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Evaluation of crushed and laminated bamboo fibers in cementitious composites

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ABSTRACT: This paper aims to analyze the mechanical properties of concrete reinforced with bamboo (Dendrocalamus giganteus) fibers. The fibers were produced by a knife mill (crushed fibers) and by manual cutting tools (laminated fibers). Moreover, the concrete fiber volumes (V_f) studied were 0.5%, 1.0%, and 1.5%. Furthermore, compressive strength, four-point bending flexural strength, and splitting strength tests were carried out in the produced concretes. The bamboo fibers had their tensile strength and water absorption characteristics measured. They were also analyzed by scanning electron microscopy (SEM). The bamboo laminated fibers promoted a better mechanical behavior than bamboo crushed fibers. SEM images evidenced a good fiber-matrix interface and the failure mode of fiber in the concrete. On the other hand, the concretes had a decrease in compressive strength with increasing V_f. The results were discussed in terms of micromechanics and microstructure.

KEY WORDS: Bamboo fiber; Vegetable fiber; Cementitious composite; Bio-concrete.

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RESUMEN: *Evaluación de fibras de bambú trituradas y laminadas en compuestos base cemento.* El objetivo es analizar las propiedades mecánicas del hormigón armado con fibras de bambú. Las fibras se produjeron mediante un molino de cuchillas (trituradas) y mediante herramientas de corte manuales (laminadas). Además, los volúmenes de fibra de hormigón (V_f) estudiados fueron 0,5%, 1,0% y 1,5%. También, se llevaron a cabo pruebas de resistencia a la compresión, resistencia a la flexión en cuatro puntos y resistencia a la rotura en los hormigones producidos. Se midieron las características de resistencia a la tracción y absorción de agua de las fibras de bambú. Las fibras laminadas de bambú promovieron un mejor comportamiento mecánico que las fibras trituradas. Las imágenes de microscopía electrónica de barrido evidenciaron una buena interfaz fibra-matriz y el modo de falla de la fibra en el concreto. Los hormigones tuvieron una disminución en la resistencia a la compresión al aumentar V_f. Los resultados se discutieron en términos de micromecánica y microestructura.

PALABRAS CLAVE: Fibra de bambú; Fibra vegetal; Compuesto base cemento; Biohormigón.

1. INTRODUCTION

Bamboo fibers are renewable and a source of raw materials for producing eco-friendly products with the possibility of lower greenhouse gas emissions. At the same time, bamboo fibers are available at low cost and with a lower carbon footprint (1, 2). Moreover, a social requirement has been imposed regarding to the reduction in consumption of materials, energy, and manpower, as well as in terms of a circular economy and the use of more efficient materials (3-5). To this end, natural fibers are lightweight, abundantly available, and they pose a minimal health hazard during their processing. In general, they have good thermal behavior and acoustic insulation characteristics, and good physical properties (1). Thus, the production of bio-based fibers has included bamboo, sisal, hemp, coco, and cellulose, among others (2-13, 14-17).

Besides that, natural fibers are biodegradable and have an interesting mechanical behavior (11). In this sense, the various species of bamboo fibers can represent an alternative to replace partially traditional fibers, such as synthetic and steel fibers (12, 18-22). Also, these fibers can be an important material for climate change mitigation and adaptation in buildings (18), as well a perspective to an Amazonian circular economy (5, 22).

In addition, some studies were carried out using bamboo straw and bamboo as structural elements, as well as timber panels (23-26), hybrid-reinforced concrete (27), bamboo particles as addition and aggregate (28), high performance concrete reinforced with bamboo fibres (29) and bamboo rods treated thermally or chemically (30-31), and bamboo pieces as concrete connectors (32).

It is interesting to note that the bamboo fibres, sticks or wood materials engineered wood can be obtained and processed from different species, cultivation conditions, soils and climates. Some researchers have used the phase bamboo fibres discontinuous with random orientations as reinforcement in cement-based matrix composites, structural form as laminate and sandwich panels and, if fibrous, in continuous or discontinuous alignment (orientation) (23-32).

On top of that, studies have presented the outstanding results of mechanical, physical, and thermal performance tests performed in bamboo-reinforced cementitious composites. These studies included the incorporation of 0.5-2.0% fiber volumes (V_f), which increased the toughness and reduced the elastic modulus of the Portland cement concrete (33). In parallel, the incorporation of 1.0-1.5% Vf of bamboo fibers led to an improvement of 24% tensile strength, increasing the modulus of elasticity from 16% to 59% (34). Similarly, Kumaraswamy et al. (35) identified that 2.0% V_f of bamboo fibers (Dendrocalamus giganteus) was the optimum level in their research.

In the three-point bending tensile test of concrete, Bittner and Oettel (29) tested cementitious composites with 1.25% and 2.50% of bamboo fibers (V_f). The composites exhibited a pseudo-ductile behaviour with higher levels of strength and displacement to failure, while the fiber-free concrete showed brittle behaviour. The fibers acted as a stress transfer bridge along the crack of the concrete. There was also a post-cracking resistance of the fibre reinforced composites.

In another experimental program, Ede et al. (30) studied cementitious composites reinforced with bamboo fibers at the 0.5%, 0.75%, and 1.0%V_f. They presented that the better compressive strength results were for the concrete with a V_f of 0.5% and 0.75%, highlighting the content of 0.75%. The composite with 1.0% bamboo fibers showed lower compressive strength than the other concretes as a result of an excessive content of bamboo fibers. Also, there was a greater splitting strength value for concrete with 0.5% bamboo fiber than other cementitious composites tested.

