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LIGNOCELLULOSIC COMPOSITES FROM BRAZILIAN GIANT BAMBOO (GUADUA MAGNA). PART 2: PROPERTIES OF CEMENT AND GYPSUM BONDED PARTICLEBOARDS

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ABSTRACT

In the first part of this study, the feasibility of manufacturing resin-bonded particleboard from the recently identified Brazilian giant bamboo (*Guadua magna*) was evaluated. In this second part, the main goal was to study the material properties of the cement and gypsum-composites made from that bamboo species. The effect of $CaCl_2$ addition in the physical and mechanical properties was also evaluated. Initially, the hydration test was performed to determine the inhibition index of the bamboo particles in the cement and gypsum setting. Three concentrations of $CaCl_2$ were used to produce bamboo cement-bonded particleboards (BCBP): 0%, 2% and 4%. $CaCl_2$ was not added into bamboo gypsum-bonded particle boards (BGBP). Mechanical and physical properties were evaluated and nondestructive testing was performed as well. The inhibition index of *Guadua magna* in the cement or gypsum setting was classified as "low inhibition". The addition of $CaCl_2$ at bamboo-cement boards increased the internal bonding and reduced the water absorption. Other properties were not significantly affected. The bamboo-cement boards presented higher bending strength and lower moisture content than bamboo-gypsum boards.

Keywords: Bamboo; cement; gypsum; inhibition; mineral-bonded composites.

INTRODUCTION

Inorganic bonded wood composites are usually made with a mixture of wood particles, mineral binder, additives and water. The most common mineral component is the cement and the setting process results in heat release due the hydration of cement in the presence of water (Iwakiri and Prata 2008). These panels can be used in many kinds of constructions (Falk 1994). Furthermore, the basic concept of production of these panels can be applied for producing shingles, blocks and bricks.

These composites have some advantages in comparison with resin-bonded composites: fire and biological resistance, high durability, good dimensional stability and low production cost (Del Menezzi *et al.* 2007, Falk 1994, Moslemi 1988). Besides, mineral composites generally use solid wood waste or other lignocellulosic material, including agricultural wastes. For this reason, these panels occupy a special place in the new eco-friendly economy as they provide for energy saving, conservation of natural resources and reduction in environmental pollution (Sudin and Swamy 2006).

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The increase in demand for raw material to manufacture wood composites, cellulose and paper have motivated many researches about the potential substitutes or complements for wood from planted and native forests (Papadopoulos *et al.* 2006). Therefore, there are many studies with bamboos species due to their good physical characteristics, low production cost. Additionally, it is probably the fastest-growing and highest-yielding natural resource and construction material available to mankind (Beraldo and Rivero 2003, Sudin and Swamy 2006). In addition, bamboos are widely distributed in the world especially in tropical and subtropical zones of Asia and some countries of Latin America (Beraldo and Rivero 2003).

In our previous study (Arruda *et al.* 2011) technical feasibility of manufacturing resin-bonded particleboard from the newest discovered Brazilian bamboo species *Guadua magna* (Londoño & Filg.) was evaluated. *G. magna* features characteristics such as 12.6-23.4 m of height and 6 - 12 cm of diameter and potential for applications in civil engineering, housing, furniture, general farm uses, etc. In rural localities of occurrence, it is traditionally used to build rustic homes, and other farm constructions, such as barns, fences, etc. (Filgueiras and Londoño 2006).

Some problems are reported in the literature regarding the utilization of bamboo into a matrix of mineral composites. Major problems are the inhibitory effect caused by bamboo on the cure of cement. Bamboo has in its composition sugars, starch and phenolic compounds all of which have a profoundly adverse effect on the setting and strength development of the Portland cement matrices (Sudin and Swamy 2006).

To solve this problem it is a common technique adding inorganic chemical additives in order to accelerate the cure of cement or use some pretreatments on the particles to remove inhibitory substances (Latorraca 2000). The accelerators mineralize the particles and neutralize the inherent substances of wood or bamboo that contains the inhibitory effect of the cure of the cement (Dix 1989). The principal accelerator used for decades is the $CaCl_2$ (calcium chloride) because is an efficient accelerator of calcium silicate hydration and has low production cost (Latorraca 2000).

This research aimed at determining the technical feasibility of using particles of *Guaduamagna* (Londoño & Filg.) to produce mineral composites bonded with cement and gypsum and study the effect of $CaCl_2$ addition in physical and mechanical properties of these composites.

