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REGULAR ARTICLE

Gypsum-based composites reinforced with bamboo particles

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Abstract

This study aimed to evaluate the quality of gypsum-based mineral composites reinforced with bamboo particles. The particles size was 1.68 mm and 0.841 mm. The density adopted for the composites was 0.80 g/cm³. The following weight replacement ratios were adopted: 0; 2.5; 5.0; 7.5 and 10.0%. The water/solid mass factor of the composite remained constant. For each treatment two slabs of composites were produced. Physical and mechanical properties were determined: humidity, apparent density, water absorption (2 and 24 hours), modulus of rupture, modulus of elasticity and compression. The results showed that the apparent density and moisture content of the composites were not influenced by the insertion of the bamboo particles, while the water absorption was significantly reduced. The addition of the bamboo reinforcement particles did not cause improvements in the MOR and MOE properties, but all the MOR values of the treatments reached the value established by EN 13279-2 (EN, 2004). Although all treatments have reached the minimum values stipulated by the standard for compressive strength, all values were reduced with the insertion of bamboo particles. In general, the *Dendrocalamus giganteus* can be used as reinforcement in gypsum composites, however new parameters should be tested, such as: particle size; increasing the proportions of particles, pre-treatment of particles, addition of other additives, such as superplasticizer to water to improve workability and even use more than one reinforcement to obtain composites with improved properties.

Keywords

Biomass; Fiber reinforced gypsum; Physical properties; Mechanical properties; Chemical analysis.

Introduction

Gypsum is a material widely used as a matrix in composites because of its advantages such as: installation speed, ease of molding and excellent finish (Pinto et al., 2016), in addition to the small shrinkage by drying, great thermal and acoustic properties and fire resistance (Sophia et al., 2016). However, it has several limitations, such as high permeability to water, porous nature, low compressive strength and low flexural and tensile strength, for these reasons are indicated to be used only indoors (Sophia et al., 2016), in addition to fragility to rupture.

Considering these characteristics, it became important to improve the low resistance of gypsum by adding a material in the form of fibers in the matrix (binder) and to develop more resistant products. The fiberglass appeared for the first time in plaster, and several studies showed that the materials of plaster reinforced with synthetic fiber had good mechanical resistance, but the cost was high, and the plates were considerably heavier, which reduced the practicality of the product. Moreover, they could have a toxic effect for the environment. In function of these facts the scientists look for another material that could substitute this type of reinforcement, as for example, the vegetable fibers (Wu, 2009; Colak, 2006; Aizi & Kaid-harche, 2020).

Plant fibers are environmentally friendly, renewable, and fully recyclable materials [Jó'zwiak-Nied et al., 2020]. They are used as a reinforcing element so that products have good mechanical properties, including crack reduction and speed of failure propagation. The specific mechanical properties, such as specific tensile modulus and other specific properties of natural fiber, provide a satisfactory result for composites compared to synthetic fiber-based composites (Lokesh et al., 2020).

The advantages of using natural fibers include strength, easy availability, non-corrosive nature, low density, low cost, good thermal properties, weight and biodegradability. In general, the properties of a composite material result from the combination of several factors: fiber length; fiber architecture;

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the fiber orientation and the fiber-matrix interface (Aizi & Kais-Harche, 2020).

Among the natural fibers, bamboo has attracted great interest as a promising reinforcement for different matrices due to its good physical and mechanical properties. They are perennial grasses, which have a woody trunk and occur naturally in most tropical regions of the world. There are more than 1200 species of bamboos, which can occupy many different habitats (Guerra et al., 2016).

They can be used in different ways, such as the manufacture of furniture, masonry, flooring, linings, brises, pergolas, food, fabrics, panels, energy generation in the industrial sector, etc. (Souza et al., 2020). Barbalho et al. (2019) highlights that the use of this grass in various areas of Engineering is an alternative for global development, due to its excellent capacity to sequester carbon, great resistance, light material, versatile and with good technological characteristics that enable various forms of natural or processed applications. According to Silva et al. (2012) in the plaster matrix, bamboo has the same behavior observed in concrete composites.

