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BEHAVIOR UNDER COMPRESSION AND BENDING OF BAMBOO FILLED WITH SISAL FIBER REINFORCED CEMENTITIOUS COMPOSITES

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ABSTRACT

Introduction: Bamboo exhibits favorable physicomechanical properties and significant potential for application in civil construction as an alternative to conventional materials. This study aimed to evaluate the geometric, physical, and mechanical characteristics of *Bambusa vulgaris* culms along their longitudinal axis, in addition to investigating bamboo absorption behavior, differential shrinkage of the culms, and the effect of filling with a sisal fiber-reinforced cementitious composite under compressive and flexural loads, in accordance with Brazilian and international standards. For this purpose, culms were harvested from *Bambusa vulgaris* specimens at the State University of Feira de Santana (UEFS), followed by cleaning, drying, and subsequent characterization. Results indicated that after 89 days of ambient air drying, the specimens attained constant mass and exhibited a reduction in external culm diameter from base to apex, with spatial variability in physical and mechanical properties along the culm length. Bamboo demonstrated higher water absorption compared to the fiber-reinforced composite. Structural performance of the filled bamboo was assessed through compressive and flexural testing of specimens measuring 12 cm and 20 cm, respectively, with and without composite filling. Specimens incorporating the composite exhibited enhanced crack propagation resistance attributable to the reinforcing effect of the vegetal fibers embedded within the matrix, thereby substantiating the efficacy of the filling technique, as corroborated by load-displacement response curves.

Objective: The objective of this study is to investigate the structural behavior of *Bambusa vulgaris* bamboo culms filled with a sisal fiber-reinforced cementitious composite, subjected to compressive and flexural loads.

Theoretical Framework: Initially, the potential of bamboo as an alternative construction material is described, highlighting its favorable physicomechanical properties and environmental advantages. The properties of natural fiber-reinforced composites, such as those reinforced with sisal fibers, and their applications in enhancing structural performance are also discussed.

Method: An experimental methodology was used, starting with the collection of Bambusa vulgaris culms at the State University of Feira de Santana (UEFS). The culms were cleaned, air-dried for 89 days until constant mass was reached, and then analyzed for their geometric, physical, and mechanical properties along their length. Specimens measuring 12 cm for compression tests and 20 cm for flexural tests were prepared, both with and without sisal fiber-reinforced composite filling. Testing adhered to Brazilian and international standards for absorption, shrinkage, compressive strength, and flexural strength analysis.

Results and Discussion: Results showed that *Bambusa vulgaris* culms exhibit variations along their length, with a reduction in external diameter from base to apex and stabilization of mass after 89 days of air drying. Bamboo absorption was higher than that of the sisal fiber-reinforced composite, which, when used as filling, significantly improved the structural behavior of the specimens under compression and bending by enhancing crack containment, as evidenced by load-displacement curves.

Research Implications: This research offers practical implications for civil construction, suggesting that filling bamboo culms with fiber-reinforced composite can increase the durability and structural resistance of construction elements. Theoretically, it contributes to the understanding of the combined behavior of bamboo and natural

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composites, encouraging the sustainable use of alternative materials. The results may impact sectors related to sustainable civil engineering, composite materials, and eco-friendly construction technologies.

Originality/Value: This study contributes to the literature by integratively investigating the properties of bamboo along its length and the effect of filling with a sisal fiber-reinforced composite under mechanical loads—an innovation not previously explored in bamboo filling research. The detailed experimental approach and use of natural fibers as reinforcement add value to advancing sustainable solutions in civil construction, demonstrating the viability of bamboo as a technically and environmentally advantageous alternative.

Keywords: Bamboo, absorption, shrinkage, compression, bending, sisal fiber-reinforced composite.

COMPORTAMENTO À COMPRESSÃO E FLEXÃO DO BAMBU PREENCHIDO COM COMPÓSITOS CIMENTÍCIOS VEGETAIS

RESUMO

Introdução: O bambu possui boas propriedades físico-mecânicas e grande potencial para ser utilizado na construção civil como alternativa aos materiais convencionais. Este estudo teve como objetivo avaliar as propriedades geométricas, físicas e mecânicas dos colmos de bambu ao longo de seu comprimento, além de investigar aspectos como a absorção do bambu, as diferentes retrações dos colmos e o efeito do preenchimento, com compósito reforçado com fibras de sisal, sob compressão e flexão, conforme as normativas brasileiras e internacionais. Para isso, foram coletados colmos da espécie Bambusa vulgaris na Universidade Estadual de Feira de Santana (UEFS), limpos, secos e avaliados. Os resultados mostraram que, após 89 dias de secagem ao ar, a espécie apresentou uma massa constante e diminuição do diâmetro externo do colmo da base para o topo, com variações nas propriedades físicas e mecânicas dependendo da localização ao longo do colmo. A absorção do bambu foi maior que a do compósito reforçado. O comportamento estrutural do bambu preenchido foi realizado sob ensaios a compressão e flexão em corpos de prova de 12 cm e 20 cm, respectivamente, com e sem o preenchimento. Os corpos com compósito apresentam maior contenção de fissuras pela contribuição das fibras vegetais inclusas na mistura, validando a eficácia do preenchimento, evidenciado pelas curvas de carga-deslocamento.

Objetivo: O objetivo deste estudo é investigar o comportamento estrutural dos colmos de bambu da espécie *Bambusa vulgaris* preenchidos com compósito reforçado com fibras de sisal, submetidos a esforços de compressão e flexão.

Referencial Teórico: Inicialmente, é descrito o potencial do bambu como material alternativo na construção civil, destacando suas boas propriedades físico-mecânicas e vantagens ambientais. Também são abordadas as propriedades dos compósitos reforçados com fibras naturais, como as fibras de sisal, e suas aplicações na melhoria do desempenho estrutural.

Método: Uma metodologia experimental foi utilizada, começando com a coleta de colmos de Bambusa vulgaris na Universidade Estadual de Feira de Santana (UEFS). Os colmos foram limpos, secos ao ar por 89 dias até atingirem massa constante, e então analisados quanto às suas propriedades geométricas, físicas e mecânicas ao longo do comprimento. Foram preparados corpos de prova com 12 cm para testes de compressão e 20 cm para testes de flexão, tanto com preenchimento de compósito reforçado com fibra de sisal quanto sem preenchimento. Os testes seguiram normas brasileiras e internacionais para análise de absorção, retração, resistência à compressão e resistência à flexão.

Resultados e Discussão: Os resultados mostraram que os colmos de *Bambusa vulgaris* apresentam variações ao longo do comprimento, com diminuição do diâmetro externo da base ao topo e estabilização da massa após 89 dias de secagem ao ar. A absorção de umidade do bambu foi maior que a do compósito reforçado com fibras de sisal, que, ao ser utilizado para preenchimento, melhorou significativamente o comportamento estrutural dos corpos de prova submetidos a compressão e flexão, promovendo maior contenção de fissuras, conforme evidenciado pelas curvas carga-deslocamento.

