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FEASIBILITY OF USING *Zanthoxylum ekmanii* (Urb.) Alain FOR PLYWOOD PANEL PRODUCTION

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Resumo

Produção de painéis compensados da espécie Zanthoxylum ekmanii (Urb.) Alain. A demanda por produtos à base de madeira pela sociedade é crescente, pois proporcionam menor restrição de uso, apresentam alta resistência e confiabilidade de utilização. No entanto, devido ao desconhecimento tecnológico ainda é restrito o número de espécies amazônicas utilizadas dentro das indústrias madeireiras, por isso conhecer o potencial de uso dessas espécies é de suma importância para o desenvolvimento do setor florestal. Nesse contexto, o objetivo deste trabalho foi avaliar as propriedades físicas e mecânicas de painéis compensados composto com lâminas da espécie *Zanthoxylum ekmanii* (limãozinho) e sua combinação com *Pinus* sp., utilizando dois tipos de resina na colagem ureia-formaldeído e fenol-formaldeído. Foram produzidos painéis com 15 mm de espessura, nas dimensões 50 x 50 cm e com gramatura de 360 g/m^2 em linha simples. Os testes físicos e mecânicos foram realizados de acordo com as especificações descritas na norma brasileira. Os resultados foram comparados aos requisitos do catálogo técnico da ABIMCI e da norma NBR ISO 12466-2. Os painéis homogêneos e intercalados com *Z. ekmanii* avaliados neste estudo, apresentaram resultados de absorção de água, inchamento em espessura, recuperação em espessura, cisalhamento da linha de cola e de flexão estática paralela e perpendicular às fibras da capa estatisticamente iguais ou superiores em relação à espécie referencial de *Pinus* sp. Portanto, os painéis produzidos com *Z. ekmanii* apresentam boa qualidade na colagem com resinas UF e FF, e potencial na produção de painéis compensados, homogêneo, ou em combinação com *Pinus* sp.
Palavras-chave: Limãozinho; Compensado; Composição de lâminas; ureia-formaldeído; fenol-formaldeído.

Abstract

The demand for wood-based products by society is growing because these products are less restrictive, highly resistant, and reliable in use. However, due to a lack of technological knowledge, the number of Amazonian species used within the timber industries is still limited. Therefore, knowing the potential use of these species is important to the forestry sector's development. In this context, this study aimed to evaluate the physical and mechanical properties of plywood panels produced with veneer sheets of *Zanthoxylum ekmanii* (lemon) and its combination with *Pinus* sp., using the urea-formaldehyde (UF) and (PF) phenol-formaldehyde resins. Panels were produced with 15 mm, dimensions of 50 x 50 cm, and a grammage of 360 g/m^2 in a single line. Physical and mechanical tests were performed by the specifications described in the Brazilian standards. The results were compared to the requirements of the ABIMCI technical catalog and the NBR ISO 12466-2 standard. The homogeneous and combined panels with *Z. ekmanii* evaluated in this study presented results of water absorption, thickness swelling, compression set recovery, glue line shear strength, and parallel and perpendicular static bending statistically equal to or superior to the reference species (*Pinus* sp.). Therefore, the panels produced with *Z. ekmanii* have good quality in bonding with UF and PF resins. This species can be used in the production of homogeneous plywood or combination with *Pinus* sp.
Keywords: Lemon; Cleared; veneer composition; urea-formaldehyde; phenol-formaldehyde.

INTRODUCTION

The production of wooden panels is important for the Brazilian economy, mainly in the development of new value-added products that the furniture and construction sectors have been demanding, along with the creation of jobs.

Over the years, the panel industry gradually increased its production as a result of the scarcity and price of sawn wood. This scenario is related to the search for efficient alternative uses for trees and better-quality panels (IRLE *et al.* 2012).