There are several works already published using bamboo as reinforcement, testing several variables, in different matrices. Some examples are mentioned, such as: Ahmad et al. (2015) produced high-performance cementitious composites using inert, microsized and carbonized bamboo particles. In this way, the performance of cementitious composites was evaluated. Three particle concentrations were tested: 0.05%, 0.08%, 0.20% in the composites. The authors concluded that the particles disperse well in the cement matrix and are capable of producing more uniform characteristics in the composites, improving their performance.

Bahari & Krause (2016) verified the production potential of polyvinyl chloride (PVC)-based composites with particulate filler from Malaysian bamboo species (*Bambusa vulgaris* and *Schizostachyum brachycladum*) and tested their properties. Different sizes of bamboo particles (75 µm and 1 mm) were tested in different proportions (25 and 50%). The results show that the use of bamboo will not only serve as an alternative to composites but will also expand the commercial use of bamboo and the development of cleaner, more environmentally friendly products.

Tan et al. (2019) tested polypropylene composites reinforced with bamboo particles from different fractions of culms. The results indicated that green bamboo particles from processing waste can be used in high-value composites.

Pang et al. (2022) evaluated the performance of composites produced with rice straw and bamboo particles. The particles were sprayed with MDI and lignin-based adhesives. The authors generally concluded that composites based on rice straw and bamboo particles can be used to produce furniture, packaging, among others.

The bamboo fiber reinforced composites are considered to have greater environmental friendliness than any other synthetic fiber reinforced composite (e.g. glass fiber) and provide less impact to the environment, the same performance for similar fiber content and allow reduced use of toxic base polymers (Ramesh et al., 2021).

The use of this raw material is an economical and advantageous solution, considering that bamboo has high productivity, low cost and fast growth. The proposal of this study is to use these bamboo fibers as reinforcement in gypsum composites, and thus provide results that can expand the scientific database about these materials. In this sense, the objective of this work was to evaluate the quality of gypsum-based mineral composites reinforced with bamboo particles.

Materials and methods

Origin and collection of materials

For the production of the matrix, the fine casting gypsum from the Araripe gypsum pole in the state of Pernambuco was used. The gypsum has a fineness modulus of 0.85, apparent specific mass of 0.78 $g.cm^{-3}$, and initial and final setting times of 9 and 22 minutes, respectively.

To produce the bamboo reinforcement particles, the species *Dendrocalamus Giganteus* was adopted. The bamboo stems were selected and collected from an existing plantation on the University *campus* where the present research was developed. The bamboo stems were selected after five years of age, due to their high resistance.

The selection occurred in two clumps randomly with preference given to stalks that did not contain biodeterioration stains (Brito et al., 2018; Garcia et al., 2021). The stalks were cut 30 cm from the base and sectioned into smaller portions to facilitate transport to the laboratory. From the sections, discs were removed, which were wrapped in plastic for determination of physical and chemical analyses of the material.

The stalks were taken to the laboratory of the Experimental Unit of Wood Panels (UEPAM), located at UFLA. The discs were conditioned in an acclimatized room (temperature of 22 ± 2 °C and 65 ± 5% relative humidity), until the humidity stabilized.

Physical and chemical characterization of bamboo

Samples were taken from the bamboo disks for physical characterization (moisture and basic density), which were determined based on the designations of the Brazilian Regulatory Standard - NBR 11941 (ABNT, 2003).

Another fraction of discs was crushed in a hammer mill with the objective of transforming them into sawdust. For the classification of the materials two sieves were used and the material selected for analysis was retained on the 60 mesh sieve. The chemical constituents were analyzed in triplicates. For analysis of the chemical constituents the contents of insoluble lignin were quantified according to the procedures of NBR 7989 (ABNT, 2010), total extractives according to NBR 14853 (ABNT, 2010b) and ashes according to NBR 13999 (ABNT, 2017). The holocellulose content was obtained by the difference method: H (%) = 100 - (Total extractives + Lignin content + Ash).