Li et al. (36) reported that the compressive strength of cementitious composites reinforced with bamboo fibers at 0.5% and 0.7% (V_f) were lower than concrete without fibers at the of ages 1, 3, 7, 14, and 28 days. These authors associated the result with the modulus of elasticity of the fiber and the cementitious matrix. Nevertheless, the flexural strengths of cementitious composites with fibers were superior to those without fibers at all ages evaluated.

However, some disadvantages of bamboo fibers in cementitious material have been related, such as the need for fiber surface treatments and free $Ca(OH)_2$ cement matrices. Vegetable fibers without treatments and free $Ca(OH)_2$ cementitious matrices have limitations in terms of durability due to the degradation of fibers (37).

This paper focuses on the analysis of the mechanical performance of cementitious composites (compressive, flexural, and splitting strengths), produced by bamboo fibers (Dendrocalamus giganteus). These fibers were from the intermediate region (approximately 12 meters up the tree) and they were cut in two different shapes (crushed and laminated). The V_f used were 0.5%, 1.0%, and 1.5%, and they were compared to the situation without fibers. Furthermore, the fibers had tensile strength and water absorption evaluated. Also, the fibers and composites were analyzed by scanning electron microscopy (SEM).

The relevance of this paper is on the bamboo fibers production processes based on more simplified and lower energy consumption for producing bamboo fibers. Therefore, this study advances with contributions from the use of these fibers in the mechanical behavior of cementitious composites.

In particular, the crushed fibers tend to be waste and this research, they were tested. Besides this, the fibers used were from pre-industrial processes. This was also a difference of this paper and it can contribute to a circular economy and more sustainability in the Brazilian Amazon region, where the bamboo species used in this study were collected and they are abundant. Also, this study can be addressed towards solutions in more economical and sustainable construction materials and processes to minimize the housing deficit in Brazil which it summarizes in the northern region, 18% of housing deficit in the Amapá state, 17% in the Roraima state and 15% of the Amazonas state (38). This means that part of the population is very vulnerable and has nowhere to live, they live in precarious conditions or live with multiple families in the same home. Therefore, this work can advance in this sense, giving social relevance as well. It was decided that no surface treatments on the fibers would be used, along with no mineral addition or supplementary cementitious materials (such as silica fume, metakaolin, and fly ash, among others) in the matrices for analyzing just the shapes of the fibers produced firstly. Further, research on durability in the medium- and long-term will be realized in these composites.

2. MATERIALS AND METHODS

2.1. Bamboo fibers: sample preparation

Firstly, bamboo (Dendrocalamus giganteus) was collected by cutting culms from the base to the intermediate region of the tree (12 meters in height). The bamboo had 5 culms and was from 2 to 6 years old. The bamboo base was removed up to the intermediate region of the tree. The bamboo culms from the intermediate region were stored in the shade in an upright position (Figure 1a). They were dried naturally in a laboratory environment for a period of 14 months under controlled conditions (temperature of 30-36^{o}C and relative humidity of approximately 70%). After this period, cross-sections of 80 cm (31.5 inches) were made using a circular bench saw. Then, longitudinal cuts of 10 cm (3.94 inches) were made (Figure 1bcd and Figure 2).

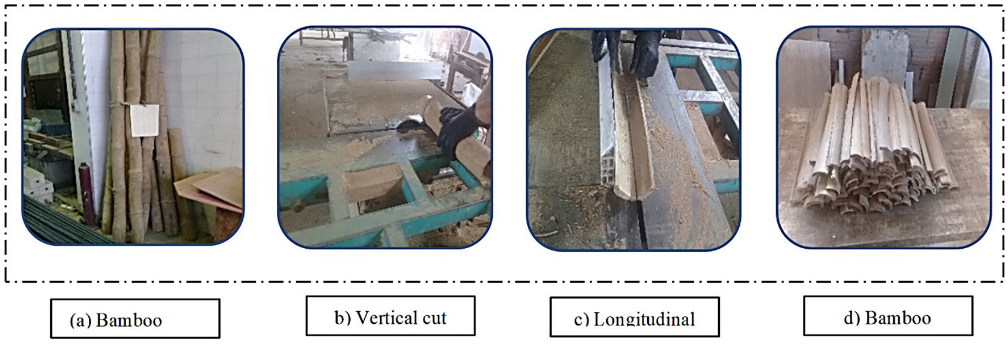

Figure 1. Obtaining the bamboo fiber: a) the laboratory environment, b) and c) the cutting process, and (d) laminated fiber.

Figure 2. Process for obtaining bamboo fibers: the 1st process from a) to d) with crushed fibers and the 2nd process from e) to h) with laminated fibers.

The criteria for choosing the factors, levels and response variables for the research was defined based on the literature (29, 39). Also, regarding the process of obtaining bamboo fibers and the physical and mechanical characterization tests, the research followed methodologies widely disseminated in the specific literature (1-39).

The bamboo pieces were subjected to two distinct processes for obtaining the bamboo fibers: by crushing the flakes in a knife mill with sieving to grade the fibers (1st process) and by laminating the bamboo bark with hand tools (2nd process) (Figure 2). In both processes, the fiber length was 40 mm (1.6 inches) (Figure 3). The fiber length of 40 mm was adopted following the literature (29, 39, 40, 41). Moreover, Figure 2 shows the processing used to obtain the bamboo fibers studied. The specific mass of bamboo fibers was 1.33 g/cm³ based on Sales (42).

Figure 3 illustrates the two types of fibers produced.