MATERIALS AND METHOD

Cement or gypsum hydration test

The reaction of cement or gypsum with water releases heat in an exothermic reaction and monitoring this heating loss can be used as a parameter to evaluate the inhibition index of cement and gypsum with bamboo (Latorraca 2000). In determining the inhibition index, an experiment was proposed according to Hofstrand *et al.* (1983), recently applied by Okino *et al.* (2005) and cited by Papadopoulos (2007). The bamboo particles were ground milled and screened in 60 mesh sieves and then mixed with cement or gypsum in a thermocouple in the following proportion: 15 g of bamboo powder (60 mesh), 200 g of cement or gypsum and 90.5 ml of water. Two replicates were prepared for each mixture of bamboo particles and mineral agglutinant and one for the neat cement to determine the inhibition index of the cement or gypsum.

The temperature was recorded by inserting a type J thermocouple, connected to a data logger, into the neat cement or the mixture. The data were recorded at intervals of one minute during 24 hours. The inhibition index (I) was calculated according to equation 1. The effect of hydration of the cement was classified according to table 1.

$$I = \left[\frac{(Tc - Tm)}{Tc} x \frac{(Hm - Hc)}{Hc} x \frac{(Sc - Sm)}{Sc} \right] x100 \quad (1)$$

Where:

Tc	=	Maximum temperature of neat cement or gypsum, (°C)
Tm	=	Maximum temperature of the cement or gypsum-water-bamboo mixture, (°C)
Hc	=	Time to reach the maximum temperature of neat cement or gypsum, (h)
Hm	=	Time to reach the max. temperature of cement or gypsum-water-bamboo mixture, (h)
Sc	=	Hydration ratio of neat cement or gypsum, (°C/h)
Sm	=	Hydration ratio of cement or gypsum-water-bamboo mixture, (°C/h)

Table 1. Classification of the lignocellulosic material according to the inhibition index.

Inhibition Index (%)	Classification
I < 10	Low inhibition
10 < I < 50	Medium inhibition
50 < I < 100	High inhibition
I > 100	Very high inhibition

Source: Okino *et al.* (2004)

Particles preparation and board manufacture

The culms of bamboo were obtained in the state of Goiás, Brazilian Central-Western region. Initially, they were pretreated in cold water (room temperature) for one week to remove inhibitory substances (starch and sugar), and then processed into particles according to Arruda *et al.* (2011). Three concentrations of $CaCl_2$ were evaluated to produce bamboo-cement boards: 0%, 2% and 4% (based on the dry weight of the cement in the mixture). $CaCl_2$ was not added to the bamboo-gypsum boards, given that the hydration test indicated that the hydration of gypsum was not affected by the addition of bamboo. Three replications were manufactured for each treatment, resultingin12 boards, with dimensions of 300 mm x 300 mm x 12.5 mm (w x l x t). The bamboo: cement or gypsum ratio used was 1:2.75 and the water: cement or gypsum ratio was 1:2.5. The target density was 1.25 g/cm^3. The particles were wetted with a mixture of water and additive, and then the inorganic materials (cement or gypsum) were added. The mat was pressed at 3.0 N/mm^2 using a hydraulic press for 24 hours at room temperature. Subsequently, boards were conditioned at (22±2)°C and (60±2)% relative humidity for 28 days to allow the complete cement and gypsum setting.

Board Properties and Statistical Analysis

The boards were trimmed and five samples measuring 50 mm x 200 mm (w x l) were cut for static bending testing (modulus of elasticity, E_M and modulus of rupture, f_m). After testing, the samples were cut into specimens of 50 mm x 50 mm to evaluate internal bonding (IB), thickness swelling (TS, 2h and 24h), water absorption (WA, 2h and 24h), moisture content (MC) and density (D). The samples were tested according to NBR 14810-3 (ABNT 2002).

Nondestructive evaluation of the samples was assessed by using Metriguard 239A Stress Wave Timer (SWT) equipment. This technique takes a wave produced by an impact in one side of the material, which travels along the length of the sample to reach an accelerometer at the other end. The time to reach this distance is displayed in the SWT device and used to calculate the stress wave velocity (v_o). This unit (v_0) in addition to the materials density and acceleration due to gravity were used to determinate the dynamic modulus of elasticity (E_d) according to Souza *et al.* (2011).

