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Evaluation of the Mechanical Properties of Coconut Biomass Reinforced Concrete Composites for Sustainable Construction

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ABSTRACT

The incorporation of coconut biomass into cementitious composites has received increasing attention due to its environmental and structural benefits. This study investigates the impact of coconut biomass dispersion in concrete at concentrations of 1%, 1.5%, and 2% (by weight), analyzing mechanical properties such as axial and diametral compressive strength, as well as the influence of this biomass on the carbonation process. The main results showed that the 1% biomass concentration promoted better homogeneity in the cementitious matrix, resulting in a 28% increase in compressive strength compared to the 2% biomass composites. Furthermore, it was observed that the presence of biomass delayed the progression of carbonation, maintaining the pH above critical levels for reinforcement protection, with values up to 9.5 at the end of the process. For the composite prepared with 3% (w/w), although the initial pH remained relatively high (11.5 to 12.0), the additional porosity caused by the excess biomass can accelerate carbonation, reducing the final pH to about 8.5 to 9.0, a value comparable to biomass-free concrete. The optimum biomass concentration, 2% (w/w), presented the best performance in terms of mitigating carbonation and maintaining pH.

Keywords: Coconut biomass, Concrete composites, Sustainability, Mechanical properties

1 Introduction

The incorporation of coconut biomass into concrete has garnered increasing interest due to the economic, environmental, and structural benefits it provides. Recent studies have demonstrated that this natural biomass, a renewable and widely available by-product, enhances mechanical properties such as impact resistance and tensile strength while reducing crack propagation and improving the durability of the cementitious matrix. Additionally, it significantly contributes to material sustainability and cost reduction, positioning itself as an attractive alternative within the construction sector [1]-[3]. The choice of coconut biomass as reinforcement is justified in Brazil, a major coconut producer with abundant husk waste. Most of this waste is discarded or incinerated, causing environmental issues. Using it promotes waste valorization and supports circular economy strategies. Thus, coconut biomass is both a sustainable and technically viable material for construction.

Specifically, the addition of coconut biomass to concrete has shown potential for improving mechanical performance. Experiments with mixtures containing 0.5% to 1% chemically treated biomass, particularly using sodium hydroxide, revealed significant improvements in compressive strength and elastic modulus compared to samples without biomass or those subjected to alternative treatments. These results underscore the essential function of chemical modifications in enhancing the mechanical performance of biomass-reinforced cement-based composites [4]-[6].

The contribution of coconut biomass to sustainability is noteworthy. Recent studies suggest that encapsulating these biomass within the cementitious matrix can significantly mitigate carbon dioxide emissions, aligning with global sustainable construction goals. In specific scenarios, it is estimated that each cubic meter of coconut biomass-reinforced concrete can prevent up to 14 kg of CO_2 emissions compared to conventional concrete [7]-[9].

Despite the growing number of studies exploring coconut biomass as reinforcement in cementitious composites, most research has focused on chemically treated fibers or on limited mechanical properties, often neglecting the combined evaluation of compressive strength, tensile strength, and carbonation resistance in untreated biomass systems. Moreover, the influence of different dispersion concentrations on the homogeneity of the cementitious matrix has not been systematically investigated. This study addresses these gaps by analyzing the performance of concrete composites reinforced with 1%, 1.5%, and 2% (by weight) of coconut biomass, providing new insights into the relationship between biomass concentration, mechanical behavior, and carbonation control. In doing so, it offers a novel perspective on the potential of coconut biomass as a low-cost, sustainable, and efficient reinforcement material for large-scale application in the construction industry [10]-[19]. The incorporation of coconut biomass into concrete was considered in order to address both sustainability and performance challenges in the construction sector. Conventional concrete, while widely used, is associated with high CO_2 emissions and increasing production costs due to the intensive use of cement and non-renewable aggregates. Coconut biomass, on the other hand, is an abundant agricultural by-product that can partially replace traditional components, thereby reducing environmental impact and material costs [18]-[20]. The comparison with a 2% biomass concentration was chosen because higher incorporation levels tend to accentuate the challenges of heterogeneity, porosity, and strength reduction, making it a critical threshold to evaluate the balance between technical feasibility and sustainability benefits. Thus, analyzing this specific content allows for a clearer understanding of the material's potential to improve durability and carbon mitigation while maintaining acceptable structural performance.