Implicações da Pesquisa: Esta pesquisa oferece implicações práticas para a construção civil, sugerindo que o preenchimento de colmos de bambu com compósito reforçado pode aumentar a durabilidade e resistência estrutural de elementos construtivos. Teoricamente, contribui para o conhecimento sobre o comportamento combinado de bambu e compósitos reforçados com fibras naturais, incentivando o uso sustentável de materiais alternativos. Os

resultados podem impactar setores ligados à engenharia civil sustentável, materiais compósitos e tecnologias de construção ecológica.

Originalidade/Valor: Este estudo contribui para a literatura ao investigar de forma integrada as propriedades do bambu ao longo do comprimento e o efeito do preenchimento com compósito reforçado com fibras de sisal sob esforços mecânicos. O estudo é uma inovação que, até o momento, não foi explorada em outras pesquisas sobre o preenchimento de bambu. A abordagem experimental detalhada e o uso de fibras naturais como reforço agregam valor ao avanço de soluções sustentáveis para construção civil, demonstrando a viabilidade do bambu como alternativa técnica e ambientalmente vantajosa.

Palavras-chave: Bambu, absorção, retração, compressão, flexão, compósito reforçado com fibras de sisal.

COMPORTAMIENTO BAJO COMPRESIÓN Y FLEXIÓN DEL BAMBÚ RELLENO CON COMPÓSITOS CEMENTICIOS VEGETALES

RESUMEN

Introduccion: El bambú posee buenas propiedades físico-mecánicas y un gran potencial para ser utilizado en la construcción civil como alternativa a los materiales convencionales. Este estudio tuvo como objetivo evaluar las propiedades geométricas, físicas y mecánicas de los tallos de bambú a lo largo de su longitud, además de investigar aspectos como la absorción del bambú, las diferentes retracciones de los tallos y el efecto del relleno con un compósito reforzado con fibras de sisal bajo esfuerzos de compresión y flexión, conforme a las normativas brasileñas e internacionales. Para ello, se recolectaron tallos de la especie *Bambusa vulgaris* en la Universidad Estatal de Feira de Santana (UEFS), que fueron limpiados, secados y evaluados. Los resultados mostraron que, después de 89 días de secado al aire, la especie presentó una masa constante y una disminución del diámetro externo del tallo desde la base hasta la punta, con variaciones en las propiedades físicas y mecánicas según la ubicación a lo largo del tallo. La absorción del bambú fue mayor que la del compósito reforzado. El comportamiento estructural del bambú relleno fue evaluado mediante ensayos de compresión y flexión en probetas de 12 cm y 20 cm, respectivamente, con y sin relleno. Las probetas con compósito presentaron una mayor contención de fisuras debido a la contribución de las fibras vegetales incluidas en la mezcla, validando la eficacia del relleno, como se evidenció en las curvas carga-desplazamiento.

Objetivo: El objetivo de este estudio es investigar el comportamiento estructural de los tallos de bambú de la especie *Bambusa vulgaris* rellenos con un compósito reforzado con fibras de sisal, sometidos a esfuerzos de compresión y flexión.

Marco Teórico: Inicialmente, se describe el potencial del bambú como material alternativo en la construcción civil, destacando sus buenas propiedades físico-mecánicas y ventajas ambientales. También se abordan las propiedades de los compósitos reforzados con fibras naturales, como las fibras de sisal, y sus aplicaciones en la mejora del desempeño estructural.

Método: Se utilizó una metodología experimental que comenzó con la recolección de tallos de Bambusa vulgaris en la Universidad Estatal de Feira de Santana (UEFS). Los tallos fueron limpiados, secados al aire durante 89 días hasta alcanzar masa constante, y luego analizados para determinar sus propiedades geométricas, físicas y mecánicas a lo largo de su longitud. Se prepararon especímenes de 12 cm para pruebas de compresión y 20 cm para pruebas de flexión, tanto con relleno de compuesto reforzado con fibras de sisal como sin relleno. Las pruebas se realizaron conforme a normas brasileñas e internacionales para el análisis de absorción, contracción, resistencia a la compresión y resistencia a la flexión.

Resultados y Discusión: Los resultados mostraron que los tallos de *Bambusa vulgaris* presentan variaciones a lo largo de su longitud, con disminución del diámetro externo desde la base hasta la punta y estabilización de la masa después de 89 días de secado al aire. La absorción del bambú fue mayor que la del compósito reforzado con fibras de sisal, que al utilizarse como relleno mejoró significativamente el comportamiento estructural de las probetas sometidas a compresión y flexión, promoviendo una mayor contención de fisuras, como evidencian las curvas carga-desplazamiento.

Implicaciones de la investigación: Esta investigación ofrece implicaciones prácticas para la construcción civil, sugiriendo que el relleno de tallos de bambú con compósito reforzado puede aumentar la durabilidad y resistencia estructural de los elementos constructivos. Teóricamente, contribuye al conocimiento sobre el comportamiento

combinado del bambú y los compósitos naturales, fomentando el uso sostenible de materiales alternativos. Los resultados pueden impactar sectores vinculados a la ingeniería civil sostenible, materiales compósitos y tecnologías de construcción ecológica.

Originalidad/Valor: Este estudio contribuye a la literatura al investigar de forma integrada las propiedades del bambú a lo largo de su longitud y el efecto del relleno con compósito reforzado con fibras de sisal bajo esfuerzos mecánicos, siendo una innovación que hasta ahora no ha sido explorada en otras investigaciones sobre el relleno de bambú. El enfoque experimental detallado y el uso de fibras naturales como refuerzo agregan valor al avance de soluciones sostenibles para la construcción civil, demostrando la viabilidad del bambú como alternativa técnica y ambientalmente ventajosa.

Palabras clave: Bambú, absorción, retracción, compresión, flexión, compósito reforzado con fibras de sisal.

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1 INTRODUCTION

Bamboo has been used as a construction material for centuries, mainly in Asian and American countries, albeit empirically. Since 1987, there has been increased discussion on the need to recognize bamboo as a construction and engineering material in the international context, resulting in the publication of the international standards ISO 22156 (ISO, 2004) and ISO 22157 (ISO, 2004). From a sustainability perspective, the incorporation of renewable materials in civil construction has been widely investigated to reduce energy consumption, mitigate pollution, and optimize costs (Cruz & Barros, 2022; Sil, 2022). Countries such as Ecuador, Colombia, Peru, and Brazil already have specific standards for the structural use of bamboo. One of the renowned architects for innovative use of bamboo in sustainable architectural projects with high structural performance is Somin Velez. Among his most recognized projects is the Privado Church, shown in Figure 1.

Figure 1

Church of Saint Anthony of Pereira.



Fonte: Shuvalov, 2016.

In Brazil, NBR 16828-1 (ABNT, 2020) establishes guidelines for the design of bamboo structural elements, while NBR 16828-2 (ABNT, 2020) defines procedures to characterize bamboo properties, which can vary due to factors such as diameter, thickness, density, and taper (Berndsen et al., 2014; Vetter et al., 2015; Anokye et al., 2016; Ostapiv & Librelotto, 2019; Rusch et al., 2020; Chaowana et al., 2021). Mechanical properties, such as compression and bending, show variability depending on species and location along the bamboo culm, with values reported by Ghavami et al. (2017), Carbonari et al. (2017), Richard et al. (2017), and Bacosa & Loretero (2023).

