Maderas-Cienc Tecnol 25(2023):13, 1-24
Ahead of Print: Accepted Authors Version

DOI:10.4067/S0718-221X2023005XXXXXX

PARTICLEBOARD EXPERIMENTAL PRODUCTION WITH BAMBOO, PINE AND MATE FOR ONE PRODUCT OF NEW APPLICATIONS

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Received: July 7, 2021
Accepted: January 11, 2023
Posted online: January 12, 2023

ABSTRACT

Particleboard can be produced from a mixture of different lignocellulosic materials, which can be chosen depending on the density required for the panel and its applications. The aim of this study was to evaluate the mechanical properties of particleboard with bamboo, pine and mate for a new product of high density for the special applications currently served by HDF. Particles of bamboo (*Phyllostachys aurea*) finely chopped sticks of mate (*Ilex paraguariensis*) and commercial particles of southern pine (*Pinus taeda*) wood were used. These particles used 100 % by weight in the panel or in mixtures of 50 % each (three mixtures) or in a triple mixture of one third each, were glued in a drum-type rotary mixer with melamine-urea-formaldehyde (MUF) resin, and pressed in hydraulic press at 120 °C and 5,88 MPa for 10 minutes, up to 6 mm thickness. The panels were produced with 0,90 g·cm^{-3} nominal density and, after pressing, were conditioned at 20 ºC and 65 % relative humidity. Statistical was performed by means the variance analysis and simplex centroid experimental design, with three replicates. It was found the use of pine particles contributed mainly to increase the panel's strength and stiffness, while the use of mate particles facilitated internal bond strength. The results compared with the ANSI A208.1 indicate that the panels with potential for use as floors and other applications requiring medium to high mechanical strength. The mixtures modeling showed that the water absorption, the strength and stiffness in bending and the internal bond strength are explained by the cubic model, while the thickness swelling and hardness are explained by the quadratic model. The best physical and mechanical properties results were found for the pine, bamboo and mate same ratio mixture.

Keywords: Alternative lignocellulosic materials, centroid simplex design, *Ilex paraguariensis*, melamine-urea-formaldehyde, particleboard, *Phyllostachys aurea*, *Pinus taeda*.

INTRODUCTION

A forecast for the global market for forest products shows that there may be a retraction in the consumption of fuelwood (30 %) and classical paper products (32 %) by 2050, towards emerging wood-based products. Wood-based panels are finding increasing application of the 196 % by 2050, mainly by taking potential markets for sawn wood (Morland and Schier 2020). In addition, forecasts are that this market will shift from Europe and North America to emerging countries in Asia and South America.

Examples of this are China and Brazil, which in recent decades had accelerated development of forestry and wood industry. China was responsible for increasing the production of wood panels in Asia to more than six times in 20 years, accounting for 2/3 of world production in 2016. Among other wood panels, China is the world's largest producer of MDF/HDF and particleboard (Barbu and Tudor 2021).

In a period of 50 years, there was a great growth in the production and consumption of wood panels in Brazil, particularly of MDF/HDF and Particleboard (Sanquetta *et al.* 2020). However, it was not until the 1990s that Brazilian particleboard companies began to invest in technology, replacing cyclic for the continuous presses and using new resins and additives (Mattos *et al*. 2008).

In this period, its traditional nomenclature was changed to Medium Density Particleboard (MDP), in an attempt to dissociate it from the so-called previously existing particleboard. Currently, particleboard or MDP are the most consumed panel's type in the world and can be produced from any lignocellulosic material as long as it provides mechanical strength and specific gravity that meet the required standards (Narciso *et al.* 2021).

In this scenario, it is important to develop new products and insert new technologies into existing ones. Thus, the use of other lignocellulosic materials in particleboard can be an alternative to meet the demand for these materials. In addition, for the use of higher density lignocellulosic particles, a High Density Particleboard (HDP) can be produced in order to meet specific applications that are currently supplied by HDF (Sugahara *et al.* 2019, Iwakiri *et al.* 2005b).

