

Characterization and Analysis of Ecological Tiles with Bacterial Cellulose and Industrial Waste

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The environmental issues arising from waste generation and extraction of natural resources, and cementitious materials in the construction sector are seeking to address these problems by substituting their main components with sustainable materials. Fibrocement, widely used in the production of roofing tiles, is composed of cement, and calcium silicate binders, and is reinforced with organic (vegetable cellulose), mineral, or synthetic fibers. However, the production of vegetable cellulose and its derivatives leads to increased wood consumption, causing environmental problems. Therefore, the aim of this project is to characterize and analyze sustainable tiles produced with bacterial cellulose (BC), combined with limestone filler (LF), textile industry waste (polyamide, PA), and sugarcane industry waste (sugarcane bagasse, SCB), comparing them with commercial tiles. The NBR 15310/2009 standard -Ceramic Components – Tiles was adopted as a comparative reference in the absorption tests and in the rupture and flexural load tests. The commercial tiles met the regulatory requirements, while the A6 samples (BC, LF, PA) showed an absorption index of 15%, within the stipulated limit. On the other hand, the A7 samples (BC, LF, SCB) exhibited an index of 20%, exceeding the maximum allowed value by 4%. In the rupture and flexural load tests, tile A6 surpassed the rupture load required by the standard by 5.4%, while tile A7 did not reach the minimum load of 1000 N required for simple bending. These results demonstrate the potential of sustainable and low-cost tiles for application in the construction industry, especially as building cladding.

1. Introduction

The growing population, combined with economic progress and urbanization, has led to significant changes in production and consumption patterns, with direct implications for the quantity and diversity of waste generated, particularly in metropolitan areas. The rapid expansion of cities and the increase in industrial activity result in increasing pressure on natural resources and waste disposal processes, which, in many cases, occur inadequately. This scenario is further complicated by the lack of effective sustainable management, which is essential for dealing with the large volume of solid and agroindustrial waste, whose negative environmental impacts are becoming increasingly evident. Among the various sources of waste, the construction industry, agroindustry, and textile production stand out, all of which have great potential for reuse in new production chains, provided that a more conscious and innovative approach to the management of these materials is implemented (Amaral, 2023). In this context, the construction sector has been searching for alternatives to reduce the environmental impact of the materials it produces. One solution found was the substitution of traditional components by recyclable elements, resulting in the development of fibrocement. This material, widely used in the production of roofing tiles, tanks, and other construction items, is made from a mixture of cement, calcium silicate binders, and fibers, which may come from different sources, such as vegetable cellulose fibers, mineral fibers, or synthetic fibers, such as glass fibers. The addition of vegetable fibers to fibrocement,

for example, has shown significant benefits, not only in increasing impact resistance but also in improving thermal and acoustic insulation, providing the material with an additional advantage in terms of sustainability and performance (Brasilit, 2021).

