DURABILITY OF BIO-BASED BUILDING MATERIALS

R. D. Toledo Filho, M. Y. R. da Gloria, V. M. Andreola
Federal University of Rio de Janeiro, Brasil
Corresponding author: e-mail: toledo@coc.ufrj.br

Abstract

This work aims to present the current status of the durability of two families of bio-concretes made with wood shavings and bamboo particles. The bio-concretes were produced with cement to biomass ratios ranging from 0.5 to 3, and presented ranges of densities from 0.7 to 1.2 g/cm^3 and compressive strength from 0.5 to 9.5 MPa. Their durability was investigated through capillary absorption test, drying shrinkage and compressive strength after 15 wetting and drying cycles. The results indicated initial absorptivity varying from 0.142 to 0.463, and capillary absorption ranging from 2 to 3.35 g/cm^2. It was also observed drying shrinkage between 3000 and 6000 με and mass loss ranging between 10% and 30% for the different mixes studied. After the aging test, the bio-concrete studied lost about 33% of their compressive strength.

Keywords:

Bio-concretes, wood shavings, bamboo particles, durability

1 INTRODUCTION

The growing increase of ecological awareness has transformed the concept of disposable goods into reusable goods and this is also applied in the case of agro industrial waste where, for example, the vegetable biomasses are employed as raw materials in the construction sector [Magniont 2010].

According to [Amziane 2016], the global warming, energy savings, and life cycle issues are factors that have contributed to the rapid expansion of plant-based materials for buildings, which can be qualified as environmental-friendly and efficient multifunctional materials.

Some of the biomasses, usually, employed for the production of cementitious composites are: wood shavings and bamboo particles. In fact, these lignocellulosic materials are, generally, available in large quantities. Moreover, the resulting bio-based composites are lightweight with a low thermal conductivity, while at the same time still presenting an adequate mechanical performance.

According to studies reported in the literature, the use of these biomasses requires some type of treatment, able to remove inorganic substances and water soluble extractives, with the purpose of improving the compatibility of these raw materials with the cement matrix. For example, [Silva 2004] studied the cement-biomass chemical compatibility using several types of biomasses (coffee husk, rice husk and bamboo). The authors concluded that the treatment that provided the highest value of ultrasonic wave speed and compressive strength was the hot water washing combined to the addition of 3% of $CaCl_2$ in the composite. Then, [Lilge 2009] evaluated the performance of panels composed by cement and different proportions of two combined wooden species with rice husk, using pressing process. The author found that the higher the rice husk addition, the lower the absorption and thickness swelling. The opposite effect was observed for mechanical resistance.

Out of the mechanical performance, the durability properties need to be investigated. One way to study the durability of materials with biomass is through, for example, the capillary absorption, drying shrinkage and accelerated aging. The presence of a high amount of vegetable material increases the total porosity of the bio-concrete, and consequently its capillary absorption capacity. Because of the high absorption of the biomass, during the bio-concretes casting, it is necessary to use a high amount of water to have a good workability. Then, at hardened state, the excessive water is released by humidity exchange and lead to a simultaneous mass loss and drying shrinkage.

In view of the above, the present study aims at studying on one hand the effect of hot water washing of wood shavings and bamboo particles on the cement hydration. On the other hand, the durability of the wood and bamboo bio-concretes was discussed based on the results of water capillary absorption test, drying shrinkage and accelerated aging test. The accelerated aging tests were performed on wood shavings bioconcrete through compressive test before and after 5, 10 and 15 cycles of wetting and drying.

2 MATERIALS AND METHODS

2.1 Bio-Aggregates

Two types of biomasses have been employed in this study as Bio-Aggregates: Wood Shavings (WS) and Bamboo Particles (BP).

The WS were obtained from a carpentry of Rio de Janeiro (Brazil). Four wood species wastes (*Manilkara salzmanni, Hymenolobium petraeum, Cedrela fissilis and Erisma uncinatum Warm*) were collected in random proportions. In order to reduce the average the of water absorption of WS, the particles characterized by a nominal diameter lower than 1.18 mm were removed due to their higher specific area (Fig. 1a).The apparent density of the WS was 550 kg/m^3 meanwhile its moisture content was 14%.

