Particleboards Manufactured from *Tectona grandis* Wood Waste with Homogeneous and Three-layer Heterogeneous Compositions for Commercial Purposes

Matheus V. de Souza,[a] Sérgio A. M. da Silva,[a] Pedro H. S. Cazella,[a]
Felipe R. Rodrigues,[a] Kely S. Bonfim,[b] Alex O. Sanches,[a] Victor A. De Araujo,[c,]*
Herisson F. dos Santos,[d] Edna M. Pinto,[e] André L. Christoforo,[c] Márcia R. M. Aouada,[b]
Fauze A. Aouada,[b] and Francisco A. R. Lahr [f]

Tectona grandis wood presents decent dimensional stability as well as highly suitable physical and mechanical properties. These characteristics have encouraged the intense usage of this species, which also includes the reuse of wood processing waste for panel production. Using teak wood waste, this study aims to manufacture and evaluate heat-pressed particleboards at 5 MPa and 100 °C, by being glued with castor oil-based polyurethane resin at proportions of 10% for the homogeneous boards and 12% for the heterogeneous solutions. Single-layer (homogeneous) boards were compared with three-layer particleboard specimens (heterogeneous) having the finer particles in the outer layers. The basic density, moisture content, modulus of rupture and modulus of elasticity in the static bending and perpendicular tensile, water absorption, and thickness swelling after 24 h were evaluated to support this comparative study. All the manufactured particleboards met the standardized requirements of performance, thus being very feasible for usage as non-structural boards. When the two different compositions were analyzed, a considerably better performance of the three-layered particleboards was identified when compared to the homogeneous panels.

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*Contact information: a: Department of Civil Engineering, Faculty of Engineering of Ilha Solteira, São Paulo State University "Júlio de Mesquita Filho" (UNESP), 550 Alameda Bahia, Ilha Solteira 15385-000 Brazil; b: Department of Physics and Chemistry, Faculty of Engineering of Ilha Solteira, São Paulo State University "Júlio de Mesquita Filho" (UNESP), 550 Alameda Bahia, Ilha Solteira 15385-000 Brazil; c: Department of Civil Engineering, Federal University of São Carlos (UFSCar), Rodovia Washington Luís, km 235, São Carlos 13565-905 Brazil; d: Federal Institute of Education, Science and Technology of Rondônia, 2717 Avenida Juscelino Kubitschek, Ariquemes 76800-000 Brazil; e: Department of Architecture and Urbanism, Federal University of Rio Grande do Norte (UFRN), 3000 Avenida Senador Salgado Filho, Natal 59066-800 Brazil; f: Department of Engineering of Structures, School of Engineering of São Carlos, University of São Paulo (USP), 400 Avenida Trabalhador Sãocarlense, São Carlos 13564-002 Brazil; *Corresponding author: va.araujo@unesp.br*

INTRODUCTION

Popularly known as teak, *Tectona grandis* is a tall woody tree native to Asian rainforests. According to Figueiredo and Sá (2015), this wood is used in the shipbuilding industry due to its high resistance to the action of seawater, rain, cold, and heat.

In addition to having very interesting physical properties, teak wood has good dimensional stability and average hardness, being easily machined (Paes *et al*. 2015). Despite the incipient presence in planted forests in Brazil, teak is still not commercially applied for the domestic production of timber houses (De Araujo *et al.* 2017, 2021). Thereby, there is a good opportunity for it to be commercially developed.

Teak wood has narrow and clear sapwood and bright brown heartwood (Pimentel *et al*. 2008). This wood species contains latex and a natural preservative (tectoquinone), which offer greater durability and dimensional stability as well as lower water absorption (Garcia and Marinonio 2016). A greater volume of teak wood per area may be obtained through a larger spacing, without visible losses in its mechanical properties (Lima *et al.* 2011).

Throughout the complete life cycle of teak, approximately 60% of its material, *e.g.*, thin trunks and branches, becomes waste and remains in the forests, as confirmed by Lima (2016), through an estimated volume of 250 m^3/ha. These residues are applied for energy generation, biomass, and animal lining, as cited by Cassilha *et al.* (2004), and therefore it is worth noting the lack of studies on the reuse of teak wood waste in the production of particleboards with respect to the potential of its physical-mechanical properties.

Shavings are industrial residues generated by the planing of solid lumber, which may be used, after their homogenization and reduction, for particleboard production (Da Silva 2018), being that the granulometry range commonly requires chips ranging from 2.00 to 6.00 mm, as mentioned by Alves (2013).