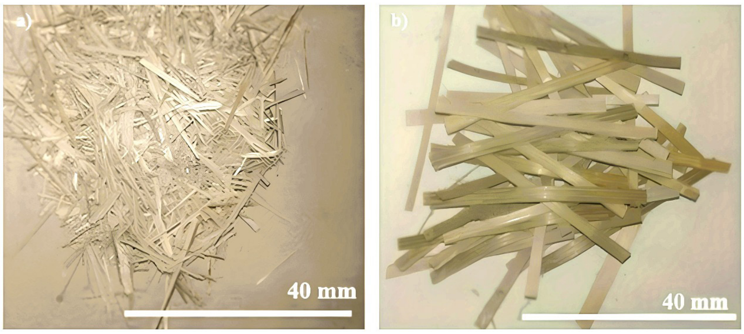

Figure 3. Detail of bamboo fibers used: a) crushed and b) laminated.

2.2. Methods for bamboo fiber characterization

The cross-sectional area, water absorption, tensile strength, elastic modulus, and morphological analysis of the bamboo crushed and laminated fibers were determined. These properties can influence the performance of the composite (fibers plus matrix).

The cross-section areas were determined by digital images. SEM imaging used the TESCAN model VEGA 3 LMU. So, the outline of 30 crushed bamboo fiber samples and 30 laminated bamboo fiber samples were drawn without coating (Figure 4). Then, the cross-sectional areas were measured using AutoCAD 2016 from Autodesk software. This number of samples was necessary because the fiber processing was more artisanal and the fibers are natural and vegetable.

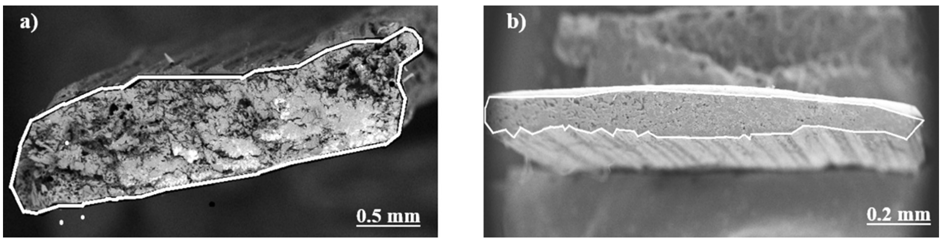

Figure 4. Representative cross-section areas of the bamboo fibers obtained by SEM images and using of AutoCAD 2016 by Autodesk software: a) crushed and b) laminated.

As mentioned before, the crushed bamboo fibers were derived from a thin layer of the inner culm wall. The laminated bamboo fibers were blades or fillets. The bamboo fiber's water absorption was calculated based on Bilcati (40), with fibers dried at 100 ± 5 °C for 24 hours. Later, the fibers were saturated in water at the temperature of 22 °C and they had their masses determined after 5 minutes, 30 minutes, 1 hour, 2 hours, and then 24-hour intervals for 196 hours, when constant masses were achieved. The excess of free water during mass measurements was removed.

Also, the fibers were characterized by tensile strength and modulus of elasticity tests according to ASTM C1557 (41). For sample preparation, an apparatus with kraft paper (300 mm x 650 mm) was used with a central opening (window) of 15 x 20 mm (Figure 5). The ends of the fibers were glued on the sides of the window in kraft paper. It was tested with 20 crushed fiber samples and 20 laminated fiber samples. Samples that suffered sliding or rupture on the glue were not considered. After positioning the sample in the grips of the testing machine, the sides of paper were cut and the tensile strength test started (Figure 6). A universal mechanical testing machine EMIC L500 was used with a maximum capacity of 5 kN, a load cell named SERIES EMIC CCE, a measuring range from 2% (1/150) to 100%, type CCE20KN. It had a minimum capacity of 400 N and a maximum of 20 KN under a strain rate of 0.5mm/min. Thus, tensile strength and the strain of fibers were determined. In addition, by tensile strength versus strain curves, the tangential modulus of elasticity was calculated (from 20% to 70%) by the maximum tensile strength (41).

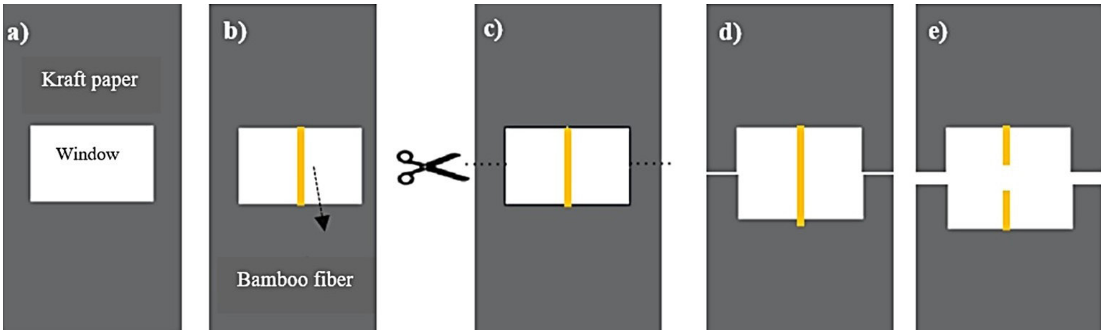

Figure 5. Preparation of samples for the tensile strength test: a) a paper for fixing the fibers with a window, b) fibers fixed in the kraft paper, c) - d) details of the cutting of the paper before the test, and e) a sample after the test.