In construction, especially at joints and foundations subjected to critical loads, both national and international standards recommend filling bamboo with mortar or similar materials (Lima et al., 2010; Li et al., 2017; Nie et al., 2022). Studies indicate that filling with concrete significantly increases load capacity and bending strength of specimens (Bacosa & Loretero, 2023). NBR 16828-1 (ABNT, 2020) also suggests using less rigid cementitious materials, opening space for composites reinforced with sisal fibers, which provide greater flexibility and crack reinforcement (Lima et al., 2014; Rocha et al., 2021; Beskopylny et al., 2022).

Despite these advances, there are still knowledge gaps regarding bamboo shrinkage and water absorption, which are essential when studying filled bamboo. This work focuses on bamboo reinforced with a sisal fiber-based composite, a material with greater toughness compared to conventional ones, aiming to validate its viability for critical structural applications where strength and flexibility are essential.

2 METHODOLOGY

The methodology of this study describes the procedures used in the preparation of the work, with essential details to ensure the replicability and reliability of the results.

2.1 BAMBOO

The bamboo used in this research, identified as Bambusa vulgaris and approximately 5 years old, was collected from the State University of Feira de Santana (UEFS). Six culms were gathered for the experiments. As a plant-based material, the bamboo underwent a prior treatment process, including high-pressure water cleaning to remove impurities after cutting. The geometric, physical, and mechanical characterization followed the guidelines of standard NBR 16828-2 (ABNT, 2020).

2.1.1 Geometric properties of bamboo

The measurements of the bamboo specimens included the external diameter and wall thickness, both taken at two sections at each end to calculate average values. The internal diameter was determined by subtracting twice the wall thickness from the external diameter, according to equation (1). The cross-sectional area of the culm (Ab) was then calculated as the area of the circular ring of the cross section, determined using equation (2).

$$d = D - 2x\,t \qquad (1)$$

$$Ab = \frac{\pi \times (D^2 - d^2)}{4} \qquad (2)$$

where:

d = average internal diameter
D = average external diameter
t = average wall thickness
Ab = cross-sectional area
D = average external diameter
d = average internal diameter

Table 1 presents the dimensions of the specimens measured and calculated using equations 1 and 2, necessary for carrying out the physical and mechanical characterization.

Table 1

Bamboo dimensions for physical and mechanical tests.

Description		D (mm)	t (mm)	d (mm)	L (mm)	Ab (mm2)
Base	1B	62,73	12,20	38,33	59,85	1936,49
	2B	62,99	11,58	39,84	65,50	1869,56
	3B	62,66	12,33	38,00	62,70	1949,82
Meio	1C	67,85	7,53	52,80	64,30	1426,11
	2C	67,70	7,61	52,49	63,33	1435,98
	3C	66,88	7,38	52,12	66,73	1379,79
Topo	1T	56,53	5,07	46,39	46,15	819,39
	2T	56,80	5,15	46,50	46,80	835,66
	3T	54,56	4,29	45,98	47,28	678,09

D = external diameter; t = thickness; d = internal diameter; L = length; Ab = bamboo area.

2.1.2 Physical and mechanical properties of bamboo

Moisture content (U) was determined by weighing the samples and monitoring their mass until a constant weight was reached after oven drying (Figure 2A), calculated according to equation (3). Bulk density (ρ) was measured by recording the mass and dimensions of the samples, with calculations based on equation (4). Shrinkage (%) was evaluated by tracking changes in the three dimensions diameter, thickness, and length of the samples (Figure 2B), using equation (5) for the calculations. Additionally, water absorption by capillarity of bamboo (C) was determined by monitoring the mass of the specimens, following NBR 9779 (ABNT, 2012) due to the absence of this test in the specific bamboo standard (Figure 2C), calculated using equation (6).

$$U = \left(\frac{m - m_o}{m_o}\right) \times 100 \quad (3)$$

$$\rho = \frac{m}{V} \text{x } 10^6 \quad (4)$$

$$\% = \frac{L1 - L2}{L1} \text{x } 100\% \quad (5)$$

$$C = \frac{A - B}{S} \text{x } 100\% \quad (6)$$

where:

m= mass of the specimen before drying in the oven, with an accuracy of 0.01 g

m_o= mass of the specimen after drying, with an accuracy of 0.01 g

ρ = bulk density, expressed in kilograms per cubic meter kg/m³

m= mass of the specimen, expressed in grams g

V= volume of the specimen, expressed in cubic meters m³

L1= initial reading measurement, specimen at equilibrium with the environment

L2= final reading measurement, taken after oven drying

C= water absorption by capillarity, in g/cm²

A= mass of the specimen with one face in contact with water, in g

B= mass of the dry specimen once it reaches the temperature of (23 ± 2) °C, in (g)

S= cross-sectional area, in cm²

Compressive strength parallel to bamboo fibers (fco): Tested using a Servo Control machine (1000 kN capacity) at 0.06 mm/min, calculated by equation (7) (Figure 2D).

$$f_{co} = \frac{f_{max}}{A} \qquad (7)$$

where:

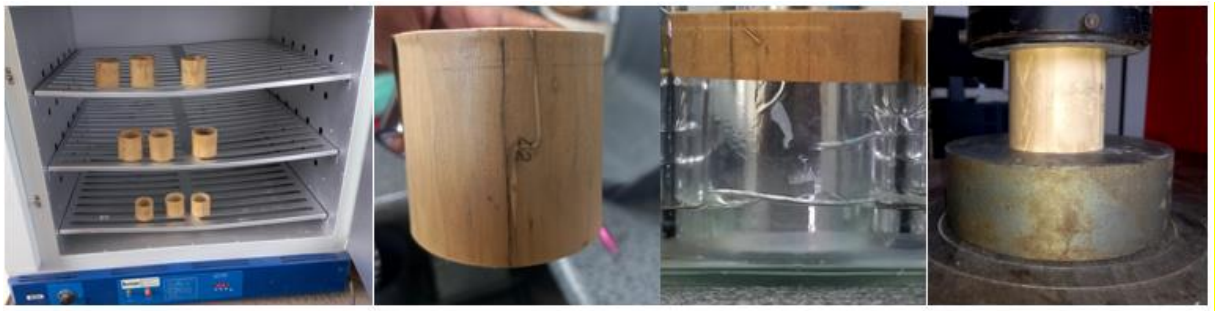
f_{co}= compressive strength parallel to the fibers, expressed in (MPa)

Fmáx = maximum load indicated by the testing machine, expressed in (N)

A= cross-sectional area of the specimen, expressed in (mm^2)

Figure 2

Physical tests: A) Bamboo in the oven, B) Measurement of different dimensions, C) Bamboo compression test and D) Compressive strength.



A) B) C) D)

2.2 SISAL FIBER-REINFORCED COMPOSITE

The cementitious composite reinforced with sisal fibers was prepared using a formulation adapted from the work of Rocha et al (2021), as shown in Table 2.