Among the wood panels produced in Brazil, the volume of plywood panels produced in 2020 was 2.7 million m^3, of which 40% were produced with tropical wood, and the other 60% with reforestation wood from the South and Southeast regions, mainly pine (FAO, 2020). It is worth mentioning that Brazil is the 7th largest producer of plywood panels. These panels are considered of great importance for the Brazilian economy, surpassing 700 million dollars annually, with the main destination for the European continent (SNIF, 2020).

Plywood is a panel made of wood veneers glued together with phenolic resins (external use) or urea-formaldehyde (internal use). The veneers are usually glued in an odd number (3, 5, 7, 9, or 11 layers), one on top of the other with the fibers of each veneer oriented perpendicular to the adjacent one.

In general, the use of plywood panels by industries is related to their excellent dimensional stability, greater added value, and the possibility of optimizing the use of this raw material. The elimination of reducing factors of wood resistance, the panels with larger dimensions, the possibility of mixing different species of wood in the same panel resulting in production flexibility, selecting and using blades with knots and even cracks in the core, and higher quality blades in the cover provide a cost reduction and, consequently, in the price of the final product (COSTA et al., 2020).

In this way, with the increase in demand for wood products with better quality, it is important to study new species and learn how they behave with the use of different resins, aiming at expanding the use of plywood panels in both external and internal environments by society in general. The study of the species *Zanthoxylum ekmanii* (Urb.) Alain, commonly known as "little lemon", is essential to understand its potential in the production of plywood panels.

Therefore, studying the physical and mechanical properties of the plywood panel is necessary to improve knowledge regarding its potential use, since the differences between the properties of the wood are present both intra and interspecifically in the tree (CORREA et al., 2020).

In this context, this study aimed to evaluate the physical and mechanical properties of plywood panels produced with veneers of *Zanthoxylum ekmanii* wood and its combination with *Pinus* sp., using two types of resin for bonding, urea-formaldehyde, and phenol-formaldehyde.

MATERIALS AND METHODS

The wood veneers of *Zanthoxylum ekmanii* (1.5 mm) and *Pinus* sp. (2.1 and 2.7 mm) used in this research had an average density of 0.42 g/cm³ and 0.46 g/cm³, respectively. They were obtained by unwinding the log around a defoliator at laminating industries located in Itinga (Pará) and Lages (Santa Catarina), Brazil, in that order. For bonding the veneer sheets, two resins were used, urea-formaldehyde (UF) and phenol-formaldehyde (FF). The resins presented solid contents of 67.34% and 51.31%, pH of 8.23 and 11, and Ford-cup viscosity of 444.75 cP and 477.20 cP, respectively.

First, the slides were sectioned with dimensions of 50 x 50 cm and dried in an oven with forced air circulation until the average final moisture content reached 12% (cover) and 8% (core).

The plywood panels were produced on a laboratory scale, according to the experimental plan shown in Table 1.

Table 1. Experimental plan used for producing the plywood panels.
Tabela 1. Plano experimental utilizado para produção dos painéis compensados.

Treatment	Resin	Panel composition
T1	Urea-formaldehyde	*Pinus* sp. (Pi)
T2		*Z. ekmanii* (Zek)
T3		Zek + Pi +Pi + Pi + Zek
T4		Pi + Zek + Zek + Zek + Pi
T1	Phenol-formaldehyde	*Pinus* sp. (Pi)
T2		*Z. ekmanii* (Zek)
T3		Zek + Pi +Pi + Pi + Zek
T4		Pi + Zek + Zek + Zek + Pi

Treatments 1 and 2 were composed of all veneers of the same species. In treatments 3 and 4, the panels were assembled by intercalating the blades (cover or core) of the species *Z. ekmanii* with *Pinus* sp. For each treatment, there were 3 repetitions with a thickness of 15 mm, totaling 24 plywood panels. Urea-formaldehyde and phenol-formaldehyde resins were used for bonding, according to the formulations shown in Table 2.