The bamboo specie was the *Dendrocalamus Asper* coming from Rio Grande do Sul (Brazil). The BP were obtained from the waste of the stems cutting process (stems length around 30 m). Once in the laboratory, the stems wastes (length around 45 cm) were reduced first in particles with length between 5 and 19 mm using an industrial crusher. Then, in a knife mill, these particles were refined to obtain aggregates with a maximum diameter of 4.75 mm (Fig. 1b). The apparent density of the BP was 580 kg/m^3 and the moisture content 12.21%.

a)

b)

Fig. 1: a) Wood Shavings b) Bamboo Particles.

2.2 Bio-Aggregates treatment

The Bio-Aggregates (BA) were washed in hot water (80°C) with the purpose of removing the water-soluble extractives which inhibit the cement setting. [da Gloria 2016] suggested to access first the amount of the water-soluble extractives in order to determine the more efficient washing number for each bio-aggregate. According to the author, after 5 washings, there is no more significant extractive removed. The BA/water proportion used was 100g/litre as proposed by [da Gloria 2016]. After each washing, the waste water was separated, filtered through the 150 µm mesh, refreshed and stored in plastic bottle of 350 ml. From the waste water, 3 samples of 35 g were weight to the nearest 0.1 mg into a recipient. Then the samples were dried at 40º ± 2°C during 48 h in order to eliminate the water by evaporation and determine the residual extractives mass. The extractives contents were calculated as expressed in the Equation 1.

$$e\% = \frac{m_1}{m_2}.100 \quad (1)$$

Where:

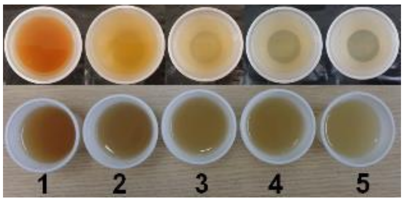
e% = Extractives content, %

m_1 = Mass of waste water residues after drying, g

m_2 = Mass of waste water, g

After the washings cycles of the BA in hot deionized water, it was observed a gradual variation of the water coloration. It can be seen in the Fig. 2a starting from the left to the right, that the first wastewaters were dark, and got clearer as the washings were done. As observed by [da Gloria 2016], the change of the color shade can be explained by the fact that the washings removed a significant amount of water soluble extractives as the extractives responsible of color. From the Figure 2b, it can be observed a high decrease of the extractives amount after the first washing. In fact, around 65% and 58% of the extractives from the BP and the WS were removed, respectively. After the third cycle, 74% and 83% of extractives were removed from the BP and the WS, respectively.

a)



b)

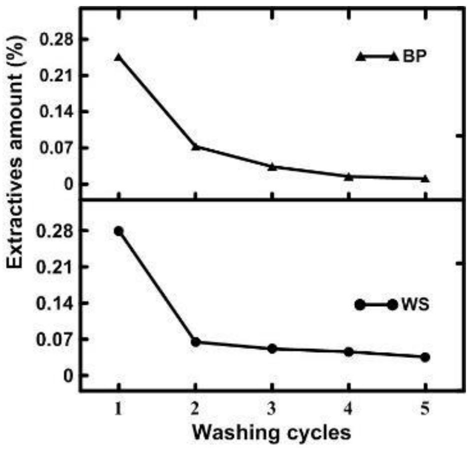


Fig 2: a) Waste water of BP and WS after washings b) Extractives amount in the waste water

The influence of the BP and WS washings on the cement hydration was accessed through isothermal calorimetry, in order to choose the best washing cycle. The approach used was based on comparing the kinetics of cement hydration of a neat cement paste, used as reference, and cement paste made with the wastewaters. An analogy between the wastewaters and the BA was set as follow: the wastewater n represented the use of the BA after n-1 washings. The following mixtures were produced:

- REF: Neat cement paste;
- W_n: Cement paste with wastewaters n (n= 1, 2, 4).

