Production of Particleboards with Bamboo (*Dendrocalamus giganteus*) Reinforcement

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The focus of this research was to study the utilization of residues from bamboo (*Dendrocalamus giganteus*) lamination in the manufacturing of panels for structural purposes. Bamboo particleboards were produced under three conditions: pure boards, reinforced with bamboo laminas, and with treated particles. Castor oil-based polyurethane was the resin binder, in view of using lower toxicity materials. The mechanical tests were performed according to Brazilian Standard (NBR) 14810-3 (2006) and European Standard (EN) 310 (2000). The results were superior to those recommended by these and other standards for internal adhesion resistance, modulus of rupture, and elasticity in static bending, as well as to the results of other studies. Starch treatment was an unnecessary stage. According to the conditions of this process, the studied panels showed a good potential for construction use. Moreover, the bamboo particleboards are an economically viable, environmentally friendly, and sustainable alternative for the use of waste generated during the processing of *Dendrocalamus giganteus* bamboo species, allied with castor oil-based polyurethane resin. The reinforced particleboard and its production process are being licensed as an Innovation Patent in Brazil, (BR 1020130133919-1-2013).

Keywords: Bamboo; Particleboards; Castor oil-based polyurethane resin; Reinforcement; Waste

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INTRODUCTION

Wood particle chipboard, among other wood-based products, has increased in popularity as a raw material, due to cost profitability and market growth. According to Buyuksari (2012), particleboard is one of the most widely used interior wood composite substrates and is commonly used for cabinetry and furniture manufacture. Nascimento (2008) mentions that the raw material for chipboard manufacturing can be forest material from paring and pruning, ragged industrial residues (*e.g.*, slabs, leavings of top cutting, and residual-roll of wood lamination), thin industrial waste (*e.g.*, sawdust and planer shavings), chips from furniture and carpentry industrial processing, or lignocellulosic materials such as sugarcane-bagasse (Acharya *et al.* 2011), rice husk (Chen *et al.* 2013), and other agricultural residues in a pure mode or mixed with wood particles.

Rasat *et al.* (2012) suggested that composite boards from oil palm frond agricultural residues have the potential to be used as a wood alternative to overcome the material shortage in the wood industry.

Campos *et al.* (2009) determined a method of near infrared spectroscopy to evaluate compositions of agro-based particleboards produced from eucalyptus and pine mixed with sugarcane-bagasse, justifying their possibile applications in research.

Yang *et al*. (2014) report that over the past decades, many non-wood lignocellulosic biomasses, including bamboo, wheat straw, cotton stalks, sunflower stalk, and kenaf stalk, have been used to produce particleboards or other end products. In searching for alternative processes, it was discovered that bamboo is a great option for particle production. Currently, it is estimated that about 1 billion people worldwide use bamboo as a source of subsistence. Bamboo has few deformations and good stability in the production of panels (Moizés 2007). Because of its qualities, there is a large industrial development for the use of this material (Lima *et al.* 2008). Pereira (1997) reports that bamboo is a unique natural resource in that it takes less time to be renewed because of the superior speed of growth and area utilization. Additionally, Pereira (1997) highlights that bamboos' structural strength-to-weight ratio is comparable to steel. This high resistance can be explained by the distribution of fiber in the outside (40 to 90%) and inside (15 to 30%) of the bamboo stalk. Bamboo processing, especially for industrial production of glued laminated boards, generates waste which can become a pollutant, in addition to representing high losses of natural resources. Bamboo material has also been studied as reinforcement of sawn wood or wood-based pieces, which have proven to be an eco-efficient alternative.

Bamboo can be an alternative to the production of particleboards as well being used to reinforce bio-composites (Abdul Khalil *et al.* 2012). In many countries, bamboo is used as a building material and industrial raw material for many industries because it has excellent shear strength and stiffness values. Bamboo has several advantages such as fast-growth, perennial plantation, and ease of propagation, maintenance, and harvesting.