Table 2

Composite consumption for 1 (m^3) of mixture expressed in (kg).

Com.	C.	Sil.	F.A.	Sa.	Water	Fib.	S.P.	M.V.
VF: 4%, A/A 0,40	360,23	120,08	320,21	800,51	321,54	21,35	13,34	1,2

Com = composite; V.F = fiber volume; W/C = water-to-cement ratio; C = cement; Sil. = silica; F.A. = fly ash; Sa. = sand; Fib = fiber; S.P. = superplasticizer; V.M. = viscosity modifier.

The mixture had a fixed spread of 250 mm ± 10 mm. The materials used were: CPV-ARI Portland cement without additives with a specific mass of 3.08 kg/dm³; active silica to consume calcium hydroxide produced by cement hydration; fly ash to improve workability and act as a pozzolanic addition; fine sand passing through a #1.2 mm sieve, with a specific mass of 2.61 kg/dm³ and fineness modulus of 1.64; superplasticizer to improve workability and cohesion; viscosity-modifying agent; and sisal fibers from the Valente region, Bahia, treated by hornification, which consists of repeated cycles of wetting and drying. The fibers were cut to a length of 40 mm.

To analyze the behavior of filled bamboo, specimens measuring 5 cm in diameter and 10 cm in length were prepared for strength and absorption tests. Curing was carried out in air, with the specimens wrapped in plastic film to prevent water evaporation.

a) water absorption by capillarity: the test was conducted as specified by NBR 9779 (ABNT, 2012), calculated using equation 6, as previously described.

2.3 BAMBOO FILLED WITH SISAL FIBER-REINFORCED COMPOSITE

To analyze the behavior of filled bamboo, specimens were cut to different lengths: 12 cm for compression tests (twice the diameter) and 20 cm for four-point bending tests, as detailed in Table 3 and Figure 3A.

Table 3

Dimensions of bamboo and filled bamboo.

Description	Samples	L (mm.)	D (mm.)	t (mm.)	d (mm.)	Ab (mm)	Ac (mm)	At (mm)
B	B-1C	115,00	57,67	12,99	31,69	1822,97	-	-
	B-2C	111,00	60,97	10,11	40,76	1614,64	-	-
	B-3C	118,00	59,98	11,68	36,63	1771,55	-	-
BCCF	BCCF-1C	110	59,5	13,73	32,05	1973,74	806,76	2780,51
	BCCF-2C	118,5	59,95	12,00	35,95	1807,67	1015,05	2822,72
	BCCF-3C	114	60,07	11,55	36,97	1760,45	1073,27	2833,72
B	B-1F	200,00	57,77	8,00	41,78	1250,98	-	-
	B-2F	200,00	68,27	12,95	42,38	2250,82	-	-
BCCF	BCCF-1F	203,9	62,37	6,85	48,67	1194,89	1860,81	3055,7
	BCCF-2F	199,3	57,47	9,8	37,87	1467,8	1126,67	2594,47
	BCCF-3F	198,4	66,12	9,3	46,27	1752,33	1681,83	3434,17

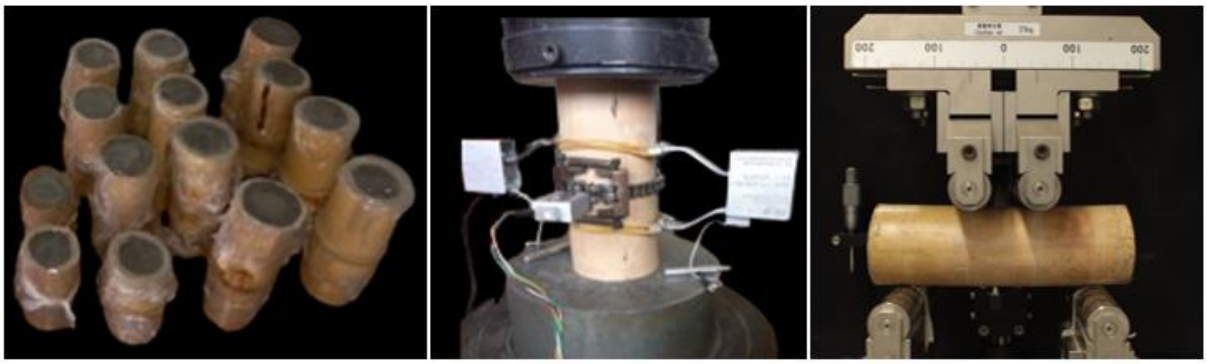
L = length; D = external diameter; d = internal diameter; Ab = bamboo area; Ac = cementitious composite area; At = total sample area; B = bamboo; BCCF = bamboo filled with sisal fiber-reinforced composite; C = compression test; F = bending test.

The specimens were prepared with outer packaging to prevent leakage and evaporation, filled using a funnel with 2 minutes of vibration for homogeneous distribution, and cured in

open air for 28 days (Figure 3A). Compression tests were conducted on specimens 12 cm long and 6 cm in diameter using a 1000 kN Servo-Control machine at 0.1 mm/min (Figure 3B). Flexural tests employed the four-point bending method on 20 cm specimens, with a 0.1 mm/min test speed and 5 cm between load points, using a Shimadzu Static Servo-Electric Universal machine (Figure 3C).

Figure 3

Specimens for mechanical testing: A) Filled bamboo, B) Compression test and C) Flexural test.



3 RESULTS AND DISCUSSIONS

3.1 BAMBOO

3.1.1 Drying

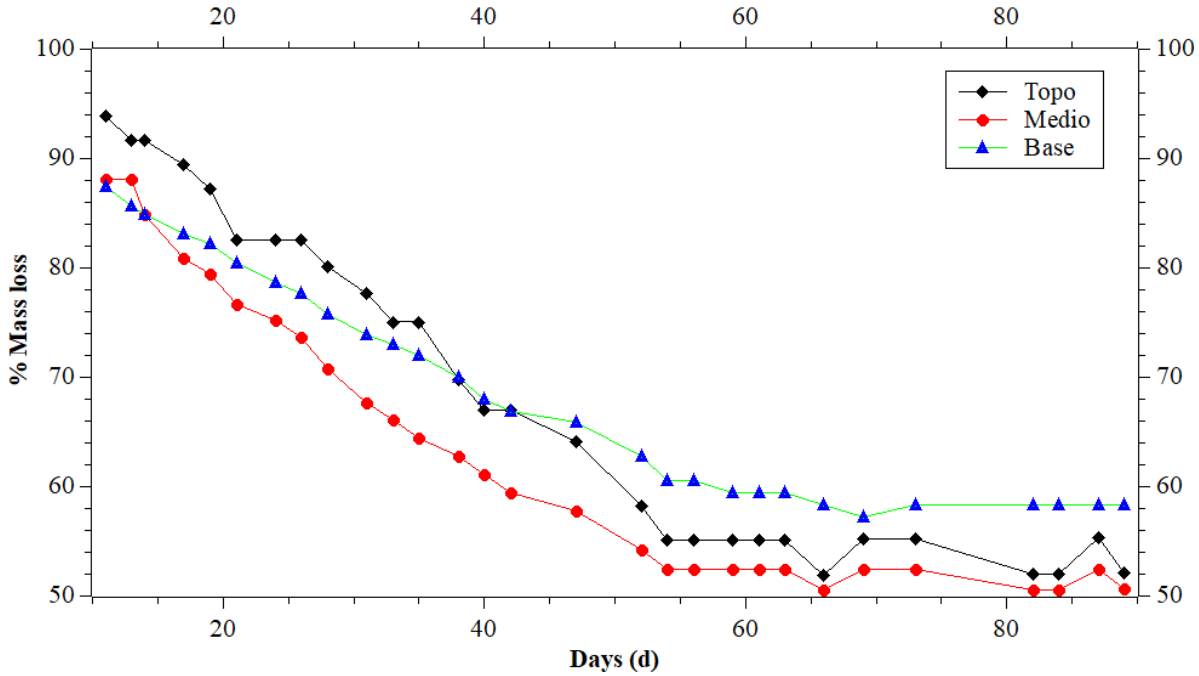
The bamboo drying process lasted about three months, following an air-drying procedure until constant mass was reached after 89 days (Figure 4). During this time, temperature and humidity data from INMET (2022) showed an average temperature of 25°C and relative humidity of 71% in Feira de Santana, Bahia, from August to November 2022.