The water-to-cement ratio was set as 0.45. The paste preparation consisted of hand-mixing of cement and water during 1 min in a glass beaker. After preparation, around 5 g of each mixture was injected into a 20 ml glass ampoule using a plastic syringe. Next, the ampoule was sealed and quickly charged into the calorimeter within 5 min after the contact between cement and water. The tests were performed into an isothermal calorimeter TAM Air - TA Instruments for 7 days, at a controlled temperature of 27ºC. Fig. 3 presented the heat flow vs time curves of the pastes during the first 24 hours.

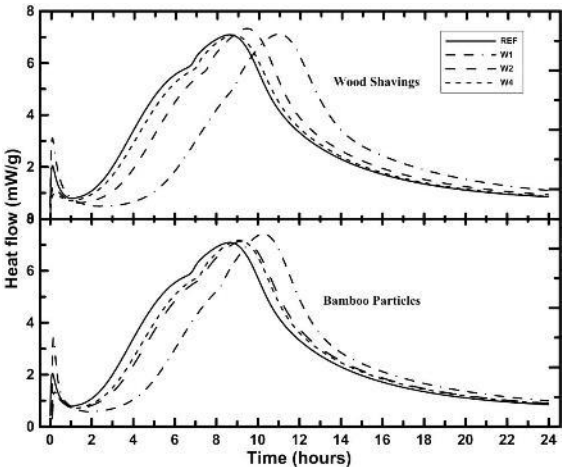


Fig 3: Heat flow vs time curves of the cement paste containing bio-aggregates waste water

According to Fig. 3, for both bamboo and wood, all the waste waters presented delay when compared with the reference. W1 presented a highest delay, and that delay decreased as long as the washing was done. As the fourth waste water was the closest to the Reference, it was decided to wash the BA three times.

2.3 Bio-concretes

Two families of bio-concretes, hand-compacted wood bio-concrete (WBC) and workable bamboo bio-concrete (BBC), were produced by using cement paste and the bio-aggregates. The main differences between the families are the biomass, and also the molding method. The WBCs were fabricated with the cement-to-biomass ratios (c/b) of 0.5 and 2.5, while the BBCs were manufactured with c/b of 2.5 and 3 (Table 1). Moreover, with the purpose of providing the required consistence at the fresh state to the BBC, a viscosity modifying agent (VMA) named Rheomac UW 410 was used, while calcium chloride CaCl2 was incorporated in the WBC as setting accelerator.

Table 1: Nomenclature of the bio-concretes based on the cement weight

	WBC 0.5	WBC 2.5	BBC 2.5	BBC 3
BA	2	0.4	0.4	0.33
Cement	1	1	1	1
Water	0.4	0.4	0.4	0.4
$CaCl_2$	0.03	0.03	-	-
VMA	-	-	0.125%	0.125%

The bio-concretes were produced in a 5L mixer under lab-conditions at a controlled temperature of 21± 1 ºC.

Wood bio-concretes production

The WBCs were produced with wood shavings in saturated superficially dry conditions. In fact, the wood shavings were previously immersed in water for 24 hours, and air dried during 30 minutes before the WBC casting. Next, they were gradually added to the cement paste (cement + water + $CaCl_2$) and the whole mixed for 4 min.

The fresh bio-concretes were moulded in three layers suavely hand compacted with 15 blows of a metal rod, and vibrated on a vibratory table (68 Hz) during 30 seconds.

Bamboo bio-concretes production

Contrary to the WBCs, the BBCs were produced with dry bio-aggregates. The bamboo particles and the cement were first homogenized, and the total water was gradually added during 2 min. The total water is composed by the nominal free water needed to hydrate the cement and an additional amount of water that depends on the water absorption capacity of the biomass. Next, 0.125% (by cement weight) of VMA was added at the 5th min. The mix continued until reach 8 min of total time.
The fresh composites were moulded in three layers. Each layer was vibrated mechanically on the vibratory table during 10 seconds.

After their production, the bio-concretes were kept in the molds, protected to the humidity and demolded after 24h. Next, the specimens were introduced and cured into a vapour chamber at 20 ± 3°C and 95 ±2% RH until 28 days of old.

