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A Comprehensive Experimental Study on the Physical Performance and Durability of Bamboo Bio-Concrete

Vanessa M. Andreola ¹, M'hamed Y. R. da Gloria ¹, Marco Pepe ² and Romildo D. Toledo Filho ^{1,*}

¹ Department of Civil Engineering, Federal University of Rio de Janeiro, (UFRJ), Rio de Janeiro 21941-972, Brazil; vanessa.andreola@numats.coc.ufrj.br (V.M.A.); yassin@numats.coc.ufrj.br (M.Y.R.d.G.)

² Department of Civil Engineering, University of Salerno, 84084 Fisciano, SA, Italy; mapepe@unisa.it

* Correspondence: toledo@coc.ufrj.br

Abstract: In recent decades, the building sector has been moving toward promoting renewable raw materials to reduce greenhouse gas emissions associated with construction materials. One of the most valuable alternatives is the use of large-volume fractions of vegetable aggregates, leading to the development of bio-based cement mixture. A review of the recent scientific literature has shown that traditional design rules cannot be applied to bio-based cement mixtures. In this context, this study summarizes the results of a comprehensive experimental campaign aimed at unveiling the influence of bamboo particles on the physical properties and durability indicators of Bamboo Bio-Concrete (BBC) designed by applying a recent methodology proposed by the authors. The mixtures were produced using bamboo particles at a volumetric fraction of 45% and 50%. Fundamental properties such as density, thermal conductivity, capillary water absorption, and drying shrinkage were measured. The results obtained herein highlight the lightweight (density lower than 786 kg/m³) and insulating properties (thermal conductivity within 0.32 to 0.52 W/mK) of the BBC. The capillary absorption ranged between 2.40 and 2.83 g/cm², whereas the drying shrinkage ranged between 2500 and 5000 µε. These properties indicate the feasibility of using this material in various applications in the construction sector.

Keywords: bamboo bio-concrete; bio-aggregates; workability; physical performance; durability



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1. Introduction

The construction sector consumes approximately 30% of the planet's energy resources [1–3]. In buildings, the greatest consumption is associated with heating in winter, cooling in summer, water heating, and lighting [4]. A significant amount of energy is required to manufacture conventional building materials, along with the release of CO₂ into the atmosphere [3–5]. Several alternatives worldwide have been investigated to improve the energy efficiency of building materials while at the same time reducing dependence on non-renewable resources and greenhouse gas emissions [1,4,5]. These alternatives are generally associated with the use of bio-based aggregates, which are used to produce new sustainable building materials with significant potential to also improve thermal characteristics [6–15].

Bio-concretes are composite materials made by a mixture of a cement-based or lime-based matrix with vegetable aggregates (bio-aggregates), chemical additives, and water [6–14]. They can be produced with bamboo waste, wood shavings, rice husk, or hemp [7–13,15–19], chosen according to regional or national availability. Bio-aggregates are used because they are lightweight, thermal insulator [11–14], and have the potential to reduce carbon emissions and, consequently, the ecological impact of construction [1,5,7].

In Brazil, bamboo is a raw material that has been used industrially [20–22] to produce laminates and construction elements. The interest in its use is encouraged by the fact

that Brazil has the greatest taxonomic diversity of native bamboo, distributed in different regions [23]. In addition, bamboo is a fast-growing plant that is easy to regenerate and does not require replanting [23]. During the primary processing of the culm, there is an excessive production of waste. For example, to obtain a laminated piece, the bamboo culm is cut and its surface levelled and this process produces approximately 64% to 84% of waste, which varies according to the species [24,25]. When bamboo culm is used as a building element (roof structure, pillars, or beams), uniform, straight pieces with geometric alignment from top to bottom are used. During the selection, irregular, distorted, and misaligned pieces are discarded, generating a high volume of waste.

One of the main issues associated with the use of vegetable waste in construction materials is the high porosity that characterizes these types of aggregates. As a consequence, the traditional design rules generally applied for designing and producing ordinary cement-based elements and systems cannot be applied in the case of bio-concrete.

In this sense, a rational mix design method to produce workable bio-concrete with a cement matrix and bio-aggregates (BAs) of bamboo, wood shavings, and rice husk was proposed in a first study by da Gloria et al. [16]. Firstly, the methodology proposed an analysis of the chemical compatibility between the BA and the cement hydration products to define the eventual pre-treatment to be applied to the bio-aggregates before the application in cementitious matrices. As a matter of fact, according to the literature, the presence of bio-aggregates can affect the cement hydration processes in terms of setting time and mechanical strength development due to the presence of “extractives” within the bio-aggregates fraction [17,26]. For this reason, before being used in a cement matrix, BAs are submitted to pre-treatment to reduce inorganic substances and soluble extractives, in order to avoid the delay or inhibition of cement hydration [18,27,28]. On the other hand, da Gloria et al. [16] determined the compensation water for each type of BA, using the water absorbed by the bio-aggregate during the production of the bio-concrete. Bio-aggregates are characterized by speedy water absorption capacity compared to conventional concrete aggregates [9,16,18,27]. As a matter of principle, compensation water is additional water used to ensure that the BAs remain saturated and do not absorb the water of cement hydration. If this water is not controlled, the presence of BAs affects the properties of the fresh mixture [7,28].