According to Rusch et al. (2020), bamboo and wood are hygroscopic materials, meaning they have the ability to absorb or lose moisture until reaching equilibrium with the surrounding environment. In the present study, the bamboo specimens were subjected to this process for 89 days, during which mass loss reached 58%, 50%, and 52% for samples located at the base, middle, and top sections, respectively. Ghavami et al. (2017) emphasize that moisture reduction in bamboo leads to a significant increase in its strength, a crucial factor for its application in

civil construction. In a study conducted by Vetter et al. (2015), the drying process was performed in an oven at 40 °C for 25 days, reducing the moisture content from 48% to 9%.

Figure 4

Mass loss during bamboo drying.



3.1.2 Geometry of Diameter and Wall Thickness Along the Length

Six culms (identified as 1B, 2B, 3B, 4B, 5B, and 6B) were collected, and for each, the external diameter and wall thickness were measured in order to construct the diameter curve (Figure 5A) and the thickness curve versus location along the culm (Figure 5B).

The reduction in diameter and wall thickness along the length of the bamboo is discussed in studies such as Ghavami et al. (2017), Ostapiv & Librelotto (2019). Vetter et al. (2015), and Chaowana et al. (2021), which conclude that the species Bambusa vulgaris exhibits a slight increase in diameter and thickness in the central region of the culm, a characteristic specific to this species. To illustrate these variations, images of the culm walls were recorded at the base region (Figure 6A), middle (Figure 6B), and top (Figure 6C).

Figure 5

Geometric variation: A) Diameter along the length and B) Thickness along the length.

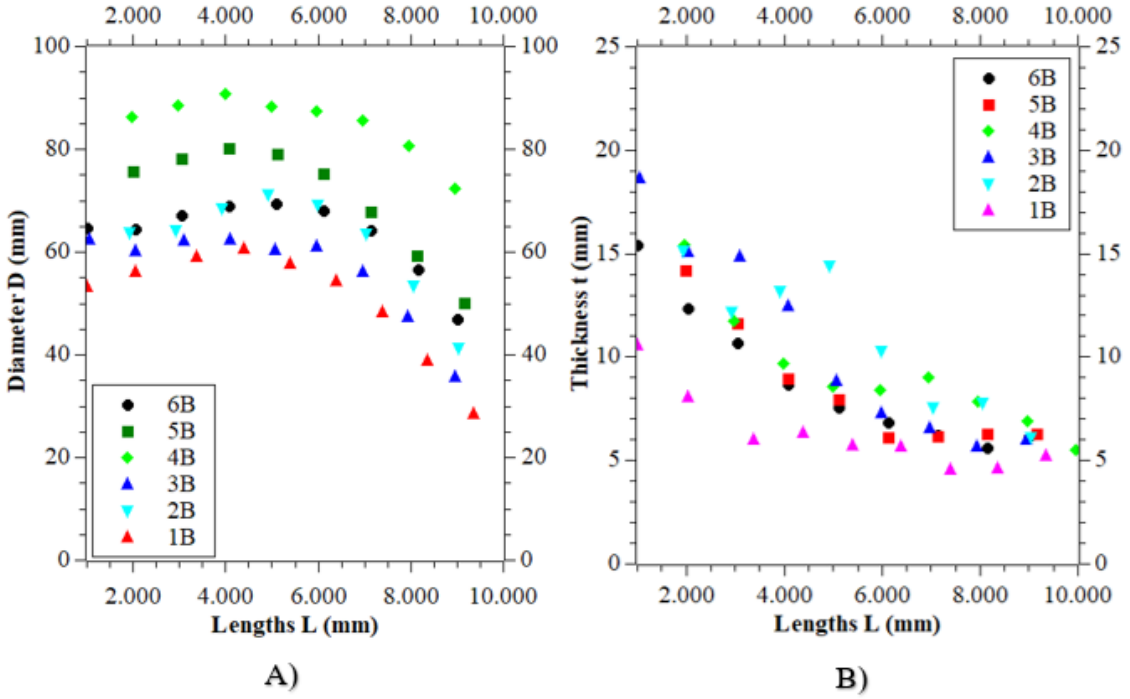
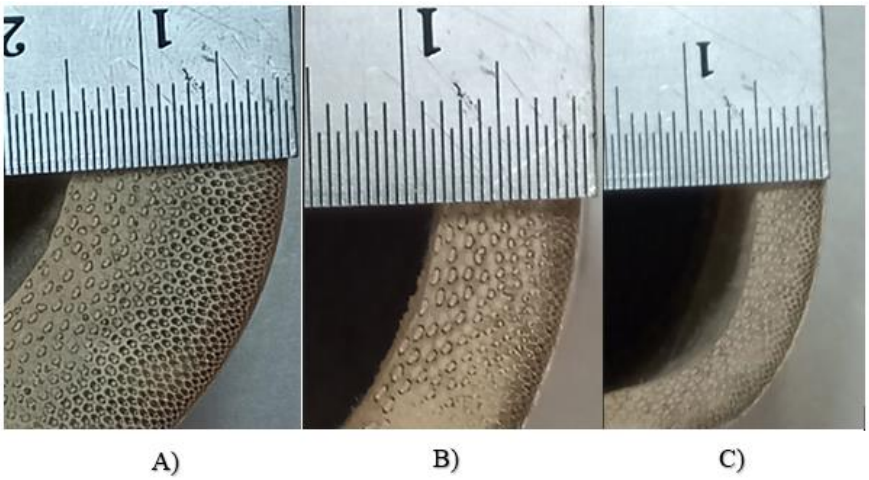


Figure 6

Thickness variation: A) Base, B) Middle, and C) Top.



3.1.3 Physical and mechanical properties

3.1.3.1 Moisture content

Table 4 presents the results obtained from the moisture content (U) test of the different parts of the bamboo.