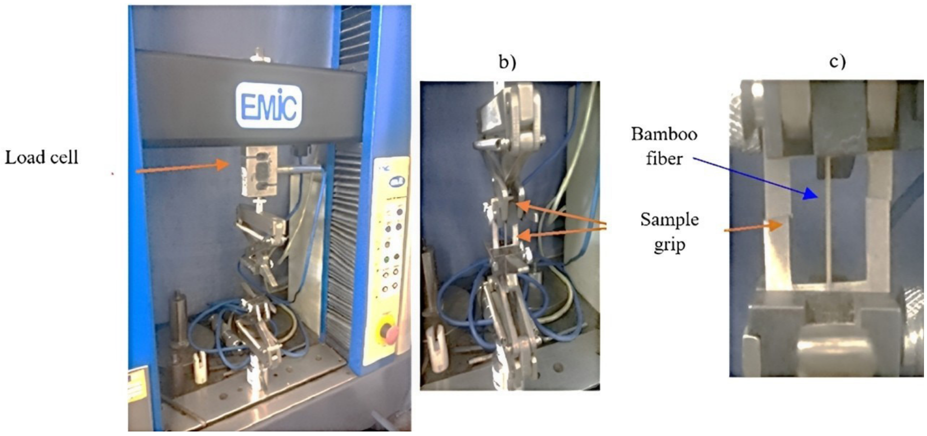

Figure 6. Setup of the tensile strength test according to ASTM C1557 (41): a) universal testing machine, b) details of clamps, and c) specimen before the test.

2.3. Cementitious composite production and methods for their evaluation

Brazilian-type CP IV Portland cement consisting of 45–85% by mass clinker and calcium sulfate, 0–10% limestone filler, and 15–50% pozzolanic material according to the Brazilian standard (43), similar to Cement Type I ASTM C150 (44) and European CEM II/A-L, was used throughout the investigations. This type of cement was used because of the lower clinker content in its composition, which can reduce attacks on the bamboo fiber. This cement has a specific mass of 2.85 g/cm^3.

Additionally, pebble coarse aggregate was used with a maximum dimension of 6.3 mm, a fineness modulus of 2.3, a specific mass of 2.6 g/cm^3, water absorption of 2%, and a unit mass of 1.5 g/cm^3 (45-47). Figure 7 shows the results of the granulometry test (for particle size) of coarse aggregate. The natural quartz river sand from the Amazon region near the municipality of Ourém, Pará state was utilized. It has a maximum dimension of 2.4 mm, a fineness modulus of 2.4, a specific mass of 2.65 g/cm^3, water absorption of 1.5%, and a unit mass of 1.6 g/cm^3. Figure 8 shows the results of the granulometry test of fine aggregate (46-48).

In addition, a chemical admixture based on polycarboxylate superplasticizer and water was used. Table 1 summarizes the properties of the cementitious composites produced. The amount of chemical admixture used was small and a high amount of water was required to maintain workability. The slump test was defined based on the workability for conventional concrete. The slump test was fixed in this experimental program from 100 mm to 160 mm (49), and the concrete compressive strength class with structural purpose was defined based on the minimum compressive strength applied to the Brazilian standard of 25 MPa (50) and the concrete´s design was based on a concrete plant in the city of Belém/Pará/Brazil.

Table 2 lists the composition of the mixture for the composites studied. It used 3 specimens for each test (compressive strength and modulus of elasticity).

The volumetric fractions were chosen based on the literature review carried out (1-39). So, the volumetric fractions (V_f) adopted were 6.0 kg/m^3 (V_f of 0.5%), 12 kg/m^3 (V_f of 1.0%), and 18 kg/m^3 (V_f of 1.5%). These volumetric fractions are based on the literature (27, 29, 51).

Table 1. Mix design for the composites studied.

Composite/ type of fiber	Mortar content (%)	Unit mixture	Water/ cement binder	Chemical admixture (%)	Slump test (mm)	Cement (kg/m^3)
Crushed	52	1: 2.12: 2.88	0.58	0.15	100-160	317
Laminated	52	1: 2.12: 2.88	0.58	0.13	100-160	317

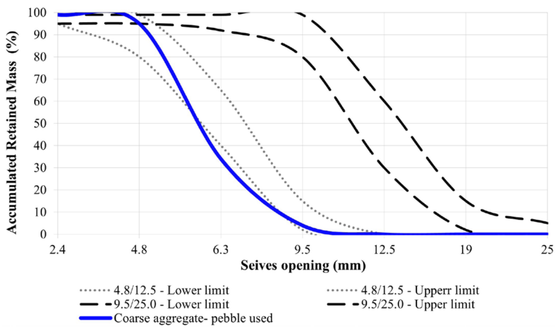

FIGURE 7. Granulometric range of particle sizes of coarse aggregate.

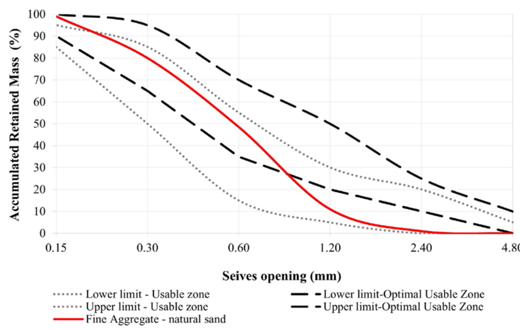

FIGURE 8. Granulometric range of particle sizes of fine aggregate.

The cementitious composites reinforced with Brazilian Amazon bamboo fibers were made in an inclined axis concrete mixer with the following mixing order: ~20% of the water, coarse aggregate, fine aggregate, ~40% of the water, cement, bamboo fiber, the rest of the water, and, lastly, the chemical admixture is used to improve workability and achieve the established slump test. During the matrix mixing process, short bamboo fibers were randomly dropped into the cement mixture, which made alignment between them impossible. This method is widely used in the literature for short and nonwoven fibers and it aims to improve the mechanical properties of the material homogeneously in all directions (2D and 3D - x, y and z-axes). Thus, the fibers in the hardened state of the matrix tend to have a dispersed spatial orientation (3D). Of course, the orientation of the fibers in the matrix will also depend on other factors, such as molding method and mold geometry, mixing energy, type of compaction, type/material and size of the fiber, type and fluidity of the matrix, among others. So, it is important to emphasize that this fiber orientation behavior in the cementitious composite in the hardened state influences the mechanical behavior and it is different for matrices with short and long fibers and for woven and nonwoven fibers.