Production of composites

At first the stem sections were processed into strips, then the strips were reduced to chips and these were processed to obtain particles, with the aid of a high rotation hammer mill. Afterwards, they were classified in a set of vibrating sieves composed with meshes of two sizes: 12 mesh (1.68 mm) and

20 mesh (0.841 mm). The particle fraction used as reinforcement was the one retained on the 20 mesh sieve. In a pilot experiment carried out in the laboratory, it was the particle size that demonstrated the best results, hence the best morphology.

The density adopted for the composites was 0.80 g/cm³. Initially, it was performed the calculation of each of the following components of the composite: gypsum, water and bamboo particles. Five treatments were adopted for the production of the composites, with variation in the percentage of bamboo particles used by weight as reinforcement: 0; 2.5; 5.0; 7.5 and 10.0%.

For each treatment two slabs of composites were produced. The water/gypsum factor varied with each treatment, however, the water/solid mass ratio remained constant. The mass amount of each material for all treatments is described in Table 1 .

Table 1. Mass quantity of materials used.

Treatment (%)	Gypsum (g)	Water (g)	Bamboo (g)	Water/gypsum
0,0	1200	720	0	0,6
2,5	1170	720	30	0,6
5,0	1140	720	60	0,6
7,5	1110	720	90	0,6
10,0	1080	720	120	0,6

The components were weighed on a precision scale and mixed manually until homogenized. Afterwards, the mass of each panel was separated, weighed and distributed in wooden molds (Figure 3) with dimensions of 20.0 x 20.0 x 1.50 cm (length x width x thickness, respectively). Solid Vaseline was used as a release agent.

After 24 hours, the composites were demolded and placed in an air-conditioning chamber (temperature of 20 ± 2 °C and relative humidity of 65 ± 3 °C) until they dried completely in order to remove the samples for the tests that would be performed. The physical characterization of composites was determined by moisture tests, bulk density, and water absorption in 2 and 24 hours. The mechanical tests performed were: compressive strength, modulus of elasticity (MOE) and rupture modulus (MOR) to static flexion. The tests followed the recommendations of BISON. (Bison Wood-Cement Board, 1978).

For the physical and chemical characterization of bamboo descriptive statistics were used. An entirely randomized design (DIC) was adopted for the evaluation of the physical and mechanical properties. The results were analyzed using the F test and, when significant, regression analysis was applied.

Results and discussion

Physical and chemical characterization of bamboo

The basic density of bamboo was 0.30 ± 0.01 g.cm^{-3}. The result was lower than those reported in the literature. Brito et al. (2015) found for *D. giganteus* mean value of 0.66 ± 0.14 g.cm^{-3}. Brito et al. (2020) have worked with *Dendrocalamus asper* and reported a mean value of 0.53 g.cm^{-3} and Garcia et al. (2021) evaluated the same species (*D. giganteus*) and obtained a mean value of 0.61 ± 0.01 g.cm^{-3}. Some factors may influence the basic density of bamboo such as age, anatomical structure, and position of sample removal in the stems. The average value obtained for the moisture content (dry basis) was 4.15% ± 1.11. The moisture content has a decisive relevance for the biological resistance of the stalks and their treatability.

The average holocellulose content obtained for the bamboo (63.03% ± 3.41) was lower than those reported by Brito et al. (2018) who found 68.11 % and Garcia et al. (2021) who obtained an average value of 64.06 %. There is a large amount of free hydroxyls, in materials that have lignin and holocellulose, which are located mainly in the amorphous region of the holocellulose fraction. If there is an increase in the percentages of these materials in the composites, these will show a tendency of higher moisture absorption (Guimarães Júnior et al., 2013).

The total extractive content (11.70% ± 2.11) is between the values reported in the literature. Gomes et al. (2021) obtained an average value of 23.25% and Garcia et al. (2021) found an average content of 6.30%. For the insoluble lignin content, it is noted that the value obtained is also in the range of the results described in the literature. Brito et al. (2018) obtained an average value of 25.59%, Garcia et al. (2021) found 23.89%. The result obtained was higher than that reported by Gomes et al. (2021) who reported an average value of 18.01%.