Table 2. Resin formulations used for producing the plywood panels.
Tabela 2. Formulações da resina utilizada na produção dos compensados.

Formulation	Resin	Wheat	Water	Catalyzer
Urea-formaldehyde	100	20	20	1.7
Phenol-formaldehyde	100	15	15	-

The resin was applied manually with a brush on the surface of the sheets, according to the established grammage of 360 g/m^2, in a single line.

The parameters used in the pressing cycle were: temperature of 110°C, specific pressure of 12 kgf/cm² and pressing time of 15 minutes for bonding with urea-formaldehyde, and temperature of 140°C, specific pressure of 12 kgf/ cm² and pressing time of 15 minutes for bonding with phenol-formaldehyde. After pressing, the panels were placed in a climatic chamber with a temperature of 20 ± 2°C and relative humidity of 65 ± 3%, until they reached a constant mass and balanced humidity of 12%.

After packaging, the specimens were removed for physical and mechanical tests. The tests were performed according to the procedures described in the Brazilian Standards NBR 9484:2011a (Moisture content), NBR 9485:2011b (Apparent specific mass), NBR 9486:2011c (Water absorption), NBR 9535:2011d (Thickness swelling and Compression set recovery), NBR 9533:2012 (Parallel and perpendicular bending), and NBR 12466:2012 (Glue line shear strength).

The Shapiro-Wilk test was used to verify the normal distribution of data, and the Bartlett test was used to assess the homogeneity of variance. Finally, after meeting these assumptions for the data set, statistical analysis and the Scott-Knott test were performed at a probability level of 95%, using the Completely Randomized Design (CRD).

RESULTS

Panels glued with urea-formaldehyde resin

Evaluation of the physical properties

The average values referring to moisture content, apparent specific mass, water absorption, thickness swelling, and compression set recovery of the panels for each treatment are shown in Table 3.

Table 3. Physical properties of the plywood panels glued with urea-formaldehyde resin in different compositions.
Tabela 3. Propriedades físicas dos painéis compensados produzidos com resina ureia-formaldeído em diferentes composições.

Treatment	MC %	ASM (g/cm^3)	WA24h %	TS24h (%)	SR24h (%)
T1-Pi	11.30 b* (3.56)	0.63 a (4.27)	58.52 a (16.36)	5.63 a (12.09)	9.30 a (4.05)
T2-Zek	12.28 a (3.28)	0.54 c (3.79)	25.59 c (8.17)	3.43 b (17.17)	8.79 a (3.68)
T3-Zek+Pi	11.36 b (4.13)	0.59 b (5.89)	56.74 a (10.72)	5.10 a (18.58)	8.20 a (19.53)
T4-Pi+Zek	12.10 a (4.93)	0.54 c (5.56)	41.61 b (6.57)	3.76 b (16.35)	7.96 a (10.76)

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; MC: Moisture content; ASM: Apparent specific mass; WA24h: water absorption; TS24h: Thickness swelling; SR24h: Compression set recovery. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance with their respective coefficients of variation (%).

Evaluation of the mechanical properties of the panels

Parallel and perpendicular static bending

The average values of the modulus of elasticity (MOE) and modulus of rupture (MOR), which were measured parallel and perpendicular to the cover fibers in the static bending tests for the plywood panels of each treatment, are presented in Table 4.

Table 4. Modulus of elasticity and rupture in static bending of plywood panels produced with urea-formaldehyde resin in different compositions.
Tabela 4. Módulo de elasticidade e de ruptura em flexão estática dos painéis compensados produzidos com resina ureia-formaldeído em diferentes composições.