To understand the composition effect of different particle mixtures in MDP/HDP panels, the mixture modeling technique can be used. For this, it must be considered that the mixture properties are determined by the components proportions and these are dependent on each other. This technique is known as "centroid simplex design" and is generally used to evaluate three component mixtures (Montgomery 2019). This method allows the modeling experiments of wood species mixture in particleboard with minimal mixtures, as opposed to using different proportions of complete model and another statistical method such as only analysis of variance or regression analysis (Hillig *et al.* 2003).

The use of species mixtures in the particleboard production presents advantages, due to the different physical, chemical and mechanical properties of each. Found that MDP panels produced with the mixture of *Cecropia hololeuca* and *Schizolobium amazonicum* showed better mechanical properties than the use of each pure species wood (Iwakiri *et al*. 2010). The use of higher density species in the production of MDP may be possible as it is mixed with low density specie wood, resulting in panels with satisfactory properties (Sanches *et al*. 2016).

Evaluated the technical feasibility of mixing bamboo particles (*Guadua magna*) with *Pinus taeda* wood for the production of MDP bonded with synthetic resins (UF and PF), being verified that there was no influence on the panel's mechanical performance with up to 25 % bamboo particles (Arruda *et al*. 2011). The use of bamboo in the MDP production proved to be technically feasible, as it meets all the stipulated by the Brazilian standard requirements and presented mechanical properties similar to commercial pine and eucalyptus panels (Mendes *et al*. 2017).

In a study with particles of different species, pure or in mixture, of mate, southern pine and eucalyptus, the addition of yerba mate particles has reduced most of the mechanical properties of MDP. The most suitable proportion for the preparation of panels is the mixing of one third particles of each species. (Souza *et al*. 2019).

The panel's compaction ratio is very important and should be around 1,3 to 1,6 (Narciso *et al.* 2021). Thus, for the production of HDP it becomes interesting to use particles of higher density species such as bamboo or it's mixture with other species. Mate sticks are a waste generated in large proportions in this industry and their use could add value in this product (Kuram 2021).

Thus, considering previous studies with high density particleboard, this study was conducted to evaluate the physical and mechanical properties of particleboards produced with different particles proportions of bamboo, southern pine and mate, considering the hypothesis that these lignocellulosic materials can be used for a new product of high density for the special applications currently served by HDF, and which may come to be called HDP.

MATERIAL AND METHODS

Material

Bamboo chip production

In the production of bamboo chips, mature individuals, estimated to be between three and four years old, were used due to their external appearance. Thirty culms with uniformity in height, stem diameter and wall thickness were selected, in order to facilitate the chip milling process. The final dimensions of the bamboo chips were approximately

3 mm, 20 mm and 40 mm in thickness, width and length respectively. Subsequently, the culms were subjected to air drying, until it reached equilibrium moisture content.

Particle production of mate and bamboo

Figure 1 shows the bamboo chips and mate sticks, which have been milled in forage chopper. Mate sticks were obtained from thin branches, usually cylindrical in shape, with a maximum diameter of 7,5 mm and varied length in the wet condition. After processing and drying, the average dimensions were 3,4 mm and 39,7 mm, diameter and length, respectively.

Figure 1: Chipping process of Bamboo chips (a) and Mate sticks (b).

The ground material of mate and bamboo chips was subjected to the sieve classification and physical properties determination: bulk density, apparent density and slenderness ratio. Tyler series classification of bamboo and mate particles using a sieve shaker were performed by subjected to mechanical agitation for 15 minutes, using those that passed through the 8 Tyler mesh sieve (2,362 mm) and were retained in the 12 Tyler mesh sieve (1,397 mm). In addition, commercial *Pinus taeda* particles produced in a local MDP panel industry and of the same granulometry were used.