According to Shiroma et al. (2016) and Weber et al. (2017) higher contents of extractives present in composites can hinder its setting process, due to the slowing of gypsum hydration kinetics and result in an incompatibility between matrix and reinforcement, impairing the strength of the material. For Simatupang and Geimer (1990), Simatupang et al., (1994); Boustingorry et al., (2005) the secondary components can alter crystalline structures of binders, besides retarding the hydration of inorganic binders.

The ash content obtained (0.15% ± 0.04) was lower than the values described in the literature. Brito et al. (2018) obtained an average value of 3.99%. Gomes et al. (2021) found an average content of 0.22%. Bamboo may contain high content of silica and mineral material (Higuchi, 1981). The inorganic components of bamboo can retard the flame in gypsum composites, being inert to the other properties (Selamat et al., 2019).

Physical properties of composites

In Figure 1 it is shown the behavior of the composites' humidity, for each treatment, in relation to the addition of the bamboo particles.

In Figure 1 it can be observed that there was no influence on the moisture content with the insertion of bamboo particles in the gypsum matrix. It was expected that the addition of bamboo particles in the composition would significantly increase the values of moisture content, due to the hydrophilic character of bamboo. Moreover, the fact that the composites have been conditioned in a climate-controlled room with temperature of 20 ± 2 °C and relative humidity of 60 ± 3%, may have contributed to results without significant variations between treatments. The values obtained in this research were similar to those reported by Chinta et al. (2013) and Villela et al. (2020), and lower than those obtained by Lopes et al. (2022).

Chinta et al. (2013) have found values from 0.48 to 1.46% for gypsum composites reinforced with coconut, jute, wool, cotton, and banana fibers. Oliveira et al. (2020) produced composites of gypsum matrix reinforced with fibers of Eucalyptus spp. The proportions used for the incorporation of the reinforcement were 0; 2.5; 5; 7.5 and 10% in substitution to the mass of gypsum by eucalyptus. They obtained average values for moisture between 0.23 and 1.06%. Villela et al. (2020) produced gypsum-based composites reinforced with multilayer packaging, with proportions of 0%, 7.5%, 15%, 22.5% and 30% in gypsum substitution and found average values between 0.34% and 0.86%. Lopes et al. (2022) evaluated the quality of gypsum-based composites reinforced with wood particles and cotton residues. They obtained average moisture content corresponding to 5.32%.

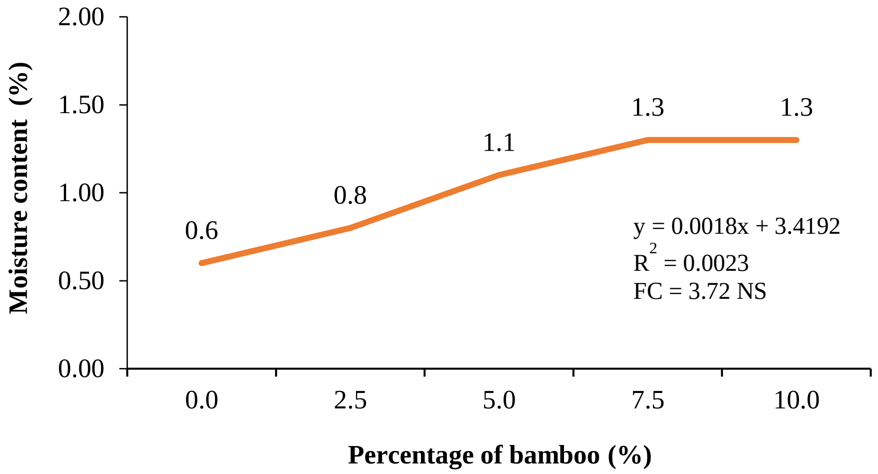

Figure 1. Moisture content of composites, as a function of the addition of bamboo particles. NS = Non-significant relation.

The Figure 2 represents the composites bulk density behavior, for each treatment, in relation to the addition of bamboo particles.