Additionally, the four-point bending test was performed (Figure 9) according to the JSCE-SF4 standard (52) on prismatic samples measuring 150 mm x 150 mm x 450 mm (15.9 x 15.9 x 47.7 inches). It used an electric strain gauge-based displacement transducer (LVDT), with a measuring base of 100 mm, and sensitivity of 0.0001 mm. It was fixed at the central region of the lateral face of the sample to avoid the effect of confining the ends. The number of replicates for this test was 3 samples.

Regarding the choice of tests in the methodology, these were chosen based on the literature so that volumetric fractions and dimensions of the macro fibers could be tested at a macroscopic level and validated experimentally.

After the bending flexural test, the cracked composite surface was observed by SEM (VEGA 3 LMU TESCAN). Samples were prepared by cutting the material into convenient sizes and covering their fracture surfaces by carbon deposition. Before starting the analysis of the samples, they were subjected to a vacuum. The operating conditions for imaging were: electron beam current of 90 µA, a constant accelerating voltage of 10 kV, and a working distance of 15 mm.

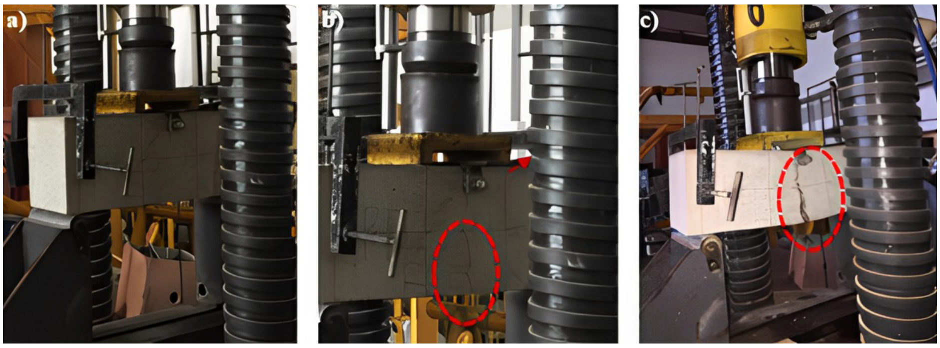

Figure 9. Four-point bending flexural test setup, performed according to the JSCE-SF4 standard (52). Prismatic composite specimens with dimensions of 150 mm x 150 mm x 450 mm are shown: (a) before the test; (b) details during the test, with a crack propagation and opening; and (c) at the end of test.

In summary, the composites were tested by compressive strength (53), splitting strength (54), and flexural strength tests (55) as well as SEM.

3. RESULTS AND DISCUSSION

3.1. Bamboo fibers

The mean cross-sectional area of crushed and laminated bamboo fiber obtained by SEM was 0.68 mm² (standard deviation of ± 0.20 mm²) and 1.96 mm² (standard deviation of ± 0.80 mm²), respectively. This can be attributed to the process for obtaining the fibers (more artisanal) and because it is a natural and vegetable fiber. This means that there is some variability in the results. This behavior is known in the literature for several types of fiber (56-58).

Figure 10 illustrates the bamboo fiber water absorption values.

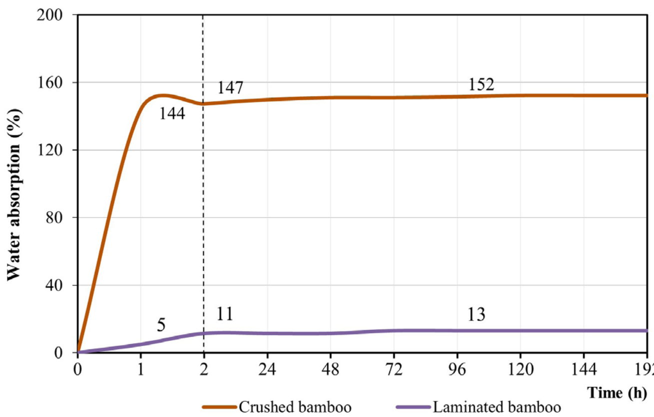

Figure 10. Water absorption for the bamboo fibers studied over time.

In the first hours, the crushed and laminated fibers increased their masses by 147% and 11% in relation to dry mass, respectively. The saturation points of crushed fibers occurred near 24 hours with an absorption of 150%, and for laminated fibers with an absorption of 12%. This is directly related to the fact that the laminated fibers were produced only from bamboo bark, unlike the crushed fibers, which were largely produced from the culm.

To explain the water absorption of fibers, the morphologies of the crushed and laminated bamboo fibers were analyzed by SEM (Figure 11) . Figure 11b shows that the laminated fiber sample had a rough, irregular longitudinal surface. However, for crushed fiber samples, Figure 11c shows a surface with empty spaces and pores.

Other studies have results for water absorption of 104% and 27% for the same fibers (59-60). This condition of low water absorption by the dry bamboo bark fibers is reported by Luis et al. (61), who observed that the outermost layer of the culm is composed of common epidermal cells with thickened walls, highly lignified and axially elongated, that act as a waterproofing agent.

Table 2 presents the results of tensile strength averages of the bamboo fibers tested, as well as the standard deviations.