For the slenderness ratio determination, 50 particles of each species were measured using a magnifying glass and specific measurement software. The ratio between the length and thickness of the particle determined the slenderness coefficient. Thus, the material used in the production of high-density particleboards (HDP) was composed of particles with size ranging from 8 to 12 mesh, as showed in Figure 2, and with the physical properties detailed in Table 1.

Figure 2: Particles commercial *Pinus taeda* (a), Bamboo (b) and Mate (c) produced in the laboratory.

Table 1: Physical properties of particles.

Particle specie	Apparent density ($g \cdot cm^{-3}$)	Bulk density ($g \cdot cm^{-3}$)	Slenderness
Bamboo	0,740	0,237	22,591
Mate	0,450	0,294	4,204
Pine	0,410	0,156	28,210

Panel production

After classification by sieves, the material taken was to the oven at 60 ºC ± 2 °C until reaching 3 % to 5 % moisture content. The panel's compaction ratio (RC) was determined by the following ratio: panel density divided by the material natural density used. For the particles gluing was used the commercial melamine-urea-formaldehyde resin (MUF), brand Pole Cola, 14 % ratio of the particles dry weight.

The use of 14 % proportion of MUF adhesive in relation to the dry weight of particles can be considered high in relation to what is normally used in particleboard. However, a higher proportion was chosen because the panels are intended for floors and applications that require higher mechanical strength.

This adhesive has a homogeneous appearance of milky liquid, 1,215 $g \cdot cm^{-3}$ to 1,225 $g \cdot cm^{-3}$ of density, 7,8 pH to 8,5 pH and 200 cP to 250 cP (at 25 °C) of brookfield viscosity, free formaldehyde (< 0,5 %), solid content (62,0 ± 0,5 %) and gel time between 60 and 80 seconds in boiling water (Pole Cola 2011).

To the adhesive was added 2 % ammonium sulfate catalyst and applied with air spray gun. After, it was applied to 1 % paraffin emulsion and the mat forming was assembled manually in the dimensions of 40 x 40 cm. The moisture content adopted in the particle mat was 13 % and water was added when necessary.

The particle mat was manually cold pre-pressing and hot pressed in a hydraulic press, at 120 °C for 10 minutes and pressure of 5,88 MPa, using two 6 mm limiting steel bars on its sides to delimit the panel thickness. The panels were produced with 0,90 $g \cdot cm^{-3}$ nominal density and, after pressing, were conditioned at 20 ºC and 65 % relative humidity.

Two specimens were cut of each manufactured panel, totaling six per panel's type, following the determinations of: - Physical properties: European standards (EN) 323/93a, 322/93b, 317/93c and Brazilian NBR 14810-2/18 for tests of Apparent density, Moisture content, Thickness swelling 24 h. and Water absorption 24 h. - Mechanical properties: European Standards EN 310/94, EN 319/94 and American ASTM D 1037/20) for the Static bending, Internal bond strength and Janka hardness, respectively.

Experimental design and statistical analysis

Assumptions of data normality and homogeneity of variance were tested by Shapiro Wilks and Bartlett tests. Statistical analysis was performed in two steps: First, variance analysis and a means test (Tukey) was applied. This analysis allowed to comparing the panel's properties between them and with the reference standards. In a second step, we used the simplex centroid design, which considers the effect of each pure species and the interactions between two or all three species. The models used are expressed in derived equations 1, 2 and 3, respectively.

$$Yi = b1 \cdot X1 + b2 \cdot X2 + b3 \cdot X3 \quad (1)$$

$$Yi = b1 \cdot X1 + b2 \cdot X2 + b3 \cdot X3 + b12 \cdot X1 \cdot X2 + b13 \cdot X1 \cdot X3 + b23 \cdot X2 \cdot X3 \quad (2)$$

$$Yi = b1 \cdot X1 + b2 \cdot X2 + b3 \cdot X3 + b12 \cdot X1 \cdot X2 + b13 \cdot X1 \cdot X3 + b23 \cdot X2 \cdot X3 + b123 \cdot X1 \cdot X2 \cdot X3 \quad (3)$$

Y_i = Response variable; b_i = Coefficients; Xi = Proportion of each species in the mixture.