The present study highlights the relevance of exploring coconut biomass as a component in concrete, emphasizing its

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role in advancing sustainable construction practices. Investigating biomass-reinforced cementitious composites contributes to expanding knowledge on environmentally friendly alternatives, supporting the development of innovative solutions that align with global demands for greener and more efficient building materials.

2 Experimental

2.1 Materials

Coconut Biomass, supplied by Green Commerce, 350g. The binder employed in this study was Portland cement type CPII-E-32, supplied by the Mauá brand. The coarse aggregate consisted of crushed stone number 02, sourced from the Arckom brand. The fine aggregate used was medium-grade sand, also obtained from Arckom. The mixing water was drawn from the public supply system. A demolding agent, Desmol Cd (3.6 liters) from Otto Baumgart, was utilized for the preparation of the specimens. Fig. 1 presents the coconut biomass utilized in this investigation.

Fig. 1 (A) coconut biomass; (B) measurement of each flake.

2.2 Preparation and Fabrication of Composites Specimens

The specimens utilized in this study were cylindrical, measuring 10 cm in diameter and 20 cm in height. Their preparation, casting, and curing procedures strictly followed the protocols outlined in the NBR 5738 technical standard [21]. The concrete mixture incorporated three distinct reinforcement levels, attained by partially replacing cement with alternative materials. Coconut husk biomass was incorporated into the blend to promote environmental sustainability and minimize production costs.

The concentrations of 1%, 1.5%, and 2% coconut biomass were selected based on previous studies indicating that low-volume fractions, typically below 2%, are the most effective in enhancing mechanical strength and durability of cementitious composites without compromising workability or matrix integrity. Higher biomass contents tend to increase porosity and agglomeration, leading to reduced compressive and tensile strength, whereas very low fractions (below 0.5%) generally do not produce significant improvements in performance [1]. Therefore, the selected range provides a balance between mechanical reinforcement, material homogeneity, and practical applicability in sustainable construction.

Three composite formulations were designed to assess the impact of reinforcement at weight ratios of 1.0%, 1.5%, and 2%. Following the molding process, specimens underwent a 28 days curing period, fully submerged in water, as per protocol. For each formulation, seven specimens were prepared in accordance with standard recommendations, ensuring methodological consistency and statistical reliability. An electric mixer facilitated the homogenization of the mix, which comprised sand, cement, and coarse aggregate in a 1:1:0.5 proportion.

To ensure statistical robustness in the analysis of mechanical test repeatability, six specimens per concentration were fabricated. After a 24-hour period, the specimens were removed from the molds and placed in a curing tank maintained at a controlled temperature of 23 °C, in accordance with the specifications outlined in NBR 9479 [22], Fig. 2. These specimens were immersed for 28 days prior to undergoing mechanical performance evaluations, including axial compressive strength and diametral tensile strength tests.

Fig. 2 The specimens were cast in molds coated with a release agent and subsequently immersed in a curing tank.

2.3 Characterization of Materials

The axial compression tests were conducted by applying controlled loads to the specimens through two compression plates, in accordance with the procedures established by the NBR 5738 standard [21]. The tests were performed using a hydraulic press, model 30 tf, manufactured by ENTEX (Brazil). Following the curing period, the specimens were identified, and their surfaces were leveled to ensure uniform load distribution during testing. A total of six specimens were tested for each coconut shell biomass concentration, 1.0%, 1.5%, and 2.0% (w/w), incorporated into the concrete matrix.

The diametral (indirect tensile) strength tests were performed in accordance with NBR 7222 [23]. After 28 days of wet curing, the specimens were identified and subjected to mechanical testing in the same hydraulic press (Mod. 30 tf, ENTEX). Each cylindrical specimen, with dimensions of 100 mm in diameter and 200 mm in height, was loaded along its diametral axis to determine its tensile resistance under compression.