Furthermore, the methodology used [16] warrants a workable mixture characterized by a spreading ranging between 275 mm and 300 mm. The aim of spreading proposed by da Gloria et al. [16] was to produce bio-concretes with adequate workability (261–290 mm) that would dispense the mechanical pressing procedure used during molding, as carried out by Nguyen et al. [29] and Frantz et al. [30].

Once the fresh state properties are defined, it is worth mentioning that at the hardened state, bio-concrete tends to release excess water previously absorbed by the BPs through moisture exchange with the environment, causing a simultaneous loss of mass and drying shrinkage [18,31]. As a result, they can present greater drying shrinkage than conventional concrete [19], shrinking more for bio-concrete with a greater volume of bio-aggregates [28,31]. Toledo Filho et al. [18] reported that, after 50 days, wood bio-concretes (produced with a bio-aggregate volume of 50%) presented drying shrinkage of $-3500 \mu\epsilon$, and when the wood shavings volume is increased to 80%, the bio-concrete registered shrinkage of $-6400 \mu\epsilon$. Furthermore, as they are porous materials, they also easily absorb water by capillarity, with absorption increasing proportionally as the volume of bio-aggregate increases [6,18]. The water absorption coefficient is related to the open pore structures of the bio-aggregates, facilitating water transfer [6,9].

In addition, the physical and thermal properties of bio-concrete are improved by incorporating bio-aggregates into the composition. Amziane and Collet [10] highlight that the low density and high porosity of bio-aggregates mainly promote the thermal insulation and lightness of bio-concrete. When compared to conventional concrete, bio-concrete is lighter and more insulating [8,9]. A concrete with a density of 2300 kg/m^3 has a conductivity of 2 W/mK , while cellular concrete with a density of 1600 kg/m^3 has a thermal

conductivity of 0.6 W/mK [11]. For bio-concrete, the thermal conductivity can range from 0.06 W/mK to 1.25 W/mK, while the density is between 700 kg/m³ and 1659 kg/m³ [7,19]. The combination of low thermal conductivity and high thermal capacity results in an increase in the building's energy efficiency performance [5,32].

Before the possible application of the methodology proposed by da Gloria et al. [16], mainly empirical dosage methods (e.g., based on the cement-to-BP mass ratio) were used in the literature [6,14] as well as in the industrial context [33–35] to produce wood bio-concrete. In these cases, the cement-to-wood mass ratios varied between 2 and 3 (wood volume fraction between 45% and 55%) and the water-to-cement ratios (w/c) varied between 0.15 and 0.17. The low w/c ratio is due to the high pressure applied during the molding process to compact the fresh bio-concrete in the formwork. Using this molding technique, it is possible to produce particle boards with a thickness of around 6 mm, obtaining density values between 1150 and 1350 kg/m³, thermal conductivity of 0.35 W/mK, and compressive strength and modulus of elasticity of 15 MPa and 4.5 GPa, respectively. They achieve adequate mechanical strength for non-structural applications [6,7,27,28,33–35] and are classified as excellent materials in terms of hygrothermal performance [36]. These materials are generally used for façade cladding and insulation, partition walls, ceiling cladding, and interior decoration. Finally, the physical characterization of bio-concrete using the rational mixing method is also relevant to understanding the particularities of bio-concrete, mostly in terms of lightness, thermal conductivity, and homogeneity.

In this context, the present article studied the influence of the treatment of bamboo bio-aggregates on cement hydration using fine BPs with cement pastes. Bio-concretes were then produced with bamboo volumes of 45% and 50% and water-to-cement ratios of 0.40 and 0.50. The influence of these proportions on density, thermal conductivity, water absorption by capillarity, drying shrinkage, and mass loss were reported.

2. Materials and Methods

The methodology of the current paper was developed in accordance with the following steps: (i) production of bamboo particles (BPs); (ii) analysis of the influence of the number of BP washing cycles on the hydration of cement pastes; (iii) washing and characterization of BPs; (iv) production of bamboo bio-concrete (BBC); (v) workability test in the fresh state; (vi) tests in the hardened state: homogeneity, apparent density, thermal conductivity, water absorption by capillarity, drying shrinkage and loss of mass; and (vii) discussion of the results.