The experimental design consisted of seven panels type: pure specie material, mixtures between two or even all materials (Table 2). In the evaluation, the three models (simple, quadratic and cubic) were tested for all properties analyzed, and the non-significant coefficients were discarded by the “t” test.

Table 2: Experimental design.

Model	Dry mass percentage proportions (%)		
	Bamboo	Mate	Pine
	100	0	0
Simple	0	100	0
	0	0	100
	50	50	0
Quadratic	0	50	50
	50	0	50
Cubic	33,3	33,3	33,3

Note: Bamboo *Phyllostachys aurea*; Mate: *Ilex paraguariensis*; Pine: *Pinus taeda*.

RESULTS AND DISCUSSION

Physical and Mechanical properties

According to the ANSI A208.1 (ANSI 2016) commercial standards, the produced panels can be classified as category H1 for high-density particleboard (greater than 0,80 g·cm^{-3}) with minimum strengths of 16,5 MPa for MOR, 2400 MPa for MOE and 0,90 MPa for internal bond strength, their use being recommended for industrial purposes (Table 1).

Table 3: Mean values of HDP physical and mechanical properties.

P	Dp (g·cm^{-3})	Dpa (g·cm^{-3})	CR	MC (%)	TS (%)	WA (%)	MOR (MPa)	MOE (MPa)	IB (MPa)	JH (MPa)
1	0,74	0,88a	1,2	9,3ab	30,9d	45,0d	14,2cd	2367ab	0,49e	40,2d
2	0,45	0,88a	1,9	9,3ab	13,3a	43,3d	12,0d	1550c	0,92c	44,6c
3	0,41	0,92a	2,2	10,9c	20,51c	24,9a	19,5^{a}	2615a	0,75d	53,3b
4	0,59	0,91a	1,5	8,8a	13,01a	35,5b	15,4bc	2125b	1,04bc	56,0b
5	0,43	0,94a	2,2	9,8abc	19,22c	41,0cd	16,8b	2197b	1,12ab	54,4b
6	0,57	0,90a	1,6	9,9abc	16,87b	32,6b	19,4^{a}	2701a	0,63de	60,8a
7	0,53	0,93a	1,7	9,3ab	20,58c	36,7bc	19,8^{a}	2489ab	1,28a	56,7ab

P = Panel type; Dp = Particle density; Dpa = Panel apparent density CR = Compaction ratio; MC = Moisture content; TS = Thickness swelling 24 h.; WA = Water absorption 24 h.; MOR = modulus of rupture in static bending; MOE = modulus of elasticity in static bending; IB = Internal bond strength; JH = Janka hardness. Averages followed by the same letter do not differ by the Tukey test at 5 % probability of error.

Bamboo particles had a higher density than mate and pine, contributing to decrease the panel compaction ratio produced with this particle type. A low particle density provides a high compaction rate and, therefore, a higher contact surface between them. This leads to a greater capacity to transmit loads between the particles, resulting in higher mechanical properties in particleboards produced with particles of low density (Dias *et al*. 2005).

The panels produced showed apparent density close to the established nominal density of 0,90 g·cm^{-3}. Although the mean values ranged from 0,88 g·cm^{-3} to 0,94 g·cm^{-3}, there was no statistical difference between the means. This fact is important since it was intended to compare panel's properties of the same density and the differences in averages were attributed to the increase in panel thickness due to stress release after pressing.

Higher thickness increase after pressing and lower panel density were observed in bamboo and mate panels, however, in the mixture between these two materials its was smaller. This fact is due to the interaction that occurred in the mixing of different densities materials (Iswanto *et al.* 2017) and different particle geometries (Cosereanu *et al.* 2015). According to the authors, higher density material and particles with lower slenderness can cause greater panel thickness increase during its conditioning and, thus, lower density.