Table 4

Moisture content.

Sample	Moisture content (%)	DP	CV %
Base	11,85	0,17	1,40
Meio	11,25	0,16	1,41
Topo	10,56	0,05	0,47
Média	11,22	0,13	1,10

SD = standard deviation; CV = coefficient of variation.

When analyzing the moisture content of the bamboo, a significant variation is observed, with higher levels at the base of the culm, gradually decreasing towards the top. This behavior can be attributed to variations in wall thickness across different regions of the culm, as well as the distribution of vessels in the respective segments. This observation corroborates the findings of Ostapiv & Librelotto (2019), Rusch et al. (2020), Anokye et al. (2016), and Gomes et al. (2021), who report an average bamboo moisture content close to 12%, a value similar to that of wood. These authors also identified higher moisture content at the base of the culm, associated with greater wall thickness and a higher presence of parenchymal cells, which decreases along the length of the culm.

3.1.3.2 Bulk Density

The results obtained from the bulk density (B.D) test are presented in Table 5.

Table 5

Bulk Density.

Sample	**Bulk Density (kg/m³)**	**DP**	**CV %**
Base	759,76	40,98	5,39
Meio	746,00	25,41	3,41
Topo	756,10	53,15	7,03
Média	753,95	39,85	5,28

SD = standard deviation; CV = coefficient of variation.

At the base, the bulk density of the studied bamboo varied between 759 kg/m³, 746 kg/m³, and 756 kg/m³ for the base, middle, and top regions, respectively. This behavior is similar to that reported by Oliveira et al. (2017), who presented values of 0.72 g/cm³, 0.75 g/cm³, and 0.76 g/cm³ for the same regions in the same species. The authors highlight that the mechanical properties of bamboo are directly related to its atomic and macroscopic structure, showing a direct correlation with the material's specific mass.

This variation in bulk density, as described in the literature, can be influenced by several factors, including the bamboo type, harvesting period, and specific characteristics of each culm, such as fiber diameter and cell wall thickness, even within the same species.

Another relevant study is by Antwi et al. (2022), which evaluated the bulk density of the species Bambusa vulgaris across three different ecological zones, obtaining values between 616 kg/m³ and 641 kg/m³. These values, lower than those found in the present research, highlight the intrinsic variability of bamboo, even within the same species.

3.1.3.3 Shrinkage

The results of the shrinkage test in the orthogonal directions radial, tangential, and longitudinal are presented in Table 6.

Table 6

Shrinkage of bamboo in the radial, tangential, and longitudinal directions.

Sample		Radial (%)	CV %	Tangential (%)	CV %	Longitudinal (%)	CV %
Posição	Base	3,55	80,67	9,93	6,23	1,78	52,94
	Meio	3,95	24,20	12,95	12,96	2,17	33,22
	Topo	2,87	48,66	20,77	25,89	2,77	53,25
	Média	3,46	51,18	14,55	15,02	2,24	46,47

CV = coefficient of variation.

From the tests conducted, the shrinkage values found in the radial, tangential, and longitudinal directions ranged between 3.55% and 2.87%, 9.93% and 20.77%, and 1.78% and 2.24%, respectively (Table 6). Similar behavior was observed by Sadiku et al (2016), who reported radial shrinkage values between 7.03% and 5.50% from the base to the top of the culm, and tangential shrinkage between 10.40% and 12.72%, for the same bamboo species.

The longitudinal shrinkage, however, exhibited an opposite behavior to that of the radial and tangential directions, differing from the results of Sadiku et al. (2016), whose values ranged from 0.82% to 1% from the base to the top. This difference can be characterized as a particular behavior of the bamboo studied.

Overall, the greatest shrinkage occurred in the tangential direction in all portions of the culm, exceeding the radial and longitudinal shrinkages. Additionally, the coefficient of variation values were presented, highlighting the material variability as a function of location along the culm, species, and aspects related to the age of the bamboo.

3.1.3.4 Compressive strength

The determination of compressive strength was carried out as described in the methodology. It was observed that the strength along the culm did not show significant variation, with the highest average strength recorded in the central region of the culm (Table 7).

Table 7

Resistência à compressão paralela as fibras.

Sample	Strength (Mpa)	DP	CV %
Base	49,54	0,80	1,61
Meio	46,36	7,49	16,16
Topo	47,82	0,21	0,43
Média	47,91	2,83	6,07

SD = standard deviation; CV = coefficient of variation.

It is observed that the strength of bamboo is higher at the base, reaching 49 MPa, while in the middle the strength is 46 MPa, and at the top it reaches 47.82 MPa. This behavior can be explained by the slight increase in external diameter and wall thickness in the central region of the culm, as described in the geometric properties of this study. Furthermore, there is a direct relationship between density and strength, with density being higher at the base, followed by the top, and lower in the middle.

The average strength obtained was 47.91 MPa, a value close to those reported by Ghavami et al. (2017), who compiled studies on the species *Bambusa vulgaris* presenting average values of 54.8 MPa, 50.8 MPa, and 56.5 MPa. Other researchers also found similar results, such as Carbonari et al. (2017) with 49.41 MPa, and Gomes et al. (2021) with 49.33 MPa. Therefore, it can be concluded that the average strength obtained in this study is consistent with values found in the literature for the species *Bambusa vulgaris*.

3.2 BEHAVIOR OF BAMBOO AND BAMBOO FILLED WITH SISAL FIBER-REINFORCED COMPOSITE

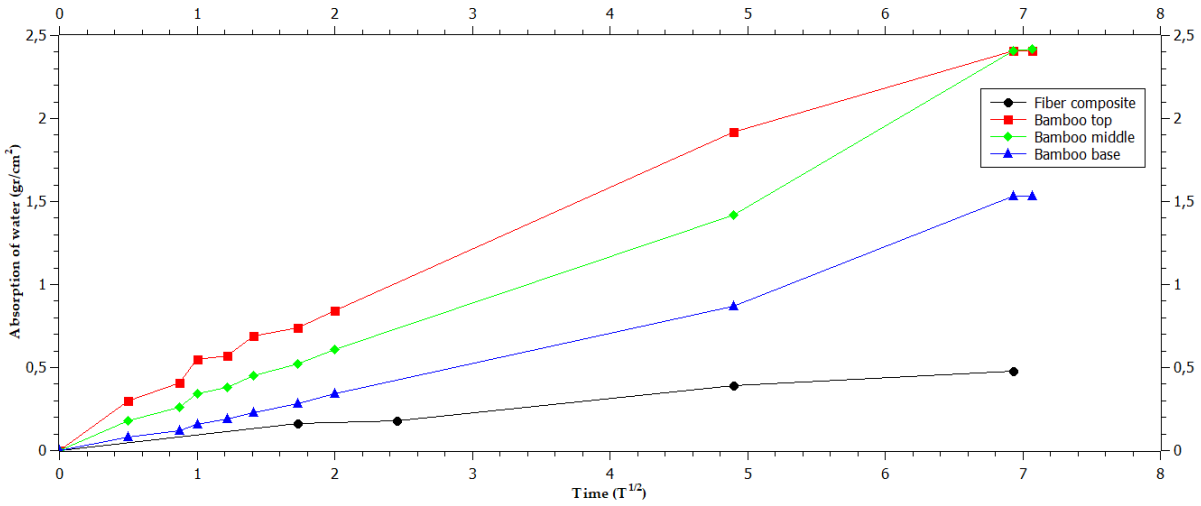
Tests performed on specimens of both bamboo and the sisal fiber-reinforced composite will be analyzed jointly.