2.1. Raw Materials

The bamboo waste used in this research was obtained from a Brazilian company that uses the culms (in standard sizes) as construction elements. The aim was to analyze the potential of this waste in the production of bio-concrete. The bamboo culms of the *Dendrocalamus asper* came from the State of Rio Grande do Sul (Brazil) and were approximately 300 mm in length (Figure 1a). To produce bamboo particles (BPs), the culms were processed in an industrial crusher to obtain the first particles with lengths between 5 and 19 mm. Then, in a knife mill, these particles were refined on a smaller scale to have the bio-aggregates. Next, the bio-aggregates were subjected to mechanical sieving, and the particles passing through the sieve of 4.75 mm were used (Figure 1b). The apparent density and moisture content were 580 kg/m³ and 11%, respectively, according to Brazilian standards [37,38]. Water absorption was 109%, according to the method proposed by da Gloria et al. [16].

A high initial strength Brazilian Portland cement, labeled CP V-ARI in accordance with the National Brazilian Standard [39], was used for bio-concrete production. The cement density was 3170 kg/m³ and the chemical composition is reported in the following Table 1. A viscosity modifying agent (VMA) of density 0.7 g/cm³ was used with the purpose of providing the required consistency at the fresh state.



Figure 1. (a) Culms waste obtained from the company; (b) bamboo particles used in the study.

Table 1. Chemical properties of cement (%).

CaO	SiO ₂	Al ₂ O ₃	Fe ₂ O ₃	So ₃	K ₂ O	SrO	TiO ₂	MnO
68.973	14.955	4.700	3.500	4.290	0.980	0.420	0.140	0.014

2.2. Isothermal Calorimetry on Bamboo Bio-Particles

As also mentioned in the introduction section, the extractives present in bio-aggregates can have a negative effect on the setting and hardening of cement matrices. Consequently, washing in hot water can reduce such effects [7]. To assess the influence of the number of BP washing cycles on the hydration of cement pastes to choose the ideal number of cycles, an isothermal calorimetry test was carried out.

Following the technique suggested by da Gloria and Toledo [7], the hydration kinetics of a neat cement paste were used as a reference and fine bamboo particles (passing the 150 μm sieve) were used to facilitate the preparation of the pastes and their placement in the 20 mL glass ampoule. Unwashed fine particles were analyzed, and then the particles were washed once and three times in hot water at 80 $^{\circ}\text{C}$ (1 h) with a mass ratio of 1:10 (bamboo: water), followed by oven drying (40 ± 2 $^{\circ}\text{C}$) for 6 h.

As suggested by Hofstrand et al. [40], the mixtures were produced with a deionized water-to-cement ratio of 0.45 and a bamboo-to-cement ratio of 0.075. The reference paste was mixed in a beaker with a glass rod for 1 min. For the mixtures containing BPs, the pastes were previously prepared, and the fine BPs were added followed by homogenization (1 min). For each condition, approximately 5 g of the mixture was weighed on a precision scale (0.001 g) and introduced into a glass ampoule using a plastic syringe. Next, the ampoule was sealed and quickly charged into the calorimeter, on average 5 min after the contact between cement and water. The tests were performed by an isothermal calorimeter TAM Air—TA Instruments (25 $^{\circ}\text{C}$) and kept for 7 days. The parameters analyzed were induction duration, start and end of the acceleration period, reaction rates, and heat flow released. The mixtures were produced in the following conditions: REF; neat cement paste and BP-x; and cement paste with fine BPs washed x times ($x = 0, 1$, and 3).

Figure 2 shows the heat flow curves up to 48 h, while Table 2 shows the information on the induction and acceleration periods. The introduction of unwashed BPs in the cement paste resulted in an inhibition and delay of cement hydration. As a result, the BP-0 curve remained with the greatest delay from the REF curve. Consequently, the information on the induction and acceleration periods of BP-0 also showed the greatest differences from the reference paste. When the fine particles are washed once, the heat release curve is closer to the reference. Using unwashed BPs increased the induction period duration of 9 h. From BP-1 to BP-3, there was a difference of 0.15 h. The acceleration period was also affected for the BP-1 paste, causing a delay in the start and end time, as well as a decrease in the reaction rate. This delay in the start and end of the acceleration period, caused by the unwashed fine

BPs, was equal to the increase observed in the induction period. There was a shift in the heat release curves, especially in BP-0. It is worth mentioning that as the number of washes increased, the closer to REF the curves remained. When the fine particles are washed once (BP-1), the heat release is only 10% lower than the REF. In terms of maximum flow, all the pastes showed close values, except for the BP-0 blend. This mixture had a maximum heat flow 48% lower than the REF, while BP-1 and BP-3 had values very close to the reference (maximum difference of 5%).