2.4 Characterization tests

The compressive tests were realized on four samples per bio-concrete using the universal testing machine Shimadzu-1000 kN, at the speed of 0.3 mm/min. The compressive strength was determined according to Brazilian standard ABNT NBR 5739 - 2007.

The capillary water absorption test and the drying shrinkage were carried out on all the bio-concretes according to the standards ABNT NBR 9779 [25] and ASTM C157 [26], respectively. The capillary test consisted of measuring the rate (sorptivity) at which water is drawn into the pores of the bio-concretes. For each bio-concrete, three cylindrical specimens (diameter 50 mm - height 100 mm) were produced. After curing, the specimens were dried at 105°C in a ventilated oven until mass constancy. Then, their lateral surfaces were coated with aluminium tape in order to guaranty unidirectional water ascension and avoid humidity loss. The exposed surface was immersed in 5 ±1 mm of water and the mass of the specimens was recorded until 28 days after the initial contact with water.

The drying shrinkage test consisted of determining the length and mass changes that occurred by moisture loss, when the specimens were exposed to relative humidity lower than their internal humidity. Three prismatic moulds of dimensions 285 x 75 x 75 mm^3 were used per bio-concrete. The specimens were cast with gage studs distant of 250 mm and mounted in the central holes of the 75 mm square sides. At the end of the curing period, an initial comparator reading of length and mass variations was taken, and the measures were done at different ages as follows: every 24 h during the first 10 days, every 48 h until 20 days, and finally every 4 days, till 50 days. The length variation and the mass loss were measured with digital length comparator and balance, respectively. The specimens were stored in air into a drying room, maintained at a temperature of 23 ± 2° C and a relative humidity of 60 ± 2%.

Accelerated aging tests were performed on the WBC 2.5, for presenting the highest compressive strength. Therefore, WBC 2.5 samples were submitted to 5, 10 and 15 wetting and drying cycles followed by uniaxial compressive test. Four cylindrical samples of diameter 50 mm and height 100 mm were used per cycle. For the drying cycles, a forced air flow chamber (FALC) of temperature of 36 ± 1ºC and wind velocity of 0.5 m/s was used. That chamber was designed in order to allow the control of the wind velocity and air temperature enabling a simulation of the environmental conditions to which the material can be subjected in real life [Silva 2009]. In order to define the required time of wetting and drying by cycle, a sample was completely saturated in water at 23ºC and left to dry in the FAFC according to the recommendation of [Silva 2009]. After 24 hours of water immersion, the sample absorbed about 85% of its total saturation capacity and after 24 hours it lost about 80% of the gained mass. Therefore, a 2 days cycle was chosen (24h immersed in water followed by 24 hours of drying under the FAFC condition). The compressive tests were performed using the testing machine Shimadzu UH-F1000 kN, at the speed of 0.3 mm/min.

3 RESULTS AND DISCUSSIONS

3.1 Density

The densities of the bio-concretes are listed in Table 2.

Table 2: Density of the bio-concretes

	WBC 0.5	WBC 2.5	BBC 2.5	BBC 3
Density (g/cm^3)	0.70	1.10	1.08	1.19

From the results, it can be observed that the bio-concretes can be classified as lightweight according to the RILEM functional classification (1978). WBC 0.5 showed the lowest density, while BBC 3, the highest. The increase of biomass leads to a decrease of the bio-concrete density. When comparing the densities of WBC 2.5 and BBC 2.5, one presented a higher density probably due to its hand compaction during the molding.

3.2 Compressive strength

The compressive strength values obtained after 28 days are summarized in Table 3.

Table 3: Compressive strength and variation coefficient in brackets

	WBC 0.5	WBC 2.5	BBC 2.5	BBC 3
fc_{28} (MPa)	0.44 (6.32)	9.45 (0.98)	2.57 (0.5)	4.20 (6.5)

According to the results, WBC 2.5 presented the highest strength while, as expect WBC 0.5 the lowest. Although BBC 3 was the bio-concrete with highest cement content, its strength was 55% lower than that of WBC 2.5. This result can be justified by the combined effect of the hand compaction used to produce the wood bio-concrete, and the use of setting accelerator. BBC 3 presented strength 39% higher than BBC 2.5, which strength was 5 times higher than WBC 0.5.