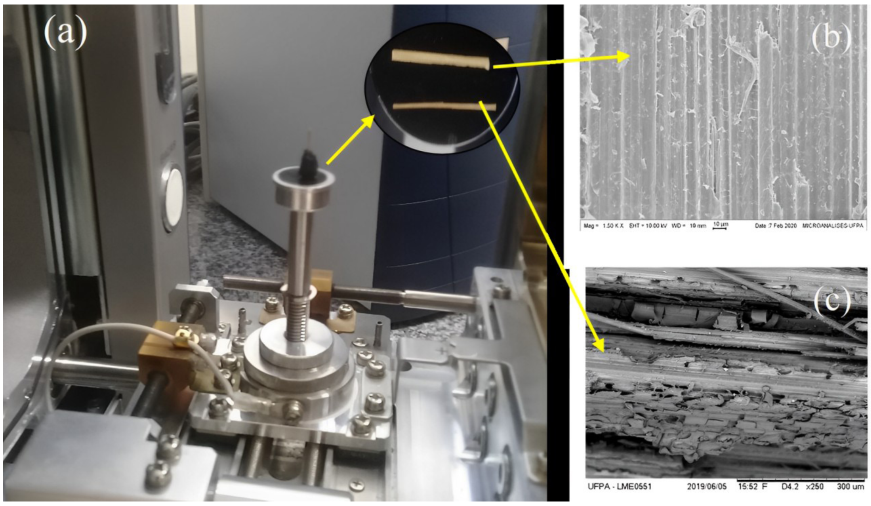

Figure 11. SEM image analysis on the bamboo fiber surfaces: a) microscope, b) laminated fibers at 1,500 x magnification, and (c) crushed fibers at 250 x magnification.

Table 2. Tensile strength averages for the bamboo fibers studied.

Composite/ Type of fiber	Tensile strength (MPa) - standard deviation is in parentheses	Elastic modulus (GPa) – standard deviation is in parentheses
Crushed	147 (75)	27 (± 35)
Laminated	432 (62)	46 (±16)

The average values of tensile strength in this study were 147 MPa and 432 MPa for crushed and laminated fibers, respectively. These results are within the range observed in the literature for vegetable fibers, such as curaua, juta, and sisal fibers, with values between 200 MPa and 500 MPa (62). The mechanical properties of vegetable fibers depend on such factors as the origin of the material, variation in rainfall, UV incidence, type of soil, chemical composition, age, extraction method, method of processing, and water absorption. One possibility for this variation is because we are dealing with a natural fiber, where resistance can be the product of supposed flaws on the surface of the material and the differences in fiber shape (Figures 2 and 4). Another important point to be highlighted in these results is that although the crushed and laminated bamboo fibers came from the same species and the same batch of stalks, the different production processes resulted in significant differences in mechanical behavior (tensile strength and modulus of elasticity). In the crushing process, it was not possible to separate the fibers consisting only of the outermost layers of the culm wall, where there are large amounts of cells that contribute to the hardness of the culms (40, 61). Some microscopic defects on the fiber are responsible for varying results, and this is common for vegetable fibers (42).

3.2. Cementitious composites reinforced with bamboo fibers

Figure 12 and Table 3 show the results of compression strength and splitting strength for the composites studied.

Table 3. Results of the mechanical behavior (compressive and splitting strengths and elastic moduli) of the composites produced.

Cementitious composites / type of bamboo fiber and V_f		Compressive Strength (MPa)		Splitting Strength (MPa)		Elastic Modulus (GPa)
		28 days	standard deviation (%)	28 days	standard deviation (%)	
Crushed	0%	21.5	3 – 13	2.1	0.3 – 12	24
	0.5%	16.2	0.5– 3	2.0	0.2 – 9	23
	1.0%	14.1	0.9– 6	1.4	0.3– 22	23
	1.5%	13.2	1.4– 10	1.4	0.1– 10	23
Laminated	0%	21.5	3 – 13	2.1	0.3 – 12	24
	0.5%	19.5	0.6 – 3	2.4	0.0 – 0	23
	1.0%	18.6	1.0– 6	2.6	0.0– 0	25
	1.5%	18.9	0.2– 1	2.7	0.0– 0	23

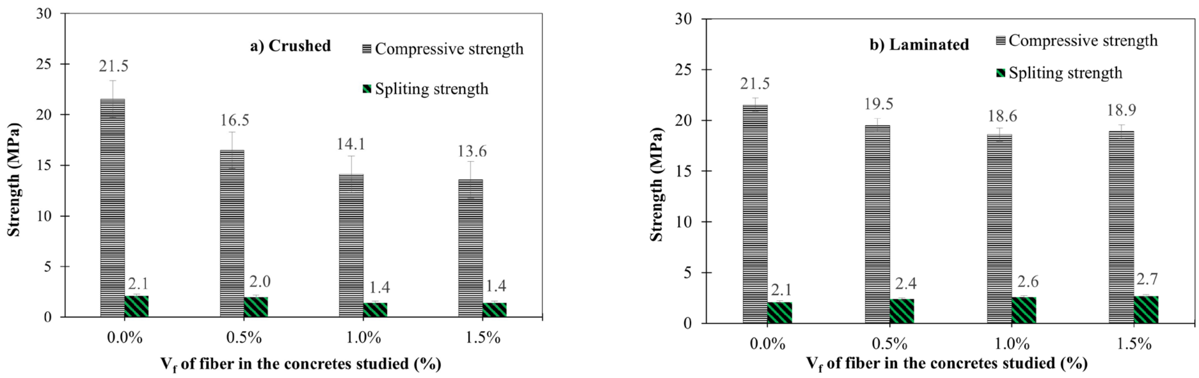

FIGURE 12. Results for compressive strength and splitting tensile strength for composites produced with crushed or laminated bamboo fibers.