According to Figure 2, it is possible to observe that there was no significant effect on the apparent density, in relation to the insertion of bamboo particles. It was expected that the density of the composites would be reduced with the addition of bamboo particles, since the density of the waste is lower than the gypsum. This behavior can be explained, in part, by the relation water/gypsum that was altered, during the production of the composites, in order to keep the density of the plates constant for all the treatments and, consequently, the composites could present a low rate of water absorption. Another factor that can be highlighted is the low specific mass of the fiber, which does not promote expressive alterations in the density of the composite.

The initial planned density was 0.80 $g.cm^{-3}$, but the apparent density of the panels reached 1.08 $g.cm^{-3}$ (Figure 4), values close to those reported in the literature. Mesquita Júnior et al. (2018) worked with gypsum composites reinforced with Eucalyptus grandis particles and adopted nominal specific mass of 1.20 $g.cm^{-3}$. The average value obtained for specific gravity was 1.11 $g.cm^{-3}$. Vilella et al. (2021) obtained values between 0.71 and 1.08 $g.cm^{-3}$.

Veloso et al. (2021) conducted an experiment with gypsum-based composites reinforced with cocoa residue particles, in the same proportions of insertion of reinforcement particles, which were used in this study and noted that the insertion of the residue in the composite has reduced the apparent density of the panels.

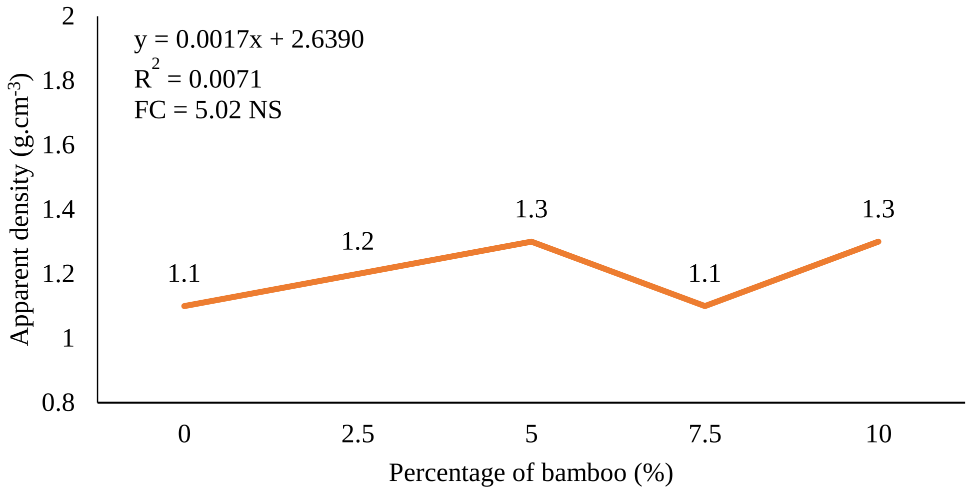

Figure 2. Apparent density of the composites, as a function of the addition of bamboo particles. NS = Non significant relation.

In Figure 3 represents the behavior of the composites regarding water absorption after 2 and 24 hours of immersion. It is possible to notice that there was a significant effect of the addition of bamboo particles in the composites for water absorption in both evaluated times. For each 1% of bamboo particles there was a reduction in the order of 0.36% for AA2h and 0.43% for AA24h.

The analysis of water absorption in composites with plant fiber reinforcement is a complex factor, since it involves different variables to be analysed such as, for example, cell morphology, variation between open cells and closed cells, fiber and composite density and fiber characteristics such as size, content, chemical composition and influence of chemical treatments on plant fibers (Santos, 2020).

The result obtained in this research, in part, can be explained by the chemical composition of the bamboo particles. The lignin confers rigidity, resistance and impermeability (Grabber, 2005), which may extend to the extractives, which occupy the wood pores (lumens and intercellular spaces), which would normally be occupied by water. Therefore, the greater the amount of these chemical components, the lower the absorption rate, as shown in Figure 3.