It was found that the moisture content of the pine panels showed higher values than the other panels, both 100 % pine and in different mixtures. This result was attributed to the chemical composition of the lignocellulosic materials of the other types of particles being similar to that of hardwoods, which contain lower lignin content and higher hemicellulose content (Frollini *et al.* 2000; Furtini *et al.* 2020).

The moisture contents of the panels were lower than the equilibrium moisture content of the lignocellulosic material used in their production, under identical climatization conditions. This is justified by the loss of constitution water in the pressing process (high temperature and pressure), combined with the addition of resin and additives (Wu 1999).

The ANSI A208.1 standard does not specify maximum values for water absorption and thickness swelling for high density particleboard. It was found that the panels produced with 100 % bamboo showed greater water absorption and thickness swelling, after 24 h of immersion. The higher water absorption was attributed to the lower density of the 100 % bamboo panels, which was also verified with the 100 % mate panels (Iswanto et al. 2017). The greater thickness swelling of 100 % bamboo panels was attributed to the lower bonding quality, as they had the lowest average value of internal bond strength. When mixed 50 % with mate particles, the bamboo panels reached the same average values obtained for the 100 % mate panels, the best values for thickness swelling.

All panel types with pine proportions reached the average values of the MOR requirements of the EN 312 (EN 2003), ANSI A208.1 (ANSI 2016), NBR 14810-2 (ABNT 2018) and CS 236-66 (CS 1968) standards. The higher MOR values for panels containing pine wood were explained by the higher particle slenderness and the high value of panel compression ratio.

The low performance of the panels produced with 100 % mate is due to the rounded shape of its particles (short and wide), resulting in lower bending values (Cosereanu *et al.* 2015, Benthien *et al.* 2019). The 100 % bamboo panels presented weak contact between their particles (TS), due they are being a less polar material (compared to wood), with higher pH and higher extractive content, promoting low retention of adhesive in the particles, justifying the MOR lower value (Soares *et al.* 2017, Furtini *et al.* 2020). The panels produced with bamboo and mate mixture, reached higher average value than 15 MPa of the standard EN 312 (2003).

Except the panels produced with 100 % mate, the other panels types showed MOE values above the 2050 MPa, minimum requirements of the EN 312 (EN 2003) standard.

The requirements of ANSI A208.1 (ANSI 2016) and CS 236-66 (CS 1968) of 2400 MPa, was reached by the panels produced with 100 % pine, mixture of 50 % bamboo and 50 % pine, and triple mixture, i.e., a third bamboo, mate and pine.

The MOE and MOR are directly correlated with the particle geometry, that is, the particles with higher slenderness (bamboo and pine) tend to enable a panel with greater strength and stiffness. In addition, the anatomical structure of bamboo, consisting of fibers considered rigid, thicker cell wall and narrow lumen than those found in wood of tree species used in this study (Dünisch *et al.* 2004; Okahisa *et al.* 2018; Miller *et al.* 2019: Rusch *et al.* 2019), allowed satisfactory values of MOE, despite the deficiency found in its bonding process.

There was a clear tendency to decrease the MOR and MOE of the panels with the increase proportion of mate particles, as a function of particle shape, the opposite was observed to the pine particles. However, in the triple mixture, the use of mate particle did not reduce the properties of MOR and MOE.

Panels produced with 100 % mate or its mixture with other species presented internal bond strength values above the 0,90 MPa and 0,86 MPa, required by ANSI A208.1 (ANSI 2016) and CS 236- 66 (CS 1968), respectively, for HDP than 0,80 $g\cdot cm^{-3}$ and phenolic bonding. The addition of the mate particles in the panel allowed an increase of 49 %, 112 % and 103 %, respectively, when compared to use of the particles of 100 % pine, 100 % bamboo and the 50 % bamboo and 50 % pine mixture. This is justified by the rounded of the mate particles, which allowed for better accommodation in the pressing process.