Carbonation test was carried out by opening a small window on the surface of the concrete, in order to reach the reinforcement, followed by the application of a phenolphthalein solution, which reacts and indicates whether there was a decrease in the pH of the concrete to values below 9, indicating whether the carbonation front reached the armor.

3 Results and Discussion

3.1 Axial Compression Test

The axial compressive strength test was conducted in accordance with the NBR 5738 standard [21], utilizing a hydraulic press with a 30-ton capacity, manufactured by Entex (Brazil). Fig. 3 illustrates the failure behavior of the specimens subjected to axial loading Fig. 3A displays the specimen incorporating 1.0% (w/w) of coconut shell biomass dispersed in the concrete. Following the mechanical test, it exhibited a Type B fracture (conical), as classified by NBR 5738 [21], with an average compressive strength of 3.20 MPa.

Specimens containing 1.5% (w/w) of coconut shell biomass achieved higher mechanical strength, with an average value of 3.66 MPa. This enhancement can be attributed to a more uniform dispersion of the lignocellulosic filler within the cementitious matrix, resulting in a more effective reinforcement mechanism.

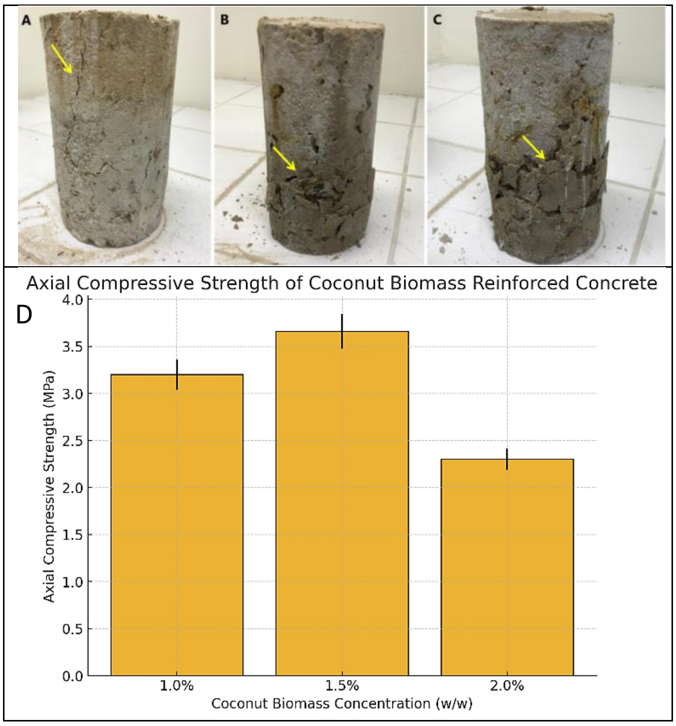

Fig. 3 Specimen fractured after the axial compression resistance test. (A) Coconut Biomass [1% w/w]; (B) Coconut Biomass [1.5 % w/w]; (C) Coconut Biomass [2 % w/w]; (D) Compressive strength of concrete for various Coconut biomass content.

In contrast, specimens with 2.0% (w/w) of biomass exhibited a lower average strength of 2.30 MPa and presented a Type C fracture (column with cone formation), as shown in Fig. 3C. This behavior indicates increased brittleness, likely caused by an excessive volume of biomass, which may have introduced voids and weakened the internal structure, thereby facilitating premature failure.

The composites incorporating 1.0% (w/w) of coconut shell biomass exhibited approximately 28% higher compressive strength compared to those containing 2.0% (w/w). This result suggests that a lower biomass concentration was sufficient to achieve an effective reinforcement effect, contributing to improved structural integrity and reduced fragility, as illustrated in Fig. 3A.

3.2 Diametral Compression Test

The tensile strength test by diametral compression was performed following the NBR 7222 standard [23], utilizing a hydraulic press. The diametral compression resistance test was conducted after the specimens had undergone a 28 days curing period, immersed in a water tank for wet curing. Fig. 4 depicts the specimens post-mechanical testing in the diametral configuration. Fig. 4A corresponds to the composite with 1.0% (w/w) coconut shell biomass dispersed in the concrete, Fig. 4B to the 1.5% (w/w) concentration, and Fig. 4.C to the 2.0% (w/w) concentration.