However, the production of vegetable cellulose (VC), the main raw material for these fibers, has raised several environmental concerns, mainly due to the high consumption of wood, which in turn contributes to deforestation and ecosystem degradation. Therefore, more ecological alternatives for cellulose production have emerged, such as bacterial cellulose (BC), which is obtained through the fermentation of organic substrates by specific microorganisms, including bacteria from the genera *Komagataeibacter*, *Acetobacter*, *Escherichia*, and *Sarcina* (Chen *et al.*, 2024). Unlike PC, BC is a pure polymer, free from lignin and hemicellulose, with a three-dimensional nanofibril structure that gives it exceptional properties, such as high tensile strength, excellent water absorption and retention capacity, and biodegradability and renewability. These characteristics make bacterial cellulose an excellent option for use as reinforcement in construction materials, offering a sustainable solution for the construction industry (Silva *et al.*, 2024). The production of BC, however, faces challenges related to the high cost of traditional cultivation media, such as Hestrin-Schramm (HS), which is widely used in the fermentation process but presents a high cost (Hestrin & Schramm, 1954). As an alternative, several studies have sought to explore alternative media for BC production, using agroindustrial by-products and food waste, such as fruit peels, corn residues, and other organic materials (Chen *et al.*, 2010; Cavalcanti *et al.*, 2023; Galdino *et al.*, 2020). These residues offer an opportunity for the reuse of materials that would otherwise be discarded, contributing not only to the reduction of environmental impacts but also to the increased economic viability of large-scale BC production. The use of these alternative materials can also improve fermentation yield, optimizing BC production while promoting a circular economy and more efficient resource utilization (Costa *et al.*, 2017). Furthermore, solid waste management has become a global environmental concern, with the textile industry playing a significant role in this scenario. The textile sector generates large volumes of fibrous waste during various stages of the production process, such as fiber harvesting, spinning, dyeing, and finishing, many of which are discarded improperly. The reuse of textile waste, especially that from beachwear and composed of polyamide fibers, has become an area of growing interest. Incorporating these textile fibers into new materials can provide a solution to reduce the waste of natural resources, as well as minimize the environmental impacts of the textile industry. The use of these residues in fibrocement production, for example, can add value to the final material by providing additional characteristics of strength and durability, while promoting better waste management in the sector (Yalcin-enis *et al.*, 2019). Considering the disparities between vegetable, microbial, and synthetic fibers, it is crucial to conduct a detailed analysis of their compatibility with fibrocement components, evaluating aspects such as water retention and absorption, as well as the thermal and acoustic properties of the resulting composite. Research on the compatibility of these different types of fibers is essential to ensure that the final material is impermeable, flexible, resistant to warping, and, at the same time, moldable to meet the needs of the construction sector (Baumi *et al.*, 2017; Henriques *et al.*, 2014). Thus, combining bacterial cellulose with textile waste, such as polyamide fibers, in the development of new sustainable materials, presents a promising opportunity to produce eco-friendly tiles and other construction components. The objective of this study is to investigate the feasibility of replacing vegetable cellulose (VC) with bacterial cellulose (BC) in the production of sustainable tiles, utilizing agroindustrial and textile waste as raw materials. Specifically, this research hypothesizes that the incorporation of BC and polyamide fibers from textile waste enhances the mechanical properties (e.g., tensile and impact strength) and sustainability profile of the final composite material. The study aims to evaluate the performance of these eco-friendly composites through comparative analyses, offering a viable alternative to conventional materials. The expected contributions include not only the development of a more sustainable route for tile manufacturing but also scientific insight into the synergy between microbial biopolymers and synthetic textile fibers, advancing the field of green construction materials.

2. Material and methods

2.1 Bacterial cellulose (BC) producing microorganism and maintenance media

The bacterium *Komagataeibacter hansenii* UCP1619, sourced from the Bank of Cultures of the Center for Research in Environmental Sciences (NPCIAMB) at the Catholic University of Pernambuco, was employed for bacterial cellulose (BC) production. This strain was maintained on solid HS medium composed of 20.00 g/L agar, 20.00 g/L glucose, 5.00 g/L peptone, 5.00 g/L yeast extract, 1.15 g/L citric acid, and 2.70 g/L disodium phosphate, adjusted to pH 6, and stored under refrigeration at 4°C (Hestrin and Schramm, 1954).

2.2 Production of Bacterial Cellulose (BC) Using Alternative Culture Media

To develop an alternative culture medium, ripe tomatoes (*Solanum lycopersicum*) were utilized due to their high discard rate in the Recife region of Pernambuco, Brazil, despite being rich in nutrients essential for cellulose

production. Tomatoes contain approximately 46% carbohydrates and 9% citric acid, making them a suitable substrate (Beckles, 2012). Ripe tomatoes, weighing approximately 150 g per unit, were blended with 100 mL of distilled water at a 1:100 ratio using an industrial blender at 18,000 rpm for 2 minutes, producing a homogeneous pulp. From this mixture, 100 mL of the resulting juice was then filtered to remove excess solids and autoclaved at 120°C for 20 minutes to ensure sterility. As a control, a standard HS medium was prepared using the same procedure but without tomato pulp.