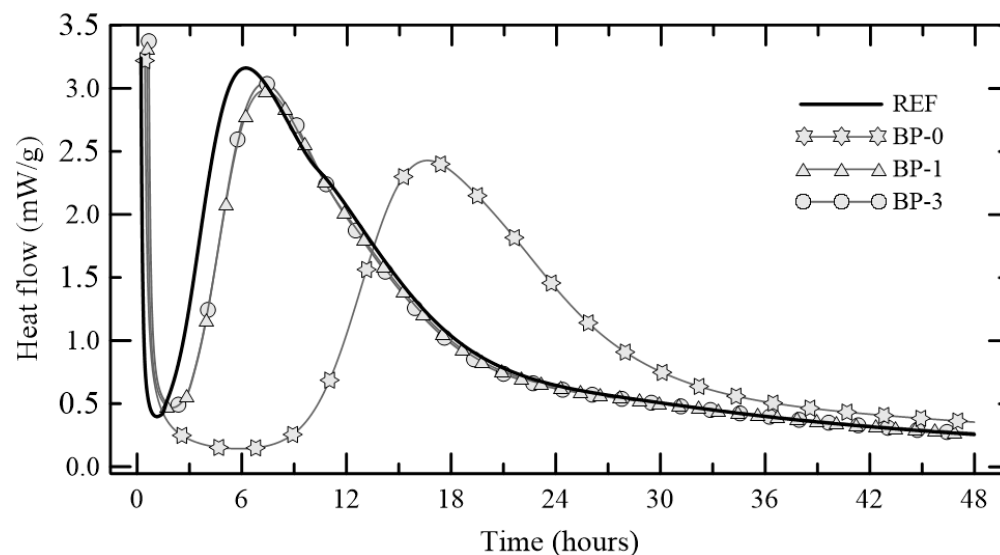


Figure 2. Heat flow vs time curves.

Table 2. Isothermal calorimetry heat indexes.

Mixtures	Induction			Acceleration	
	Duration (h)	Beginning (h)	Ending (h)	Reaction Rate (k)	Maximum Heat Flow (mW/g)
REF	1.625	0.885	6.20	0.885	3.161
BP-0	9.116	0.419	16.58	0.419	2.127
BP-1	2.607	0.790	7.29	0.790	2.981
BP-3	2.453	0.771	7.27	0.771	2.995

2.3. Bamboo Particles Preparation

Before producing the bio-concrete, the BPs were washed in hot water (80 °C) for one hour. The BPs were then air-dried for 72 h, enough time to reach an equilibrium moisture content of 13%. After washing all the particles needed to produce the bio-concrete (± 150 kg), the elongated pile method was used to ensure that the BPs were homogenized.

2.4. Bamboo Bio-Concrete (BBC) Fabrication and Testing

2.4.1. Bio-Concretes Production

In this study, four BBCs were produced with the following cement-to-bamboo ratios by weight: 2.5 and 3, equivalent to BP volumetric fractions of 50% and 45%, respectively. The water-to-cement (w/c) ratios were 0.4 and 0.5, and these choices were made based on a recent article proposed by the authors [16]. Thus, the aim was to obtain a minimum consistency index of 255 mm, which is the normative standard defined for mortars with good workability [41]. This index is also indicative of the good moldability of bio-concrete [7,28], making it possible to mold it into different architectural shapes, such as organic molds that use a curved design.

As the BPs are characterized by high water absorption capacity, the amount of water in the mixture must be sufficient to keep particles saturated and also allow the cement

hydration and the consistency of the mixture. Therefore, in addition to the water of hydration (W_h), compensation water (W_c) was used, which is based on the absorption capacity of the bio-aggregate and was quantified according to the method suggested by da Gloria et al. [16]. To control exudation and prevent segregation, a viscosity modifying agent (VMA) was used at a fixed dosage of 0.13% of the cement mass. The mass relations between the mixture components are summarised in Table 3, where the 28-day compressive strength is also presented, but this study mainly focused on the physical properties of the bio-concrete.

Table 3. Mass relation based on the cement and compressive strength.

	Cement	BPs	W_h	W_c	Compressive Strength (MPa)
BBC 2.5-0.40	1	0.4	0.4	0.44	3.46
BBC 2.5-0.50	1	0.4	0.5	0.44	3.22
BBC 3-0.40	1	0.33	0.4	0.36	4.57
BBC 3-0.50	1	0.33	0.5	0.36	3.82

The mixtures were produced using a 50 L mixer, and the production process of the bio-concrete consisted of homogenizing the dry materials (cement and bamboo particles) for 1 min. Subsequently, the water of hydration and compensating water were added over a period of 2 min. Then, the VMA was added, and the mixture was homogenized until the 8th minute.

At a fresh state, the workability test was carried out by the flow table test [41].

The specimens were cast in cylindrical molds (diameter 50 mm—height 20 mm) and prismatic molds with dimensions of $285 \times 75 \times 75 \text{ mm}^3$ (length $\times$ width $\times$ thickness) in three layers. Each layer was mechanically vibrated at a frequency of 68 Hz for 30 s. After 24 h, the samples were demolded and introduced into a humid chamber at a temperature of $22 \pm 2^\circ\text{C}$ and a relative humidity of $95 \pm 2\%$ until the testing age.