In general, with an increasing V_f, the compressive strength was reduced. This happened for composites reinforced with both crushed and laminated fibers. The fibers promoted major imperfections, voids, and defects in the composites. The literature also noted this behavior, (30, 35, 59). Moreover, the reductions of the compressive strengths of the composites with V_f from 0% to 1.5% were lower for composites reinforced with laminated fibers. Following on from this, the composites reinforced with crushed bamboo fibers showed a decrease in splitting strength with an increasing V_f. The decrease in the splitting strength with the increase of V_f was not expected for the composites reinforced with crushed fibers. The addition of fibers was not so efficient in transferring stresses from the matrix to the fibers. Also, the modulus of elasticity for the composites with and without fibers showed similar values.

Other compressive strength results from 8.7 MPa to 41.0 MPa and splitting strength values from 2.0 MPa to 4.3 MPa were achieved in the literature for V_f of laminated bamboo fibers in the range from 0.5% to 1.5% (25, 35, 59). Figure 13 and Table 4 present flexural strength results.

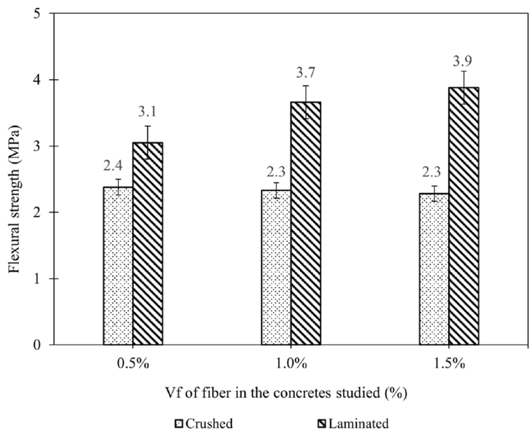

FIGURE 13. Flexural strength (MPa) behavior over V_f.

TABLE 4. Flexural strength results for cementitious composites reinforced with crushed and laminated bamboo fibers.

Cementitious composites and V_f		Flexural strength average (MPa) (standard deviation – MPa and coefficient of variation - %)
Crushed fiber	0.50%	2.4 (0.25-2.0)
	1.00%	2.3 (0.98-4.3)
	1.50%	2.3 (1.02-3.8)
Laminated fiber	0.50%	3.1 (0.5-1.3)
	1.00%	3.7 (1.0-6.4)
	1.50%	3.9 (1.2-5.1)

The incorporation of laminated fibers in the composite gradually increases the flexural strength, unlike the crushed fibers. Also, there is an important aspect to be taken into consideration: crushed and laminated cementitious composites did not have sudden breakage. The characteristic that fiber-reinforced composites did not suffer sudden failure is attributed mainly to the high tensile strength of the fibers and a dependence of their interaction with the matrix (60-63). The fibers allowed for ductility in the studied composites reinforced with bamboo fibers.

In parallel, researchers have presented results of flexural strengths from 1.7 MPa to 19.0 MPa for composites reinforced with laminated bamboo fibers with V_f from 0.5% to 1.8% (23, 30, 59).

Figure 14 shows the flexural test on a composite beam without fiber (a) and with a V_f of 0.5% laminated fiber (b) distributed in the matrix (some of them indicated by arrows). Failure occurred in a more brittle manner in the composite without fiber, while with bamboo fiber, failure occurred in a ductile form due to the fiber's contribution to matrix reinforcement, generating an increase in the composite's toughness.

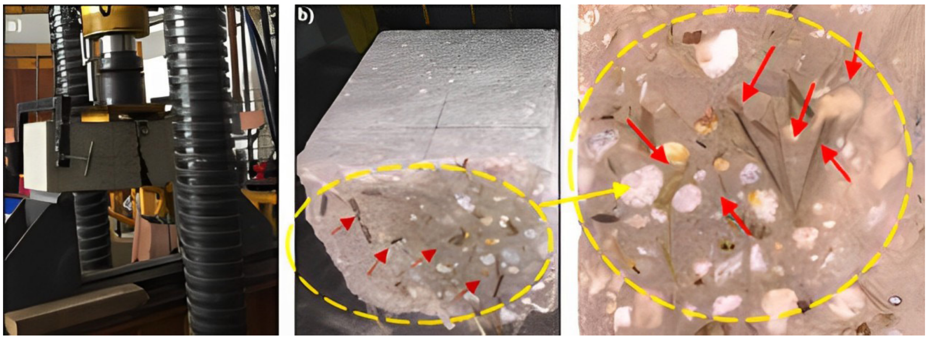

Figure 14. Flexural test, according to JSCE SF4: cementitious composites (a) without fiber (0%), b) with V_f of 0.5% and c) detail of the arrangement of fibers in the matrix.

Figure 15 shows the flexural toughness factor of the composites studied according to the Japanese JSCE–SF4 method (52). In general, for an increase in the V_f from 0.5% to 1.5%, the tenacity increased for these composites. In particular, the flexural toughness factor for the composite reinforced with laminated fibers showed higher values than composite reinforced with crushed fibers. This is due to the tensile strengths (MPa) and elastic moduli (GPa) of the laminated fibers.