The results obtained were subjected to an analysis of variance (ANOVA) at 5% significance level to identify significant differences. Fisher LSD test (Least Significant Difference) evaluated the means differences among treatments by pair wise comparisons, based on estimated marginal means and Tukey test at 5% significance level. One model was tested to evaluate NDT variable to estimate mechanical properties (E_M and f_m) from E_d and v_0.

RESULTS AND DISCUSSION

Effect of bamboo on hydration of cement and gypsum

The inhibition index of bamboo *Guadua magna* with cement was 10.1% and may be considered low. This low inhibition of bamboo *Guadua magna* can be explained by the removal of inhibitory substances in the pretreatment with water. This value is consistent with the ones obtained by Ma (2005), for the bamboo *Phyllostachys heterocycla*, which presented inhibitory indices of 6% and 9% after treatments of extraction with hot water and cold water, respectively. Jorge *et al.* (2004) mention that just cold water treatment (at room temperature) was enough to several hardwood species to improve compatibility. Papadopoulos (2007) reported for eight Greek wood species, inhibition indexes from 7.44% for poplar to 52-57% for beech and cypress.

In the present study, the addition of bamboo resulted in reduction in hydration ratio, in maximum hydration temperature (MHT) and increased the maximum hydration time to reach MHT. In cement mixed with bamboo the MHT reduced from 51°C to 34.9°C and the time to reach MHT increased 38% (Figure 1) and the hydration ratio reduced abruptly as much as 84.4%, from 5.21°C/h to 0.81°C/h.

The inhibition index of bamboo with gypsum was very low, 1.2%, indicating that the hydration of gypsum was not affected by the addition of bamboo. The MHT increased slightly with addition of bamboo from 43.6°C to 45.7°C, and the time to reach MHT increased, from 1.17 hours to 1.63 hours (Figure 2). Inversely, hydration ratio of gypsum increased from 19.6°C/h to 31.7°C/h. The effect of bamboo on hydration curve of gypsum was not similar to the effect on cement hydration.

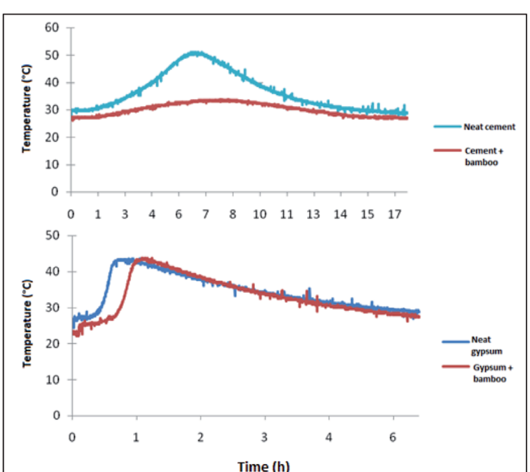

Figure 1. Hydration curve over the time of cement (a) and gypsum (b) mixtures.

Density of the boards

Table 2 shows the results for density in each treatment. The bamboo-cement board with 4% of $CaCl_2$ reached the highest density, 1.24 g/cm^3, and bamboo-gypsum without $CaCl_2$ the lowest, 1.17 g/cm^3. According to table 2, density was not significantly different between bamboo-gypsum and bamboo-cement boards without additive (1.17 g/cm^3 and 1.18 g/cm^3, respectively), taking in account only the type of binder.

Table 2. Density means for bamboo-cement and bamboo-gypsum composites.

Treatment $CaCl_2$	Density (g/cm^3)	CV (%)[1]
Bamboo-gypsum 0%	1.17 ^{A}	3.74
Bamboo-cement 0%	1.18 ^{A}	4.15
Bamboo-cement 2%	1.22 ^{B}	1.34
Bamboo-cement 4%	1.24 ^{C}	1.98
Structural board type HZ[2]	1.20	-

[1]Coefficient of variation. [2]Cement-wood composites according to Bison (1978). Different letters in the same column indicate significant differences by the Tukey´s test at 5% significance level.

The results are closed to the value proposed by Bison (1978) for a structural board type HZ. Boards type HZ are resistant to fungi, termites, fire and weathering, and have also good mechanicals properties. The methodology adopted by Bison (1978) is pioneer in producing mineral composites and for this reason is used in comparisons in literature (Okino *et al.* 2004). In boards with cement, the addition of $CaCl_2$ increased the density.