2.4.2. Test Methods

The apparent density of the bio-concrete was analyzed from six cylindrical specimens (diameter 50 mm—height 100 mm). At the end of the 28-day curing period, the cylindrical samples were dried for eight consecutive days in an oven ($97 \pm 2^\circ\text{C}$), which was enough time to achieve mass constancy. They were then placed in a controlled room (22°C ; 55% RH) and reweighed after 28 days. The procedure was adopted to investigate the bio-concrete in humid conditions of use. The analysis was completed, and the apparent density was calculated by dividing the mass by the volume.

The insulating capacity of the bio-concrete was analyzed using the thermal conductivity test, utilizing eight specimens (diameter 50 mm—thickness 20 mm). Before testing, the samples were dried in the same way as the apparent density samples. The test was carried out on the TCi C-Therm Thermal Conductivity Analyzer, based on the Modified Transient Plane Source (MTPS) technique, at a controlled temperature of $22 \pm 2^\circ\text{C}$. It was necessary to use a sample-sensor contact agent. A thermal paste (Wakefield 120) was applied to ensure that the presence of air voids on the surface did not interfere with the results [7]. Four measurements were taken for each specimen and the average thermal capacity was calculated.

Water absorption by capillarity was analyzed using four cylindrical specimens (diameter 50 mm—height 100 mm) for each mixture produced. After complete curing, the samples were dried at $97 \pm 2^\circ\text{C}$ in a ventilated oven for eight days (mass consistency). In the dry condition, the lateral surfaces were coated with aluminum tape, which ensured the unidirectional ascension of water and prevented moisture loss during the test. Only the base and top were removed from the aluminum tape. In an acrylic box, the base of the sample was immersed in $5 \pm 1 \text{ mm}$ of water and the mass of the samples was recorded. Readings were taken every 10 min (until the first hour of the test) and every 1 h (until the first 10 h of the test). After that, measurements were taken twice a day until the 5th

day and, finally, once every 2 days until the 28th day. Water absorption by capillarity was calculated according to the procedures described in the Brazilian standard ABNT NBR 9779 [42], according to Equation (1).

$$W_c = \frac{M_w - M_d}{S_t} \quad (1)$$

where:

W_c = Water absorption by capillarity (g/cm²);

M_w = Mass of the test specimen in contact with water (g);

M_d = Mass of the dry specimen in constant mass (g);

S_t = Cross-sectional area of the specimen (cm²).

The drying shrinkage test was carried out using four prismatic samples measuring 285 × 75 × 75 mm³ (length × width × thickness) for each bio-concrete. During molding, gage studs 250 mm apart were mounted (in the middle) on the 75 mm square sides. After 28 days of curing, an initial comparator reading of length and mass variations was taken to compare the variations in length and mass. Measurements were taken every 24 h during the first 20 days and every 5 days until the 90th day. Length variation and mass loss were measured using a digital length comparator and a balance, respectively. The samples were stored in the open air in a drying room (23 ± 2 °C; RH 60 ± 2%). In accordance with ASTM C157 [43], drying shrinkage was calculated according to Equation (2) and the loss of mass was based on Equation (3).

$$\varepsilon = \frac{L_t - L_i}{L_p} \quad (2)$$

$$W_m = \frac{m_t - m_i}{m_i} \quad (3)$$

where:

ε = Drying shrinkage deformation (%);

W_m = Mass loss during drying shrinkage (%);

L_t = Length reading at time t (mm);

L_i = Length reading after 28 days of curing (mm);

L_p = Distance between gage studs (mm);

m_t = Mass of the specimen at time t (kg);

m_i = Mass initial of the specimen after 28 days of curing (kg).

3. Experimental Results

3.1. Workability

Figure 3 shows the spreading at the fresh state of the BBC, as well as the consistency indices achieved. The bio-concretes produced in this study were homogeneous and presented a consistency index in the desired range (between 268 mm and 290 mm), which indicated good workability. It is important to remark that the obtained spread allows easy molding, without the need for manual or mechanical compaction. On the other hand, the experimental evidence highlights that the bio-concrete mixtures are sensitive to the volume of paste as well as to the w/c ratio: the mix with 45% bamboo particles (BBC 3-0.50) showed the highest spread of 290 mm. This is because the greater volume of paste favored filling the voids between the BPs [44].

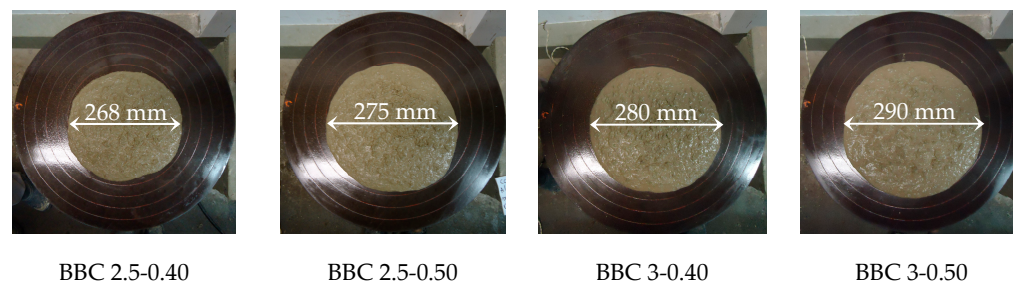


Figure 3. Spreading and consistency index of bio-concrete mixtures.

