) 1** (6), 432–438.

DAER (1998), **Base tratada com cimento**, in ‘ES-P11/91’, DAER, Rio Grande do Sul, Brasil.

DAVIS, K., WARR, L., BURNS, S. & HOPPE, E. J. (2007), ‘Physical and chemical behavior of four cement-treated aggregates’, **Journal of materials in civil engineering 19** (10), 891–897.

DER/PR (2018), **Pavimentação: brita graduada tratada com cimento**, in ‘ES-P 16/18’, DER/PR, Paraná, Brasil.

FEDRIGO, W., NÚÑEZ, W. P., LÓPEZ, M. A. C., KLEINERT, T. R. & CERATTI, J. A. P. (2018), ‘A study on the resiliente modulus of cement-treated mixtures of rap and aggregates using indirect tensile, triaxial and flexural tests’, **Construction and Building Materials 171**, 161–169.

FIGUEIREDO, A. D. (2011), **Concreto reforçado com fibras**, M.S. thesis, Universidade de São Paulo, São Paulo, Brasil.

GHANI, R., AL-JUMMAILY, M. A. & AL-ZERJAWI, A. K. (2018), ‘Study of cement-treated base aggregate properties for pavement structure’, **International Journal of Information Research and Review**, January 5(01), 5093–5100.

HAIFANG, W., BALASINGAM, M., JINGAN, W., XIAOJUN, L., TUNCER, E.&TINJUM, J. M. (2014), **Characterization of cementitiously stabilized layers for use in pavement design and analysis**, Rep. No. 789, National Academies of Sciences, Engineering, and Medicine,WASHINGTON, D.C.

HALSTED, G. E., LUHR, D. R. & ADASKA, W. S. (2006), **Guide to cement-treated base (CTB)**, Portland Cement Association, Illinois, USA.

HOSSAIN, M. S., NAIR, H., OZYILDIRIM, H. C. (2017), **Determination of mechanical properties for cementtreated aggregate base**, Technical report, Virginia Transportation Research Council.

HOU, X. Y., ZHANG, P. & ZHANG, M. E. (2011), ‘Study on fracture toughness of cement treated aggregate’, **Advanced Materials Research 280**, 76–79.

JITSANGIAM, P., NIKRAZ, H. (2011), Mix design of cementitious basecourse, in ‘**Proceedings of the International Conference on Advances in Geotechnical**

Engineering', Australian Geomechanics Society, pp. 379–385.

JSCE (1984), **Method of test for flexural strengt and flexural toughness of steel fiber reinforced concrete**, in 'JSCE-SF4', JSCE, Japan.

KLINSKY, L. & FARIA, V. (2015), '**Estudo da influência do teor de cimento portland, da energia de compactação e da umidade no comportamento mecânico da brita graduada tratada com cimento (BGTC) para duas gêneses de agregados**', Relatório. Centro de Pesquisas Rodoviárias (CPR), Concessionária CCR Nova Dutra, Grupo CCR, Rio de Janeiro.

NUSIT, K. & JITSANGIAM, P. (2016), 'Damage behavior of cement-treated base material', **Procedia engineering 143**, 161–169.

OKLAHOMA-DOT (2013), **Method of test for cement treated base mix design**, in 'Oklahoma DOT', Oklahoma DOT, Oklahoma, USA.

PENG, Z. & QINGFU, L. (2009), 'Effect of polypropylene fibre on mechanical and shrinkage properties of cement-stabilised macadam', **International Journal of Pavement Engineering 10** (6), 435–445.

SANTOS, M. A. Z. (2019), **Análise do efeito da adição de fibra de polipropileno no comportamento mecânico de uma brita graduada tratada com cimento**, M.S. Thesis, Universidade Federal de Uberlândia, Uberlândia, Brasil.

SONGTAO, L., LIU, C., LAN, J., ZHANG, H., ZHENG, J. & YOU, Z. (2018), 'Fatigue equation of cement-treated aggregate base materials under a true stress ratio', **Applied Sciences 8** (5), 691.

SOUZA, D. A. (2018), 'Aplicações de materiais compósitos na construção civil', **Revista Perspectivas Online: Exatas e Engenharias** – Anais do VI CICC V 08, N 22.

SUZUKI, C. Y. (1992), **Contribuição ao estudo de pavimentos rodoviários com estrutura invertida (Sub-base Cimentada)**, PhD thesis, Universidade de São Paulo, São Paulo, Brasil.

XUAN, D., HOUBEN, L., MOLENAAR, A. & SHUI, Z. (2012), 'Mechanical properties of cement-treated aggregate material–a review', **Materials & Design 33**, 496–502.

ZHANG, P., LIU, C.-H., LI, Q.-F. & ZHANG, T.-H. (2013), 'Effect of polypropylene fiber on fracture properties of cement treated crushed rock', **Composites Part B: Engineering 55**, 48–54.