The pre-inoculum was prepared by cultivating *K. hansenii* at 30°C for 48 hours under static conditions in 100 mL of liquid HS medium without agar. Subsequently, 3% (v/v) of this pre-inoculum was transferred to 500 mL Scott flasks containing 100 mL of the sterilized tomato-based medium. The cultures were incubated statically at 30°C for 14 days to facilitate BC production. The experiment was conducted in triplicate, and the yield was evaluated in both wet and dry mass to determine the total cellulose production (g/L). Statistical analyses, including ANOVA, will be used to assess the significance of the results between the treatments (tomato-based medium vs. control).

2.3 Determination of the composition and the ideal proportion of materials to be used in the production of the tile.

The materials used to produce the tile were: Deionized Water (DW), CP V-ARI Cement (C), Limestone Filler (LF), which serves to reduce the permeability of the tile, BC, BCA, and PA from the fashion beachwear garment industries in Caruaru, Pernambuco, Brazil.

It is worth noting that the mass proportions of the materials were balanced equally, considering the inclusion or exclusion of all components. This approach allowed for the evaluation of the influence of the respective materials on the performance of the tiles.

2.4 Application of Reconstituted Cellulose and Preparation of Bagasse and Polyamide Fibers

For this application, the bacterial cellulose (BC) membranes were ground using an industrial blender at 18,000 rpm for 2 minutes under humid conditions, forming a homogeneous mass (Galdino *et al.*, 2022). The tiles were produced in flat plate format (2 cm x 20 cm) with an approximate thickness of 5 mm and were air-dried at room temperature (25°C) for 10 days until the material was fully cured. All experiments were carried out in duplicates. For the use of bagasse fibers (BCA) as reinforcement, the material was triturated and sieved through a mesh with a 48 mesh opening, resulting in fibers with an approximate thickness of 0.29 mm. The fibers, after sieving, were immersed in water to provide a more efficient fixation and finish in the composite.

The methodology used for preparing polyamide (PA) involved heating glycerin to 190°C. Gradual additions of Polyamide/Elastane fabric pieces were made, with mechanical stirring, until the fabric was completely dissolved, maintaining the temperature above 180°C. The resulting mixture was processed in a blender with the addition of water for 5 minutes. Finally, the material was dried and sieved through a 48 mesh, resulting in fibers with an approximate thickness of 0.29 mm (Baumi *et al.*, 2017).

2.5 Water absorption capacity (WAC)

The water holding capacity (WAC) is related to the amount of moisture the tile can absorb. The tiles were submerged in water for 24 hours at room temperature. Then, the wet mass and dry mass (after drying in an oven at 105±5°C for 24 hours) were measured. All experiments were carried out in duplicates. The WAC (%) will then be calculated using Equation 1:

$$WAC\% = \left(\frac{BC \text{ wet mass} - BC \text{ dry mass}}{BC \text{ wet mass}} \right) \cdot 100\%$$

2.6 Mechanical Tests – Flexion

The flexural analyses were performed using a universal testing machine from the brand Emic, model DL500 MF. The data analysis will use the software from the MTest machine, Version 3.00. The warping and bending of the tiles followed the methodology of (Henriques *et al.*, 2014).

2.7 Determination of Water Permeability

For this test, a straight circular-section PVC tube was used, open at one end with a faucet, with an internal diameter of 24.5 mm, sufficient to form a water column, as suggested by Henriques, 2014. The setup was maintained for 24 hours in a covered environment. After this period, the lower surface of the tile was inspected to verify the occurrence of leakage or droplet formation. To pass the test, no leakage or droplet formation on the lower surface of the specimen is acceptable after the test is completed.