Adhesives represent most of the manufacturing costs of wood-based composites (Iwakiri 2005). Currently, 90% of the resins applied for panel production using dried processes are based on urea-formaldehyde and phenol-formaldehyde (Maloney 1993; Pizzi 1994). However, castor oil-based polyurethane resin has emerged as an excellent alternative for composites, and Araújo (1992) and Wechsler *et al*. (2013) suggest that it is a biomass-derived product that is biodegradable and has lower pollution emissions. The relevant potential of castor-oil based polyurethane resin is evidenced by the gluing of different lignocellulosic raw materials, *e.g.*, bamboo to bamboo (Jose and Beraldo 2010; Zaia *et al.* 2015), wood to wood (Ferro *et al.* 2014), and wood to bamboo (De Almeida *et al.* 2017). In contrast, its industrial use is still globally limited, justifying further studies.

Panels are distinguished according to particle distribution, as heterogeneous ones have a random distribution of particles and homogeneous panels, featured as a multi-layered product, are differed by layers with dissimilar granulometries (Iwakiri 2005).

Many studies have regarded the application of castor oil-based polyurethane resin for particleboard production, for example, in single- and multiple-layer panels (Iwakiri *et al.* 2012; Bertolini *et al.* 2014; Bueno 2015; Fiorelli *et al.* 2019; Brito *et al.* 2020; Da Silva *et al.* 2021), mixed with residues or lignocellulosic products (Cravo *et al*. 2015; Gava *et al*. 2015; Buzo *et al*. 2020; Sugahara *et al*. 2020; Bispo *et al*. 2022). The market cost of this resin is the main barrier cited by these authors, but such a condition might be reversed through the intensification of commercial applications of castor oil-based resins.

From these perspectives, this study aims to evaluate two particleboard types, *i.e.*, homogeneous and heterogeneous compositions, to verify their performance in terms of satisfying the standardized requirements of particleboards manufactured *via* the reutilization of *Tectona grandis* wood waste, as well as to investigate the possible differences in their physical-mechanical properties according to their compositions.

EXPERIMENTAL

Materials

A 24-year-old tree was collected at the Experimental Farm of the São Paulo State University "Júlio de Mesquita Filho", Ilha Solteira city, Brazil. The particle-shaped waste of *Tectona grandis* was collected from the waste of the sawmilling process.

Castor-oil based polyurethane resin was used to glue the wooden particles, being purchased from its manufacturer (IMPERVEG®, Aguaí, Brazil). Its two components were polyol and pre-polymer, which were formed by a 1 to 1 proportion. According to product label, this material has a fluid consistency, greenish color, toxic gas free, with mass losses with temperatures above 210 °C, and 20-minute reaction after the mixture of components.

Methods

After collection, the teak wood logs were processed in a thickness planer, that is, at the condition of moisture saturation of fibers. Wooden particles (chips) were obtained and dried in an oven at a temperature of 70 °C ± 2 °C to reach a 2% to 3% moisture content, as performed by Klimek *et al.* (2016) and Borysiuk *et al.* (2019).

Subsequently, these particles were processed in a knife-mill with #10-mm sieves. Milled particles were classified according to the ABNT standard NBR NM 248 (2003).

Next, the characterization by the moisture content was carried out using the ABNT standard NBR 9939 (1987). The moisture content was tested to verify the dried mass, every 2 h, to measure the weight and obtain a dried mass variation of less than 0.1%. The stove was controlled to a temperature of 103 °C ± 2 °C for 24 h.

Before panel production, the last stage also included the particle density test of teak wood to measure the compression ratio, which was adapted from the ABNT NBR 6457 and NBR 6458 standard documents (ABNT 2016, 2017); the test uses a pycnometer (#2) calibrated to 500 milliliter anhydrous ethyl alcohol (99.3 °C - INPM) and 10 grams of teak wood, and a thermometer with 0.1 °C graduation at -10 °C to 100 °C interval.

Sequentially, homogeneous panels were produced without uniformity of the particle sizes, which were randomly collected from sawmill, and defined as T1 particleboards. After panel tests and respective insufficient results for this treatment T1, the same parameters of initial density and particle masses were maintained with changes in the particle distribution of panels to control particles and propose a second alternative.

A three-layered composition, described by Gava *et al.* (2015) as a heterogeneous panel (and defined here as T2 particleboards), was produced with 4.75 mm to 19.1 mm wooden particles in the core layer (internal) and 1.19 mm to 4.75 mm particles in the surface layers. The size classification of the wood particles was carried out using screens having the stated size openings. In addition, the distribution of the panel mass (mat) was considered using percentage of 30% for surface layers and 40% for core layer, whose proportion was applied to previous studies for oriented-particles, as mentioned by Iwakiri *et al.* (2003).