The same behavior was observed by Magalhães & Almeida (2010) in their study of a natural additive (cactus mucilage) that was inserted into gypsum pastes. The value obtained for the AA rate of the control treatment was corresponding to 27.64%, a result close to the values obtained in this research. The authors observed that the cactus mucilage reduced the water absorption rate of the composites.

Veloso et al. (2021) also observed this trend for AA2h. The values ranged from 18.37 to 5.28%, i.e., as the amount of waste in the matrix increased, the AA values were reduced. According to the authors, the reduction of water absorption in the composites can be explained by the contents of extractives and lignin that have the ability to repel water (hydrophobic) and therefore there was a greater difficulty of absorption after the curing of the composites.

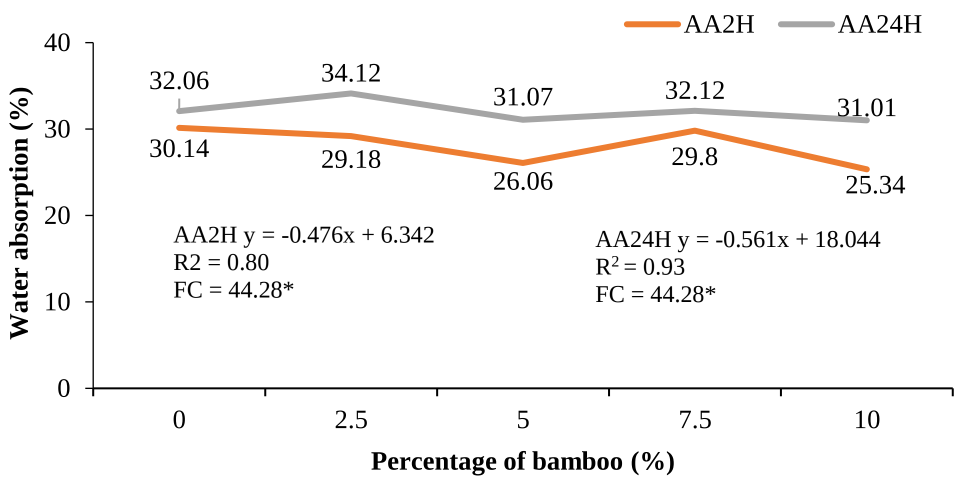

Figure 3. Water absorption after 2 hours (AA2h) and 24 hours (AA24h) of immersion, as a function of the addition of bamboo particles. * = Significant relation.

An opposite behavior to that obtained in this research was described by Villela et al. (2020) and Oliveira et al. (2020). Villela et al. (2020) observed an increase in the values with the insertion of packaging particles in the gypsum matrix. They obtained average values of 31.67% to 56.37% for water absorption. Oliveira et al. (2020) worked with composites with gypsum matrix reinforced with eucalyptus wood fibers and obtained average values of 19.48 to 26.14%. According to the authors there was an increase in water absorption rate with the insertion of reinforcement particles in the composites matrix.

Villela et al. (2020) and Oliveira et al. (2020) described a behavior contrary to that obtained in this research. Villela et al. (2020) observed an increase in the values with the insertion of packaging particles in the gypsum matrix. They obtained average values of 31.67% to 56.37% for water absorption. Oliveira et al. (2020) worked with composites with gypsum matrix reinforced with eucalyptus wood fibers and obtained average values of 19.48 to 26.14%. According to the authors there was an increase in water absorption rate with the insertion of reinforcement particles in the composites matrix.

It is interesting that the gypsum composites reinforced with lignocellulosic material are resistant to moisture and have lower coefficients of water absorption. In this aspect is also relevant to work with composites reinforced with bamboo, because they showed improvements in dimensional stability of composites.

Mechanical properties of composites

The following Figures 4 and 5 represent, respectively, the composites behavior for the properties of Modulus of Rupture (MOR) and Modulus of Elasticity (MOE) to the static flexion. For both properties there was no significant effect regarding the insertion of bamboo particles in the composites.