Treatment	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)
	Parallel		Perpendicular	
T1-Pi	10818.87 a* (31.20) [1]	75.11 a (26.65)	5725.70 b (19.27)	42.63 a (16.71)
T2-Zek	12640.42 a (9.63)	74.39 a (4.25)	8530.86 a (6.45)	54.81 a (11.90)
T3-Zek+Pi	12839.71 a (8.93)	70.79 a (20.40)	9263.81 a (10.88)	57.96 a (33.86)
T4-Pi+Zek	12173.60 a (13.94)	72.07 a (23.87)	5535.32 b (6.55)	40.41 a (16.46)

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; MOE: Modulus of elasticity; MOR: Modulus of rupture. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance. [1]: The values in parentheses are the coefficient of variation (%).

The mean MOE and MOR parallel to the fibers ranged from 10818.87 to 12839.71 MPa (T1 and T3) and from 70.79 to 75.11 MPa (T3 and T1), respectively.

Glue line shear strength

The treatments average values of glue line shear strengths for the wet test of the panels are shown in Table 5.

Table 5. Glue line shear strength.
Tabela 5. Resistência da linha de cola aos esforços de cisalhamento.

Treatment	GSS wet test (MPa)
T1-Pi	3.04 (30.93) b
T2-Zek	4.28 (18.45) a
T3-Zek+Pi	3.36 (22.42) b
T4-Pi+Zek	2.14 (20.96) c

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; GSS: Glue line shear strength. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance with their respective coefficients of variation (%).

The mean values of glue line shear strength ranged from 2.14 MPa (T4) to 4.28 MPa (T2).

Panels glued with phenol-formaldehyde resin

Evaluation of the physical properties

The average results of moisture content, apparent specific mass, water absorption, thickness swelling, and compression set recovery of the panels for each treatment are shown in Table 6.

Table 6. Physical properties of the plywood panels produced with phenol-formaldehyde resin in different compositions.
Tabela 6. Propriedades físicas dos painéis compensados produzidos com resina fenol-formaldeído em diferentes composições.

Treatment	MC %	ASM (g/cm^3)	WA24h %	TS24h (%)	SR24h (%)
T1-Pi	11.08 a* (6.34)	0.52 b (2.81)	77.52 a (7.99)	5.84 a (8.48)	8.52 a (8.87)
T2-Zek	11.22 a (5.54)	0.54 a (4.54)	45.43 c (13.14)	4.84 b (23.57)	7.95 a (14.84)
T3-Zek+Pi	11.10 a (6.21)	0.55 a (5.44)	54.64 b (12.44)	6.06 a (13.35)	9.35 a (20.76)
T4-Pi+Zek	11.18 a (5.81)	0.51 b (4.94)	53.90 b (4.19)	3.83 b (14.05)	7.38 a (10.38)

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; MC: Moisture content; ASM: Apparent specific mass; WA24h: water absorption; TS24h: Thickness swelling; SR24h: Compression set recovery. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance, with their respective coefficients of variation (%).

Evaluation of the mechanical properties of the panels

Parallel and perpendicular static bending

The average values of modulus of elasticity (MOE) and modulus of rupture (MOR), which were measured parallel and perpendicular to the cover fibers in the static bending tests for the plywood panels of each treatment, are shown in Table 7.

Table 7. Modulus of elasticity and modulus of rupture in static bending of the plywood panels produced with phenol-formaldehyde resin in different compositions.
Tabela 7. Módulo de elasticidade e de ruptura em flexão estática dos painéis compensados produzidos com resina fenol-formaldeído em diferentes composições.

Treatment	MOE (MPa)	MOR (MPa)	MOE (MPa)	MOR (MPa)
	Parallel		Perpendicular	
T1-Pi	9066.60 b* (15.78) [1]	54.65 a (10.62)	4950.54 c (13.37)	34.71 b (30.13)
T2-Zek	12110.43 a (28.32)	76.80 a (25.37)	4732.66 c (10.16)	31.53 b (9.34)
T3-Zek+Pi	12127.68 a (11.28)	67.86 a (19.06)	7959.64 a (17.03)	51.09 a (7.32)
T4-Pi+Zek	9152.93 b (5.38)	60.71 a (5.16)	6311.95 b (6.94)	49.72 a (2.11)

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; MOE: Modulus of elasticity; MOR: Modulus of rupture. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance. [1]: The values in parentheses are the coefficient of variation (%).