The IB values of 100 % bamboo and 100 % pine panels not reached the minimum recommended by ANSI A208.1 (ANSI 2016). There was difficulty in adhered the adhesive to the bamboo particles during the bonding process, due to their chemical constitution since they are being a less polar material, with higher pH and higher extractive content (Soares *et al.* 2017) and also due to its anatomical structure where parenchyma cells predominate (Zheng *et al.* 2020). Among the alternatives, adjustments in the adhesive pH and pre-treatment of the particles may improve the bonding process and, consequently, panel's mechanical properties.

The ANSI A 208.1 standard (ANSI 2016) establishes for Janka hardness a minimum value of 22,7 MPa, and all panels produced exceed this parameter. Janka hardness values between 34,1 MPa and 50,5 MPa in MDP panels (0,63 $g \cdot cm^{-3}$ to 0,71 $g \cdot cm^{-3}$) produced with mixed *Eucalyptus urophylla* and *Schizolobium amazonicum* woods and broom fibers (*Sida* spp.), with 6 % or 8 % urea-formaldehyde (Bianche *et al*. 2012).

Mixture modeling

In Table 4 were presented the simplified equations in which the non-significant coefficients were discarded by Student's t-test for the mechanical properties of HDP panels.

For thickness swelling (TS) and water absorption (WA), the linear coefficients were all significant and different and the quadratic interaction coefficients were negative in the mixtures of 50 % bamboo with 50 % matt and 50 % bamboo with 50 % pine, showing that the mixture of bamboo with the other species improved these properties. The cubic interaction coefficient was not significant for TS and was significant and positive for WA, so the mixture of the three species contributed to a greater water absorption of the panels.

Table 4: Simplified equations for HDP physical and mechanical properties, using only the "t" test significant coefficients.

Equations Physical and Mechanical properties	F	R^2
$TS = 0{,}309 \cdot B + 0{,}133 \cdot M + 0{,}205 * P - 0{,}004 \cdot B \cdot M + 0{,}001 \cdot M \cdot P - 0{,}004 \cdot B \cdot P$	4145,18	0,990
$WA = 0{,}450 \cdot B + 0{,}433 \cdot M + 0{,}249 \cdot P - 0{,}003 \cdot B \cdot M + 0{,}003 \cdot M \cdot P - 0{,}001 \cdot B \cdot P + 2{,}28 \cdot 10 - 5 \cdot B \cdot M \cdot P$	1128,37	0,901
$MOR = 0{,}142 \cdot B + 0{,}120 \cdot M + 0{,}195 \cdot P + 0{,}001 \cdot B \cdot M + 0{,}001 \cdot B \cdot P + 5{,}13 \cdot 10^{-5} \cdot B \cdot M \cdot P$	966,76	0,804
$MOE = 23{,}675 \cdot B + 15{,}499 \cdot M + 26{,}150 \cdot P + 0{,}066 \cdot B \cdot M + 0{,}046 \cdot M \cdot P + 0{,}084 \cdot B \cdot P + 0{,}003 \cdot B \cdot M \cdot P$	639,92	0,709
$TS = 0{,}005 \cdot B + 0{,}009 \cdot M + 0{,}007 \cdot P + 4{,}67 \cdot 10^{-6} \cdot B \cdot P + 7{,}73 \cdot 10^{-6} \cdot B \cdot M \cdot P$	645,00	0,907
$JH = 0{,}402 \cdot B + 0{,}446 \cdot M + 0{,}533 \cdot P + 0{,}005 \cdot B \cdot M + 0{,}002 \cdot M \cdot P + 0{,}006 \cdot B \cdot P$	3316,41	0,931

F = calculated F value; R^2 = coefficient of determination; B = Bamboo ratio; M = Mate ratio; P = Pine ratio; TS = Thickness swelling 24 h.; WA = Water absorption 24 h.; MOR = modulus of rupture in static bending; MOE = modulus of elasticity in static bending; IB = Internal bond strength; JH: Janka hardness. Significant values at the Tukey test at 5 % probability of error.