3.2.1 Absorption

As presented in the methodology of this research, the capillary absorption test was conducted on both bamboo and the sisal fiber-reinforced composite, allowing for the development of the Time vs. Capillary Absorption curves, shown in Figure 7.

Figure 7

Absorption of bamboo and sisal fiber-reinforced composite.



Based on the data collected throughout the testing period, it was possible to construct the capillary absorption curve of bamboo and the cementitious composite. It was observed that bamboo exhibited a rapid mass increase due to fiber absorption in the first hours, with increments of 18.71%, 27.22%, and 46% in the base, middle, and top regions, respectively, between the fifth and twentieth hour. After this period, the mass variation stabilized.

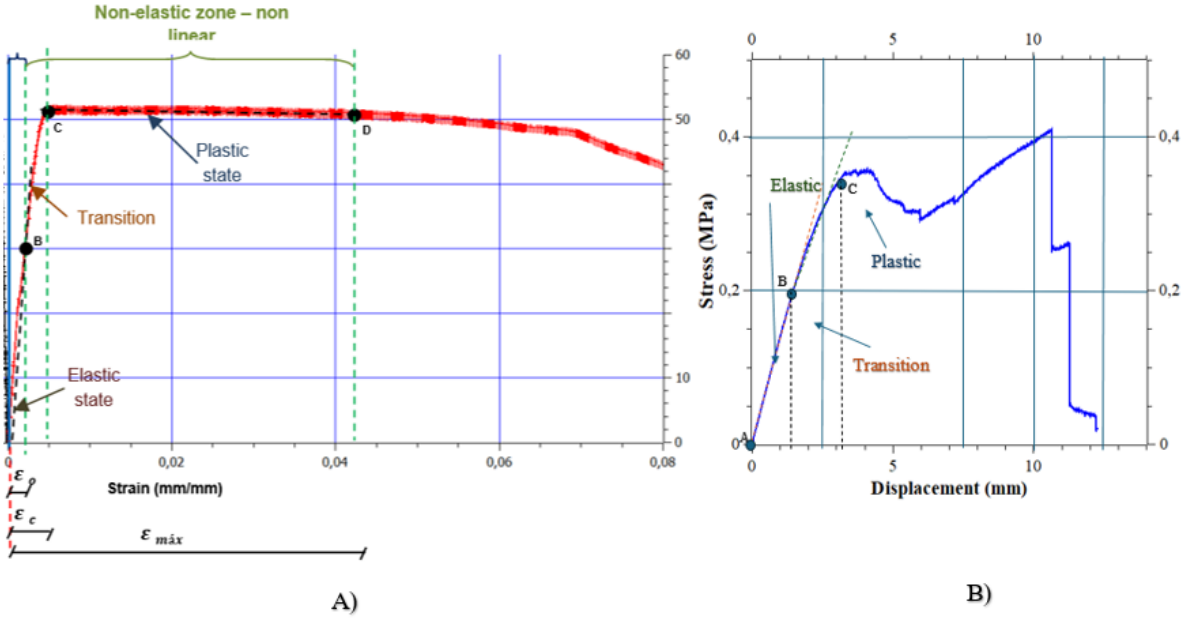
In turn, the fiber-reinforced composite showed a mass absorption 0.66% lower than that of bamboo. This behavior indicates potential interest for future research involving bamboo-cement composite materials, especially regarding the amount of water required for the hydration of the mixture components.

3.2.2 Mechanical Behavior

Initially, the behavior of unfilled bamboo is analyzed through the axial and radial stress–displacement curves, evidencing behavior reported in the works of Zhang et al. (2017), Gong et al. (2017), and Fozao & Foudjet et al. (2020), which are presented in Figure 8.

Figure 8

Typical bamboo curves tension vs displacement: A) compression and B) bending.



As curvas tensão-deformação nos ensaios de compressão e flexão apresentam três estágios principais: (a) estágio elástico linear, caracterizado por deformação elástica e comportamento aproximadamente linear até o limite elástico; (b) estágio de transição, onde inicia a não linearidade do material e ocorre o fenômeno de encruamento (strain hardening), com aumento significativo da tensão e desaceleração da deformação, acompanhado pelo enfraquecimento devido à formação de microfissuras, conforme Zhang et al. (2017) e Gong et al. (2017); e (c) estágio plástico, que marca o início do amolecimento do material após a tensão máxima, com perda de rigidez e deformação contínua até a falha, conforme descrito por Zhang et al. (2017).

To perform a comparison between bamboo and filled bamboo, the following load test data were obtained, as shown in Table 8:

Table 8

Load of bamboo and filled bamboo under compression and bending.

Description	Sample	L (mm)	Ab (mm²)	Max Load (KN)	Avg Load (KN)	DP	CV %
B	B12SN-1C	115,00	1822,97	94,62	84,39	9,02	10,69
	B12SN-2C	111,00	1614,64	77,59			
	B12SN-3C	118,00	1771,55	80,96			
BCCF	BCCF12SN-1C	110,00	1973,74	57,07	73,59	15,09	20,5
	BCCF12SN-2C	118,50	1807,67	77,06			
	BCCF12SN-3C	114,00	1760,45	86,65			
B	B20SN-1F	200	1250,98	2,24	3,30	1,5	45,45
	B20SN-2F	200	2250,82	4,36			
BCCF	BCCF20SN-1F	203,9	1194,89	22,08	22,47	2,85	12,69
	BCCF20SN-2F	199,3	1467,80	19,83			
	BCCF20SN-3F	198,4	1752,33	25,49			

L = length; Ab = bamboo area; B = bamboo; BCCF = bamboo filled with sisal fiber-reinforced composite; C = compression test; F = bending test; Max = maximum; SD = standard deviation; CV = coefficient of variation.

Based on the presented values, it was possible to develop the relative load curve as a function of the maximum load obtained for both materials and tests. Additionally, the displacement values did not show significant changes compared to the data obtained during the tests, as illustrated in Figure 10A for compression and Figure 10B for bending.

When analyzing the load-relative displacement curves from the compression and bending tests on specimens without filling, the typical behavior with distinct linear, transition, and nonlinear stages is observed. however, with the incorporation of the sisal fiber-reinforced composite, the curves exhibit multiple peaks, attributed to crack formation in the composite during loading (Figures 10A and 10B). these cracks reflect the interaction between the composite fibers and bamboo, resulting in increased deformation, as documented and illustrated in photographs of the specimens (Figure 11).

Figure 9

Unit load curve of bamboo with and without filling: A) Compression and B) Bending.