The mean MOE and MOR parallel to the cover fibers ranged from 9066.69 to 12127.68 MPa (T1 and T3) and from 54.65 to 76.80 MPa (T1 and T2), respectively.

Glue line shear strength

The average glue line shear strengths of the wet and boiling tests for each treatment are shown in Table 8.

Table 8. Glue line shear strength.
Tabela 8. Resistencia da linha de cola aos esforços de cisalhamento.

Treatment	GSS wet test (MPa)	GSS boiling test (MPa)
T1-Pi	1.34 (17.82) b	1.31 (24.75) b
T2-Zek	3.77 (16.54) a	3.64 (19.86) a
T3-Zek+Pi	1.69 (16.16) b	1.64 (11.70) b
T4-Pi+Zek	1.56 (18.81) b	1.55 (11.50) b

Pi: *Pinus* sp.; Zek: *Zanthoxylum ekmanii*; GSS: Glue line shear strength. *: Means followed by equal lowercase letters in the columns do not differ statistically by the Scott-Knott test at 5% significance with their respective coefficients of variation (%).

DISCUSSION

Panels glued with urea-formaldehyde resin

Evaluation of the physical properties

As shown in Table 3, moisture contents were close to what was expected, considering that the treatments were kept in a climate-controlled chamber at a humidity of 12%. The PNQM technical catalog (2009) determines that the maximum moisture content of the panels is 18%, so the results are under the mandatory requirement.

The apparent specific mass results indicate that there was a significant effect between the treatments. The panels produced with all the sheets and core of *Pinus* sp. (T1 and T3), despite being different from each other, showed an average value that was statistically higher than the panels produced only with the sheets and core of *Z. ekmanii* (T2 and T4). This may be due to the characteristics of the species, as well as the manufacturing conditions of the panels, such as humidity, temperature, and pressure. Kazmierczak et al. (2017) report that the pressing pressure causes a reduction in the thickness of the individual sheets or the panels that they comprise, and also it causes an increase in the specific mass of the plywood when compared to the wood that originated it.

Regarding the water absorption (24h), there was also a significant difference between the produced panels. The lowest average WAs were obtained for the homogeneous and combined treatments of *Z. ekmanii*, and the treatment that absorbed water the most was the pure *Pinus* sp. Treatment. Such behavior can be explained by the anatomical characteristic of the *Z. ekmanii* species. Even presenting a density (0.42 g/cm³) similar to the *Pinus* sp. (0.46 g/cm³), it has smaller dimensions and a lower frequency of vessels. Iwakiri (2005) and Silva et al. (2020) highlight in their studies that the anatomy of wood is directly related to the dimensions, arrangement, and frequency of cell cavities, inferring the porosity, permeability of the wood and, consequently, the penetration of resins during the production of the panels.

Similar to the water absorption (24h), the plywood panels produced and combined with *Z. ekmanii* showed the lowest TSs and SRs, however, there was a significant difference in thickness swelling between the treatments. Costa et al. (2020), when working with plywood panels of *Schizolobium amazonicum*, found an average thickness swelling of 4.56%. The TS of a panel is related to the hygroscopic characteristics of the wood and the release of compressive stresses originating in pressing (MELO, 2013).