The average value obtained for the MOR (2.64 MPa) was among those obtained by Lucolano et al. (2015) who studied the interaction between abaca fibers and gypsum matrix in proportions of 1.0; 2.0 and 3.0% and found average values between 2.46 and 2.95 MPa. Oliveira et al. (2020) noted a significant increase with the addition of eucalyptus fibers in the gypsum matrix, for the modulus of rupture.

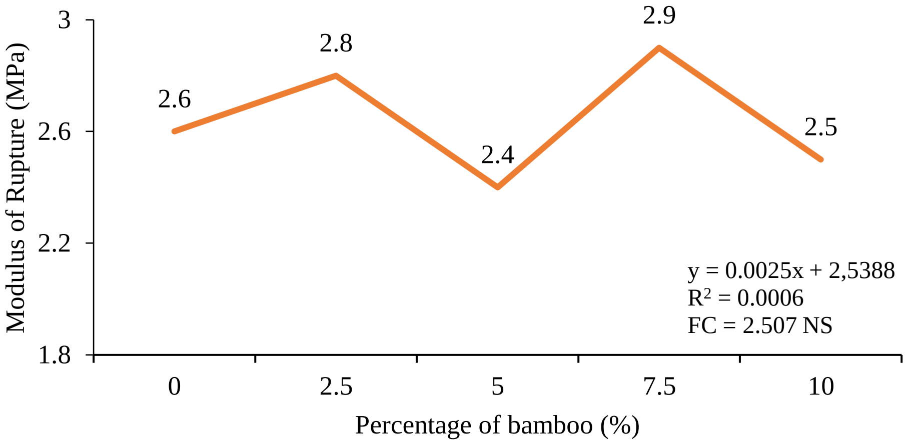

Figure 4. Modulus of rupture of composites, as a function of the addition of bamboo particles. NS = Non significant relation.

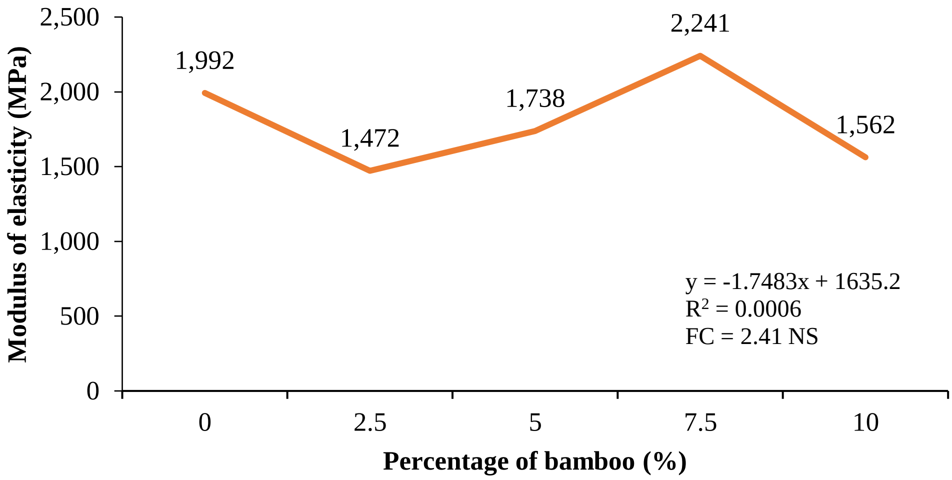

Figure 5. Elasticity modulus of the composites, as a function of the addition of bamboo particles. NS = Non significant relation.

The values obtained ranged from 3.38 to 5.52 MPa. The values obtained for all treatments were satisfactory, as they were higher than those stipulated by EN 13279-2 (EN, 2014), which establishes as minimum requirement 1.0 MPa for flexural strength in gypsum matrix composites.

The mean value obtained for the MOE was corresponding to 1,801.00 MPa, lower than the result obtained by Mesquita Júnior et al. (2018) who found 4,329.78 MPa for gypsum-wood composites but situated between the values obtained by Veloso et al. (2021), who observed a significant reduction in strength with the addition of the cocoa waste particles in the composites. The composites free of reinforcement particles reached an average value of 2,528.24. With the increase of the particles, the strength decreased until reaching 442.99 MPa, for those produced with 10% of particles of cocoa waste.