Both types of particleboards were produced with 350 mm × 350 mm × 12 mm dimensions and a mass of 810 grams to reach a minimum density of 0.550 g/cm³. The particles were glued using a percentage of castor-oil polyurethane resin according to the dried masses of particles: 10% resin for homogeneous panels (T1), 12% resin for heterogeneous panels (T2), and 4% for each of the three layers due to the need for a greater resin amount for the finer particles from the surfaces. In both particleboard types, resin was manually mixed and sequentially added in a mixer for a fluid homogenization.

The panel mats were heat-pressed at a pressure of 5 MPa and a temperature of 100 °C for 10 min, with a 30 s period after the initial 5 min to depressurize and, consequently, release gases from the interior of panels, as suggested by Sugahara *et al.* (2020) and Buzo *et al.* (2020). For each treatment (T1 and T2), three panels were made. After the pressing stage, the particleboards were conditioned at room temperature for 7 d to activate and therefore complete the adhesion curing process.

Specimens were standardized and prepared according to the NBR 14810-2. Subsequently, all panels were cut in 50 mm x 50 mm samples to be tested under different parameters.

Static bending tests for the modulus of rupture (MOR) and modulus of elasticity (MOE), density (D), moisture contents (MC), perpendicular tensile (PT), thickness swelling (TS), and water absorption after 24 h (WA) tests for both the TI and T2 particleboards were carried out based on the following premises: 10 specimens per panel type for each physical and mechanical property under study, as outlined by ABNT standard NBR 14810-1 (2013). For the statistical analysis, Tukey's range test was utilized at a 5% significance level to evaluate the influence of the particleboards, with homogeneous and heterogeneous compositions, for each studied property.

RESULTS AND DISCUSSION

Table 1 shows the results of the granulometry composition of the teak wood particles for two treatments, *i.e.*, the T1 homogeneous particleboards and the T2 heterogeneous particleboards. There was a visible particle variation in the homogeneous particleboards between the 9.52 mm to 1.19 mm sieves (88.01% of the total mass) with approximately 11% of the material in the bottom part. The particle size did not provide adequate surface packing along the panel (Fig. 1a and 1b). However, the three-layer (heterogeneous) particleboards revealed better packing and, therefore, a smaller amount of void spaces in the resin curing due to the distribution control of the particle sizes in the surface layers (Fig. 1c and 1d). Based on Fig. 1a through 1d, it is possible to verify that there are no specific resin concentrations on the panel surfaces, which evidenced the good homogenization of the resin among the particles.

Table 1. Fractional Composition of the Particles of Two Treatments

Sieve		T1 panels	T2 panels (three-layer configuration)	
Number	D (mm)	Single layer % retained	Core layer % retained	Surface layer % retained
3/4"	19.10	0.00	3.71	-
1/2"	12.50	0.00	21.71	-
3/8"	9.52	6.00	16.57	-
1/4"	6.30	18.29	18.86	0.00
N° 4	4.75	16.86	20.00	0.00
N° 8	2.36	32.29	16.86	6.57
N° 16	1.19	14.57	1.71	72.57
N° 20	0.084	-	-	20.57
Bottom	Bottom	11.43	0.00	0.00

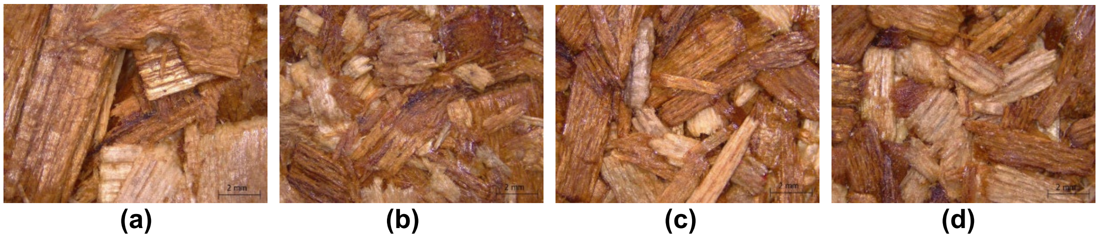

Fig. 1. Surfaces of homogeneous (T1) and heterogeneous (T2) particleboards (8x magnification): (a) surface of T1, (b) surface of T2, (c) core of T1, and (d) core of T2 samples.

Single-layer (homogeneous) particleboards presented large voids on their surface (Fig. 1a), even with the dispersion of particles (Table 1), and their core particles were quite disordered by gravity (Fig. 1c). There was a greater grouping of particles in the T2 (Fig. 1b). In addition, a greater homogenization of core region was confirmed when T2 was compared to T1 (Figs. 1c and 1d). Table 2 shows the results of particle density according to (ABNT 2016, 2017).