Evaluation of the mechanical properties of the panels

Parallel and perpendicular static bending

There was no significant difference between the homogeneous and combined treatments, as shown in Table 4. However, the highest means of parallel MOE in absolute terms were presented by the pure panels and the ones with the inclusion of *Z. ekmanii* in their composition. For the MOR, the means were lower concerning the pure *Pinus* sp. panels, however, the homogeneous *Z. ekmanii* panels presented higher values concerning the panels with also *Pinus* sp. in its composition. These results were superior to the ones obtained by Matos et al. (2019) for panels of *Pinus oocarpa* (Po) and *Schizolobium amazonicum* (Sa) with different compositions. The authors found mean values of 2154 MPa (100% Sa), 3610 MPa (Sa core), 3635 MPa (Sa cover), and 4907 MPa (100% Po) for parallel MOE. They also claimed average values of 22.48 MPa (100% Sa); 28.95 MPa (Sa cover); 33.43 MPa (Sa core) and 40.28 MPa (100% Po) for parallel MOR.

The mean MOEs and MORs perpendicular to the cover fibers ranged from 5535.32 to 9263.81 MPa (T4 and T1), and from 40.41 to 57.96 MPa (T4 and T3), respectively.

Based on the perpendicular MOE and MOR results, it appears that there was a significant difference only for the perpendicular MOE. The values of the homogeneous panels and the ones with *Z. ekmanii* sheets for perpendicular MOE were significantly superior to the other treatments (T1 and T4). Although there was no statistical difference, the highest values can also be verified for the perpendicular MOR for the same compositions. These results were reasonable when compared to the literature. Iwakiri et al. (2012), evaluating the mechanical properties of ureic plywood with a grammage of 360 g/m^2, found values of 2769.17 MPa (perpendicular MOE) and 34.97 MPa (parallel MOE), and 3474.22 MPa (perpendicular MOE) and 42.17 MPa (perpendicular MOR), for *Pinus* sp. and *Eucalyptus* sp., respectively.

In general, variations in values may be due to the wood species, the weight of the glue, and the plywood characteristics, such as thickness and number of veneer sheets.

In addition, compared to the ABIMCI technical catalog (2007), it was verified that the average values obtained with the panels produced with *Z. ekmanni* and *Pinus* sp. meet the minimum requirements of MOE and MOR in both senses of tests established for 15 mm thick commercial Brazilian pine panels, whose average values vary in the range of 6774.74 MPa and 38.71 MPa, for parallel MOE and MOR, respectively, and 3305.442 MPa and 28.91 MPa, for perpendicular MOE and MOR, in that order. Even though the panels were produced with ureic glue, the results in this study presented values higher than those mentioned, inferring a product of satisfactory resistance.

Glue line shear strength

Table 5 shows the results of the wet test. The homogeneous panels of *Z. ekmanii* presented mean glue line shear strengths (GSSs) that were statistically superior to the other compositions. However, all values are above the minimum allowed by the NBR ISO 12466-2 (2012) (1 MPa), which rules out the wood failure mandatory requirements.

According to Iwakiri (2005), the performance of the glue line is influenced by the composition of the resin and the anatomical, chemical, and physical characteristics of the wood for both sides of the veneer sheets. The mean GSS values in this study were higher than those found by Iwakiri et al. (2012) in ureic plywood panels of some species of *Pinus* sp. and *Eucalyptus* sp. These authors presented glue line strength values ranging from 0.85 to 1.59 MPa and 1.25 to 2.39 MPa, respectively. In another research, Cunha et al. (2016) presented ureic plywood panels of *Pinus taeda* with mean GSS values of 0.93 MPa.

Overall, the results reflect satisfactory glue line shear strengths of the panels of *Z. ekmanii* glued with urea-formaldehyde, even in the humid test. This indicates that the evaluated compositions can be destined for interior and intermediate use, considering the manufacturing conditions employed in this study.

Panels glued with phenol-formaldehyde resin

Evaluation of the physical properties

There was no significant effect between treatments for moisture content, which presented an average of 11.14% (Table 6). This indicates that the period the panels stayed inside the climatic chamber before the tests were adequate. Also, the moisture contents are under the maximum mandatory requirement, which is 18% (ABIMCI, 2009).