3. Results and discussion

The formulations of the prepared composites, detailed in Table 1, are illustrated in Figure 1. Each combination was assessed for the presence or absence of reinforcing materials such as PA and SCR to evaluate their effect on the bonding with the CB fibers, adhesion to the cement, and the overall properties of the material.

Table 1: Sample composition

	Samples											
Materials	A1	A2	A3	A4	A5	A6	A7	A8	A10	A11	A12	A13
BC (g)	60,00	61,50	61,50	67,50	75,00	86,25	86,25	67,50	75,00	75,00	-	-
W (g)	25,71	26,57	26,57	27,85	24,00	28,12	28,12	-	-	-	42,45	42,45
C (g)	45,00	46,50	46,50	48,75	-	-	-	48,00	52,50	52,50	72,45	72,45
LF (g)	6,00	6,75	6,75	6,00	6,00	6,00	6,00	6,00	6,00	6,00	-	-
PA (g)	7,50	9,00	-	-	22,5	30,00	-	15,00	15,00	-	35,10	-
SCR (g)	7,50	-	9,00	-	22,5	-	30,00	15,00	-	15,00	-	35,10
WT (g)	27,74g	24,23g	23,05	22,15	20,76	20,55	20,15	22,31	21,98	22,05	22,73	22,56

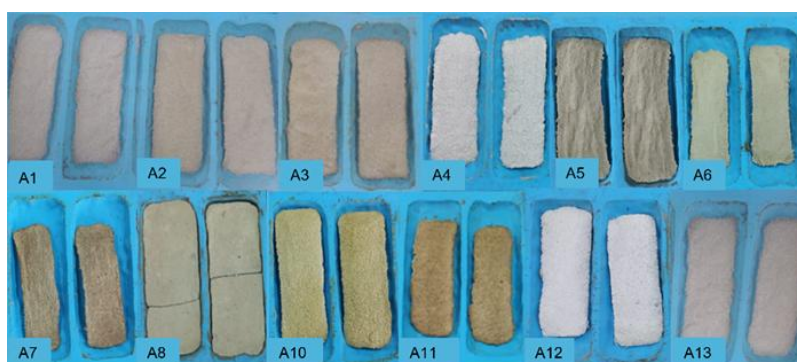


Figure 1: Prepared mortars.

The samples that exhibited the best formulation according to the research objective were A6, made with BC, W, LF, and PA, as well as A7, prepared with BC, W, LF, and SCR. Both were successfully formed without the need for cement and did not show any breakage points after demolding. Each of them displayed relevant characteristics that will be further explored in the following characterizations.

3.1 Water absorption capacity (WAC)

The water absorption capacity (WAC) results for samples A6 and A7 were evaluated based on the NBR 15210/2009 standard, which establishes that the wet weight of a 5 kg tile sample must not exceed 16% of its dry weight. Sample A6, which incorporated polyamide (PA) fibers, exhibited a water absorption of 15%, remaining within the acceptable limit and indicating a satisfactory formulation in terms of moisture resistance. Conversely, sample A7, produced with sugarcane residue (SCR), presented a 20% increase in weight due to water absorption, exceeding the standard's limit. To assess the statistical relevance of these differences, a one-way analysis of variance (ANOVA) was performed. The results showed a statistically significant difference between the water absorption values of A6 and A7 ($p < 0.05$), confirming that replacing PA with SCR negatively affects the composite's moisture resistance. This finding reinforces the importance of fiber type selection to ensure the long-term durability and performance of the material.

3.2 Mechanical Tests – Flexion

Flexural strength is a critical property for tile composites, as they are subjected to bending forces during installation and use. Sample A6 withstood a tensile force of 1054 ± 3.78 N and exhibited a Young's modulus of 5.27 ± 2.31 MPa. Sample A7 resisted 984 ± 2.6 N and showed a modulus of 3.42 ± 2.19 MPa. An ANOVA was conducted to determine the statistical significance of these mechanical differences. The analysis revealed that both the tensile load and the Young's modulus differed significantly between A6 and A7 ($p < 0.05$). These results suggest that PA, due to its structural compatibility with the BC matrix, enhances the mechanical integrity of the composite. In contrast, the heterogeneity in SCR fiber distribution may reduce the material's cohesion, resulting in inferior performance.