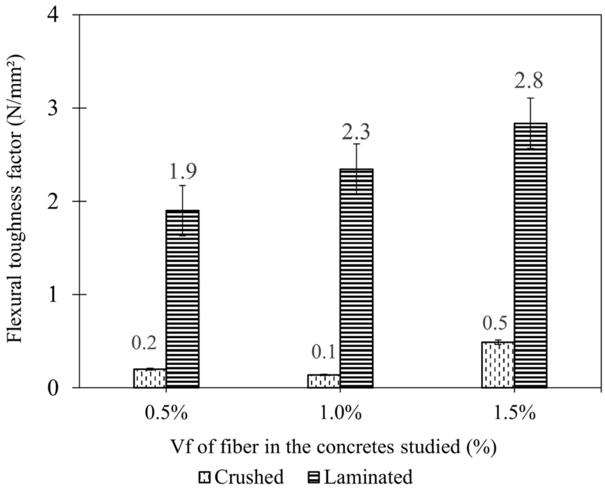

Figure 15. Flexural toughness factor according to the Japanese JSCE–SF4 method (52).

4. GENERAL DISCUSSION

The mechanical behavior (tensile strength and modulus of elasticity) of the crushed and laminated bamboo fibers from Dendrocalamus giganteus indicated different values as a result of both using different parts of bamboo during the process of obtaining the fibers and the morphological characteristics. Also, the water absorption property of the laminated and crushed fibers reflected differences.

As the composites are the result of the fiber characteristics, the laminated bamboo fiber composites showed better mechanical behaviors on the properties studied than crushed bamboo fiber composites. These properties increased with an increase in V_f from 0.5% to 1.5%.

An important point is that the crushed bamboo fibers contributed to an increase in the mechanical properties and the ductility of the composites in lower proportions than laminated fibers. Therefore, this crushed bamboo fibers can be useful. For understanding the interface and bonding, Figure 16 shows the fiber-matrix interface and the bamboo defibrillation by SEM images.

Figure 16 shows a good bond between the crushed and laminated fibers in the cement matrix studied. Both shapes of fibers presented rupture and defibrillation during the flexural test.

Furthermore, Figure 16 illustrates the typical defibrillation process from the morphological analysis that helps to corroborate the major mechanism by which natural fibers provide toughness to concrete, ensuring a gain of residual energy for the composite. In this sense, the references (34, 59) verified that laminated bamboo fibers had a smooth lateral surface, which can influence the matrix/fiber bonding interface and promote the formation of voids and brittle regions. Good matrix-fiber adhesion produced a good interface with the failure of fibers and defibrillation. The fiber bond in the matrix will be investigate by pullout tests in the next steps of this study.

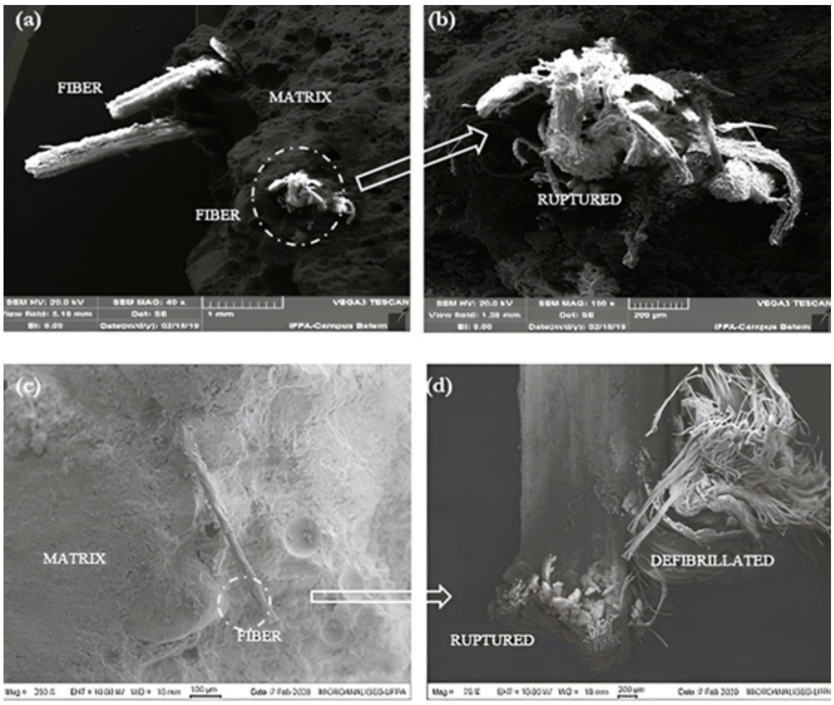

Figure 16. SEM images of composites reinforced with bamboo fibers after flexural strength tests: a) - b) crushed fibers at 40 x and 150 x of magnification, respectively and c) d) laminated fiber at 250 x and 75 x magnification, respectively.

5. CONCLUSIONS

The following conclusions can be drawn:

The production of crushed bamboo fibers resulted in the highest productivity due to the use of a knife mill. However, after grinding the bamboo strips, this productivity decreased with the need to classify the fibers according to the stipulated length through sieving.

Bamboo fibers produced by lamination showed lower water absorption, higher tensile strength, and higher modulus of elasticity compared to results from crushed fibers.

Cementitious composites reinforced with laminated bamboo fibers obtained better mechanical strength results than cementitious composites reinforced with crushed bamboo fibers. This is related to the different physical and mechanical behavior of laminated fibers.

The SEM images showed the fiber-matrix interface of the fiber with the cementitious matrix and the failure mode of the fibers in the concrete. The composites with fibers suffered failures (ruptures) due to defibrillation, ensuring ductility and toughness in the composites.

Authorship contribution statement

Robson da Silva Fernandes: Investigation, Methodology, Writing, Editing, Formal analysis.
Víctor H. Barbosa: Investigation, Methodology, Writing.
Marco A. Oliveira: Investigation, Methodology, Writing.
Andrielli Morais de Oliveiraa: Writing, Review.
Marcelo Picanço: Conceptualization, Funding acquisition, Data curation, Formal analysis, Original draft, Writing, Review & editing.

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