3.2. Homogeneity of Bio-Concretes

Figure 4 presents representative longitudinal and transversal section pictures of the produced bio-concretes (i.e., BBC 2.5-0.50 samples) to illustrate the bio-aggregates' distribution within the cementitious matrix. The proposed images highlight the uniform distribution of the BPs, the absence of segregation in the sample sections, and the overall homogeneity of the produced mixtures.

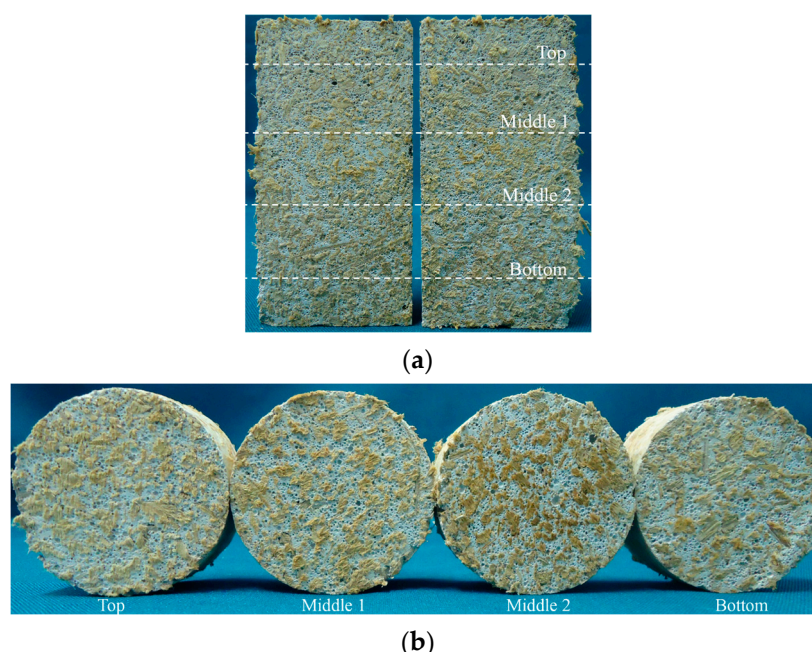


Figure 4. BBC 2.5-W0.50 samples images: (a) longitudinal section; (b) transversal section.

3.3. Density and Thermal Conductivity

The average experimental values obtained in terms of thermal conductivity and density of the bio-concretes are graphically reported in the following Figure 5.

Based on Figure 5, the thermal conductivity and the density ranged from 0.315 to 0.519 W/mK and 693 to 786 kg/m³, respectively. Overall, the results showed that increasing the amount of BPs reduced the thermal conductivity and density of the bio-concrete. As they are highly porous and have a structure composed of voids [9–11], they promoted reductions in thermal and physical properties. Consequently, BBC 2.5-0.40 and BBC 2.5-0.50 showed the lowest values.

It is worth mentioning that according to ABNT NBR 15220-2 [45], which recommends thermal conductivity and density values for construction materials, all the bio-concretes in this study can be classified as insulating for presenting conductivity values lower than 0.6 W/mK. In addition, they can also be classified as lightweight since their densities are always lower than 1600 kg/m³.

These properties are also influenced by the characteristics of the bio-aggregates, such as the volume of bio-aggregate in the mix, the change in geometry, the species of biomass

used, the water-to-cement ratio [6–14,24], the method of producing the bio-concrete, and molding by compaction or vibro-compaction. For these reasons, BBC 2.5-0.50 had the lowest density, while BBC 3-0.40 had the highest (difference of 13.3%). Da Gloria and Toledo [7], analyzing wood bio-concrete, obtained densities between 905 and 957 kg/m³, in relation to thermal conductivity in the range of 0.46 to 0.535 W/mK, with similar bio-aggregate volumes and ratios w/c.