Bamboo particleboards emerged with the objective to reuse residues of bamboo processing such as small-diameter culms, bases, and stem tops (Kai and Xuhe 2005). Therefore, according to these authors, the great advantage of these boards are an ample raw material supply and the fact that the manufacturing process is similar to the technology of wood particleboards. Calegari *et al.* (2007) concluded that the use of bamboo culms (*Bambusa vulgaris* Schr.) provides a viable alternative in the production of chipboards, since they behave similarly to those produced exclusively from wood. Ultimately, novel products are being developed; an example of this is corrugated bamboo particleboards, manufactured from bamboo waste originating from planers. In this case, Yang *et al.* (2014) made panels with a simple technology using urea-formaldehyde resin at three press temperatures and two density levels. This study increases the perspectives on the reuse of bamboo waste.

Recently, rising wood prices and the declining availability of wood resources have led people to seek other analogous alternatives. Similar to wood, bamboo is a material of natural origin that is strong, lightweight, renewable, and displays a strong adaptability to the environment. The best way to utilize bamboo on a large scale is to design and produce a series of bamboo-based panels with different structures and functions according to the properties of bamboo (Kai and Xuhe 2005).

Regarding the chipboards produced with bamboo waste, Sampaio *et al.* (2008) made homogeneous bamboo particleboards (*Dendrocalamus giganteus*) with the addition of urea-formaldehyde with the culm and bract; this last leaf stem derived from the same bamboo clump, which is rich in fibers, as is an alternative to replace the solid wood and to add economic value to the material. The variation on percentage occurred in the waste of bamboo and bract. The board contents were: 25% bract and 75% bamboo; 50% of each; 75% bract and 25% bamboo; and 100% of each bract and bamboo.

Vieira *et al.* (2010) produced particleboards of bamboo and pine. The materials included urea-formaldehyde as an adhesive in the proportion of 10% of the dry weight of material, bamboo particles originating from the apical part of the culm, and pine particles derived from industrial processing. Laemlaksakul (2010) manufactured chipboards using bamboo culm waste from the species *Dendrocalamus asper* Backer, which were collected from the production process of chips, with urea-formaldehyde adhesive, varying the temperatures in the packaging of the specimens prior to testing at 25, 40, and 55 °C. Homogeneous panels of bamboo (*Guadua magna*) with a nominal density of 0.65 g/cm^3, particle sizes of 1.0 and 1.5 mm, and urea-formaldehyde and phenol-formaldehyde resins at 8% were produced by Arruda *et al.* (2011).

Regarding the use of bamboo reinforcements, Cortez-Barbosa *et al.* (2011) analyzed the mechanical characteristics of wood-bamboo composite material, where the samples were developed from combinations of bamboo lamina as structural reinforcement in solid wood pieces of pine and in edge glued panels (EGPs). The wood species used was *Pinus taeda* and the bamboo species were *Dendrocalamus giganteus* and *Guadua angustifolia*. The values obtained in the tests showed an increase in strength and stiffness compared to pieces without any reinforcement.

Ferro *et al*. (2014) realized an evaluation of the influence of castor-oil based polyurethane resin formulation (particularly proportion of pre-polymer/polyol) in static bending properties (modulus of elasticity and modulus of rupture) of particleboards produced with Paricá wood (*Schizolobium amazonicum*). These authors considered that the proportion of 1:1 (polyol/pre-polymer) could be the best solution, because it showed better mechanical performance and it used the least amount of petroleum derivative.

Whilst most research related to manufacturing of wooden composites considers the use of chemical-based resin, new applications with vegetable-based resin could be realized, as for example, the castor oil-based polyurethane. This resin has been used in Brazilian studies with promising results. This resin is more ecological than solely chemical-based adhesives, such as urea-formaldehyde, because it uses castor beans as a natural material.

In the 21st century, the triad formed by the sustainability, waste utilization and development of new materials has often been commented upon. In addition to this, the Brazilian legislation "12.484-2011" established a national policy for the sustainable management and bamboo cultivation (Cortez-Barbosa *et al*. 2014).

Due to this Brazilian legislation, some sectors will probably generate in the future a considerable amount of bamboo waste, especially through the bamboo lamination manufacturing process. Therefore, the objective of this research was to produce particleboards from bamboo *Dendrocalamus giganteus* residues of the bamboo lamination process, reinforced with laminas of the same bamboo species for structural purposes in construction.

EXPERIMENTAL

Materials

The *Dendrocalamus giganteus* bamboo species used in this work has culms with heights from 24 to 40 m, internodes from 0.40 to 0.50 m, diameters from 0.10 to 0.20 m, and wall thicknesses of 1 to 3 cm, varying according to culm height.