3.3 Capillary absorption

Capillary water absorption results of all bio-concretes after 28 days of testing are presented in Fig. 4 and Table 4. It can be observed that WBC 0.5 showed the highest absorption, and this behaviour could be expected since WBC 0.5 content more bio-aggregates. WBC 0.5 absorption curve can be divided into two distinct stages: initial sorptivity (S1) which took place during first the 24 hours ($h^{0.5}$ = 4.90) and secondary sorptivity (S2) which occurred from day 1 onwards. The initial and secondary sorptivities are characterized by the filling of big and fine capillary pores, respectively. According to Table 2, the initial sorptivity was 40 times above the secondary and the absorption just increase of 14% during the whole secondary sorptivity. This behaviour was due to the elevated amount of WS, which created a high porosity in the WBC, and consequently fast saturation.

Table 4: Capillary water absorption and sorptivity

		WBC 0.5	WBC 2.5	BBC 2.5	BBC 3
Capillary absorption (g/cm^2)	**1 day**	2.99	1.07	2.10	1.42
	28 days	3.35	2.72	2.77	2.15
Sorptivity (g/cm^2.h$^{0.5}$)	**S1**	0.463	0.142	0.35	0.30
	S2	0.011	0.04	0.015	0.012

WBC 2.5 initial sorptivity occurred during the first 168 hours ($h^{0.5}$ = 12.96), while the secondary took place from day 7 onwards. When compared to WBC 0.5, WBC 2.5 showed an initial sorptivity 3 times lower while its secondary sorptivity was 3 times higher. This suggests that the addition of cement paste reduced the presence of big pores in the bio-concrete, which are responsible for rapid absorption, according to [Gupta 2018].

The initial sorptivities of BBC 2.5 and BBC 3 were observed during the first 10 and 11 hours, respectively, and BBC 2.5 presented a sorptivity 30% higher than BBC 3. As observed with the WBC, the bio-concrete of high bio-aggregate content presented the higher sorptivity. Comparing BBC 2.5 and WBC 2.5, BBC 2.5 showed a faster absorption during the first 16 days. After 16 days, both presented similar trend. This phenomenon can be explained by the different absorption rate of the wood shavings and the bamboo particles, and also the amount of pores in the bio-concrete.

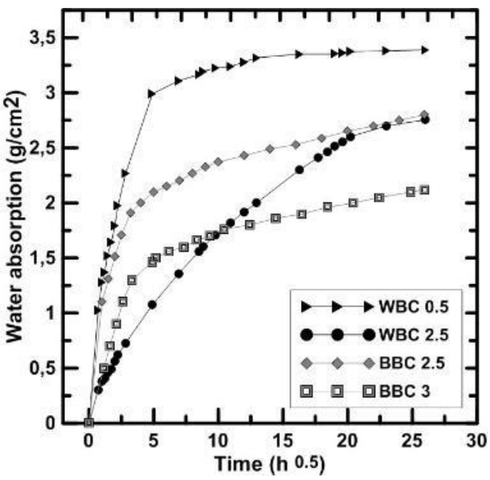


Fig.4: Water capillary absorption vs square root of time

At the end of the test, it was observed (Fig. 5) the presence of white mold on top of the WBC 0.5, probably due to the high humidity in the sample, combined with the lack of ventilation within.

Fig. 5: Top of the WS 0.5 Samples after capillary test

3.4 Drying shrinkage

The evolution of the bio-concretes shrinkage after 52 days of drying is illustrated in Fig. 6. It can be seen that WBC 0.5 showed the highest shrinkage. As observed by [Bederina 2012], the shrinkage rose by increasing the quantity of wood shavings in the mixture. After one day of measurements, the WBC 0.5 presented a length variation of 2.5 times higher than that of the WBC 2.5, a mass loss 2.6 times higher. The same trend was observed after 5, 10, 15 and 50 days of test where the length variation and the mass loss of WBC 0.5 were in average 1.8 and 2.4 times higher, respectively.