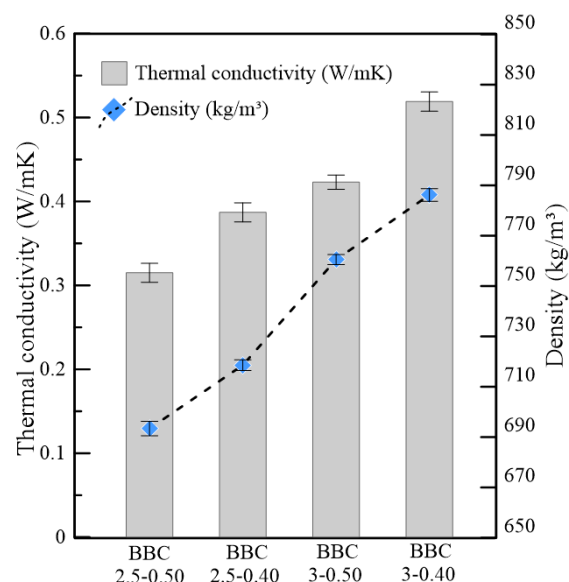


Figure 5. Results of the thermal conductivity of BBC and its relationship with density.

3.4. Capillary Absorption

The results obtained from water absorption by capillarity during 28 days of testing are plotted as a function of water absorption *vs* the square root of time and are shown in Figure 6 and Table 4. The absorption curves can be divided into three distinct stages: initial sorptivity (S_1), second sorptivity (S_2), and final sorptivity (S_3). The initial occurred during the first four hours of the test ($h^{0.5} = 2$), where water absorption increased almost linearly at a high velocity.

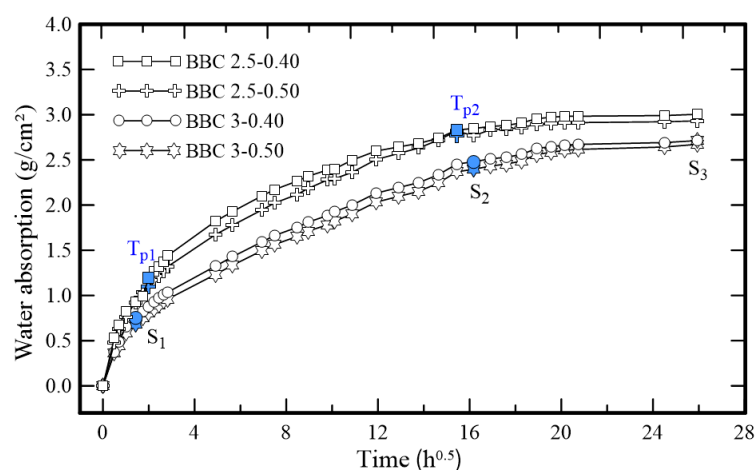


Figure 6. Water capillary absorption *vs* square root of time.

The second sorptivity occurred from the first hours of the test onwards, until the 10th ($h^{0.5} = 15.42$) and 11th day ($h^{0.5} = 16.18$), characterized by the absorption of less water, with mass gain following a non-linear behavior, where the BPs were almost saturated. During the final sorptivity (S_3), the BBC was practically saturated, and the absorption curve reached a plateau at the end of the test ($h^{0.5} = 25.92$). The highest absorptions were from

the BBC 2.5 mixture, which has the highest BP volume and consequently the greatest ease of water absorption due to the hygroscopic characteristic of biomass [8,18,27]. Based on the results reported in Table 4, the initial sorptivity of BBC 2.5 was 4.4 and 4.1 times higher than the secondary for water-to-cement ratios of 0.40 and 0.5, respectively. The BBC 3-W0.5 showed an initial and secondary sorptivity 1.1 times lower than BBC 2.5-0.5. This suggests that the addition of cement paste reduced the presence of large pores in the bio-concrete, responsible for rapid absorption, as highlighted by Walker et al. [8].

Table 4. Capillary water absorption and sorptivity.

	Transitional Point (T_{p1})		Sorptivity ($\text{g}/\text{cm}^2 \cdot \text{h}^{0.5}$)		Transitional Point (T_{p2})		Sorptivity ($\text{g}/\text{cm}^2 \cdot \text{h}^{0.5}$)
	g/cm^2	$\text{h}^{0.5}$	S_1	S_2	g/cm^2	$\text{h}^{0.5}$	S_3
BBC 2.5-0.40	1.19	2.00	0.522	0.121	2.83	15.43	0.016
BBC 2.5-0.50	1.10	2.00	0.518	0.125	2.77	15.43	0.012
BBC 3-0.40	0.75	1.41	0.536	0.116	2.48	16.19	0.023
BBC 3-0.50	0.68	1.41	0.478	0.114	2.40	16.19	0.027

The capillary behavior of the studied bio-concretes was similar: the absorption kinetics is high in the first hours and after ten days it decreases until it reaches a plateau. The main difference observed was between mixtures of the same w/c, during T_{p1} , where BBC 2.5 absorbed, on average, 38% more than BBC 3 and only 12% more at T_{p2} , which is the end of the test. For the same cement/bio-aggregate ratio, increasing the water-to-cement ratio does not significantly change the absorption kinetics, since the absorption increases, on average, by 8% (T_{p1}) and 2% (T_{p2}). The capillary kinetics of the BBC was determined by the BB, increasing as the biomass volume increased. Therefore, the water absorption coefficient is related to the porous structure of bio-based materials [9,18,29].