The laminas for reinforcement were extracted in the basal section of bamboo culms, and preferentially near the external part of the culm, with the presence of knots. Bamboos approximately five years old were collected in the Southeast region of São Paulo State, Brazil.

The castor oil-based polyurethane was the resin used both in the production of the particleboards and in the reinforcement of these particleboards.

Methods

To produce the laminas that were used as reinforcement, it was necessary to machine the bamboo pieces using a circular saw (trimmer saw with adapter for cylindrical pieces) as a safety guide. Bamboo was machined longitudinally into six parts (cleats), and the diaphragms were removed afterwards with a band saw. The cleats were machined in a three-side planing machine to standardize the desired thickness of the laminas, which ranged from 1.63 to 2.13 mm, in according to culm thicknesses and also because of the variation in the cutting process. The lamina length was 350 mm, and its width was about 30 mm.

The waste collected during the processing of the laminas was separated by a vibrating screen and divided into three groups: dust, particulates retained in sieves of 3-mm diameter, and particulates retained in sieves of 7-mm diameter. Part of the residues were pre-treated by submerging in warm water for 20 h and then drying at 100 °C in a drier (with and without air circulation) to remove starch present in the bamboo culms. The starch removal was realized to avoid future insect attacks and also to verify if this starch could interfere in the adhesion process of resin, once it is known that its presence affects some healing processes, for example with cement. Treated and untreated residues were dried in the same manner, through a final drying at 60 °C.

The processed particles of *D. giganteus* were mixed in a gluing machine to make the mat, using castor oil-based polyurethane resin in proportions of 15% of dry mass. Nine boards were produced, each one with the same volume of particles, and pressed at high temperature (100 °C), using a hydraulic press by a pressing time of 10 min and pressure of 3.5 MPa. Four boards used pre-treated residues (with reinforcement), three boards did not undergo this treatment (with reinforcement), and two boards did not undergo treatment (without reinforcement), to examine the influence of reinforcement and treatment. A reinforced board sample is shown in Fig. 1.

Fig. 1. Particleboard manufactured with bamboo waste and reinforced with bamboo laminas

All the boards had nominal dimensions of 350 x 350 mm. The panels' thicknesses were 10 mm, 13 mm, and 14 mm for pure boards (PB), reinforced non-treated boards (RNB), and reinforced-treated boards (RTB), respectively. These thickness were different due to the presence of laminas of reinforcement.

Specimens were removed from the particleboards for testing of internal adhesion resistance (bonding) and static bending, to determine modulus of rupture (MOR) and modulus of elasticity (MOE). The tests were conducted in universal testing machines (of 30 ton and 10 ton), according to the standards NBR 14810-3 (2006) and EN 310 (2000), respectively. The static bending specimens were obtained according to the orientation of the laminas in the reinforced panels, which were arranged all in the same direction, one parallel to each other. Analysis of Variance (ANOVA) and Tukey tests, conducted at 5% significance levels, were applied to identify the difference in average values.

RESULTS AND DISCUSSION

Table 1 presents the average values for modulus of rupture in static bending.

Table 1. Average values of the MOR (MPa)

	RTB1	*RTB2*	*RTB3*	*RTB4*	*RNB1*	*RNB2*	*RNB3*	*PB1*	*PB2*
ẋ	111	133	139	165	140	154	156	44	31
sd	21	21	11	20	31	31	18	12	10
CV	19	16	8	12	23	20	12	27	30

RTB: reinforced-treated boards - 4 boards, RNB: reinforced non-treated boards - 3 boards, PB: pure boards - 2 boards. *ẋ*: average, *sd*: standard deviation, *CV*: coefficient of variation (%)

Average values of MOR for the reinforced-treated boards, reinforced non-treated boards, and pure boards (without treatment and without reinforcement) were 137, 150, and 38 MPa, respectively. This situation could suggest that the bamboo pre-treatment process caused some chemical modification in the bamboo particles, generating a decrease in the static bending resistance, and showing that a pre-treatment of particles for the composite manufacturing is not necessary. This also suggests that the addition of the bamboo lamina reinforcements generated an increase in static bending strength more than 200%, even though the laminas did not influence the final density (Table 3) of the composite. Despite of a major quantity of raw material in reinforced boards, the volume was lower than in non-reinforced boards, because of the compaction stage. These values surpassed the requirements of standards NBR 14810-2 (2002) of 16 MPa for wood particleboards and EN 300 (2000) for wooden-OSB type 4 of 28 MPa in the longitudinal direction, even for non-reinforced chipboards. Table 2 shows the average values for modulus of elasticity in static bending.