Regarding the apparent specific mass (ASM), there were significant differences between the compositions. The homogeneous plywood panels and those with a *Z. ekmanii* layer (T2 and T3) were statistically superior to the homogeneous panels and those with a *Pinus* sp. layer. The average ASMs of all compositions are within the range established by ABIMCI (2007) for commercial panels of *Pinus* sp. and outer type with a thickness of 15 mm, which is between 0.51 and 0.59 g/cm^3.

In terms of water absorption (WA24h), there was also a significant difference between the panels produced with phenol-formaldehyde. The compositions with *Z. ekmanii* presented the lowest WA averages, both in homogeneous and combined conditions. The one that most absorbed water was the pure *Pinus* sp. composition. The WA results in this research are lower than those obtained by Machado et al. (2018), who obtained the following average numbers for the homogeneous and combined panels of paricá (86.29%), embaúba (71.53%), paricá/embaúba (78.31%), embaúba/paricá (69, 02%) and *Pinus* sp. (66.45%). Moreover, Albino et al. (2011), who produced plywood from *Toona ciliata* and combinations with *Pinus* sp. also found higher values, ranging from 56.67 to 84.67%.

The lowest thickness swellings (TS24h) of the panels glued with phenol-formaldehyde were obtained for the homogeneous ones and those with *Z. ekmanii* core. As for the compression set recovery (SR24h), there were no significant differences between the different panel compositions. Iwakiri et al. (2001), working with plywood panels produced with five species of tropical pine bonded with phenol-formaldehyde resin, found mean values of 4.85% to 7.75% and 0.79% to 2.17%, for TS and SR, respectively. Furthermore, Machado et al. (2018), studying homogeneous and combined panels of the Amazonian paricá and embaúba species, found mean values of 5.44% to 6.48% for TS and 0.55% to 1.21% for SR, which are similar to the ones found in this study, except for SR.

Concerning the physical properties of the panels, both species present approximate densities of 0.42 g/cm^3 and 0.46 g/cm^3, respectively. However, the lowest numbers were observed for the homogeneous *Z. ekmanii* or combined with *Pinus* sp. This behavior can be associated with the smaller dimensions and lower frequency of vessels of this species, which favored a lower absorption and a swelling in panel thickness. In general, the homogeneous panels combined with the *Z. ekmanii* were more resistant than the homogeneous panels of *Pinus* sp., therefore, they would have better performance for outdoor use.

Evaluation of the mechanical properties of the panels

Parallel and perpendicular static bending

The results in Table 7 indicate that there was a significant difference only for the parallel MOE. Note that the mean values of the homogeneous panels and those with the cover of *Z. ekmanii* (T2 and T3) for the parallel MOE were significantly higher than the other compositions (T1 and T4). For the parallel MOR, no differences were found, however, the highest values in absolute terms were also obtained from treatments T2 and T3.

Machado et al. (2018), working with homogeneous and combined panels of *Pinus elliottii* (Pi), paricá (P) and embaúba (E), found mean values of 3784.50 MPa (Pi), 4915.17 MPa (P), 5585.33 MPa (P/E), 6351.83 MPa (E/P), and 7186.50 MPa (E) for parallel MOE. Also, they found mean values of 34.82 MPa (P/E); 34.93 MPa (P); 39.50 MPa (Pi) and 42.53 MPa (E/P), and 47.52 MPa (E) for parallel MOR.

The mean perpendicular MOEs and MORs ranged from 4732.66 to 7959.64 MPa (T2 and T3), and from 31.53 to 51.09 MPa (T2 and T3), respectively.

There was a significant difference between the different compositions of the panels, which infers that the panels with the cover and core of *Z. ekmanii* were significantly superior to the other homogeneous treatments (T1 and T2).