The MOR of the panels produced with pine particles was significantly higher in relation to bamboo and mate. The coefficients of quadratic and cubic interactions were significant and positive, except for the mixture between mate and pine.

The MOE of pine and bamboo panels presented the highest estimates, being significantly higher in relation to those of mate. The coefficients of quadratic interactions were significant and positive for the mixtures 50 % bamboo with 50 % mate and 50 % bamboo with 50 % pine. The cubic interaction was significant and positive.

Internal bond strength presented higher estimates for mate compared to bamboo. The coefficient of quadratic interaction was significant and positive in the mixture of 50 % bamboo and 50 % pine and there was triple and positive interaction.

For Janka hardness the highest estimates were observed for pine. The coefficients of quadratic interactions were all significant and positive. In the mixture of the three particle types, the triple interaction was not significant.

In general, it was found that all significant interactions contributed to improve the properties of the panels, except for the cubic interaction of water absorption, demonstrating that the particles mixture was better for the panels in relation to the properties sum of each species. The variations caused by the characteristics of each species in the HDP physical and mechanical properties were showed in Figure 3. The ternary graphs of the panel`s mechanical properties as a function of each species proportion allows to visualized the effect of each pure species and the interactions between them.

For static bending strength and stiffness (Figures 3a and 3b), the use of pine particles provided the highest mean values, both pure and mixed with bamboo and triple mixed. This effect was more pronounced in MOR than in MOE and was attributed to the higher compaction ratio provided by pine particles. In addition, pine wood has physical and chemical characteristics that provide better bonding than bamboo and mate.

In Figure 3c it is shown that the lowest internal bond strength values occurred in the pure bamboo and pine panels and their corresponding mixture, however, the maximum values occurred in the mixture of the three components. This shows that mixing particles with different shapes and chemical and physical characteristics facilitated the bonding process.