Table 2. Average values of the MOE (MPa)

	RTB1	*RTB2*	*RTB3*	*RTB4*	*RNB1*	*RNB2*	*RNB3*	*PB1*	*PB2*
ẋ	14,531	14,917	15,209	18,561	13,982	15,397	14,275	5,972	5,738
sd	3,603	1,271	1,490	1,410	1,550	1,573	2,183	1,724	1,298
CV	25	9	10	8	11	10	15	29	23

RTB: reinforced-treated boards - 4 boards, RNB: reinforced non-treated boards - 3 boards, PB: pure boards - 2 boards. *ẋ*: average, *sd*: standard deviation, *CV*: coefficient of variation (%)

The average values of MOE of the data shown in Table 2 for the reinforced-treated boards, reinforced non-treated boards, and pure boards (without treatment and without reinforcement) were 15,804, 14,551, and 5,855 MPa, respectively. These values also surpassed the requirements of EN 300 (2002) for OSB type 4 of 4,800 MPa in the longitudinal direction, even for particleboards produced without reinforcements. This situation suggests that the addition of the bamboo lamina reinforcements generated an increase in modulus of elasticity in static bending greater than 100%, even though the laminas did not influence the final density of the composite (Table 3), as aforementioned. As MOE values reached for both RTB (reinforced-treated) and RNB (reinforced non-treated) boards were higher than the prescripted values by this European standard, it could be verified that the pre-treatment of particles is not convenient.

Table 3 presents the MOR and MOE values obtained in studies by other authors related to bamboo and wooden particleboards as compared to the current study. This table shows the result of applying the Tukey test for this current study, where similar characters (a or b) are statistically equivalent averages.

Table 3. Values for Mechanical Properties of the Lignocellulosic Particleboards

Authors	*Compositions*	*Densities (kg/m³)*	*Resins*	*MOR (MPa)*	*MOE (MPa)*
Zaia *et al.* (2014) **current study*	PB RTB RNB	912 890 911	CP (15%)	38^{a} 137^{b} 150^{b}	$5{,}855^{a}$ $15{,}805^{b}$ $14{,}551^{b}$
Sampaio *et al.* (2008)	100% Bract 50% Bract / 50% Bamboo 100% Bamboo	<1000	UF	11 15 21	1,335 2,105 3,901
Laemlaksakul (2010)	Bamboo	600	UF (13%)	16	1,541
Arruda (2011)	Bamboo	650	UF (8%) PF (8%)	13 14	1,819 1,722
Ferro *et al.* (2014)	Paricá wood *(S. amazonicum)*	800	CP (12%)	20	2,001

RTB: reinforced-treated boards, RNB: reinforced non-treated boards, PB: pure boards (panels).
UF: urea-formaldehyde, PF: phenol-formaldehyde, CP: castor oil-based polyurethane (resins)

ANOVA showed that the MOR and MOE values of reinforced-treated board were statistically equivalent to the reinforced non-treated boards, suggesting that the prior treatment of particles to reduce the starch did not influence the bonding process of the boards with the castor oil-based polyurethane resin, as cited by Beraldo (2008), however, it showed that there is a statistical difference between the non-reinforced and reinforced bamboo particleboards.

From the data in Tables 1 and 2, it can be seen that the values for strength and modulus of elasticity in static bending for particleboards were higher in this study than those found by other authors, listed in Table 3, regardless of the treatment applied, presence of reinforcements, or panel composition (bamboo or wood and resin type). The reinforcement with bamboo laminas noticeably increased the values for these properties. This is probably because the bamboo was manufactured from the outside of culms, which contained a higher amount of fibers.

The boards in this study reached a density similar to Sampaio *et al.* (2008) and Ferro *et al*. (2014), *i.e.*, greater than 800 kg/m^3. However, these boards reached values of MOR and MOE superior to other studies, probably due to the reinforcement and use of castor oil-based polyurethane resin.