The higher shrinkage of the WBC 0.5 can be explained by the increase of the porosity due to its elevated wood content. According to [Bederina 2007], the total porosity of the WBC is constituted by the porosity of the wood itself and the porosity induced by the wood in the matrix. Drying shrinkage is also linked to the amount of water lost from the specimen to the external environment.

The bamboo bio-concretes presented a similar behaviour with that of wood. BBC 2.5 showed a higher mass loss and drying shrinkage. They showed around -25% of mass loss after 50 days, and shrinkage about -5300 µε. Because of their higher porosity provided by the molding method, they presented a higher mass loss and shrinkage than WBC 2.5.

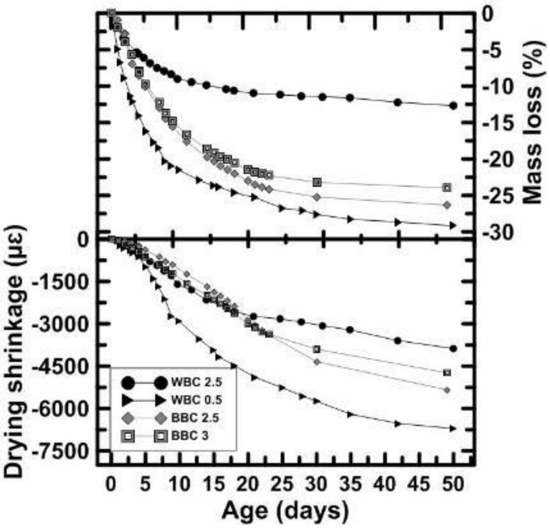


Fig. 6: Drying shrinkage results of WBC and BBC

3.5 Wetting and drying cycle

Figure 7 presents the compressive strengths obtained after the wetting and drying cycles of the WBC 2.5. The results revealed that the strength was significantly affected by the 5 first cycles (20% of loss). From the 5th to the 10th cycle, the loss was 8% and from the 10th to the 15th, 5%. This suggests that the more cycles would affect less the WBC strength.

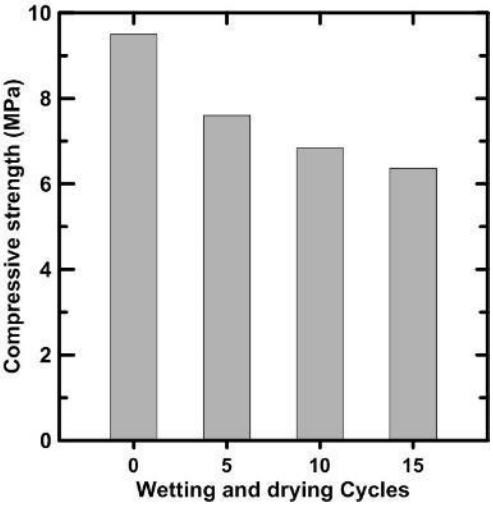


Fig. 6: Compressive strength after accelerated aging cycles of WBC 2.5

4 CONCLUSION

Based on the results obtained herein, the following main points can be remarked:

- The isothermal calorimetry confirmed that hot water washing was efficient to remove water-soluble extractives of the biomass;

- The bio-concretes produced presented lightness and mechanical strength that showed possibilities of different application in building.

- Concerning the water capillary absorption, the results showed that the porosity increased according to the quantity of wood or bamboo. In bio-concrete with the highest biomass amount (WBC 0.5), it was observed a fast absorption in the initial stage that lead to a fast saturation. The mold that appeared on the WBC 0.5 after 50 days of capillary test demonstrated that it cannot be used alone in humid environment. This problem can be resolved by coating the WBC, or introducing it as cores into a sandwich system

- The bio-concretes presented the same trend observed in the drying shrinkage, where the materials with high biomass content showed the highest shrinkage and mass loss. They presented a range of shrinkage equivalent to a dimensional variation of 3 to 6 mm/m.

- The capillary absorption and the drying shrinkage results were highly influenced by the molding method of the two bio-concrete families and biomass content.

- The accelerated aging showed that WBC 2.5 is more affected by the first 5 wetting and drying cycles. After 15 cycles, the strength loss was 33%.

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