Lima and Pio (2007), studying two Amazonian species bonded with phenol-formaldehyde, obtained means of 7570.01 to 6819.31 MPa (perpendicular MOE) and 55.31 to 55.52 MPa (perpendicular MOR) for *Eperua oleifera* and *Copaifera duckei*, respectively. Therefore, the results of this study presented a pleasing performance when compared with the results presented in the literature for some Amazonian species. Furthermore, the means obtained in this research are higher than the ones mentioned by ABIMCI (2007) for commercial panels of *Pinus* sp. (outdoor type), which are from 4731.64 to 8817.84 MPa (parallel MOE), 25.77 to 51.74 MPa (parallel MOR), 2128.46 to 4482.42 MPa (perpendicular MOE), and 18.03 to 39.69 MPa (perpendicular MOR). Thus, the evaluated panels have good resistance and rigidity characteristics and can be indicated for the production of plywood panels.

Glue line shear strength

Considering the requirements presented by NBR ISO 12466-2 (2012), all treatments reached the specified minimum values of 1 MPa in the wet and boiling tests, as shown in Table 8, which removes the requirements of wood failure.

Regarding the wet test, the averages ranged from 1.34 MPa (T1) to 3.77 MPa (T2). These results infer that the homogeneous panels of *Z. ekmanii* presented, statistically, the best performance of glue line shear strength (GSS). Also, the panels with the cover and core of *Z. ekmanii* presented higher values than the pure panel of *Pinus* sp., in absolute terms. Machado et al. (2018) studied homogeneous and mixed panels of *Pinus elliottii* (Pi), Paricá (P), and Embaúba (E). They found average GSSs in the wet condition of 1.00 MPa (E/P), 1.15 MPa (P), 1.26 MPa (P/E), 1.26 MPa (E), and 1.32 MPa (Pi).

For the most demanding test (boiling and drying cycle), the average GSSs were in the range of 1.31 MPa (T1) to 3.64 MPa (T2). As it happened in the humid condition, the pure panel of *Z. ekmanii* presented, statistically, superior GSSs than the other compositions. Cunha et al. (2016), when evaluating the influence of phenol-formaldehyde resin in the production of plywood panels using *Pinus taeda*, obtained a mean GSS in the boiling test of 1.34 MPa. In another study, Albino et al. (2011) found mean GSSs for phenolic plywood panels of 1.82 MPa (*T. ciliata*), 2.00 MPa (*Pinus* sp./*T. ciliata*), and 1.98 MPa (*T. ciliata*/*Pinus* sp.). These results are similar to the ones found in this study.

In addition, the GSS results obtained in this study are satisfactory and promising when compared to the ones mentioned by ABIMCI (2007) for commercial pine plywood panels in the wet and boiling tests, the mandatory values vary in the range of 0, 88 to 1.96 MPa.

Overall, the homogeneous panels and the ones combined with *Z. ekmanii* presented a better bonding quality with the phenol-formaldehyde resin than the panels of *Pinus* sp., therefore, this species is recommended to produce plywood panels for internal, intermediate, and outside use.

CONCLUSIONS

Based on the results obtained in this research:

- The moisture content of the produced panels meets the mandatory requirements set by ABIMCI for plywood panels.
- There was no influence of the apparent specific mass of the panels on the results of parallel and perpendicular MOE and MOR.
- The results regarding the physical properties indicate the feasibility of using veneer sheets of *Z. ekmanii* in the production of plywood panels.
- The homogeneous panels and the ones combined with *Z. ekmanii* showed suitable glue line shear strengths and static bending when compared to the reference species (*Pinus* sp.).
- The results of glue line shear strength and parallel and perpendicular static bending were compatible with the reference numbers found in the literature for commercial pine panels produced in Brazil.
- Among the evaluated plywood compositions, the homogeneous panels of *Z. ekmanni* presented the best performance.
- The general evaluations of the results indicate that *Z. ekmanii* presents satisfactory physical-mechanical properties and good quality in bonding with urea-formaldehyde and phenol-formaldehyde resins. Therefore, this species has the potential to be used in the production of plywood panels, homogeneous or in combination with *Pinus* sp.

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