Effect of addition of CaC_{l2} in bamboo-cement boards

To evaluate exclusively the effect of addition of $CaCl_2$ (0%, 2% and 4%) in bamboo-cement boards, given the significant difference among boards means, the values of mechanical and physical properties were estimated by the ANCOVA taking density as covariate to estimate the properties (Table 4).

The results in table 3 show that the addition of $CaCl_2$ increases the moisture content (MC). The MC increased from 7.92% in bamboo-cement with 0% $CaCl_2$ to 10.5% in bamboo-cement with 4% of $CaCl_2$. This may have occurred due to hygroscopic character of $CaCl_2$, it is also a deliquescent substance has a strong affinity for moisture and absorb relatively large amounts of water from the atmosphere if exposed to it, forming a liquid solution. Only the boards without $CaCl_2$ are within the limit of humidity specified by Bison (1978).

Table 3. Physical properties of bamboo-cement boards.

Treatment	MC (%)	TS (%)		WA (%)	
		2h	24h	2h	24h
Bamboo-cement 0% $CaCl_2$	7.92 ^{A}	0.92 ^{A}	0.94 ^{A}	19.32 ^{A}	20.70 ^{A}
Bamboo-cement 2% $CaCl_2$	9.88 ^{B}	0.78 ^{A}	0.87 ^{A}	16.93^{AB}	19.61 ^{B}
Bamboo-cement 4% $CaCl_2$	10.50 ^{C}	1.20 ^{B}	0.92 ^{A}	15.50 ^{B}	19.28 ^{B}
Structural board type HZ[1]	9.0	0.8-1.3	1.2-1.8	-	-

MC=moisture content; TS=thickness swelling; WA=water absorption. [1]Cement-wood composites according to Bison (1978). Different letters in the same column indicate significant differences by the Tukey test at 5% significance level.

In TS 2h, boards with addition of 4% of $CaCl_2$ obtained values 30.4% higher than boards without the chemical additive. After 24 hours, the addition did not affect the TS. However, the addition of $CaCl_2$ reduced the WA, indicating that the effect of the hygroscopicity of $CaCl_2$ is more pronounced on TS. Sudin and Swamy (2006) also experimented using bamboo particles mixed with and without $CaCl_2$ and obtained values of TS slightly higher than those in this study. They also reported values of WA in the range of 24.6% to 26.1%, above the ones observed in the present study.

In cement-wood composites made with *Eucalyptus urophylla* and 4% of $CaCl_2$ as additive, Silva *et al.* (2006) obtained similar values of those from bamboo composites. After 2 hours immersion, TS was 0.68% and 1.49% after 24 hours. These authors observed lower values for WA (5.41% in 2 hours and 8.51% after 24 hours), indicating that cement-wood composites are more resistant to water absorption than bamboo-cement ones.

Table 4 shows the results to mechanical properties of bamboo-cement composites. The IB values are below the minimum required by Bison (1978), 0.40 N/mm^2. The IB ranged from 0.21 to 0.31 N/mm^2, increasing 31% with addition of 2% of $CaCl_2$ and 45.2% with addition of 4% of $CaCl_2$. The IB values for bamboo-cement composites are lower than values obtained for wood-cement composites, possibly due to the higher density of wood species over bamboo, however this study provided boards with higher strength as compared to the values of 0.12 to 0.19 N/mm^2 reported by Sudin and Swamy (2006). Regarding wood-cement bonded composites, Silva *et al.* (2006) reported an IB value of 0.68 N/mm^2 and average density of 1.35 g/cm^3 for composites of *Eucalyptus urophylla* with addition of 4% $CaCl_2$. Iwakiri and Prata (2008) producing similar composites, with *Pinus taeda* reported an IB value of 0.46 N/mm^2 with an average density of 1.19 g/cm^3. It is clear that the addition of $CaCl_2$ did not affect flexural properties.

Table 4. Estimated mechanical properties of bamboo-cement boards.