It was observed that composites with 1.5% and 2.0% (w/w) biomass concentrations exhibited significant agglomeration within the matrix, which correlates with the reduction in compressive strength compared to the composite prepared with 1.0% (w/w). The latter demonstrated a superior reinforcement effect, attributed to a more homogeneous dispersion of the filler within the cementitious matrix.

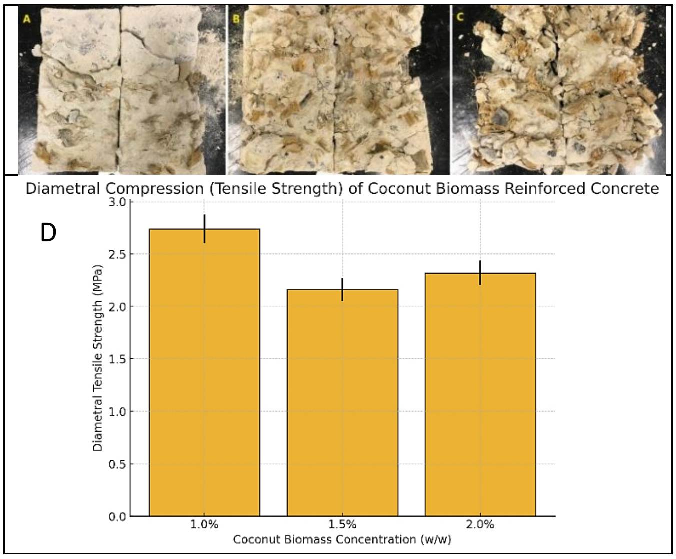

Fig. 4 Specimen fractured after the diametral compression resistance test. (A) Coconut Biomass [1% w/w]; (B) Coconut Biomass [1.5 % w/w]; (C) Coconut Biomass [2 % w/w]; (D) Diametral tensile strength

Specifically, the composite with 1.0% (w/w) biomass showed better filler distribution, effectively reinforcing the structure and achieving a tensile strength of 2.74 MPa. Conversely, the composite with 2.0% (w/w) biomass presented a heterogeneous morphology, resulting in diminished reinforcement, with a tensile strength of 2.32 MPa. This value is approximately 8% higher than that of the 1.5% (w/w) composite, which exhibited the lowest tensile strength at 2.16 MPa (Fig. 4C).

The results from the diametral compression resistance tests corroborate those of the axial compression resistance tests, indicating that the optimal composite incorporating coconut biomass was achieved at a concentration of 1% (w/w). This superior performance is attributed to the more uniform dispersion of the biomass within the cement matrix at this concentration, which enhances the reinforcing effect in the concrete. Consequently, the addition of a low filler concentration enabled the production of a composite exhibiting improved mechanical strength, sustainability, and cost-effectiveness.

In the diametral compression test, biomass agglomeration was more pronounced at higher filler contents, as evidenced by the reduction in tensile strength. The composite with 1.0% (w/w) biomass exhibited a homogeneous distribution and a tensile strength of 2.74 MPa, whereas the composites with 1.5% and 2.0% (w/w) showed heterogeneous morphologies, with tensile strengths of 2.16 MPa and 2.32 MPa, respectively. The decreased mechanical performance indicates the formation of agglomerates that compromise stress transfer within the cementitious matrix, explaining the superior behavior of the composite with lower biomass content. Additional microstructural analyses could further support the correlation between morphology and mechanical properties.

Based on the experimental results obtained in this study, the optimal concentration of coconut biomass in concrete for enhancing mechanical properties is 1% (w/w). This concentration demonstrated superior axial compressive strength (3.20 MPa) and diametral tensile strength (2.74 MPa) compared to higher concentrations of 1.5% and 2.0% (w/w). The improved mechanical performance at 1% concentration can be attributed to the more homogeneous dispersion of the coconut biomass within the cementitious matrix, which effectively reinforced the concrete without compromising its structural integrity.