3.5. Drying Shrinkage

The evolution of drying shrinkage and the mass loss of the bio-concretes are illustrated in Figure 7. It can be observed that among the mixtures, BBC 3-0.40 showed the lowest shrinkage and lowest mass loss. The shrinkage increases with the increase in BB volume in the mixture. As the water contained in the bio-concrete structure evaporates, the samples suffer deformations and weight variations. For mixtures with a greater volume of bio-aggregate and a higher water-to-cement ratio, the deformation and weight variation are increased, as noted by Bederina et al. [31]. As a result, variations were always higher for BBC 2.5-0.50 bio-concrete and lower for BBC 3-0.40.

After 24 h from the start of the test, the BBC 2.5-0.40 mixture had shrunk 2.2 times more than the BBC 2.5-0.50. On the second day, the shrinkage was close (43.90 $\mu\epsilon$), and after the 3rd day, the mixture with the highest w/c shrank 1.1 times more, remaining with greater shrinkage until the end of the test. Despite this, until the 22nd day of reading, the drying shrinkage remained similar between the samples (average of 3280 $\mu\epsilon$). From the 23rd day until the end of the test, the BBC 2.5-0.50 was the one that shrank the most (39.5%), followed by the BBC 2.5-0.40 (36.2%) and the BBC 3 mixtures (both 33.9%). Weight loss showed the same trend, and mixtures BBC 2.5 and BBC 3 lost, respectively, 23% and 19% of weight up to the 22nd day. From the 23rd day onwards, BBC 2.5-0.50 lost the most mass (8.4%), followed by the BBC 3-0.50 mixture (6.4%).

As exposed, the evolution of drying shrinkage and mass loss can be divided into a variable stage and a stable stage. This is because it can be observed that the retraction increases rapidly until the first twenty days followed by a plateau that is gradually reached. After the samples reached the stable stage, no difference greater than 3% was observed between the mixtures studied. According to the literature [6,18,31], drying shrinkage of concrete is caused by moisture loss in capillary pores. This phenomenon will depend on the relative humidity, the porosity of the material, and also the porosity induced by the bio-aggregate in the matrix [9,31].

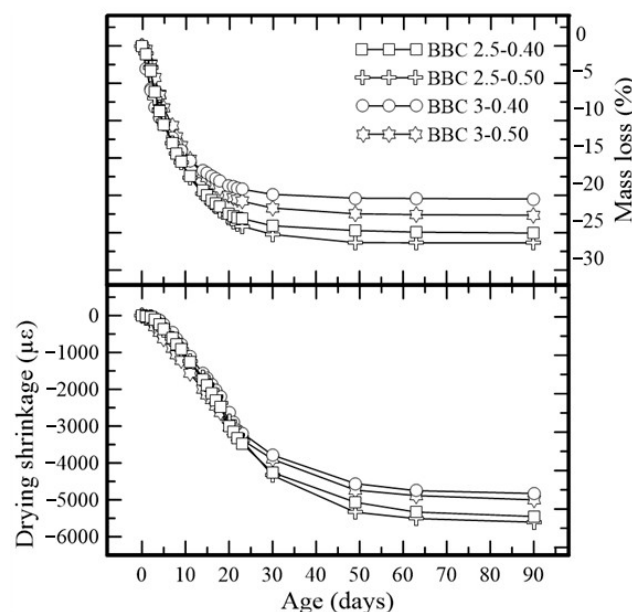


Figure 7. Drying shrinkage results.

4. Conclusions

According to the results obtained from this study, the following conclusions can be drawn:

The isothermal calorimetry test showed the retarding effect of the extractives present in the raw bamboo particles on the cement setting. A washing cycle in hot water (80 °C) was effective in preventing hydration delay.

All the mixtures in the fresh state are homogeneous and free of segregation, with spreads between 268 mm and 290 mm and good workability.

The results of the density test indicated that the bio-concretes are lightweight, with densities ranging from 693 kg/m³ to 786 kg/m³.

The results of the thermal conductivity test showed that the bio-concrete is insulating, with thermal conductivity values between 0.315 and 0.519 W/mK.

The parameters for water absorption by capillarity showed that the absorption kinetics increase in bio-concrete with a greater volume of bio-aggregates, resulting in rapid initial absorption and greater saturation, and increasing the water/cement factor does not significantly affect the kinetics.

The bio-concretes show greater deformation and weight variations in the samples with a greater volume of bio-aggregates and a higher water/cement ratio.

All the mixtures have the potential to be applied as internal partitions and furniture, false ceilings, cladding or finishing existing walls, retrofitting façades, or open elements (hollow brick wall).

Additional studies are being carried out to improve the cementitious matrix of bio-concrete by replacing cement with pozzolanic materials, in addition to analyses of natural durability (external weathering) and biological durability (fungal attack).

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