Treatment	E_M	f_m	IB	E_d	v_0
	-------------------------- N/mm^2			----------------------	----m/s----
Bamboo-cement 0% $CaCl_2$	3,083 ^{A}	7.66 ^{A}	0.21 ^{A}	4,518 ^{A}	1,908 ^{A}
Bamboo-cement 2% $CaCl_2$	3,114 ^{A}	7.91 ^{A}	0.28 ^{B}	4,484 ^{A}	1,902 ^{A}
Bamboo-cement 4% $CaCl_2$	3,022 ^{A}	7.36 ^{A}	0.31 ^{C}	4,339 ^{A}	1,869 ^{A}
Structural board type HZ[1]	3,000	9.0	0.40	-	-

E_M = modulus of elasticity; f_m = modulus of rupture; IB = internal bond; E_d= dynamic modulus of elasticity; [1]Cement-wood composites according to Bison (1978). Different letters in the same column indicate significant differences by the Tukey´s test at 5% significance level. v_0 = stress wave velocity.

The values of the flexural properties are within a range usually encountered in the literature. Compared with Sudin and Swamy (2006), that reported maximum value of 5.48 N/mm^2 for modulus of rupture on boards of bamboo with and without $CaCl_2$, the strength of the boards of this study were superior, in the range of 7.36 to 7.91 N/mm^2. Silva *et al.* (2006) and Iwakiri and Prata (2008) reported for wood-cement composites values to E_M (3,224 N/mm^2 and 4,290 N/mm^2) and fm (20.75 N/mm^2 and 9.41 N/mm^2). The modulus of rupture of the treatments did not reach the minimum value required specified by Bison (1978), 9.0 N/mm^2. On the other hand, all treatments reached the minimum required (3,000 N/mm^2) to modulus of elasticity.

The E_d values determined using NDT methods are usually higher than E_M. Targa *et al.* (2005) suggest that it occurs due to viscoelastic behavior of wood, and it is a negative point of the nondestructive evaluation. However, NDT assessment provides a quickly evaluation of quality control of the panels (Ross and Pellerin 1988) and can be used to estimate static bending properties.

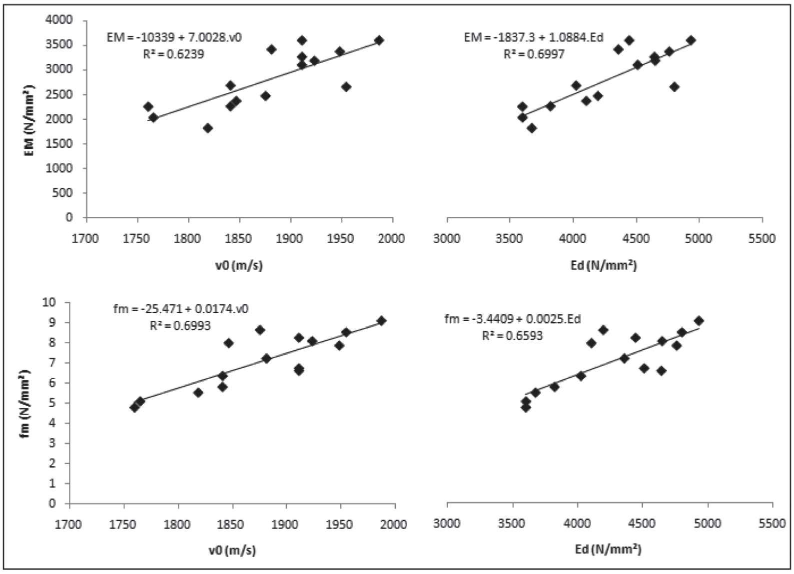

Figure 2. Simple linear regression to estimate flexural properties of bamboo-cement board (0% $CaCl_2$) using stress wave method.

Using linear regression models to estimate E_M and f_m from E_d and v_0, only the treatment without additive had acceptable coefficient of determination (R^2) i.e., $R^2 > 0.60$. In treatments with addition of $CaCl_2$, E_d and v_0 did not present a significant relationship with E_M or f_m. Figure 2 shows the regressions of bamboo-cement 0% of $CaCl_2$. With relation to stress wave velocity, the values reduced as the addition of $CaCl_2$ increased

Effect of mineral binder

In physical properties, gypsum provides an increasing in MC, TS 24h and WA 2h and 24h (Table 5). In TS 2h, the values are not significantly different. The MC of bamboo-gypsum boards was almost two fold the MC of bamboo-cement boards. In addition, gypsum increased in 15% the TS 24h, 9.67% the WA 2h and 10.81% the WA 24h. This probably occurred because gypsum is more hygroscopic than cement. Haselein *et al.* (2002) observed that the addition of lignocellulosic materials to gypsum reduces WA and increase the TS.