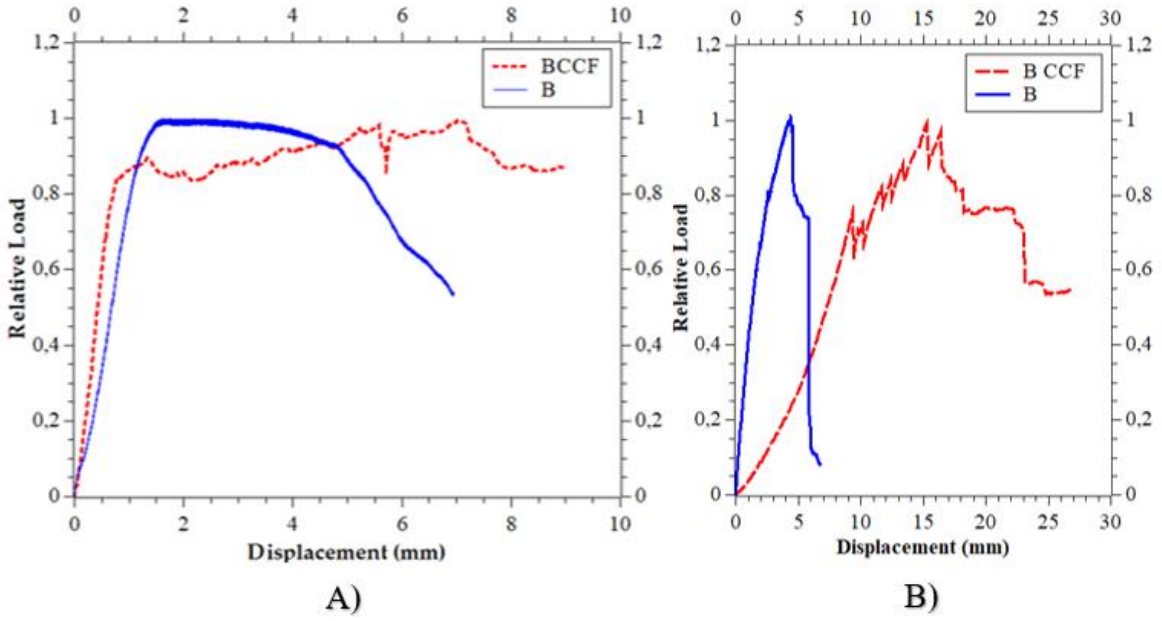
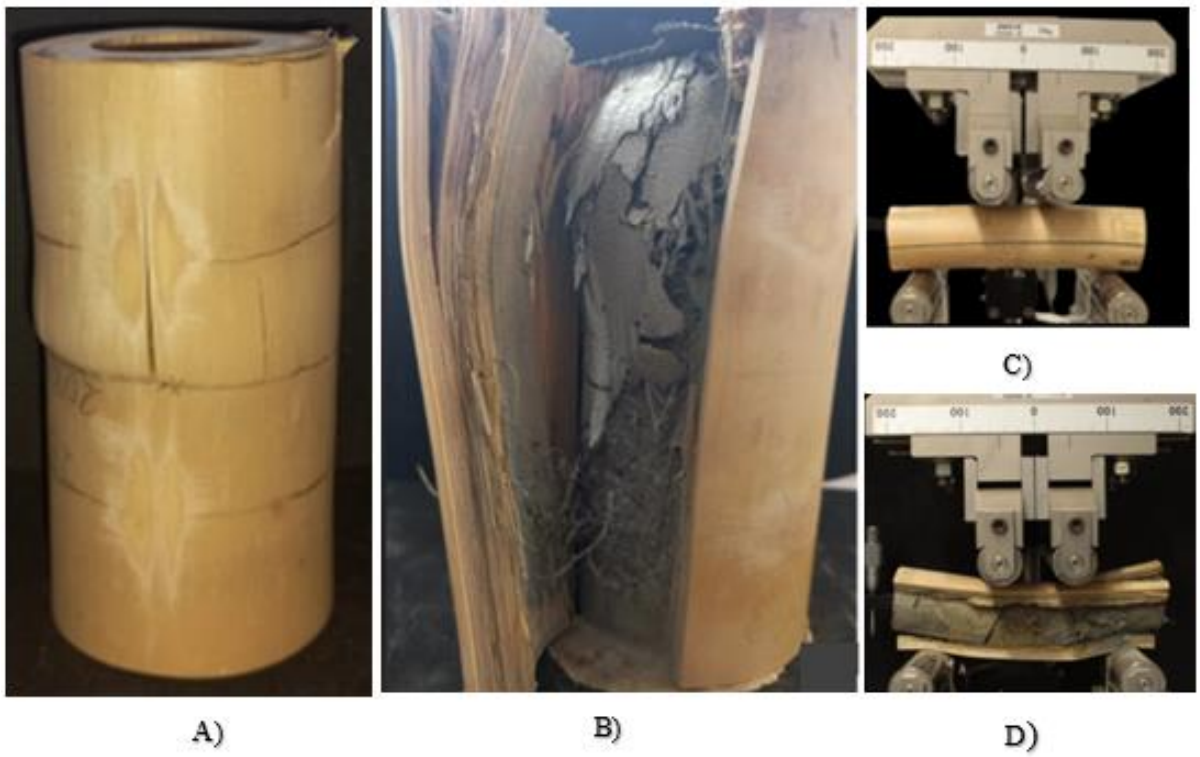


Figure 10

Failure mode: A) Bamboo without filling under compression, B) Bamboo filled under compression, C) Bamboo without filling under bending, D) Bamboo filled under bending.



Figures 11A and 11B show photographs of the specimens tested in compression, clearly demonstrating strong adhesion between the materials. The amount of fibers between the bamboo walls indicates that under compression, the composite behavior is confined, contributing to structural integrity. In the bending tests (Figures 11C and 11D), failure was characterized by a 45° shear due to the applied load and supports; however, no detachment of the composite occurred because the fibers helped retain the material. From the lateral view, the fibers remained adhered to the bamboo walls, and failure did not occur solely at the load application points but at multiple locations along the filled specimen.

4 CONCLUSION

This study characterized the properties of bamboo from the species *Bambusa vulgaris*, which was dried for about three months until reaching constant mass. The geometric properties showed typical behavior of the species, with a slight increase in external diameter in the central region and a progressive decrease in the culm wall thickness from base to apex. Physical properties indicated higher moisture content and density at the base due to greater cellular density in that region. Radial, tangential, and longitudinal shrinkage varied along the culm, reflecting the heterogeneous nature of bamboo influenced by age and harvesting season.

In compression tests, maximum strength was observed at the base (49.54 MPa), decreasing toward the apex and mid-region, with an overall average of 47.91 MPa, consistent with the literature. Both compression and bending tests identified linear (elastic) and nonlinear (transition and plastic) phases, in which bamboo exhibits progressive deformation and microcracking until failure.

The addition of the sisal fiber-reinforced composite demonstrated an efficient synergistic action, with multiple peaks in the load-displacement curves, indicating microcrack control and improved load distribution. It was also observed that bamboo absorbs more mass than the cementitious composite, suggesting future research on the integrated study of these materials and their chemical characteristics.

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