These values were also superior to average values obtained, for basal part of cleats of *Dendrocalamus giganteus* bamboo (with knots), by Pereira and Beraldo (2010), for MOR and MOE equal to 118.7 MPa and 12,600 MPa, respectively. It emphasizes the potential of this composite for structural applications. Figure 2 shows the types of rupture in some static bending specimens of the bamboo particleboard.

Fig. 2. Types of ruptures after the static bending test

From the specimens tested in static bending, after breaking, the specimens for internal adhesion testing were selected. For RNB there was a smaller number of specimens. Different types of ruptures in the specimens of static bending test caused shorter reusable sections. Thus, it was possible to prepare for internal adhesion testing five specimens for reinforced-treated boards, three for reinforced non-treated boards, and ten specimens for pure boards, providing the average values of 2.21, 2.25, and 3.01 MPa, respectively.

Internal adhesion (or internal bonding) values collected in this study are listed in Table 4, along with data obtained from other studies. It is observed these values exceed those found by other authors, regardless of the treatment, especially for non-reinforced particleboards. This table shows the result of applying the Tukey test for this current study, where similar characters are statistically equivalent averages.

Table 4. Values for Internal Adhesion for Particleboards

Authors	*Compositions*	*Densities (kg/m³)*	*Internal Adhesion (MPa)*
Zaia *et al.* (2014) **current study*	PB (CP)	912	3.01^a
	RTB (CP)	890	2.21^a
	RNB (CP)	911	2.25^a
Laemlaksakul (2010)	Bamboo (UF)	600	0.19
Arruda (2011)	Bamboo (PF)	650	0.26
	Bamboo (UF)	650	0.32
Sampaio *et al*. (2008)	100% Bract	<1000	0.13
	50% Bract / 50% Bamboo		0.24
	100% Bamboo		0.22

RTB: reinforced-treated boards, RNB: reinforced non-treated boards, PB: pure boards (panels). UF: urea-formaldehyde, PF: phenol-formaldehyde, CP: castor oil-based polyurethane. (resins)

The results show the values found were higher than those prescribed by the standards: 0.40 MPa of NBR 14810-3 (2006) for wood particleboards and 0.45 MPa of EN 300 (2000) for wood OSB panels of type 4, regardless of the treatment and presence or absence of bamboo reinforced laminas. The prior treatment of the bamboo particles to remove starch did not lead to different results for bamboo boards without treatments.

ANOVA shows that the resistance in internal adhesion values of reinforced and treated board were statistically equivalent to the reinforced non-treated boards, even as this last equivalence occurred with non-treated and non-reinforced particleboards.

The higher apparent values of internal adhesion for the particleboards without reinforcement, or pure boards, can be explained by the rupture of the reinforced boards in some specimens precisely at the glue line between the reinforcement bamboo laminas and the bamboo particleboards. In the non-reinforced boards, the ruptures occurred in the center of the specimens, as seen in Fig. 3.

Fig. 3. Boards without reinforcement after internal adhesion test

CONCLUSIONS

1. Treatment for the removal of starch did not result in differences in mechanical properties, which can be explained by the castor oil-based polyurethane resin displaying no change while in the presence of starch.
2. The particleboards presented consistent and satisfactory results. Even for lower values between boards with and without reinforcement, these values conformed to the standard requirements or they presented similar or superior values to particleboards reported in the literature. This situation also was particularly seen for OSB type 4, which is used in structural applications.
3. Therefore, this study shows an economically viable, sustainable, and environmentally friendly alternative for the use of the waste generated in the processing of *Dendrocalamus giganteus*, combined with a castor oil-based polyurethane resin (CP), forming a panel that can be applied in structures.

ACKNOWLEDGMENTS

This research was realized in the Laboratory of Wood and Timber Structures at School of Engineering of São Carlos of University of São Paulo (USP), and in the Laboratory of Materials Properties at Campus of Itapeva-SP of São Paulo State University (UNESP). The Research Group LIGNO of UNESP-Itapeva and some of its researchers and professors also helped and shared information, contributing to this initiative. In short, we are thankful for the support of all the involved laboratories and staffs.

The authors are grateful for the financial support of São Paulo State University (UNESP), and in particular, their respective executive departments: FUNDUNESP and PROPe.

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Article submitted: July 7, 2014; Peer review completed: October 15, 2014; Revised version accepted: December 19, 2014; Published: January 15, 2015.