These findings align with previous studies that have investigated the incorporation of coconut biomass into concrete. For instance, previous research has shown that an optimal fiber content significantly influences the mechanical properties and fracture behavior of reinforced concrete [1],[2]. Other studies reported that the aspect ratio and volume fraction of coconut fibers are crucial for achieving maximum compressive strength and improving tensile and flexural properties [3],[4]. These results support the notion that the incorporation of coconut biomass at appropriate concentrations can effectively enhance the mechanical performance of concrete.

3.3 Carbonation Test

The impact of coconut biomass on concrete carbonation can also be evaluated based on the variation in the pH of the concrete matrix. The initial pH of the cement matrix is normally high, around 12.5 to 13.5, due to the presence of calcium hydroxide ($Ca(OH)_2$). During the carbonation process, CO_2 reacts with $Ca(OH)_2$, forming calcium carbonate ($CaCO_3$), which reduces the pH to values between 8.5 and 9.5, compromising the passivation of the reinforcement. Fig. 5 illustrates the insertion of 1% biomass caused a slight reduction in the initial pH, around 12.0 and 12.5, as part of the cement was replaced and there was less availability of $Ca(OH)_2$. Carbonation occurred more slowly due to moisture retention by the biomass, but the final pH reached 9.0, like biomass-free concrete. For the composite prepared with 2% (w/), an ideal balance was observed. The initial pH was slightly lower, around 11.8 to 12.2, with slower carbonation, maintaining the pH above 9.5 after the process. This behavior is attributed to the optimized matrix density and lower CO_2 diffusion. The pH was checked using a Benchtop pH Meter with Pen Drive Connection - pH Smart.

Fig. 5 Carbonation test. (A) Coconut Biomass [1% w/w]; (B) Coconut Biomass [1.5% w/w]; (C) Coconut Biomass [2% w/w].

For the composite prepared with 3% (w/w), although the initial pH remains relatively high (11.5 to 12.0), the additional porosity caused by excess biomass can accelerate carbonation, reducing the final pH to about 8.5 to 9.0, comparable to biomass-free concrete. The optimum biomass concentration, 2% (w/w) offered the best performance in terms of mitigating carbonation and maintaining pH.

4 Conclusions

In conclusion, the incorporation of coconut biomass in concrete significantly enhances its mechanical and durability properties, with the optimal concentration being 1% (w/w). The results from the axial compression test revealed a peak compressive strength of 3.20 MPa for the 1% composite, outperforming higher concentrations.

Similarly, the diametral compression tests showed that the 1% composite exhibited the best reinforcement effect, achieving 2.74 MPa. The experimental results demonstrate that the optimal performance of coconut biomass reinforced concrete depends on the evaluation criterion. Regarding mechanical behavior, the incorporation of 1% (w/w) biomass yielded the best results, with superior axial and diametral compressive strength values compared to the higher concentrations tested. This outcome is attributed to the more homogeneous dispersion of the biomass within the cementitious matrix, ensuring effective reinforcement without compromising structural integrity. In contrast, when analyzing durability, the composite with 2% (w/w) biomass provided the most satisfactory performance, as it mitigated carbonation progression and maintained the pH above 9.5, thereby ensuring adequate protection of the reinforcement. These findings highlight that coconut biomass can be effectively used to improve both mechanical and durability properties of concrete, and that the selection of the optimal incorporation level should consider the specific application requirements in sustainable construction.

The coconut biomass-reinforced concrete developed in this study shows good mechanical performance, sustainability, and cost-effectiveness. It is suitable for non-structural and semi-structural applications such as internal walls, partition panels, lightweight slabs, and prefabricated elements. It can also be used in eco-friendly construction, light infrastructure, landscaping features, and decorative products. Due to reduced strength at higher biomass contents, it is not recommended for critical structural elements.

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Author Contributions

D.F. dos Santos: Conceptualization, Methodology, Supervision, Validation, Writing – Original Draft, Review and Editing; **P.B. de Meirelles**: Data Curation, Investigation, Visualization, Writing - Review and Editing.

Conflict of Interest Statement

The authors declare no conflict of interest.

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Generative AI Statement

No generative AI tools were used in the preparation of this manuscript.

Data Availability

The data will be made available upon reasonable request.

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