Table 5. Observed physical properties of bamboo-gypsum and bamboo-cement boards.

Treatment	MC (%)	TS (%)		WA (%)	
		2h	24h	2h	24h
Bamboo-gypsum 0% $CaCl_2$	15.40 ^{A}	0.93 ^{A}	1.07 ^{A}	21.53 ^{A}	24.18 ^{A}
Bamboo-cement 0% $CaCl_2$	7.83 ^{B}	0.97 ^{A}	0.93 ^{B}	19.63 ^{B}	21.82 ^{B}

TS = thickness swelling; WA = water absorption. Different letters in the same column indicate significant differences by the Tukey´s test at 5% significance level.

In static bending, only f_m values were significantly different (Table 6). The bamboo-cement boards were more resistant than bamboo-gypsum, whose values were 7.13 N/mm^2 and 5.0 N/mm^2, respectively. The IB was very similar in cement and gypsum boards (0.21 N/mm^2x 0.20 N/mm^2). Haselein *et al.* (2002) studied gypsum-wood composite with *Pinus elliottii* and obtained an f_m value slightly lower than bamboo-gypsum composite. When scraps of paper reinforced these gypsum-wood composites, the f_m increased in 102% (from 4.13 N/mm^2 to 8.35 N/mm^2).

Table 6. Observed mechanical properties of bamboo-gypsum and bamboo-cement boards

Treatment	E_M	f_m	IB	E_d	v_0
	------------------------- N/mm^2 -----------------------				---m/s---
Bamboo-gypsum 0% $CaCl_2$	2,655 ^{A}	5.00 ^{B}	0.20 ^{B}	4,435 ^{A}	1,924 ^{A}
Bamboo-cement 0% $CaCl_2$	2,812 ^{A}	7.13 ^{A}	0.21 ^{A}	4,272 ^{A}	1,878 ^{B}

E_M = Modulus of Elasticity; f_m = Modulus of Rupture; IB = Internal Bond; E_d = Dynamic Modulus of Elasticity. Different letters in the same column indicate significant differences by ANOVA at 5% significance level.

In table 6, E_d overestimated the EM in 67% to bamboo-gypsum boards and in 51.9% in bamboo-cement boards. The values are not significantly different, but E_d in gypsum was higher than in cement boards. This is directly correlated to the highest value obtained by the v_0 in gypsum boards. This independent variable had low correlation with f_M and E_M. Otherwise, E_d had good correlation with E_M and f_M, especially in gypsum boards, $R^2 = 0.75$ (Figure 3).

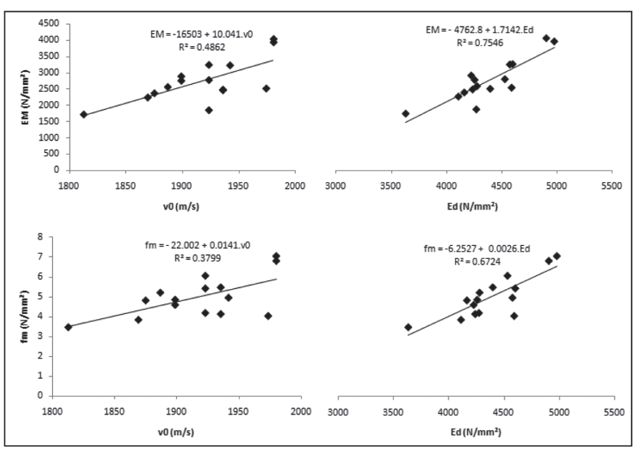

Figure 3. Linear regressions of bamboo-gypsum 0% of $CaCl_2$

CONCLUSIONS

According to the hydration test, the inhibition index of *Guadua magna* in cement and in gypsum was classified as "low inhibition", although this value for gypsum is almost insignificant. The addition of $CaCl_2$ to bamboo-cement boards increased the IB and reduced the WA. Other properties were not affected significantly. The bamboo-cement boards were more resistant in fm and had lower MC than bamboo-gypsum boards. In general, *Guadua magna* is suitable to produce cement and gypsum composites, although some aspects still need to be studied: the influence of particle size; others chemical additives and their proportions; and addition of other lignocellulosic materials, such as wood.

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