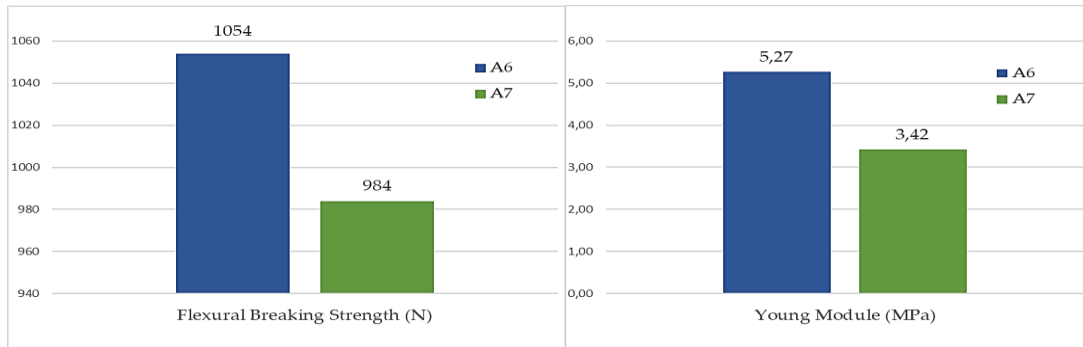


Figure 2: Mechanical strength (tensile load and Young's modulus) of Samples A6 and A7 under standardized bending tests.

The elongation capacity and high mechanical strength of sample A6 can be explained by the PA structure within the BC nanofibers, resulting in high mechanical strength.

3.3 Determination of Water Permeability

The results obtained after the duplicate analyses are presented in Table 2. As observed, the sample that showed the best performance was A6. This result may be attributed to the presence of PA in combination with LF, which may have acted as an impermeabilizing material, improving the overall resistance and performance of the sample. On the other hand, sample A7 showed lower performance. This behavior can be explained by the lack of homogenization of the SCR fibers with the other components of the formulation, resulting in a more spaced-out structure and, consequently, higher permeability. The heterogeneity in the fiber distribution may have compromised the resistance properties of the sample, explaining its lower efficiency compared to A6.

Table 2: Visual evaluation of water permeability test (duplicate analysis). Stains or drops indicate sample failure under standard conditions.

Test	Sample	
	A6	A7
1°	-	Watermark
2°	Watermark	Drip / Leakage

4. Conclusions

In this study, composites reinforced with bacterial cellulose (BC), polyamide (PA), and sugarcane residue (SCR) were evaluated as sustainable roofing tile alternatives. Replacing cement with limestone filler (F) enabled the production of 100% cement-free composites. Sample A6 (BC, PA, F) showed the best performance, with 15% water absorption (within the 16% limit per NBR 15210), tensile strength of 1054 ± 3.78 N, and Young's modulus of 5.27 ± 2.31 MPa. In contrast, A7 (BC, SCR, F) exceeded the absorption threshold (20%) and had lower strength (984 ± 2.6 N; 3.42 ± 2.19 MPa), likely due to fiber heterogeneity and increased porosity. Though PA improved flexibility, its solubilization requires high energy input, which may affect scalability. However, the economic viability of these composites is promising: the use of agroindustrial and textile waste (e.g., tomatoes, SCR, PA) can reduce raw material costs by up to 30–40%. Moreover, the process is compatible with conventional manufacturing, supporting decentralized and low-cost production. Despite the small sample size, which limits statistical validation, the results support further studies at pilot scale to assess durability, optimize energy use, and confirm market readiness.

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