Table 2. Results of Teak Wood Density and Compaction Ratio

Panels	Particle Density (g/cm³)	Initial Density (g/cm³)	Effective Density (g/cm³)		Compression Ratio
			X_m	CV (%)	
T1	0.602	0.550	0.6853 B	2.78	1.14
T2	0.602	0.550	0.7307 A	2.02	1.21

X_m: average results; CV: coefficient of variation
Note: equal letters imply statistically equivalent means and, if different, A is greater than B

The physical and mechanical properties for the two particleboard compositions are described in Table 3; in addition, the values are compared to those from the ANSI A208.1 (2009) and ABNT NBR 14810-2 (2018) standards.

Table 3. Performance Results of Particleboards Produced from Teak Wood

	T1 panel		T2 panel		NBR14810 – 2 (P2)	A 208.1 (P2)
	X_m	CV (%)	X_m	CV (%)	(ABNT 2018)	(ANSI 2009)
TS - 24h (%)	11.74 A	35.14	8.67 B	19.03	22	–
WA - 24h (%)	46.18 A	16.12	38.41 B	10.29	–	–
MC (%)	4.52 B	8.05	6.13 A	4.68	5 to 13	–
D (g/cm^3)	0.6853 B	2.78	0.7307 A	2.02	0.550 to 0.750	–
MOR (MPa)	9.72 B	14.26	11.92 A	13.85	11	11
MOE (MPa)	1751 B	7.24	2141 A	8.40	1800	1725
PT (MPa)	0.46 B	26.32	0.73 A	20.77	0.40	0.4

X_m: average results; CV: coefficient of variation
Note: The same letters imply statistically equivalent means and, if different, A is greater than B

All properties were affected at a 5% significance level by the type of manufactured particleboard (1-layer homogeneous and 3-layer heterogeneous structures) as detailed by Tables 2 and 3. The comparative study of homogeneous and heterogeneous particles revealed an improvement in the thickness swelling and water absorption properties (TW and WA); being reduced by 26.15% and 16.82% when compared.

There was a significant increase (35.5%) in the moisture content (MC) between these different compositions, the manufacture of which had been carried out in different climate and humidity conditions (Table 2). The density (*D*) was in the estimated interval by the NBR 14810-1 (2013) and NBR 14810-2 (2018) standards for medium density panels, *i.e.*, 550 g/cm³ to 750 g/cm³, showing a greater panel densification due to the greater compression ratio between both panel types. Both treatments significantly surpassed the minimum expectation of 550 g/cm³ density as declared in the methodology, whose goal considered the minimum value of this recommended range of the aforementioned standard documents for panels produced from conifer woods.

Homogeneous panels (T1) obtained a value slightly higher than the central point of this range. In contrast, three-layer particleboard (small-sized for the surface layers and large-size for the core layer) reached a better condition, as its density value was close to the maximum value cited by the standard document for medium density particleboards.

As physical properties, the mechanical properties also indicated visible increases. When the heterogeneous panels were compared to the homogeneous panels, the modulus of elasticity and modulus of rupture increased by 22.61% and 22.20%, while the greatest increase was observed in the perpendicular tensile (PT), with 58.70%.

As expected, these results were justified by the greater panel densification, as it can be verified by the results exemplified in Tables 2 and 3; in addition, the results were in accordance with the outcomes from Gava *et al.* (2015) for particleboards made from *Hevea brasiliensis* woods to produce homogeneous and heterogeneous panels using 12% castor oil-based polyurethane resin for both solutions.

The homogeneous particleboards did not reach a standardized classification. But, the heterogeneous particleboards were classified as “non-structural panels for internal uses at dried conditions” in accordance with the prescriptions of ABNT standard NBR 14810-2 (2018) and ANSI standard A208.1 (2009). In this scenario, the authors suggest the utilization of heterogeneous solutions for furniture parts, and homogeneous solutions for furniture coating and wooden objects.

CONCLUSIONS

1. According to the requirements, the authors demonstrated the viable production and use of particleboards from the waste reuse from teak wood. Larger particles must be inserted into the core layer of the particleboards, because the intense granulometry dispersion otherwise could lead to manufacturing defects and, therefore, reduce the panel properties.
2. Through statistical analysis, the authors also concluded that the wooden particles of the heterogeneous particleboards (three layers) showed a significant improvement in all the studied properties compared to the single-layer (homogeneous) particleboards.

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