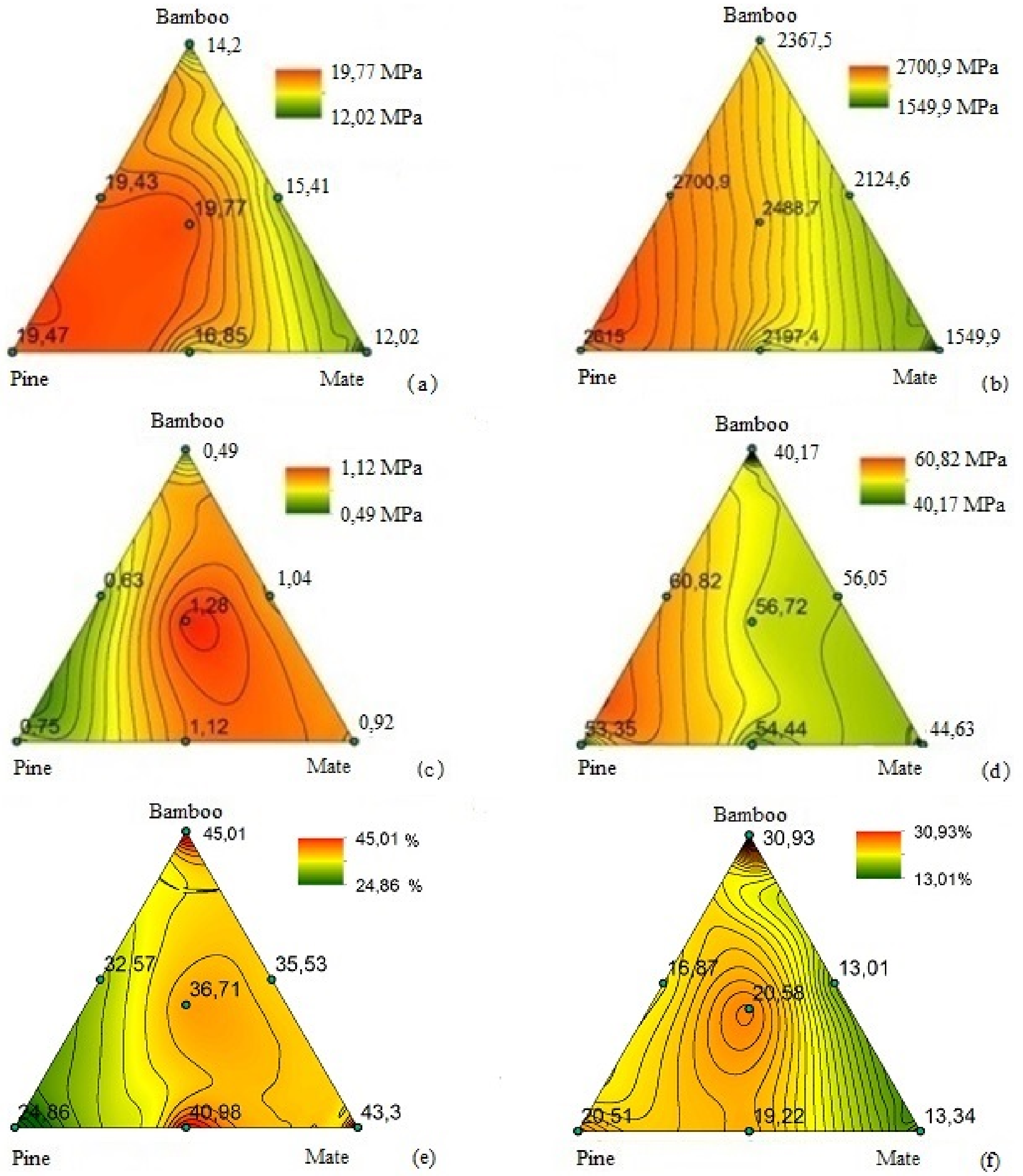

Figure 3: Modulus of rupture in static bending (a), Modulus of elasticity in static bending (b), Internal bond strength (c), Janka hardness (d), Water absorption (e) and Thickness swelling (f) of High-Density Particleboard (HDP).

In Figure 3d it is observed that all mix compositions provided panels with Janka hardness higher than the 100 % pine panel. Highlight that the panels produced with 100 % bamboo and 100 % mate presented the lowest hardness values, but when in mixtures they reached values equivalent to pine panels. Moreover, although the 100 % bamboo panel presented the lowest value, when produced in mixture with pine presented the highest Janka hardness value.

In Figures 3e and 3f it can be seen that the bamboo panels presented high percentages, both for thickness swelling and for water absorption. This can be attributed to the fact that the bamboo fiber did not provide a good bonding, allowing greater water absorption and increased dimensions. For mate, there was reduced thickness swelling, but water absorption is high. In relation to pine, it was found the lowest value for water absorption.

CONCLUSIONS

The produced panels, in the different mixtures, presented satisfactory mechanical properties and reached the ANSI A208.1 specification. The use of pine particles contributed mainly to increase the panel's strength and stiffness, while the use of mate particles facilitated bonding.

The mixture modeling showed that the cubic model explains the water absorption, bending strength (MOR and MOE) and internal bond strength, while the quadratic model explains the thickness swelling and hardness. In general, it was found that the species mix was more advantageous than using each species individually, which was attributed to the different physical and chemical characteristics of each species.

The results allow us to classify the produced panels with potential for use as structural elements, floors and other applications requiring medium to high mechanical strength.

ACKNOWLEDGEMENTS

This work was carried out with the support of the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior - Brasil (CAPES) - Código de financiamento 001.

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