Chinta et al. (2013) have observed an inverse behavior with the addition of higher proportions of vegetable fibers in gypsum composites, which provided a gradual increase in flexural strength. Also, according to the authors, this was due to the lack of adhesion of the fiber with the gypsum surface that generated less weight transfer from the matrix to the reinforcement. Gallala et al. (2021) produced biocomposites of palm fiber waste and gypsum and stated that the reduction in flexural strength is generally caused by the loss of flexibility, which is due to the poor distribution of fibers in the fresh state and leads to increased porosity.

Figure 6 shows the behavior of the compressive strength of composites for the different treatments performed.

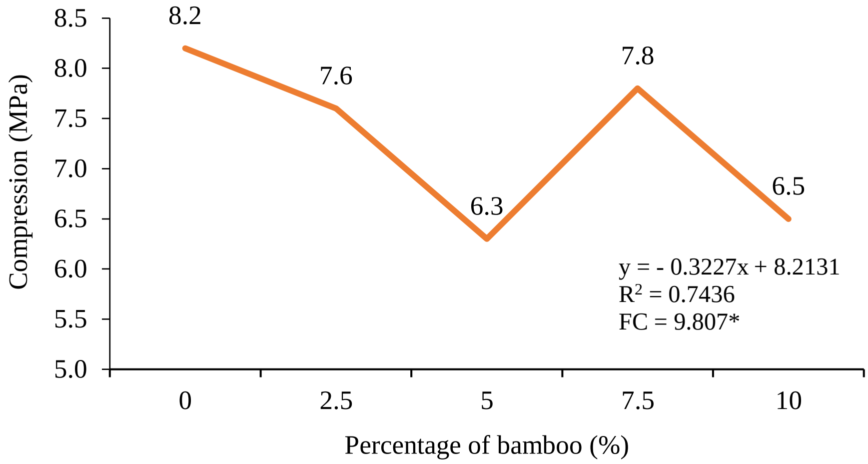

Figure 6. Compressive strength of the composites, as a function of the addition of bamboo particles. * = Significant relationship.

In relation to the compressive strength, it was observed that the values decreased with the addition of bamboo particles, i.e., the composites constituted only with gypsum showed higher compressive strength, as can be seen in Figure 6. For the addition of 1% of bamboo particles there was a reduction equivalent to 0.32 MPa in this property.

In addition, the chemical structure of the bamboo may also have influenced the results. Miller and Moslemi (1991) state that tannins, acetic acid, hemicellulose, and lignin may not reduce the mechanical performance of the inorganic binder significantly, but glucose may have a greater effect, in up to 40% reduction. Therefore, the higher the addition of bamboo particles (higher amount of glucose), the lower the resistance of the composites.

Another factor that can be cited is the concentration of fibers, in some points of the matrix, generating zones of concentration of fibers causing fracture in the matrix and in other parts there is a void of fibers, thus generating a certain decrease in the strength of the composite with addition of bamboo fibers (Silva et al., 2022).

A treatment applied to the bamboo particles, would probably be interesting, as the improvement in compressive strength can be attributed to a better fiber-matrix adhesion, as the fibers become rougher and thinner after a water treatment, for example, which can improve their adhesion capacity with the matrix (Sawsen et al., 2015).

In general, the different results found in this research and in the literature can be explained by the following factors: type of binder, manufacturing methodology, plant fiber morphology, chemical composition that are essentially linked to the origin of the organic fiber and the plant itself.

Conclusions

The insertion of bamboo particles in the composites caused improvements in dimensional stability of the panels, since the water absorption rate was significantly reduced.

In relation to the properties of MOR and MOE there was no increase in the improvement with the insertion of the bamboo reinforcement particles, but all composites produced were higher than the values stipulated by the standard for the MOR. The results obtained for the MOE were equivalent to the results described in the literature.

Although all treatments have reached the minimum values stipulated by the standard for compressive strength, all values were reduced with the insertion of bamboo particles.

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